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Greenhouse gas mitigation at maritime chokepoints: The case of the Panama Canal

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ABSTRACT

In this study, we investigate the impact on shipping emissions from improving operational efficiency in a maritime chokepoint such as a canal. We consider several scheduling proposals that allow for different levels of speed reduction for incoming vessels and estimate the resulting emission reduction compared to a benchmark established from ship position data. For our case study of the Panama Canal, we estimate that the canal could have removed up to 1.8 million tonnes of CO_2e per year for the period of 2019 to 2021. Our findings suggest that emission reduction can be easier to obtain at intermediate points as many of the contractual barriers to improving operational efficiency do not apply.

1. Introduction

According to the Fourth International Maritime Organization (IMO) greenhouse gas (GHG) study (2020), shipping contributed to about 2.89 % of global anthropogenic GHG emissions in 2018, equivalent to 1,056 million tonnes. Emissions generated by ships burning fossil fuels can have both a global effect on climate change, caused by Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O), and local effects on human health and the environment caused by Sulphur Oxides (SO_x), Particulate Matter (PM) and Nitrogen Oxides (NO_x).

In this study, we explore the potential contribution of chokepoints in the reduction of shipping GHG emissions. This is based on the observation that the inefficiencies caused by some key chokepoints in global maritime trade – such as congestion, waiting times and resultant need for speed adjustments during a voyage – will directly affect emissions.

A chokepoint refers to locations that limit the capacity of throughput and cannot be easily bypassed, if at all (Rodrigue, 2004). As for some important chokepoints such as the Panama and Suez Canals, and the Bosphorus strait, transit is based solely on the scheduling

Abbreviations: UNGP, United Nations Global Platform; AB, Auxiliary Boiler; AE, Auxiliary Engine; AIS, Automatic Identification System; CH_4, Methane; COG, Course Over Ground; CO_2, Carbon Dioxide; CO_2e, Carbon Dioxide equivalent; CWT, Canal Water Time; DBSCAN, Density-based Spatial Clustering of Applications with Noise; ETA, Estimated Time of Arrival; GHG, Greenhouse gas; GWP, Global Warming Potential; IMO, International Maritime Organization; ITT, In Transit Time; JIT, Just In Time; LNG, Liquefied Natural Gas; LPG, Petroleum Gas; MARPOL, International Convention for the Prevention of Pollution from Ships; ME, Maine Engine; MMSI, Maritime Mobile Service Identity; NOAA, National Oceanic and Atmospheric Administration; NOR, Notice of Readiness; NO_x, Nitrogen Oxides; N_2O, Nitrous Oxide; PCA, Panama Canal Authority; PM, Particulate Matter; RTA, Required Time of Arrival; SFC, Specific Fuel Oil Consumption; SOG, Speed Over Ground; SO_x, Sulphur Oxides.

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discretion of the chokepoint, they could help in reducing shipping emissions by promoting speed reduction of the incoming vessels.

Speed reduction is an operational measure with a high emissions reduction potential (Bouman et al., 2017). An important feature of its implementation is that a reduction of waiting time in port can be used (in part or in full) to reduce the sailing speed of arriving vessels without increasing the duration of the voyage. Despite its theoretical simplicity and its high potential for emission reduction, its implementation at the vessel or voyage level is often hindered by barriers such as misaligned incentives and contractual constraints (Rehmatulla and Smith, 2015) leading to unproductive waiting times at port (Johnson and Styhre, 2015; Jia et al., 2017).

Until now, the challenges and benefits in implementing the concept of speed reduction due to operational efficiency has only been analyzed in the context of cargo-handling ports, that is, the end points of ships' voyages. However, unproductive waiting time may also occur at intermediate points during a voyage, such as during bunkering stops and at maritime chokepoints such as canals and straits. Such waiting times could be caused by factors such as dynamic demand, lack of resources to serve the vessel, weather closures and restrictions on throughput etc. As any unproductive waiting can be considered an opportunity for improving operational efficiency and implementing speed reduction measures, thereby reducing fuel consumption and emissions, this focus on cargo-handling ports creates a gap in the literature. Arguably, some maritime chokepoints are so central to global seaborne trade that they are as important to consider as very large ports and key trade lanes.

For our empirical case, we focus on the emissions from the vessels crossing the Panama Canal. Our motivation is twofold. Firstly, the potential reduction in emissions could be substantial given that approximately 13,000 vessels transit the Canal every year according to the Panama Canal Authority (PCA) (2021c). Secondly, and more importantly, the Panama Canal scheduling system is highly flexible, with several options to pre-book a vessel transit based on commercial criteria. Our idea is to develop strategies where the canal could use that flexibility to assign slots based on vessels' GHG emissions.

The primary contribution of this study is to expand the literature on emission mitigation from speed reduction due to improving efficiency to the case of maritime chokepoints, specifically the Panama Canal. There are at least two additional reasons why canals and straits should be considered separately from the literature on speed reduction and port efficiency. Firstly, as in the case of the Panama Canal, scheduling policies for transits (the equivalent of berthing during a port call) can be substantially more complex, involving not only a chronological queue of vessel arrivals but also Canal Authority discretion, pre-booked slots and rules determining priority by vessel type. Secondly, the centralization of authority matters for the ability to implement such measures successfully, compared to port operations where several stakeholders related to cargo, vessel and port interests determine the outcome. As a secondary contribution, we develop new algorithms, based on the processing of (AIS) vessel position data, to generate more accurate statistics for canal waiting times and transits by vessel type, size and direction.

The rest of the paper is organized as follows: Section 2 presents our literature review. Section 3 introduces our strategies of implementation with due consideration of the PCA transit scheduling rules. Section 4 includes the methods for estimating the transits and emission information. In section 5, we present the results derived from the algorithm. In section 6 we discuss the implications of speed reduction implemented by a chokepoint and report the limitations of the proposals. Finally, Section 7 concludes and proposes extensions for future research.

2. Literature review

The potential of speed related measures in the emissions abatement is a popular topic in the academic literature as evidenced by the 26 studies summarized by Bouman et al. 2017, in part because the measure has a low burden of implementation (Lindstad et al. 2011). Additionally, speed reduction is found to be a cost-effective measure as the emission reductions can be achieved with zero or negative marginal abatement cost (Corbett et al., 2009; Eide et al., 2009; Eide et al., 2011; Lindstad et al., 2011; Schwartz et al., 2020). However, Corbett et al. (2009) suggest that the real marginal abatement cost is higher than reported in some studies as more vessels are needed to maintain a certain service frequency or level of trade, therefore increasing the cost for operating a fleet. Regardless of the interpretation of cost effectiveness, there is consensus in the literature of the high emissions reduction potential from speed reduction measures.

Speed reduction could be enabled by an increased fleet size (Corbett et al., 2009; Cepeda et al., 2017) to compensate the loss in cargo transported or, alternatively, by reducing unproductive waiting times at port (Lavon and Shneerson, 1981; Psaraftis et al., 2009; Johnson and Styhre, 2015; Andersson and Ivehammar, 2017, Jia et al., 2017). Our focus is on the latter concept, named by Johnson and Styhre (2015) as *speed reduction due to port efficiency.* The large emission reduction potential from implementing this concept was presented by Jia et al. (2017) in the case of Very Large Crude Carriers. As extensions to their study, they encouraged the introduction of algorithms to recognize waiting times with higher accuracy and expanding studies to other vessel sizes and types. Slack et al. (2018) also recognized the absence of time related metrics in port operations and related this to the difficulties of gathering consistent data from different stakeholders.

Port efficiency has been extensively studied in the academic literature (see, Krmac and Mansouri, 2022, for a review) particularly in the context of container port infrastructure (e.g., container throughput and vessel port calls). However, in our context, studies dealing with the barriers to increasing efficiency and the causes of inefficiency are more relevant. To summarize, the main factors are presented by Johnson and Styhre (2015) as being the port opening hours, early arrivals, congestion and clearance procedure, unspecific reasons, and waiting for pilot; Slack et al. (2018) point out the role of port officials in the port waiting time and Poulsen and Sampson (2020) argue that a large group of stakeholders influences the causes of inefficiencies (e.g., waiting for berth, availability of cargo, waiting for surveyors, etc.) and the corresponding waiting times.

Together with operational factors that lead to inefficiency in ports, there are also contractual barriers to implementing speed reduction. Firstly, a vessel on a voyage charter currently has an incentive to tender the Notice of Readiness (NOR)[1] to load as early as possible irrespective of the port availability to serve the vessel (Rehmatulla and Smith, 2015), both due to the First-in-first-out scheduling policy operated by most ports and to reduce the risk of contract cancellation due to late arrival (not meting the agreed laycan[2]). Poulsen and Sampson (2019) suggest that this rationale to "rush to wait" could also be attributed to the owners of ships engaged on voyage charters aiming for the counting of laytime to start as early as possible[3]. For a time-chartered vessel, they argue that the behaviour could be due to the perceived reduction in uncertainty of having a buffer of vessels ready in port. Note that this is the only barrier specified for time-chartered vessels.

A second contractual barrier is the 'utmost dispatch' clause for voyage charters (Rehmatulla and Smith, 2015; Jia et al. 2017; Global Industry Alliance, 2020) that instructs the vessel to proceed to a destination port without delay[4]. Consequently, an owner is not generally free to reduce the sailing speed on the laden voyage in the interest of reducing emissions or fuel costs, unless an exemption clause exists to that effect.

The third barrier is the split incentives problem arising from the principal-agent relationship in a voyage charter (Rehmatulla and Smith, 2015). Under such a contractual arrangement, the shipowner bears the cost of fuel and, therefore, has an incentive to increase operational efficiency. However, the charterer has no other concern for the vessel speed than the vessel arriving on time. We note that there is no split incentive in the time charter case, as the charterer is the one benefiting from the speed reduction as they cover the fuel cost.

To our knowledge, there is not yet any literature on the impact and implementation of speed reduction as a consequence of increasing efficiency in maritime chokepoints such as canals and straits.

3. Strategies for speed reduction on voyages to the Panama Canal

Our proposals for implementing speed reduction measures, enabling vessels slow-steaming, are based on suggested changes to the existing Panama Canal scheduling rules. Therefore, in this section, we review the relevant scheduling rules from the PCA and the general modeling assumptions applied to our proposals. Thereafter, we present our four proposals for the speed reduction of inbound vessels.

3.1. PCA transit scheduling rules

Panama Canal transits are scheduled in two categories: Non-booked and Pre-booked transits. Non-booked transits are scheduled at the discretion of the PCA and are based on the number of pre-booked vessels and certain operational factors. Pre-booked transits pay an extra fee and have a guaranteed slot on a particular date, but the transit time is subject to operational discretion. The last booking period closes two days before a transit date.

An important feature of the reservation system is that vessels with booked transits must arrive at the canal before an arrival cutoff. Vessels not arriving at the cutoff time must pay a penalty, which is a function of how late the vessel is and equivalent to up to 100 % of the original booking fee. More importantly, they may not be able to re-book the same slot, with the risk of waiting in a queue as a regular transit vessel.

According to the PCA reservation system rules (2021b), the time limit for arrival is at 2200 h of the day before transiting for Neo-Panamax vessels except Liquefied Natural Gas (LNG) tankers, 0200 h for LNG Neo-Panamax and Super/Regular[5] with restrictions, and 1400 h of the same day for Regular vessels. Also, in the transit reservation rules, a vessel becomes an arrived vessel for a booked transit when the vessel is physically sighted or is within eight nautical miles from either of the canal entrances. No reference is made to regular transit vessels; therefore, we assume that such "physical" arrival also is their trigger for being included in a day's transit schedule.

The scheduling rules refer to priority based on vessel types or a customer ranking. For example, cruise vessels can book a reservation up to two years in advance while other vessel types can book at the earliest, one year in advance (PCA, 2021b). This implies that if policies need to be implemented in steps, then the PCA could easily segment their strategy (e.g., by market, vessel type or customer ranking).

3.2. General modeling assumptions

There are two important modeling assumptions that are common across all of our strategies. The first assumption is that speed reduction is only implemented on the voyage leg before the canal and that the historically observed transit time does not change. This

[1] A NOR is a critical statement that indicates the vessel has arrived and is prepared to begin cargo operations at the charterer's disposal. This declaration is of significant importance as it initiates the laytime counting process and has a direct impact on demurrage calculations.

[2] Laycan is short for Laydays/Cancelling and is an agreed range of days where the vessel must be at port.

[3] Laytime in voyage charters is the time allowed to charterers for loading and/or unloading the vessel. The laytime starts counting from the NOR been tendered. If the laytime is passed, the owner is entitled to claim for demurrage (damages per delay).

[4] Dockray (2013) review the most notorious cases where the utmost dispatch clause was disputed.

[5] Vessels transiting the Panamax locks are subdivided for scheduling purposes in Supers (higher or equal to 27.74m beam) and Regulars (lower than 27.74m beam). Neo-Panamax are vessels that can only transit through the Neo-Panamax locks or has a beam of more than 32.62*m*.

is due to the complexity of generating alternative scenarios for the dynamic fleet movements through the canal. We acknowledge that this limits the emission reduction potential compared to an optimization model that had more degrees of freedom, including the rescheduling of vessel transits in time.

The second assumption is that the canal leg is composed of the interval of time that the vessel is within canal waters, including anchorage, access lanes and transit lanes. consistent with the definition of canal water as defined by the PCA (2019).

3.3. Proposal 1: Coordinated voyage

A coordinated voyage, as illustrated in Fig. 1, implies that speed reduction is implemented for the full duration of the leg from the time vessels depart the last port until the arrival cutoff for the Panama Canal transit as declared in the PCA transit reservation rules (2021b).

Arguably, the strategy is unrealistic, as the canal would be unable to assign transits for vessels given the large uncertainty in the Estimated Time of Arrival (ETA) for long voyages. However, our motive for calculating the effects of this proposal is to investigate the limits of the speed reduction implementation and to estimate the theoretical upper bound based on our assumptions.

3.4. Proposal 2: JIT speed orders 48 h before arrival

For a strategy based on JIT, a vessel is accepted as an arrived vessel without being sighted and instructed to reduce speed to arrive at a Required Time of Arrival (RTA). For the purpose of estimating the effect of this proposal, as illustrated in Fig. 2, we assume the RTA is the time when the vessel leaves the anchorage prior to transit. We also assume there is no distinction between non booked and booked transits, and that vessels with less than 48 h sailing reduce the speed upon leaving the last port.

3.5. Proposal 3: Green slots

This proposal is based on the existing rules that the Panama Canal has for JIT arrivals. To avoid confusion with proposal 2, we refer to this proposal as ‘green slots’.

In the current scheduling system, the PCA has a limited number of green slots to assign per day. These slots are only assigned by request from a booked vessel that is capable of transiting immediately upon arrival[6]; therefore, it is natural that some of them remain unused. According to PCA rules, they can assign up to four green slots for *Supers* (max two per direction) and two for *Regulars* without restriction (max one per direction).

We propose that the PCA assigns the unused green slots based on a ranking of available vessels by the highest emission reduction. This highlights the benefit from involving fewer stakeholders (PCA and the vessel) compared to the challenge of implementing JIT in a port setting (Global Industry Alliance, 2020). We note that the difference between this and proposal 2 is that the green slots are allocated only to some vessels while the rest follow business as usual (i.e., arrive before an arrival cutoff or wait at anchorage for its transit assignment).

3.6. Proposal 4: Blend of JIT 24 h before transit and green slots

This proposal is an alternative if the potential limitations in previous proposals (i.e. uncertainty of vessels’ ability to comply with the RTA for JIT with 48 h notice or not being within the rules for JIT assignment), hinder their implementation.

In this blended strategy, we propose that green slots be assigned as per proposal 3 and that the remaining vessels reduce their speed from 24 h before arriving at the canal.

4. Methodology

4.1. Input data

Our model uses three sources of information: maritime geofences[7], including the Panama Canal and coastal lines; vessels specifications from IHS Markit, and AIS data from the UN Global Platform (UNGP) encompassing worldwide vessel records (3.6 TB) from January 2019 to December 2021.

Geofences are used to define an area and reduce the search space for recognizing a vessel’s operational phase. We use vessel specifications to segregate our Panama Canal statistics by vessel type and transit type. The AIS data is filtered by querying records within our geofences for the Panama Canal and coastlines from the National Oceanic and Atmospheric Administration (NOAA) (2017). Our estimation methods and filtering of data is processed using Apache Spark and Apache Sedona from the UNGP.

[6] This requires that the operational conditions are in place to transit the vessel directly on arrival (e.g., the vessel has free pratique, customs clearance, etc.).

[7] The term geofences and polygons are used interchangeably in this study.

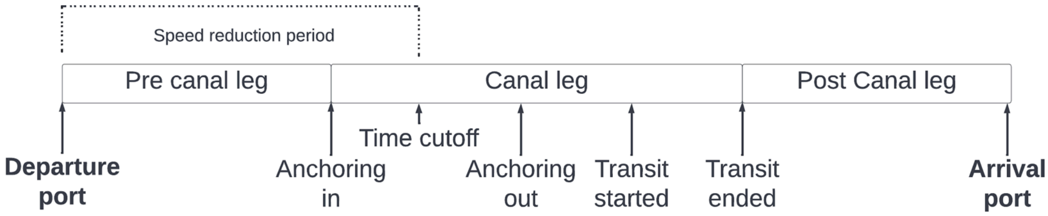

Fig. 1. Coordinated voyage strategy principle.

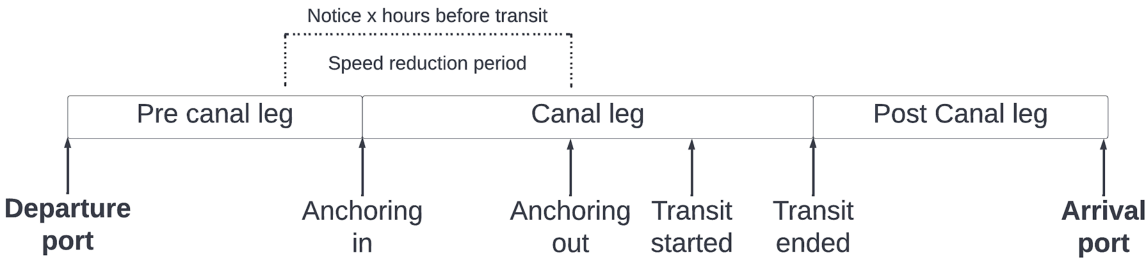

Fig. 2. JIT strategy principle.

4.2. Generating Panama Canal statistics

The algorithm used in this study is adapted from Fuentes and Adland's (2020) algorithm for recognizing transits in the Suez Canal. We estimate the waiting times by recognizing anchoring patterns before transits, and the transit times and time at ports are derived from the vessel track through the Canal and visits to the adjacent ports. We introduce our version of the algorithm for generating Panama Canal statistics in Fig. 3.

The first step (*polygons and time cutoff*) recognizes when a vessel leaves and enters a polygon. A detailed description of the polygons and time cutoff test is presented in Algorithm 1 of Appendix A.

Also in step one; data is interpolated into fixed intervals of ten minutes using a Kalman filter (1960) corrected by positions, SOG and COG. The Kalman filter is an algorithm that estimates unknown variables given the measurements observed over time (Youngjoo and Hyochoong, 2018). As shown in Fig. 4, the frequency of positions, calculated as the difference between subsequent timestamps for the same vessel, is not fixed, causing some assumptions used in the algorithm, such as those for vessels swinging on the anchor, to be invalid if not tuned.

For interpolating the vessel records inside the canal and its locks, we take advantage of the limited navigable options inside a canal and use historical transit routes, a method described in Fuentes and Adland (2020).

After the frequency interpolation of anchorage records, in ***step two*** we derive the waiting times by recognizing the vessel at anchor using the Density-based Spatial Clustering of Applications with Noise (DBSCAN) algorithm. The DBSCAN hyper parameter ϵ is calibrated from the external natural forces producing the movement of the vessel swinging on the anchor based on the discussion in Fuentes (2021). For port records (i.e., when the vessel is deemed to be alongside a quay) the DBSCAN cluster is defined by an arbitrary small ϵ ($1x10^{-6}$) to reflect small changes in the vessel position caused by slight inaccuracies in the AIS-reported position.

We create the *transit cutoff* by completing two tests: 1) refining the anchorage clusters with time and polygon cutoffs (Algorithm 2 of Appendix A), and 2) comparing consecutive visits to anchorage polygons on opposing sides of the Canals as a complete transit, to create a mapping of positions to recognize separate transits through the canal (Algorithm 3 of Appendix A).

In **step three**, we use the interpolated position records and the mapping of transits from the previous steps to generate a full sequence of positions that are part of a canal transit. We also check if a minimum set of polygons (locks, transit, and anchorage polygons) have been visited by each vessel to ensure accurate results and minimize faulty records.

In **step four**, we record key information of each vessel transit like waiting time, transit time, direction, type of locks used and any stops. We also calculate the Canal Water Time (CWT) as time from anchoring to completing transit minus any port stop. To test the performance of our algorithm, we compare in the next subsection (4.3) the resulting CWT statistics to the official statistics of the PCA.

4.3. Performance testing for the algorithm that generates the Panama Canal transit statistics

The PCA (2021a) publishes a summary of their operations in monthly reports as part of their Advisories to Shipping. The performance of our algorithm relates mainly to the ability to generate timely statistics, yet it is also important that the generated statistics are robust as a correct representation of the operations. To verify the robustness, we test our results against official statistics from the PCA for canal transits.

In Fig. 5, we observe that our algorithm discovers slightly fewer transits than officially reported by the PCA, with an average

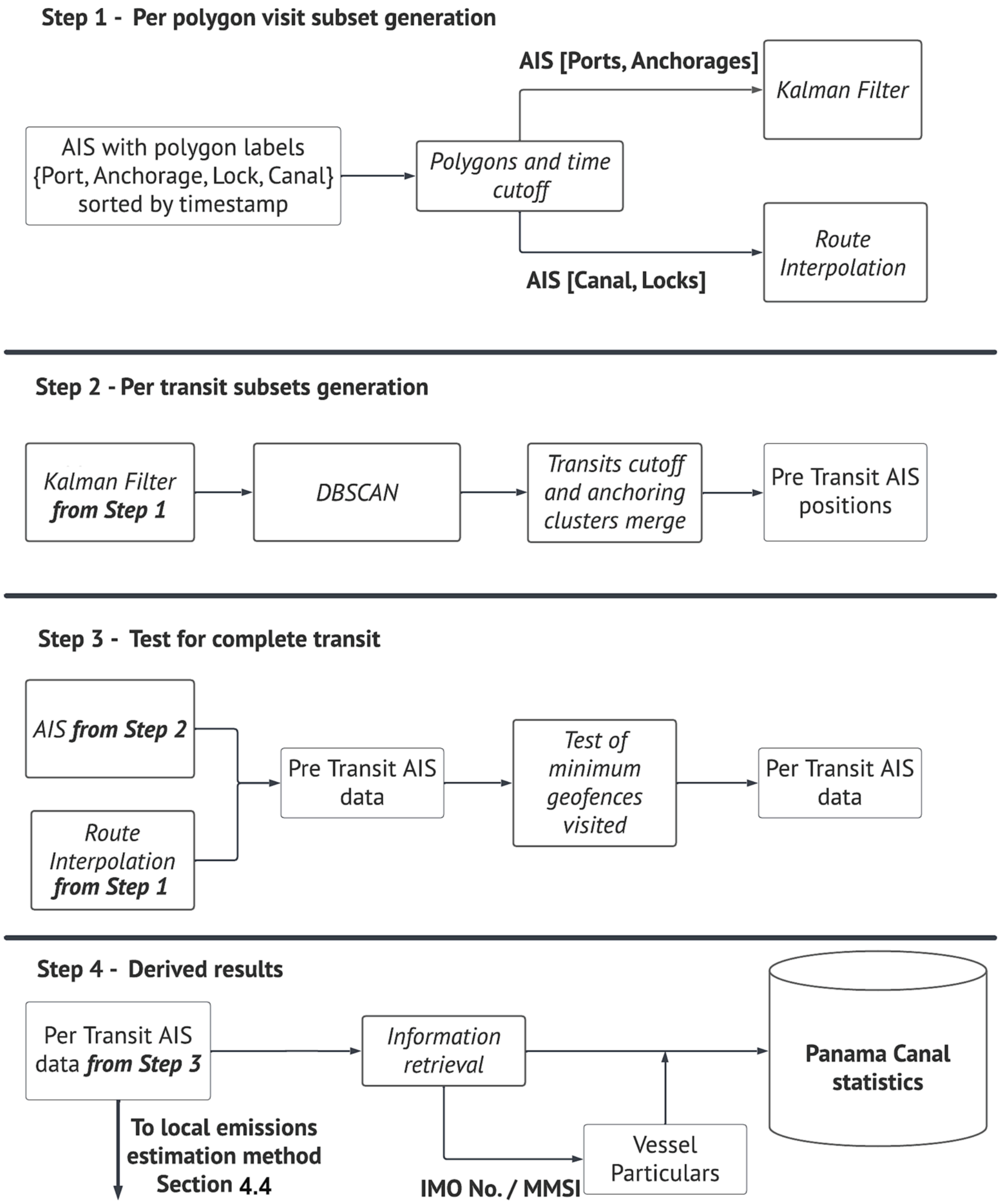

Fig. 3. Framework for generating Panama Canal statistics Note: MMSI stands for Maritime Mobile Service Identity.

difference of 33.3 transits per month. The algorithm's accuracy ranges from 88.9 % to 99.8 %. The difference is expected as our algorithm aims for accuracy by not reporting vessels with incomplete sequences.

Fig. 6 compares the monthly In-Transit Time (ITT) calculated by our algorithm with official statistics from the PCA. ITT is the time lapsed from the moment a vessel enters the first lock until it exits the last lock (PCA, 2021b). Our algorithm results are within 97.1 % and 99.9 % of the official statistics and can also generate information for months where official statistics were not reported (March and April 2020).

The PCA reports CWT as a measure of service performance, which is the total time from when a vessel is declared "ready" for transit until it completes transit, including waiting time and in-transit time. Fig. 7 shows that our algorithm is compatible with the official records. The fit between both values is of an R^2 of 0.84 and the difference is on average 15.52 h, which is likely the average time taken to clear a vessel for transit after it has arrived at the anchorage.

From this evaluation, we can conclude that our generated statistics are suitable proxies of the underlying operations at the Panama Canal.

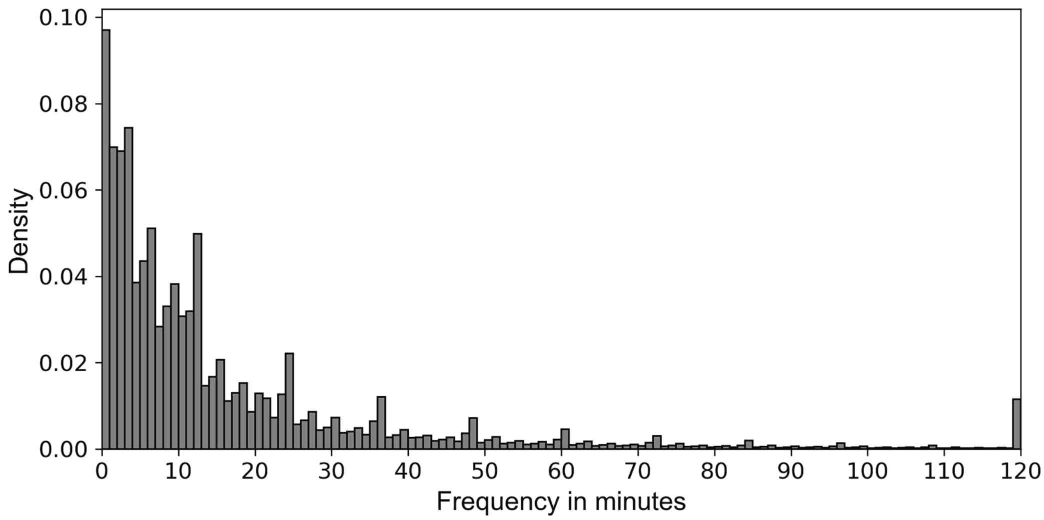

Fig. 4. Histogram of AIS time frequency between positions Note. The rightmost vertical bar includes all frequency observations above 120 min.

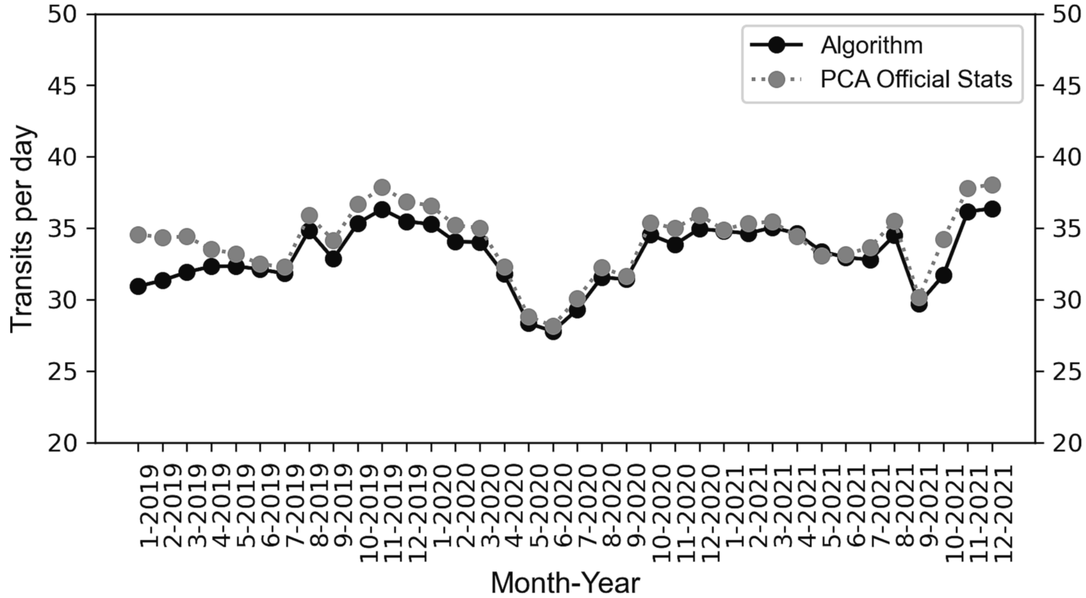

Fig. 5. Monthly Panama Canal transits from the algorithm and official statistics.

4.4. *Estimating emissions*

In this study, we estimate the canal-related emissions based on the bottom-up method and the assumptions used in the Fourth IMO GHG study (2020). The canal-related emissions, in our context, refer to CO_2, CH_4 and N_2O (GHG's) emissions during a vessel's canal transit and on the legs before and after a transit. Our focus on strategies for reducing the three main shipping contributors to the greenhouse effect (IMO, 2020); aligns to the scope of the IMO strategy on reduction of GHG emissions from ships presented by the Marine Environment Protection Committee (2018). Other shipping related emissions (e.g., SO_x and NO_x) that are not relevant to the efforts for reducing the shipping GHG footprint are not presented in this study.

The bottom-up method, as presented in the Fourth IMO GHG study (2020), derives shipping emissions by solving three sub-problems: recognizing the vessel operational phase, estimating power and fuel consumption, and transforming that consumption to emissions via emissions factors. It derives emissions at the individual vessel level using AIS data and vessel's technical specifications, enabling aggregation into various statistics such as per geographical region, time, vessel type, etc.

The bottom-up method has been extensively used in the literature for generating emissions inventory (see Andersson and Ivehammar, 2017; Chang et al., 2013; Chen et al., 2017; Coello et al., 2015; Jia et al., 2017; Toscano et al., 2021, Tran et al., 2021). The

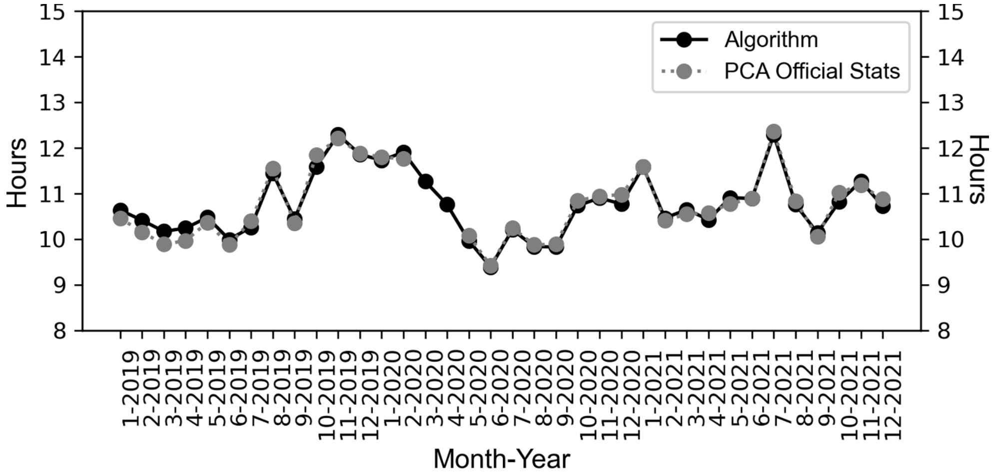

Fig. 6. Monthly Panama Canal In transit time (ITT) from the algorithm and official statistics Note: PCA missing values as months not reported in their Monthly Operations Summary.

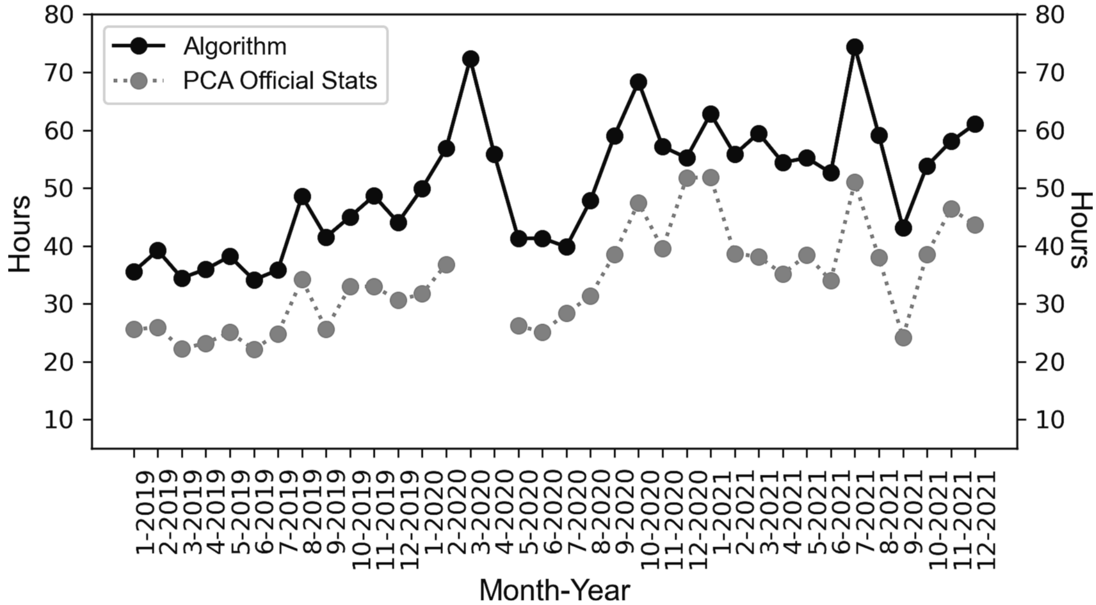

Fig. 7. Monthly Panama Canal water times from the algorithm and official statistics Note: PCA missing values as months not reported in their Monthly Operations Summary.

Fourth IMO GHG study method has been subject to quality control, have known limitations and enable comparison of results. For example, they compared their bottom-up results to the EU-Monitoring, Reporting and Verification system[8] database for 2018 and found a discrepancy of less than 5 %. By replicating their assumptions, we assume that the quality assurance elements of their study are equivalent in our study.

As a slight adaptation to the original method, we propose to use the information derived from our Panama Canal statistics to recognize the operational phases of the vessels within Panama Canal waters. We introduce the complete algorithm for generating

[8] The system entered into force as a European regulation in 2015 and mandates vessels (commercial or passenger transport) greater than 5,000 GT to report their CO_2 emissions and fuel consumption of following voyages in EU (and EFTA) regions.

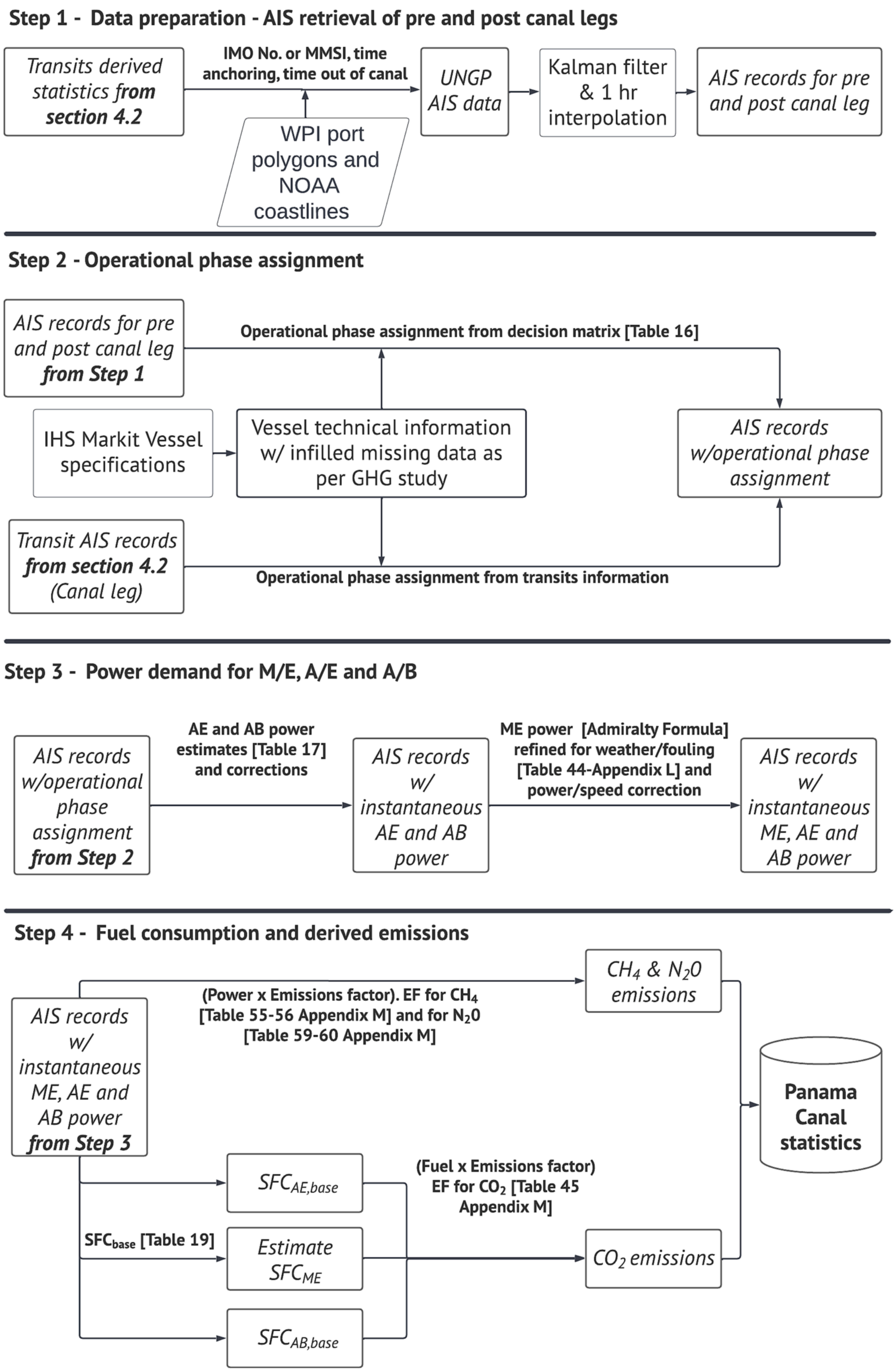

Fig. 8. Framework for estimating Panama Canal related emissions Note: Information in square brackets refers to the Fourth IMO GHG study. ME stands for Main Engine, AE is for Auxiliary Engines, AB is Auxiliary Boilers and SFC is Specific Fuel Oil Consumption.

vessel emissions in Fig. 8. From **step one,** we retrieve vessel records six months before and after a vessel has transited the canal. Thereafter, we keep the records from the vessel's last port call before a transit until the first port call after the transit. Such port visits are assumed to occur when a vessel maintains a speed below 1 knot inside a port polygon for at least 6 h, an assumption consistent with the IMO GHG study.

In **step two**, for positions outside the canal, we assign the operational phase of the vessel (i.e., at berth, at anchor, maneuvering, in slow transit or normal cruising) per the vessel's position record. Note that records inside the canal are labelled as maneuvering, except for periods where, from our derived Panama Canal statistics, the vessel is at anchorage or is stopped at a local port. In these cases, the records are assigned to at anchorage and at berth, respectively. For the remainder of the voyage (i.e. the legs before and after the canal), we assign the operational phases according to the decision matrix described in the IMO GHG study (2020, pp. 80–81).

Finally, in **step three** and **step four,** we replicate the estimation of the vessels' engine power and the related emissions from the method used in the IMO GHG study.

4.5. Coordinated voyage and JIT emissions reduction

For generating the emissions reduction information, we assume every vessel is a booked vessel such that the date of transit is known. A different interpretation would be that a vessel is assigned a slot as it departs from the last pre-canal port, so no distinction is made between booked transits or regular transits.

We assume that a vessel will only reduce speed if four conditions are fulfilled. First, the proposed RTA (i.e., the arrival cutoff for a coordinated voyage or heaving up anchor time for the JIT strategy), must be after our benchmark arrival time but no later than one hour before a transit begins. Second, we assume that vessels will not be instructed to reduce speed below the equivalent of 55 % main engine load – a typical limit to slow-steaming (Dere et al., 2022). This implies that very low speeds are not feasible, and we avoid suboptimal loads that are potentially harmful to the main engine. Third, a vessel would have reduced emissions if the new emissions for the leg before the canal is lower than the benchmark emissions. It could be the case that a vessel speed reduction would end up with a higher consumption, particularly around the vessel optimal speed. Fourth, vessels that have no waiting time already arrive JIT and are excluded as they have no scope for emission reduction.

4.6. Green slots emissions reduction

Our proposal for green slots allocation is based on hindsight from the Panama Canal statistics, as presented in this study. In this case, we allocate the remaining (non-requested) green slots for vessels in the 48 to 96 h interval prior to transit.

Our motive for using 96 h as the start of our planning window is based on the PCA (2019) requirement for vessels to submit their intention of transiting at least 96 h before arriving to the Canal waters. Vessels with a voyage time less than 96 h, can submit their information as they depart from the last port preceding its transit. By using 48 h as the end of the planning window, it follows that the last green slots are assigned on the final day of the booking period (2 days before transiting).

The result for our proposed strategy is modeled using the following four steps. In **step one**, we estimate the emissions reduction for every vessel at time $t \in \{96, 72, 48\}$. The emissions reduction per vessel is the difference between the pre-canal leg plus the canal leg emissions, estimated as of time *t*, and the benchmark estimates for the same legs. For **step two**, we estimate the non-available (used) green slots by counting those transits with lower waiting times than 30 min. In doing so, we assume that a vessel that did not stop before transit was allocated a green slot upon request. From our anchoring recognition method, 30 min is the minimum detected cluster based on our assumptions. Finally, we calculate the per day and per direction green slots transits for Super, Regular and Neo-Panamax vessels and estimate the number of remaining slots according to the PCA rules. Note that according to the rules, Neo-Panamax vessels are not assigned green slots. Therefore, we assume that the Neo-Panamax JIT transits take the position of Supers' green slots, transiting in the same direction.

In **step three**, the slot assignment model matches candidates and available green slots based on the following mathematical model:

$$max \sum_{i \in I} \delta_i e_i \tag{1}$$

s.t:

$$\sum_{i \in L} \delta_i \leq P_d; \forall d \in D \tag{2}$$

$$\sum_{i \in F} \delta_i \leq M_{dv}; \forall d \in D; \forall v \in V \tag{3}$$

$$\sum_{i \in S} \delta_i \leq R_{dbv}; \forall d \in D, \forall b \in B, \forall v \in V \tag{4}$$

$$\delta_i \in \{0, 1\} \tag{5}$$

The objective function (1) maximizes the emission reduction from the green slot assignments, where δ_i is a binary variable for every transit candidate *i* and e_i is the CO_2e reduced from candidate *i*. Constraint (2) ensures that the maximum number of available slots per day is not surpassed, where P_d is the maximum green slots for all transits on day d. Constraint (3) limits the green slots per type per day, where M_{dv} is the maximum green slots per day d per type v. Constraint (4) limits the transits per day, direction, and time according to the PCA JIT assignment rules. Here, R_{dbv} is the maximum availability of green slots per day d, per direction $b \in \{North, South\}$ and for transit type $v \in \{Super, Regular, Neo\}$. Constraint (5) defines the decision variable as a binary variable. The set I includes all the transit candidates, L is a subset of I and holds the transit candidates per day, F is a subset of L, including the transit candidates per day per vessel type, and the set S is a subset of F with transit candidates per day, per vessel type and transit direction. Note that this model only assigns the vessels that may arrive JIT without being penalized (i.e., after the arrival cutoff). Therefore, the transit assignment is not changed from what was observed in our statistics.

In **step four**, the resulting assigned green slots and related emissions reductions are stored. Thereafter, in a rolling horizon approach, the input parameters for candidates and options are updated, and the model is rerun. The iteration stops when no more slots are available, there are no more candidates, or after a solution is obtained for $t = 48$.

5. Results

5.1. Panama Canal transits derived statistics

Our algorithm generates 36,812 records of Panama Canal transits between January 2019 and December 2021. Table 1 highlights the differences in waiting and transit times based on transit direction and lock size. As shown in Table 1, 26,853 records are vessels transiting the original Panamax locks and 9,959 are Neo-Panamax vessels. If subdivided by transit direction, 18,870 records were northbound[9] transits (Gulf of Panama to Caribbean Sea) and 16,371 records were southbound transits (Caribbean Sea to the Gulf of Panama). The greater number of northbound vessels is also reflected in the waiting times, as southbound vessels average 33.6 h waiting compared to 43.0 h for northbound vessels, both with large variations. The variation in waiting times is in part driven by the booking system, where different types of vessels have different transit priorities and prevalence of paying a premium for faster transits via pre-booking or auctions.

The AIS-generated statistics has the advantage, compared to official statistics, that it can be customized based on selected criteria, e.g., vessel type, vessel size, transit direction, etc. As an example of this flexibility, we present a count of transits per vessel type (defined consistently with the Fourth IMO GHG study) in Table 2. We can observe that bulkers have the most transits, mainly using the Panamax locks. This reflects how the canal is frequently used by medium-size bulk carriers on the US East Coast to Asia route, this being one of the most important trade routes connected by the canal (PCA, 2022). Neo-Panamax locks are mostly used by large containerships, followed by Liquefied Petroleum Gas (LPG) and LNG tankers.

The boxplot in Fig. 9 shows there is a difference in waiting times depending on vessel types. For container vessels, 75 % of values are within 10.8 h, showing a compact distribution in expected waiting times. Cruise vessels have the lowest median with 7.0 h, followed by container vessels with 7.1 h and vehicle carriers with 10.3 h. Conversely, crude tankers and bulk carriers have the highest third quartile, with 79.7 and 77.6 h respectively, as well as a larger standard deviation. The larger variance could result from the mix of strategies for requesting a transit slot: awaiting a turn to be assigned by the PCA, requesting a booked transit, participating in slot auctions, or requesting just-in-time slots. Other factors affecting the assignment of transit slots could be the mix of scheduled vessels under consideration and the customer ranking. A comprehensive description of the transit slot allocation process can be found in the rules for the Panama Canal transit reservation system (2021b).

A policy based on green slots (limited to Supers and Regulars) could significantly reduce emissions from LPG tankers, chemical tankers, oil tankers and bulk carriers - the vessel types mainly transiting through the old locks.

LNG tankers also face prolonged waiting times, and while a green slot strategy is not currently applicable, their inclusion could lead to important emission reductions if allowed to arrive JIT. We also note here that many use LNG as a fuel, and so there would not only be a reduction of CO_2 emissions but also methane (CH_4), which is a powerful GHG as highlighted by the Global Warming Potential (GWP) of 25. The GWP can be interpreted as how much energy a gas will absorb over a period compared to one tonne of CO_2 (United States Environmental Protection Agency, 2022).

5.2. Emissions from existing canal scheduling

We derive the canal related emissions for 36,112 transits (98.1 % of the reported transits) of our generated Panama Canal statistics[10]. The results are used to describe the current emissions generated and as a benchmark to compare our proposed strategies.

The estimated emissions per leg and per year are summarized in Table 3. For the period under consideration (2019–2021), the voyages of vessels transiting the Panama Canal emitted approximately 101.9 million tonnes of CO_2 equivalent (CO_2e), of which 97.0 % are emissions of CO_2 and the rest are CO_2e transformations[11] of CH_4 and N_2O. The share of CO_2 to the total is consistent with the global estimates of the Fourth IMO GHG study. The total, 31 million tonnes of CO_2e for the year 2019, represents 2.9 % of shipping emissions in 2018 per the Fourth IMO GHG study.

[9] Some readers might relate to a westbound route being a south transit and eastbound route been a north transit.

[10] Some of our transits are not considered for the emissions inventory if, based on our assumptions, no port was identified either before or after the canal transit.

[11] Global Warming Potential on 100-year basis assumes a transformation factor of 25 for CH_4 and 298 for N_2O.

Table 1
Derived statistics of Panama Canal transits.

	Mean	St.Dev	Median	Min	Max	Sample
Waiting Northbound (hours)	43.0	46.9	27.0	0	351.6	16,042
Waiting Southbound (hours)	33.6	43.2	19.5	0	351.1	12,623
Waiting Panamax (hours)	37.9	42.4	23.0	0	351.6	22,150
Waiting Neo (hours)	42.2	54.2	20.1	0	351.1	6,875
Transit time Northbound (hours)	9.8	5.3	8.1	5.5	47.9	18,870
Transit time Southbound (hours)	11.8	6.2	9.0	5.6	49.3	16,371
Transit time Panamax (hours)	9.4	4.2	8.0	5.6	47.9	26,016
Transit time Neo (hours)	14.6	6.9	12.0	5.5	49.3	9,225

Table 2
Transits per vessel type.

Type of Vessel	Transits	Regulars	Supers	Neo-Panamax
Bulk carriers	7,966	356	6,348	1,262
Containers	7,176	562	2,554	4,060
Chemical tankers	5,727	1,144	4,511	72
LPG	3,934	441	1,138	2,355
Others	2,859	1,008	1,568	283
General cargo	2,137	1,424	705	8
Vehicle	2,065	0	1,925	140
Oil tanker	1,774	133	1,145	496
Refrigerated bulk	1,641	1,577	64	0
LNG	1,256	0	0	1,256
Cruise ships	277	123	127	27

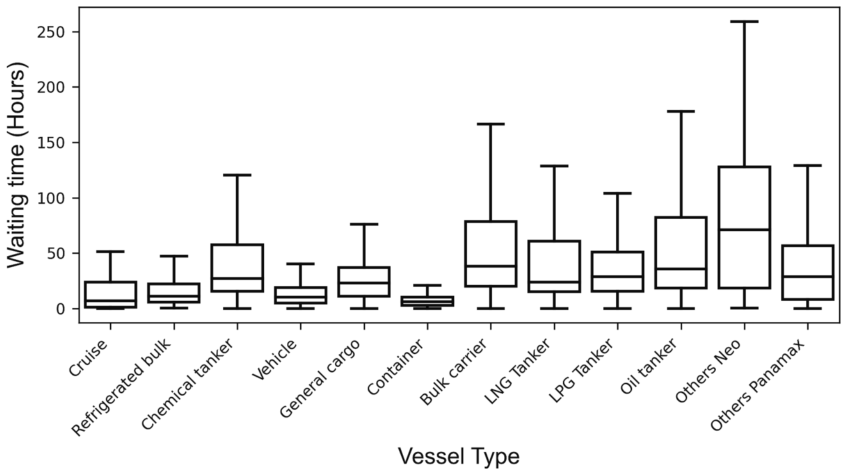

Fig. 9. Waiting time per vessel type.

Table 3
Estimated emissions.

	CO_2 $x10^3$ (tonnes)			CH_4 $x10^3$ (tonnes)			N_2O $x10^3$ (tonnes)		
	Before	Canal	After	Before	Canal	After	Before	Canal	After
2019	15,081.6	375.70	14,713.5	6.387	0.261	7.693	0.863	0.022	0.840
2020	16,446.2	468.81	15,543.0	8.155	0.324	8.251	0.942	0.027	0.888
2021	17,585.7	689.19	18,008.2	9.811	0.449	11.265	1.003	0.040	1.026
Total	49,113.6	1,533.7	48,264.7	24.353	1.034	27.209	2.808	0.089	2.755

Table 4
Total estimated emissions per vessel and transit type (Top 10).

	Transit type	$CO_2e\ x10^6$ (tonnes)			
		2019	2020	2021	Total
Container	Neo-Panamax	7.94	9.10	10.80	27.84
Liquefied gas tanker (LPG)	Neo-Panamax	3.43	3.77	4.47	11.67
Bulk carrier	Super	2.99	3.63	3.85	10.47
Liquefied gas tanker (LNG)	Neo-Panamax	2.82	3.27	3.93	10.02
Chemical tanker	Super	2.49	2.36	2.39	7.24
Container	Super	2.50	2.35	2.17	7.02
Vehicle	Super	1.74	1.35	1.66	4.75
Bulk carrier	Neo-Panamax	0.90	1.44	1.49	3.83
Refrigerated bulk	Regular	1.23	1.17	1.09	3.49
Liquefied gas tanker (LPG)	Super	0.70	0.90	1.50	3.10

In Table 3, it can also be observed how emissions are roughly even between the voyage legs before and after the canal transit, with slightly higher emissions occurring on the leg before.

Emissions segregated by vessel types are presented in Table 4. The higher emitters are container vessels followed by LPG tankers, both transiting through the Neo-Panamax locks. Container vessels emit approximately one third of the total, despite having the lowest waiting time before transiting (as seen in Fig. 9). The result might be driven by 1) more vessels transiting through the Neo-Panamax locks, 2) larger main engines and 3) higher average sailing speeds than other vessel types. For LPG tankers, their overall emissions are driven by their high speed (12.9 knots), number of transits and higher power demand from auxiliary engines from activities such as cargo liquefaction. The highest emitter for the Panamax locks is the bulk carrier segment, with the large number of transits being the main reason.

If we compare the emissions per vessel type to the waiting times presented in Fig. 10, there is seemingly a significant opportunity for reducing emissions from LPG and LNG via JIT and for bulk carriers and chemical tankers transiting the Panama locks via JIT and green slots. The potential mitigating effect on emissions from implementing arrival policies by vessel type is presented in the next section.

If speed reduction is to be assigned to a small number of vessels, then a PCA strategy could be to focus on vessels trading on the specific routes (or origin–destination port-pairs) that would have the highest impact on emissions.

The results in Table 5 suggest that the highest-emitting routes are dominated by container routes from Asia to the East Coast of the USA, with the Busan-NY/NJ route producing the most emissions. If based on individual ports, an initial strategy should consider Busan port and the Port of Houston, covering four and two of the top routes, respectively. The idea of a per route focus is inspired in the proposal of green corridors presented by the Getting to Zero coalition (2021). Green corridors are “specific trade routes between major

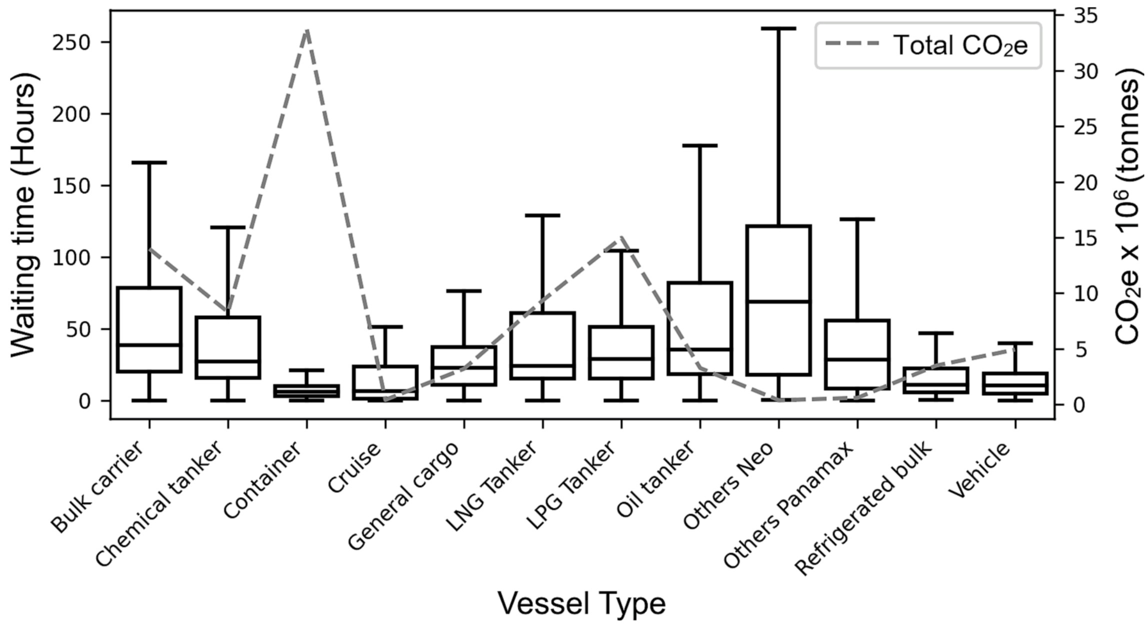

Fig. 10. Waiting time and total CO_2e emissions per vessel type.

Table 5
Top 10 estimated emissions per origin destination pair from Jan. 2019 to Dec. 2021.

Origin	Destination	$CO_2e\ x10^6$ (tonnes)	Main vessel type
Busan port	Port of New York and New Jersey	2.23	Container
Busan port	Port of Houston	1.98	Container
Xiamen	Port of New York and New Jersey	1.35	Container
Hong Kong/ Shekou/ Yantian	Port of Savannah	1.12	Container
Busan port	Port of Savannah	1.05	Container
Port of Houston	Tokyo Bay ports	0.97	LPG/Chemical
Busan port	Kingston	0.94	Container
Hong Kong/ Shekou/ Yantian	Port of Houston	0.82	Container
Port of Houston	Ulsan	0.80	LPG/Chemical
Ulsan	Port of Houston	0.73	LPG/Chemical

Note: Estimates from vessel transiting the canal with no intermediate ports (i.e., Panama ports inside canal waters). Port of Houston incl. Galveston Bay, Trinity Bay and Houston Channel ports.

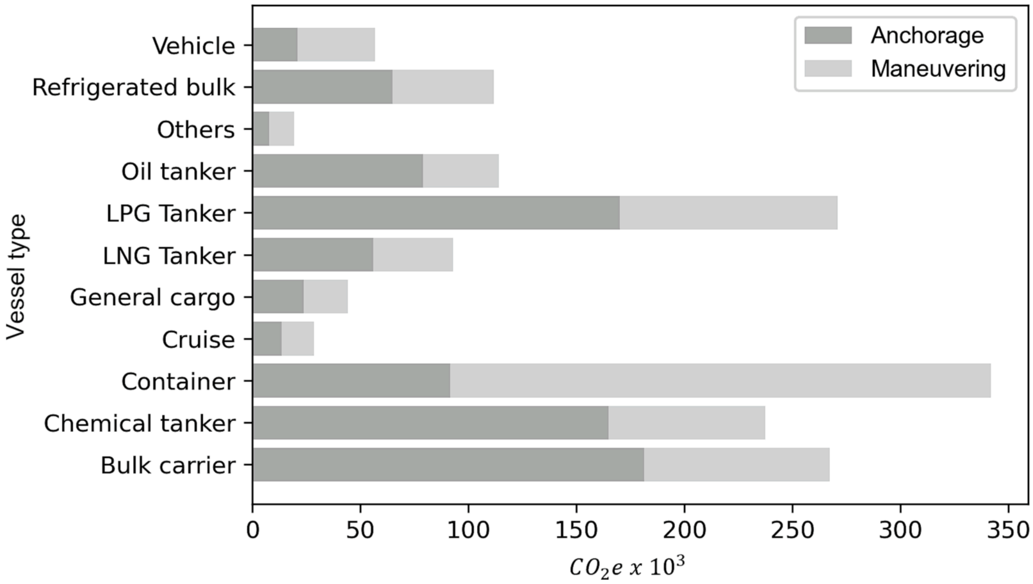

Fig. 11. Estimated emissions at the Panama Canal per operational phase from Jan. 2019 to Dec. 2021 Note: Berth CO_2e emissions for container vessels only (21.4 tonnes).

port hubs where zero-emission solutions have been demonstrated and are supported"- (Getting to Zero Coalition, 2021). Despite the coalition criteria having more elements for selection of green corridors than just the emissions reduction potential (e.g., share of global trade, carbon intensity on route, national policy incentives and regulations, etc.), we recognize that the Panama Canal being part of a green corridor could have a similar effect in terms of leveraging favorable conditions for accelerated action and creating a spill-over effect to other maritime chokepoints and routes.

Lower waiting times can reduce emissions at canal anchorages, which are close to populated areas, thus reducing health hazards such as particulate matter and Nitrogen Oxides. Fig. 11 shows the estimated emissions per operational phase and vessel type inside canal waters. While all vessels produce some emissions from auxiliary engines when awaiting transit, certain vessel types like LNG, LPG, and refrigerated bulks have higher power demand related to cargo handling activities such as liquefaction for LNG and LPGs, and cooling for refrigerated cargo. Still, significant emissions for vessel types with lower power demand from auxiliary engines (bulk carriers, chemical tankers, and oil tankers) are mainly driven by their longer anchorage stays before transiting and higher number of vessels.

5.3. Emissions reduction from the speed reduction strategies

Under proposal 1, vessels could have saved 5.2 million tonnes of CO_2e in total and an average of 1.8 million tonnes per year (Jan 2019 to Dec 2021). The results are limited by our conservative assumptions of vessel not reducing speed below the 55 % ME load and vessel arriving to their arrival cutoff before transiting. Yet despite the assumptions, 17,132 transiting vessels (47 % of transiting

Table 6
Emissions reduction (tonnes ×,000) and waiting time (hours) reduction per proposal.

Vessel type	Coordinated voyage plan		JIT 48 h		Green slots		Green slots and JIT 24 h	
	AWTR*	CO_2e	AWTR	CO_2e	AWTR	CO_2e	AWTR	CO_2e
Container	2.0	1,163.2	2.5	291.8	0.1	9.8	2.0	219.0
LPG	26.1	1,037.7	18.5	323.3	1.7	31.4	11.8	200.0
Bulk carrier	21.7	965.3	16.2	393.3	3.5	91.0	12.1	289.4
LNG	33.0	725.8	17.0	130.6	0	0	7.8	69.1
Chemical tanker	18.0	554.4	15.0	274.4	3.7	78.0	11.5	216.4
Oil tanker	21.9	217.8	15.1	87.9	2.2	13.7	10.6	60.4
General cargo	14.4	210.9	12.5	74.5	3.2	24.2	9.6	58.0
Ref. bulk	6.8	123.6	6.4	61.3	1.2	14.2	5.6	50.8
Vehicle	3.2	102.2	5.7	66.3	0.8	10.4	4.2	47.4
Other Neo vessels	50.6	39.1	16.6	7.9	0	0	8.3	4.6
Other Panamax	7.8	19.6	5.1	9.4	0.7	2.4	3.5	7.2
Cruise vessels	1.3	7.8	2.4	4.5	0	0	2.6	5.8
Total CO_2e (%)		5,167.4 (5.2 %)		1,725.2 (1.7 %)		275.1 (0.3 %)		1,228.1 (1.2 %)
2019 CO_2e (%)		1,423.4 (4.6 %)		544.4 (1.8 %)		79.3 (0.3 %)		364.6 (1.2 %)
2020 CO_2e (%)		1,860.0 (5.6 %)		570.1 (1.7 %)		92.8 (0.3 %)		392.4 (1.2 %)
2021 CO_2e (%)		2,051.2 (5.5 %)		644.6 (1.7 %)		101.7 (0.3 %)		445.9 (1.2 %)

* Average Waiting Time Reduction (hours).

vessels) could have reduced their speed subject to coordination between the canal and the vessels since their departure from the last port.

Table 6 shows the emission reduction per vessel segment, with the biggest effect from speed reduction for container vessels (1.16 million CO_2e tonnes) and LPG transits (1 million CO_2e tonnes savings). Additionally, bulk carriers, LNG vessels and chemical tankers benefit from reducing waiting times, affecting both average sailing speeds and removing emissions while at anchor.

From the results, we also highlight that for the two highest-emitting vessel types (LPG tankers and container vessels), implementing an incentive policy based on this strategy could be customized for vessel departing from specific origin ports.

A strategy based on proposal 2 (JIT 48 h before arrival) could have saved 1.7 million tonnes of CO_2e (1.7 % reduction) from 21,952 transits and an average of 586 thousand tonnes of CO_2e per year. Table 6 shows that the largest reduction is caused by bulk carriers, followed by LPG's and container vessels. Despite a higher waiting time reduction, the impact for container vessels is reduced when compared to the coordinated voyage strategy, emphasizing the significant effect of reducing speed over a longer distance for certain vessel types (i.e., container vessels and LNG).

We also estimate that proposal 3 (green slots) could have saved 275,090 tonnes of CO_2e (a 0.3 % reduction as compared to the benchmark) an average of 91.3 thousand tonnes of CO_2e per year, a lower reduction compared with the previous proposals. However, this reduction results from just 1,924 new assignments of green slots. From Table 6, the largest reduction would arise from bulk carriers, chemical tankers, and LPGs; vessels with estimated long waiting times and more transits through the Panamax locks. A lower reduction is observed for container vessels, caused by the restriction that JIT slots are assigned just to vessel transiting the old Panamax locks.

Finally, a strategy based on proposal 4 (blend of JIT 24 h before transit and green slots) would save approximately 1.2 million tonnes of CO_2e (1.2 % reduction as compared to the benchmark) from 22,718 transits and an average of 401 thousand tonnes per year. To put this in perspective, this strategy saves more emissions than the highest emitting vessel type in the coordinated voyage strategy, a strategy that is perceived to be more difficult to implement. Importantly, the emission reduction is obtained with less uncertainty (i.e. whether the vessel would arrive on time) than when instructing a vessel to reduce speed over a long distance.

6. Discussion and limitations

The analysis shows a tradeoff between the complexity of implementation and the potential for emission reduction. Complexity in this context can be thought of as a measure of the number of vessels reducing speed and how early the speed reduction is enforced, leading to uncertainty regarding vessel arrival versus the proposed RTA. The most complex strategy is the coordinated voyage plan, followed by JIT 48 h before transit for all vessels, blend of JIT 24 h before transit and green slots and the simplest strategy being a green slot assignment under existing rules. The potential for emission reduction also follows this ranking.

The complexity of implementation is driven by limitations of the strategies presented. The first observed limitation is the uncertainty of vessels arrival versus their RTA. To mitigate this limitation, we suggest implementing instructions closer to the canal, focusing on specific market segments or ports where the emissions effect is the highest, or based on past vessel reliability. A per-route policy could also be developed to make the Panama Canal part of green corridors.

An additional limitation is that a vessel needs to be "within sight" to be considered arrived and physically arrived before a cutoff time, similar to the barriers in ports with NOR and laycan. These regulations are enforced to maintain control of vessel arrivals and the daily transit schedule, however, most of the proposals assume these requirements are lifted.

Clearly, scheduling strategies that imply speed reduction for only a small subset of vessels have a lower impact on emission reduction compared to other strategies with more flexibility. Such is the case for the green slot strategy which is limited to the assignment of any unused slots. A more balanced measure such as the blended strategy adds flexibility to the green slot assignment by instructing speed reduction to all vessels 24 h before arrival. As the speed reduction is enforced closer to the time of transit, the Canal could provide accurate transit assignments based on updated information on their resource availability (e.g., pilots, tugboats, canal slots capacity due to weather, etc.).

An additional observation from Table 4 is that many vessel types have a higher potential emission reduction in 2020 and 2021, despite having fewer overall transits as per the official statistics of the PCA (2021c). This suggests that a strategy for reducing emissions prior to a chokepoint has a stronger effect when there are inefficiencies caused by longer waiting times. It follows that for chokepoints with less waiting time uncertainty, such as the Suez Canal where the assignment is based on the time of arrival in a convoy system, there is less opportunity for reducing emissions. There may also be restrictions on reducing vessel speeds in neighboring areas for security reasons, such as piracy threats in the Gulf of Aden.

We recognize that there are additional barriers to improve efficiency in canal operations that are related to the broader discussion of contractual barriers to operational efficiency in shipping. Firstly, under the simplifying assumption that the time of transit does not change, our scheduling proposals – and the accompanying speed and emission reduction - would not affect the tendering of NOR in any subsequent loading port on the post-canal leg. However, we acknowledge that this restriction may not produce the overall societal optimal solution.

Secondly, the utmost dispatch barrier in a voyage charter (Global Industry Alliance, 2020; Jia et al., 2017; Rehmatulla and Smith, 2015) remains to be solved as a matter of contractual wording, typically including an exemption clause. However, the PCA could promote a fairer (to the charterer) exemption clause enforcement. It might be the case that the charterer is the carrier and held liable to the shipper for the cargo on board (Hague Visby Rules, 1979) and an unreasonable deviation, caused by speed reduction, would make them lose rights and liability limitations if an accident occurs. If the PCA enforces the rule that a vessel may reduce speed only under PCA instruction, then it gives the charterers assurance that the "deviation" is not an arbitrary decision to suit the shipowner's commercial interests, but a matter of operational efficiency. On the charter party side, a new exemption clause could be drafted in the spirit of the Baltic and International Maritime Council Just in Time clause (2022).

Thirdly, regarding the split incentives problem on a voyage charter (Rehmatulla and Smith, 2015), the charterer would remain unaffected as the speed reduction takes place before an expected stop and not on the final leg to the destination port. This assumes that the charterer has agreed to waive the utmost dispatch clause (if applicable), for the period the vessel is instructed to reduce speed. The same argument holds for the rush-to-wait behavior (Poulsen and Sampson, 2019) in the destination port, which is not affected by changes on the pre-canal leg.

7. Conclusions

In this study, we explore the implications of implementing speed reduction measures driven by increasing operational efficiency at chokepoints such as the Panama Canal. We find that the barriers to implementation discussed in the literature, such as the rush-to-wait behavior caused by first-come-first-served port policies and the potential for earning demurrage, and split incentives for fuel cost savings, are broadly mitigated in the case of intermediate stops such as a canal transit. This highlights how changes to scheduling policies in the Panama Canal can be an important source of emission reduction in shipping that has hitherto not been considered in the literature.

In our Panama Canal case study, we measured the effect of implementing speed reduction measures from increasing operational efficiency in the canal. Our results show potential reductions from 275,090 tonnes to 5.2 million tonnes of CO_2e emissions from January 2019 to December 2021 (an average of 91,000 to 1.8 million tonnes of CO_2e per year) by promoting speed reduction measures based on four separate proposals with due consideration of their scheduling rules. Our study also highlights the tradeoff between effect and perceived complexity of implementation, and shows how proposals could be implemented gradually by market segmentation.

As a methodological contribution, we introduced a framework for estimating the Panama Canal operational statistics and derived emissions from AIS data. We also adapted the bottom-up method in the Fourth IMO GHG study to fit our case study.

This study focuses solely on emissions reduction during the pre-canal leg of a voyage. We recognize that to achieve emissions reduction during the post-canal leg, a proposal must also incorporate a scheduling model for assigning transits. As a community planner, the canal could assign the most efficient transit mix while taking into account the emissions savings before and after each transit, within their operational constraints.

Future research should make a similar assessment for other maritime chokepoints, such as the Suez Canal and Bosphorus Strait, and consider the impact of changes to their existing scheduling rules. Ideally, a more advanced model would also consider optimization of the entire voyage, as well as arrival uncertainty caused by weather and operational constraints within the canal. With the help of our empirical methodology, future studies could also consider the strengths and weakness of the Canal for being part of a green corridor and propose a strategy for improving such weaknesses.

CRediT authorship contribution statement

Gabriel Fuentes: Conceptualization, Software, Methodology, Data curation, Visualization, Formal analysis, Validation. **Roar Adland:** Funding acquisition, Supervision, Writing – review & editing, Formal analysis, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. . Tests for generating Panama Canal statistics

Inputs:
  $Z_s \leftarrow [\text{i-j}]_{Ix5}$ $(\{\text{i}|:\text{i} \in \{1, ..., I\} \wedge \text{i} \in \mathbb{Z}\}$; j $\in$ {polygon,time,cutoff,group,groupPosition})
  s$\in$S; S is a set of vessels
  A is a set of anchorage polygons
Default Parameter:
  timeCutoff $\leftarrow$ 48, hours between ordered records to declare a time cutoff
for s $\in$ S **do**
  set $Y_s \leftarrow 0_{Mx5}$
  $z_{ij} \leftarrow Z_s$
  $y_{mj} \leftarrow Y_s$
  m$\leftarrow$0
  for i $\in \{1, ..., I\}$ **do**
    $z_{i,groupPosition} \leftarrow 0$
    if $z_{i,time} - z_{i-1,time} >$ timeCutoff $\vee$ $z_{i,polygon} \neq z_{i-1,polygon}$ **then**
      $z_{i,cutoff} \leftarrow 1$
      $z_{i,groupPosition} \leftarrow 1$
      $z_{i-1,groupPosition} \leftarrow 2$
    else
      $z_{i,cutoff} \leftarrow 0$
    end if
  end for
  for i $\in \{1, ..., I\}$ **do**
    $z_{i,group} \leftarrow \sum_{t=1}^{i} z_{t,cutoff}$
    if $z_{i,polygon} \in A \wedge (z_{i,groupPosition} = 1 \vee z_{i,groupPosition} = 2)$ **then**
      m$\leftarrow$m+1
      $y_{m,:} \leftarrow z_{i,:}$
    end if
  end for
end for

Inputs:
  $Y_s \leftarrow [\text{m-j}]_{Mx5}$ $(\{m|m \in \{1,...,M\} \wedge m \in \mathbb{Z}\}$; $j \in$ {polygon,time,cutoff,group,groupPosition}) ;
  from Algorithm 1
  $Z_s \leftarrow [\text{i-j}]_{Nx5}$ $(\{i|:i \in \{1,...,N\} \wedge i \in \mathbb{Z}\}$; $j \in$ {polygon,time,cutoff,group,groupPosition})
  $s \in S$; S is a set of vessels
Default Parameter:
  timeCutoff $\leftarrow$ 48, hours between consecutive visits to a same polygon
for $s \in S$ **do**
  set $X_s \leftarrow 0_{Vx5}$
  $y_{mj} \leftarrow Y_s$
  $x_{vj} \leftarrow X_s$
  $v \leftarrow 0$
  for $m \in \{1,...,M\}$ **do**
    if $y_{m,polygon} \neq y_{m-1,polygon}$ **then**
      $y_{m,cutoff} \leftarrow 1$
    else
      $y_{m,cutoff} \leftarrow 0$
    end if
  end for
  for $m \in \{1,...,M\}$ **do**
    $y_{m,group} \leftarrow \sum_{t=1}^{m} y_{t,cutoff}$
  end for
  for $m \in \{1,...,M\}$ **do**
    if $y_{m,group} = y_{m-1,group} \wedge y_{m,groupPosition} = 1$ **then**
      if $y_{m,time} - y_{m-1,time} \leq$ timeCutoff **then**
        if call PortInBetween($y_{m-1,time}$,$y_{m,time}$,Z_s)=TRUE **then**
          $y_{m-1,cutoff} \leftarrow -1$
          $y_{m-2,cutoff} \leftarrow -1$
        else
          $y_{m-2,cutoff} \leftarrow 1$
          $y_{m-1,cutoff} \leftarrow -1$
          $y_{m,cutoff} \leftarrow -2$
        end if
      end if
    end if
  end for
  for $m \in \{1,...,M\}$ **do**
    if $y_{m,cutoff} \geq 0$ **then**
      $v \leftarrow v+1$
      $x_{v,:} \leftarrow y_{m,:}$
    end if
  end for
end for

```
Inputs:
    X_s←[v-j]_{Mx5} ({v|v ∈ {1, ..., V}∧v ∈ℤ}; j ∈ {polygon,time,cutoff,group,groupPosition}) ;
    from Algorithm 2
    Z_s←[i-j]_{Nx5} ({i|:i ∈ {1, ..., N}∧i ∈ℤ}; j ∈ {polygon,time,cutoff,group,groupPosition})
    s∈S; S is a set of vessels
for s ∈ S do
    set G_s←0_{Px5}
    x_{vj}←X_s
    g_{pj}←G_s
    p←0
    for v ∈ {1, ..., V} do
        if x_{m,polygon}=x_{v−1,polygon} ∧x_{v,groupPosition}=1 then
            x_{v,cutoff}←1
        else
            x_{v,cutoff}←0
        end if
    end for
    for v ∈ {1, ..., V} do
        x_{v,group}←∑_{t=1}^{v} x_{t,cutoff}
    end for
    row←0
    for v ∈ {1, ..., V} do
        if x_{v,cutoff}=1 then
            row←1
        else
            row←row+1
            if row>4∧x_{v,groupPosition}=1 then
                if (x_{v,time}-x_{v−1,time})<(x_{v−2,time}-x_{v−3,time}) then
                    x_{v−2,cutoff}←1
                else
                    x_{v,cutoff}←1
                end if
            end if
        end if
    end for
    for v ∈ {1, ..., V} do
        x_{v,group}←∑_{t=1}^{v} x_{t,cutoff}
    end for
    row←0
    for v ∈ {1, ..., V} do
        if x_{v,cutoff}=1 then
            row←1
        else
            row←row+1
            if row=4 then
                p←p+1
                g_{p,:}←x_{v−3,:}
                p←p+1
                g_{p,:}←x_{v,:}
            end if
        end if
    end for
end for
```

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