Port call optimization and CO_2-emissions savings – Estimating feasible potential in tramp shipping

Axel Merkel [a], Joakim Kalantari [a], Abdalla Mubder [b,c,*]

[a] *Swedish National Road and Transport Research Institute (VTI), Malvinas väg 6, KTH Campus, se-114 28, Stockholm, Sweden*
[b] *Swedish National Road and Transport Research Institute (VTI), Olaus Magnus väg 35, SE-581 95, Linköping*
[c] *Linköping University, Department of Technology and Science, Communication and Transport Systems, se-602 47, Luntgatan 2, Norrköping, Sweden*

A R T I C L E   I N F O

A B S T R A C T

The promise of Port Call Optimization (PCO) measures such as Virtual Arrival (VA) for increased fuel efficiency in shipping is emphasized in the literature and professional ranks alike. Despite their envisioned benefits and feasibility, the implementation of such measures has largely remained lacking. Recent studies indicate that the potential of VA on fuel efficiency might be overestimated. In this paper we propose a new approach to estimate the fuel efficiency potential of VA based on traffic data from the Swedish tramp shipping sector. Our results indicate that the feasible fuel efficiency potential of VA is significantly smaller than what has previously been reported with no discernible benefit to large cohorts of voyages. We conclude that further empirical analyses are required for increased accuracy of the estimation of the potential of PCO for increased fuel efficiency in shipping and that more measured approaches in implementation and evaluation of PCO are called for.

1. Introduction

Some CO_2 abatement measures are associated with negative cost e.g., through a reduction of the fuel bill that is greater than the cost of its implementation (Eide et al., 2011; Acciaro et al., 2013). In tramp shipping, Port Call Optimization (PCO) measures in general and Virtual Arrival (VA) in particular, is recognized as a promising measure to reduce fuel consumption and CO_2-emissions without negatively impacting the service quality from the cargo owners' perspective (Jia et al., 2017; Du et al., 2015; Andersson and Ivehammar, 2017). VA is commonly regarded as an operational process allowing the ship to reduce its speed to be able to meet a Required Time of Arrival (RTA), given a known delay at its destination port (INTERTANKO and OCIMF, 2011). This means that VA enables the time spent anchored waiting to berth at ports to be used as extra sailing time, potentially allowing for lower average sailing speed with corresponding reduction in fuel consumption and CO_2-emissions (Poulsen and Sampson, 2019). Since the extra sailing time does not add to the total voyage time from quay-to-quay, no additional costs are incurred in terms of more ships for maintaining the same capacity or reduced service level for the cargo owners.

Several studies have estimated the fuel savings potential of implementing VA with estimates ranging from about 20% at the high end (Jia et al., 2017) and less than 10% at the low end (Johnson and Styhre, 2015). Realizing fuel savings of this magnitude would result in a substantial reduction in CO_2-emissions from the concerned shipping sector. For example, Andersson and Ivehammar (2017) estimate that a fleet-wide implementation of VA on tankers in the Baltic Sea would result in up to 10 000 tonnes reduction of

---

* Corresponding author.
E-mail addresses: Axel.merkel@vti.se (A. Merkel), Joakim.kalantari@vti.se (J. Kalantari), Abdalla.mubder@vti.se (A. Mubder).

CO_2-emissions annually from that shipping segment. The perceived promise of VA as a feasible CO_2 abatement strategy is also apparent in the different initiatives from relevant industry organizations, aimed at enabling the wide-spread adoption of these practices. For instance, in 2013, BIMCO developed a VA clause to facilitate contractual agreements in Charter Parties for adjusting speed to meet a revised time of arrival due to foreseeable delays to berthing in the destination port (BIMCO, 2013). Other examples are the IMO-GIA roundtable for Just-in-Time (JIT) ship operations and Sea Traffic Management (Büssow, 2020).

Notwithstanding promising research results and industrial efforts, the implementation of VA remains limited (Poulsen and Sampson, 2019; Poulsen et al., 2018; GioMEEP, 2018). There are several reasons for the slow uptake of VA, despite the purported merits that are brought forth in the literature. Poulsen and Sampson (2019) argue, among other things, that the validation of fuel savings from VA and cost effective and equitable benefit sharing schemes remain as difficult issues to resolve. Rehmatulla and Smith (2015) and Dewan et al. (2018) both suggest that the lack of reliable information on costs and savings from VA is a barrier limiting its implementation. Having accurate and reliable estimates of the fuel saving potential of VA is hence crucial in understanding the relative weight and feasibility of this measure for emission reduction from the shipping sector as a whole. This is also a key component for understanding the business consideration to underpin a large scale and wide-spread implementation of VA in the shipping industry. Ultimately, regarding the tramp shipping sector, a prerequisite for the wide-spread adoption of VA is that port authorities facilitate queueing policies that promote VA, as opposed to the predominant first-come-first-served (FCFS) rule. Otherwise, shipping companies and shippers who would be prepared to apply VA, run the risk of getting overtaken by other, faster ships and hence risk not avoiding unproductive waiting time at anchor and suffer longer transport time from quay-to-quay in the process.

Examining the literature regarding the potential of VA, there appears to be an overestimation of the expected fuel savings and emission reduction potential of VA as a share of total fuel consumption. Most papers estimating the potential of VA rely on the cubic relation for ships' fuel consumption functions, i.e., the fuel consumption varies to the third power in relation to sailing speed (Kontovas and Psaraftis, 2011; Venturini et al., 2017; Meng et al., 2016). This assumes a constant elasticity across all speed ranges. In contrast, Adland et al. (2020) demonstrates empirically that the cubic law is a valid estimation of speed/fuel consumption function only near the design speed of vessels, and that the elasticity of fuel consumption with regards to vessel speed can be substantially lower in the speed ranges under that of the design speed. As a result, studies estimating the impact of speed reduction on emissions and fuel reduction on the basis of the "cubic law" risk systematically overestimating the effect of such measures, given that a significant portion of ships in the tramp shipping sector operate at lower speeds already (Berthelsen and Nielsen, 2021; Adland et al., 2020; Bouman et al., 2017). For instance, Clarkson research (2020) reports an average of 18% and 21% speed reduction for tankers and bulk vessels respectively, compared to 2008.

Other modeling assumptions that likely lead to an overestimation of the potential of VA in the literature are, considering the total amount of anchoring time as available for sailing and not explicitly considering a minimum sailing speed. The former assumes that there are no limitations to how far in advance a delay at anchor can reliably be known. The latter disregards the fact that below certain speeds a ship cannot be safely maneuvered. Furthermore, below certain speeds the fuel saved due to the reduction in speed will be outweighed by the extra fuel consumed due to the additional time spent sailing, meaning that speed reduction would increase the fuel consumption for the voyage in total.

The focus of this paper is on the potential of the implementation of a VA for increased fuel efficiency and reduction of CO_2-emissions. Our objective is to estimate this potential using a dataset of traffic and vessel information covering all calls to Swedish ports within the tramp shipping segment during 2019. Rather than assuming that the cubic law holds at observably low speeds, we apply various speed-dependent elasticities from the relevant literature to test how estimated potential fuel savings are affected. This means that the speed-power exponent in the fuel consumption function is allowed to vary with sailing speed. For practical modeling reasons, we assume fixed values over certain speed ranges. More detail on this procedure is given in Section 3.1.

Firstly, we estimate the actual time that ships spent at anchor waiting to berth. Secondly, we apply a speed-dependent elasticities for estimating the speed/fuel function at different speeds to estimate the potential of fuel savings when waiting time at anchor is used for sailing. For this estimation, feasible length of time for advance notice of delay and minimum economic sailing speeds are considered. The results are then compared to an alternative scenario in line with the models from previous studies i.e., only considering the "cubic law".

The remainder of this paper is organized as follows. In Section 2, a frame of reference is stablished from reviewed literature. The data and the methodology of this paper is presented in Section 3 and in Section 4 the results of the study are presented. Finally, concluding remarks and future research are presented in Section 5.

2. Frame of reference

Ship's waiting time is an important efficiency indicator (Tongzon, 2009). The waiting time in ports is described differently by different researchers in the literature. For instance, Poulsen and Sampson (2020) categorize tankers waiting time in port in six phases: 1) Approach to port, 2) Mooring, 3) Tank inspection, 4) Cargo-operation, 5) post-cargo operation, and 6) Departure Kontovas and Psaraftis (2011). categorize ship's waiting time in ports in two phases: 1) Waiting time before berthing and 2) Service time. It is of relevance to distinguish between the variety of waiting phases during port calls because different measures are relevant for different phases.

VA in particular is only relevant to the waiting time before berth. Schwartz et al. (2020) mention that ships spend considerable time in ports waiting in queues. Andersson and Ivehammar (2017) and Jia et al. (2017) declare the same, arguing that tankers in particular, spend considerable amounts of time waiting to berth, at anchor. In Texas' terminal, tankers awaiting berth represents 23% of the total delay at the terminal (Song and Panayides, 2015). On average, and depending on ship type, a ship may spend up to 9% of its time

waiting to berth, at anchor (IMO, 2020b). For instance, both wet and dry bulk ships spend on average 9% of their annual time at anchor. For container ships and LNG carriers, the annual numbers are 4.5% and 4%, respectively (IMO, 2020b). This indicates that the biggest potential for increased fuel efficiency through the implementation of VA is in those sectors that typically do not sail according to a predefined schedule, i.e., the tramp shipping sector.

One of the reasons why ships wait at anchor is the FCFS queueing policy applied in ports (Schawrtz et al., 2020). This policy drives speed competition among ships and therefore the "rush-to-wait" phenomena. By consulting relevant industrial actors, Adland and Jia (2018) list some rationales driving this behavior: 1) Demurrage rates are higher than the earnings from sailing. As a result, shipowners rationally attempt to maximize expected demurrage by arriving on the first lay-day. 2) Early arrival allows the shipowner to create a buffer ahead of the cancelling date, which reduces the risk for charter party cancelation. Poulsen and Sampson (2019) also indicate a number of reasons related to business rationale, operational considerations and crew welfare and safety as accounting for the persistence of anchored waiting time, before berthing.

Adland and Jia (2018) and Schwartz et al. (2020) describe the rush-to-wait phenomena as highly inefficient vis-à-vis fuel consumption and ship-to-air emissions. Therefore, by modifying the application of FCFS with the introduction of VA that allows for dynamic management of a ship's arrival time with regard to berth availability in ports, ships may avoid significant amounts of emissions and consume less fuel by spending the would-be waiting time at anchor, sailing at a lower average speed (Kontovas and Psaraftis, 2011; Yu et al., 2021).

VA differs from scheduled sailing insofar as the purpose is not to reserve time slots for berthing at ports in advance, but merely to allow for speed adjustments in response to known delays without running afoul the FCFS principal, lest the ships rush to wait at anchor before berthing. It is also important to differentiate VA from slow-steaming regarding two critical aspects. Firstly, as VA only minimizes the time at anchor before berthing through slower sailing speed, the transport capacity is not affected (Poulson and Sampson, 2019). Secondly, because the total voyage time remains the same, the cargo in-transit inventory costs will not increase as in the case of slow-steaming. The service produced with or without VA is indistinguishable from the cargo owners' perspective, save for the potentially reduced fuel costs.

The fuel savings potential of VA has been analyzed in several studies. Jia et al. (2017) applied an AIS-based (Automatic Identification System), bottom-up approach to estimate the potential of fuel and emissions savings if VA is implemented for oil tankers in global trade during 2013–2015. As described earlier, VA is only relevant for the portion of time spent at port anchored, waiting to berth, and not other categories of delay at port. Therefore, to accurately estimate the potential impact of VA on fuel consumption, time spent anchored needs to be distinguishable from time spent on other activities, in the data. However, Jia et al. (2017) did not have detailed information regarding what is referred to as "excess port time" (unnecessary waiting time). As a remedy, it is assumed that the excess port time (duration of a port call over and above the minimum port time for cargo handling) is reduced through the implementation of VA by 25%, 50%, 75% and 100%, respectively. Their results show that the fuel savings depend on how much unnecessary waiting time could be utilized for sailing. At 25% waiting time reduction, fuel savings of 7.26% could be reached, while 19% fuel savings are possible if all waiting time is eliminated. In their study, it is assumed that all of the eliminated waiting time would be available as extra sailing time for the duration of the entire voyage and that the cubic speed/fuel consumption function is valid for speeds as low as 7 knots.

Johnson and Styhre (2015) conducted a case study in which they analyzed the effect of VA on two 5 000 gross tonnage (GT) ships in a short sea shipping (SSS) context during 2011. They combined interviews with Statement of Facts data to quantify the total waiting time during port calls for the two ships. Based on interviews, three "likely scenarios" for the number of hours that a port call duration may be reduced by slower sailing speed was developed. The results indicate that a reduction of 2–8% in fuel can be obtained depending on which scenario is deployed. The estimates are based on ship specific operational and design specification. The ship-specific empirical data in the case study adds to the validity of the outcome, however, the methodology and sample size limit the generalizability of the results.

Andersson and Ivehammar (2017) used AIS-data from the Baltic Sea countries to estimate the effect of VA compared to a conventional approach with significant amount of waiting at anchor. Firstly, they identified the number of hours that ships were anchored at ports. To calculate fuel consumption with and without the implementation of adjusted speed, the authors specified a model wherein fuel consumption was assumed to be quadratically related to ship speed per unit of distance.[1] This approximation was assumed to hold regardless of the initial speed of vessels. For calculation purposes, they highlighted two important factors that may affect the potential fuel savings: 1) how much a ship can reduce its speed and 2) how long before original Estimated Time of Arrival (ETA) a ship receives reliable information. For speed reduction, they assumed a possible reduction of 5%, 10%, 25% and 50%. In addition, they assumed that a ship may reduce its speed by 1 hour, 4 h, 12 h, and 24 h prior to arrival. For 10% speed reduction 4 h prior to arrival, their results indicate annual total savings of 3 135 tonnes of fuel and 9 812 tonnes of CO_2.

The validity of the cubic function, also termed the admiralty formula, for estimating the impact of speed reduction on fuel consumption and emission needs to be revisited in order to avoid overestimation (Wang and Meng, 2012). The admiralty formula is commonly known to be a fair approximation of the speed fuel curve close to vessels' design speeds (IMO, 2014; Psaraftis and Kontovas, 2013). Adland et al. (2020) investigate whether the cubic approximation of the speed-power relationship is appropriate for crude oil tankers at actually observed speeds. Their findings give support for an alternative formulation, which is to model the speed-power

---

[1] The 'cube rule' formulation refers to the effect of speed on fuel consumption per unit of time. Since a slowdown in speed implies less distance covered, the reduction in fuel consumption per unit of distance is smaller. Assuming a cubic relationship between speed and per-hour fuel consumption, this relationship is approximately quadratic.

relationship as a function of speed. The findings of Adland et al. (2020) for instance indicate that for Aframax tankers with design speeds around 15 knots, the elasticity of fuel consumption with respect to sailing speed is around 0.4 at speeds below 10 knots, between 2 and 2.5 at speeds between 10 and 14 knots and around 3 at speeds higher than 14 knots. Analogously, for Suezmax tankers with a similar design speed, the elasticities are for a speed range below 10 knots, 1.3, for a speed range between 10 and 14 knots, 2.3, and for speeds above 14 knots, 2.84. These findings were reinforced by Berthelsen and Nielsen (2021).

We apply the speed-dependent estimation of elasticities from Adland et al. (2020) in our modeling in lieu of direct observation of the empirical speed/fuel curve of the vessels in our sample.

3. Data and methodology

This study uses three sources of data. Firstly, we make use of ship positional data from the automatic identification system (AIS), provided by the Swedish Maritime Administration (SMA). The AIS data provided for this study covers all ship movements within Swedish territorial waters during 2019. It is updated at frequent intervals (several times per minute depending on ship type) and contains vessel identifying information (IMO/MMSI number), reported draft, speed over ground, navigational status and geographic location. Secondly, we utilize a complete record of vessel calls at Swedish ports during 2019 provided by the SMA. This dataset contains details for each call, including date of arrival, port of origin/destination, ship type and IMO number, which enables matching with other datasets. Finally, vessel-specific technical and operational data required for the calculation of fuel consumption is provided by IHS Markit. This data includes information regarding service speeds, maximum drafts, main engine powers and fuel types for all vessels. Using these sets of data, we identify relevant tramp shipping port calls in Sweden in 2019 which could potentially have benefited from the implementation of VA and estimate the fuel and CO_2-emission savings which could have been realized under varying assumptions. This procedure is detailed below.

First, we extract from the AIS data all vessels which reported to be at anchor prior to calling a Swedish port. The time each ship spent at anchor is calculated as starting from the initial reporting of navigational status "anchor" and the length of time at anchor is calculated as the duration for which a ship stays approximately (within a nautical mile) in the same position. Identified instances of anchoring are matched with port call records to filter out any vessels that did not proceed within 48 h after anchoring to call a Swedish port. Further, the data is filtered so that only typical tramp shipping vessel types are retained. Vessel types categorizable as gas/liquid tankers, general cargo carriers and dry bulk carriers are retained.[2] This approach yields 3023 instances of anchoring preceding a port call.[3] Some vessels appear more than once in the data; the number of unique IMO-numbers is 1091. For each instance, the identified time at anchor is calculated, as well as the average transmitted speed over ground during the last 12 and 24 h preceding anchorage, respectively. The observed speed of vessels prior to anchorage is of importance for calculating potential fuel savings that would result from implementation of VA, which is detailed later in this section. Divided into three rough categories of vessel (tanker, dry bulk and general cargo), summary statistics regarding identified anchorages preceding a port call are detailed in Table 1.

The average time at anchor preceding a port call was roughly 23 h, though this value is affected by a small number of outliers as illustrated in Fig. 1 where the solid blue line highlights the sample mean (22.6 h) and the dashed line highlights median (13.2 h). Another important feature of the sample is related to the port-to-port distance of voyages. This is illustrated in Fig. 2, which shows that most of the sample concerns voyages with a distance of less than 1000 nautical miles, with some additional voyages mostly falling in the range of 1000 – 2000 nautical miles. The average voyage distance in the sample is around 500 nautical miles, which corresponds to a sailing time of 1 – 2 days depending on sailing speed. Overall, these features of the data highlight that the sample of voyages for which we can identify anchoring time prior to arrival skews toward relatively short distance operations, and that time elapsed in the identified instances of anchoring prior to arrival may account for a significant share of the total voyage times.

The distribution of average speed over ground readings per vessel prior to anchoring is illustrated in Fig. 3. The solid blue line indicates the mean *speed over ground* reading, which is 10.3 knots. In Fig. 3, the average *service speed*, which reflects vessel speed under normal service conditions, is highlighted through the dashed line. The average service speed of vessels in the sample is roughly 13 knots, and it is clear from Fig. 3 that the vessels in the sample are generally already sailing at lower-than-normal speeds.

3.1. Modeling approach for implementation of VA

For each port call in the sample, we construct a counterfactual 'pseudo' speed (see Jia et al., 2017), which represents the speed at which the vessel could have sailed to avoid waiting at anchor. The basic formulation of the pseudo speed for vessel i is:

$$v_i^* = \max\left[\frac{D_i}{t_{0,i} + t_{a,i}},\ v_{l,i}\right] \tag{1}$$

In Eq. (1), v^* represents the counterfactual pseudo speed for vessel i, D_i represents the sailing distance between the vessel's position when speed optimization can begin and the port of call, $t_{0,i}$ represents the original sailing time to port at the time when speed optimization can begin, $t_{a,i}$ represents the time spent by vessel i at anchor and $v_{l,i}$ represents a lower bound beyond which speed reduction does not generate fuel savings. The expression $D_i/(t_{0,i} + t_{a,i})$ thus shows the speed which would be required for a vessel to eliminate the

---

[2] The precise vessel types are based on IHS's StatCode 5 classification.

[3] For reference, the number of declared port calls for tankers, general cargo vessels and dry bulk vessels in Sweden during 2019 was around 19 000.

Table 1
Sample details per vessel category.

Vessel type	Number of voyages	Average time at anchor (h)	Median time at anchor (h)	Average speed prior*	Average DWT**
Tanker (various types)	1 689	23.50	13.63	10.51 (10.55)	15 282
Dry bulk	151	20.94	11.47	10.65 (10.60)	28 850
General cargo	1 183	21.45	12.82	10.03 (10.05)	6 280
Full sample	*3 023*	*22.57*	*13.23*	*10.33 (10.36)*	*12 418*

 * Note: Main values correspond to average speed over ground transmissions during the last 12 h preceding anchorage. Values in parenthesis correspond to average transmissions during the last 24 h preceding anchorage.

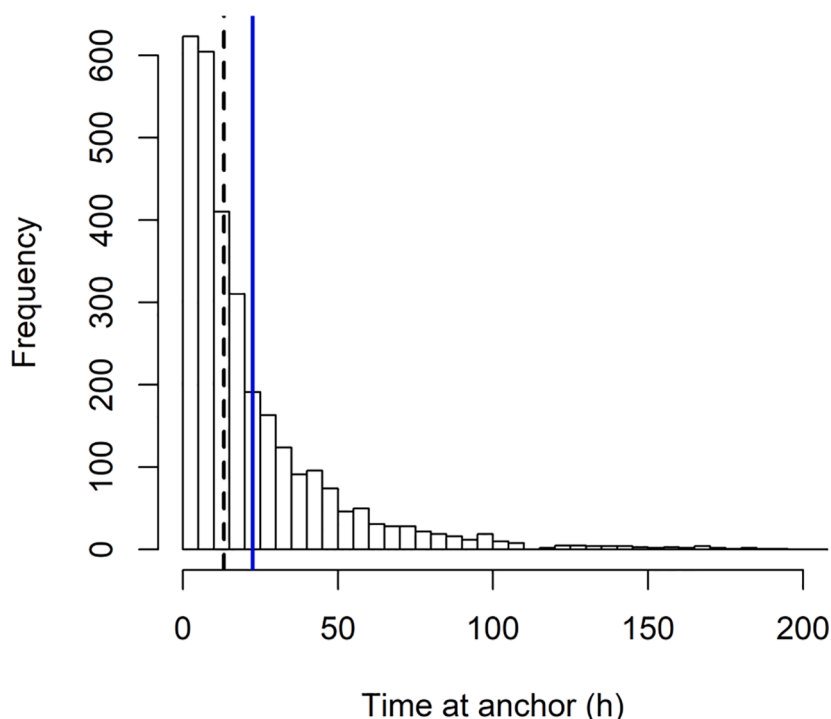 ** Note: Deadweight tonnage (DWT) expresses vessel size in terms of weight carrying capacity.

Fig. 1. Distribution of times at anchor preceding a port call. Dashed black line indicates median time at anchor (13 h), while solid blue line indicates average time at anchor (23 h).

need for waiting at anchor preceding a port call. In some instances, adjusting the speed in order to entirely eliminate anchorage time is not plausible. This might be because the time spent at anchor is very long and/or because the vessels' original speed is already very low. For this reason, we apply a lower bound to optimized speed. The general lower bound applied is 7 knots, which is assumed to be the minimum feasible sailing speed.[4] In cases where $D_i/(t_{0,i} + t_{a,i}) < v_{l,i}$, the adjusted speed will instead be equal to the lower bound. In such an instance, waiting time prior to berthing will be reduced but not eliminated.

An important question concerns the time at which speed adjustment can be expected to be feasible to begin prior to a port call. In their calculations of potential fuel savings following the implementation of a VA scheme, Jia et al. (2017) assume that speed adjustment can be implemented during the entire voyage, i.e., from the time of original departure. Andersson and Ivehammar (2017) calculate a range of scenarios where the timing of speed adjustment prior to arrival depends on when vessels receive updated and reliable information on terminal readiness. In Andersson and Ivehammar's (2017) scenarios, vessels can implement speed adjustments in response to such information anywhere from 1 hour prior to original ETA to 24 h prior to original ETA. The question of how early speed optimization can commence plausibly depends on when a reliable estimate of terminal readiness can be produced. The reliability of such an estimate should increase as the time of arrival draws closer, since fewer unforeseen events are able to affect berth availability. Adjusting speed at a very early stage in the voyage could be inefficient if the time of berth availability is subsequently expedited and the vessel must adjust its speed upwards to make time. Following discussions with nautical experts at the SMA, we consider three

---

 [4] This is argued by Jia et al. (2017) to apply for VLCCs. Following discussions with nautical experts at the SMA, 7 knots is considered a reasonable lower bound for the sample of vessels in this study.
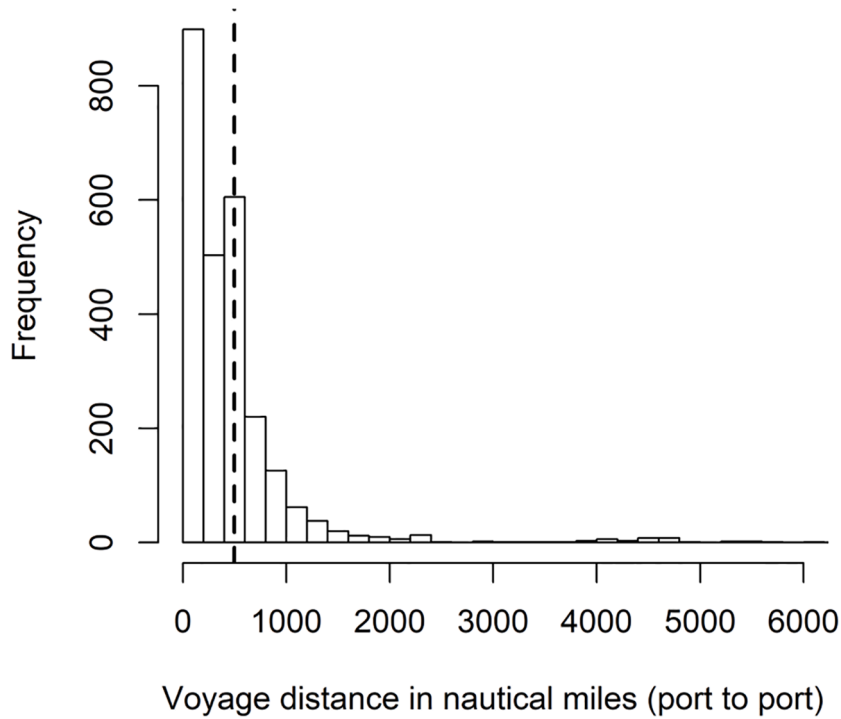
Fig. 2. Distribution of voyage distances from port of origin to port of destination for the samples voyages which conclude with time at anchor prior to arrival. Dashed line indicates the mean voyage distance (495 nautical miles).
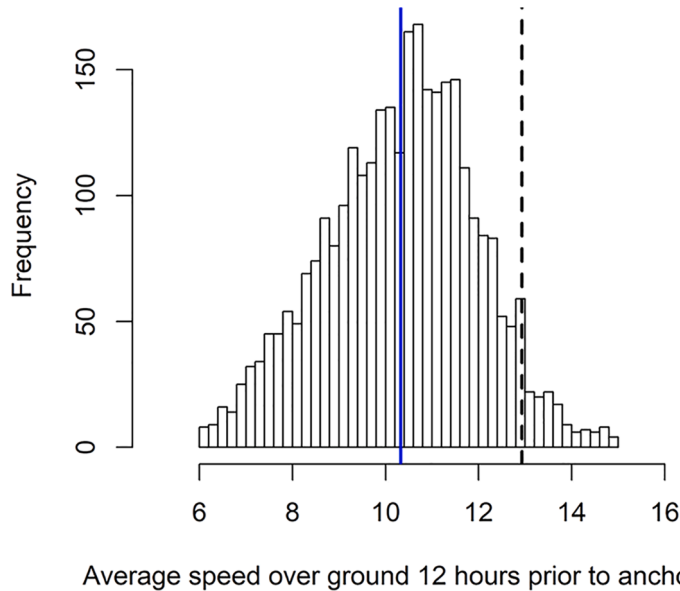

Fig. 3. Distribution of average recorded speed over ground from AIS per vessel during 12-hour period prior to anchoring (10.3 kn). Solid blue line indicates average of sampled vessels, dashed black line indicates average service speed of sampled vessels (ca. 13 kn).

main scenarios regarding the timing of speed optimization: 12 h, 8 h and 4 h prior to planned arrival. This is to reflect what is considered reasonable while being careful not to overstate the fuel savings potential of speed adjustment. The scenarios are also considered reasonable in light of the distribution of voyage distances in the sample; as illustrated above the majority of voyages with identified instances of anchoring prior to arrival have a total voyage time of two days or less, which lessens the scope for early arrival planning.

Having identified the operational speed of vessels prior to anchorage ($v_{0,i}$) and calculated the pseudo speeds (v_i^*), we can calculate

the expected difference in fuel consumption that would be realized following speed adjustments. This is done by calculating the main engine fuel consumption at both speeds for the period of time from commencement of speed adjustment to arrival.[5] The methodology for calculating fuel consumption is similar to the approach used in the IMO's fourth GHG study (IMO, 2020a). We apply the so-called admiralty formula:

$$W_i = W_{ref,i} * \left(\frac{v_i}{v_{d,i}}\right)^n * \left(\frac{r_i}{r_{d,i}}\right)^m \tag{2}$$

In Eq. (2), W_i is the hourly propulsive power demand of vessel i while sailing at the current speed to design speed ratio $v_i / v_{d,i}$ and the current to maximum draft ratio $r_i/r_{d,i}$. The design speed, approximated by service speed, and the maximum draft are both gathered from the IHS vessel database. The reference power W_{ref} is calculated as 85 percent of the main engine output capacity in kilowatts,[6] also gathered from the IHS database. The parameter m is set to 2/3, as recommended by IMO (2020a). The parameter n is commonly set to 3, according to the so called admiralty formula, which is known to approximately hold close to vessels' design speeds (IMO, 2014; Psaraftis and Kontovas, 2014). Since the fleet in our sample is operating in a lower-than-normal speed range, the issue of how to model the speed-power relationship is clearly important in this context since it is likely to affect the estimated savings achievable through speed reduction. Modeling fuel savings according to the cubic approximation without regarding low observed speeds is likely to result in an overestimation of the fuel savings potential. Because of these uncertainties we apply two modeling approaches. Firstly, we apply a 'naïve' approximation wherein $n = 3$, in accordance with IMO (2020a). Secondly, we apply speed-dependent elasticities according to Eq. (3):

$$n = \begin{cases} 0.4 \ \text{if} \ v < 10 \\ 2.25 \ \text{if} \ v \leq v_d \\ 3 \ \text{if} \ v \geq v_d \end{cases} \tag{3}$$

This means that under the speed-dependent modeling approach, fuel savings realized from a downward adjustment of speed diminish with lower vessel speeds. For speeds below a certain threshold (set to 10 in the main analysis in accordance with findings of Adland et al. (2020) regarding tankers), there is very little to gain from a downward adjustment in speed. In fact, since W_i in the above equation refers to the *hourly* power demand, it is important to note that a reduction in speed can lead to an overall increase in fuel consumption, if the increased fuel demand following an increase in voyage time outweighs reductions in hourly fuel consumption. Since total fuel consumption varies linearly with voyage time, any additional downward speed adjustment where $n < 1$, leads to *increased* fuel consumption per unit of distance. This effectively sets a lower bound (v_l) equal to 10 rather than 7 for the speed-dependent modeling approach.

The difference between the speed-power curves between the modeling approaches (cubic vs. speed-dependent) is illustrated in Fig. 4 for four different values of v_d. Blue lines illustrate the speed-power relationship under the assumption of speed-dependent elasticities using the threshold described above. Black lines illustrate the speed-power relationship using the cubic approximation. As can be seen from the figure, modelled power demand under both approaches coincides when vessels are sailing at or above design speed.

3.2. Modeling fuel consumption and CO_2-emisions

For both modeling approaches, fuel savings following the hypothetical implementation of v_i^*, h hours in advance of original arrival time, can be calculated as:

$$\Delta FC_i = \left[W_i(v_{0,i}) * SFC_i(v_{0,i}) * h\right] - \left[W_i(v_i^*) * SFC_i(v_i^*) * \frac{v_{0,i}}{v_i^*}h\right] \tag{4}$$

In Eq. (4), the first half of the right-hand expression gives the main engine fuel consumption from propulsion at original speed ($v_{0,i}$) for h hours and the second half of the expression gives the corresponding fuel consumption for propulsion at adjusted speed (v_i^*), though the sailing time is scaled by $v_{0,i}/v_i^*$ to reflect the slowdown in speed. Specific Fuel Consumption (SFC) is calculated by taking into account main engine load L_i at current speed and using the formula parametrized by IMO (2020a):

$$SFC_i = SFC_{base,i} * \left[0.455 * L_i^2 - 0.71 * L_i + 1.28\right] \tag{5}$$

In Eq. (5), SFC_{base} represents the baseline SFC, which varies by type of engine, type of fuel and year of build. For each vessel in the dataset, we use information from IHS's ship database to determine baseline SFC based on IMO (2020a).

From calculated fuel savings, we can also calculate the corresponding reduction of CO_2-emissions. Following IMO (2020a), we assume emission factors (EF), kg CO_2 emitted per kg of fuel consumed, corresponding to 3.114, 3.206 and 2.75 for HFO/LSHFO, MDO and LNG fuels, respectively. Depending on the type of fuel used by a vessel, potential CO_2 savings can thus be calculated as (Eq. (6)):

---

[5] Auxiliary engine fuel consumption is assumed to be invariant to speed (Kontovas & Psaraftis, 2011) and therefore not relevant to the calculation of fuel savings due to speed adjustment.

[6] 85 percent of installed capacity typically corresponds to the power output at design speed.
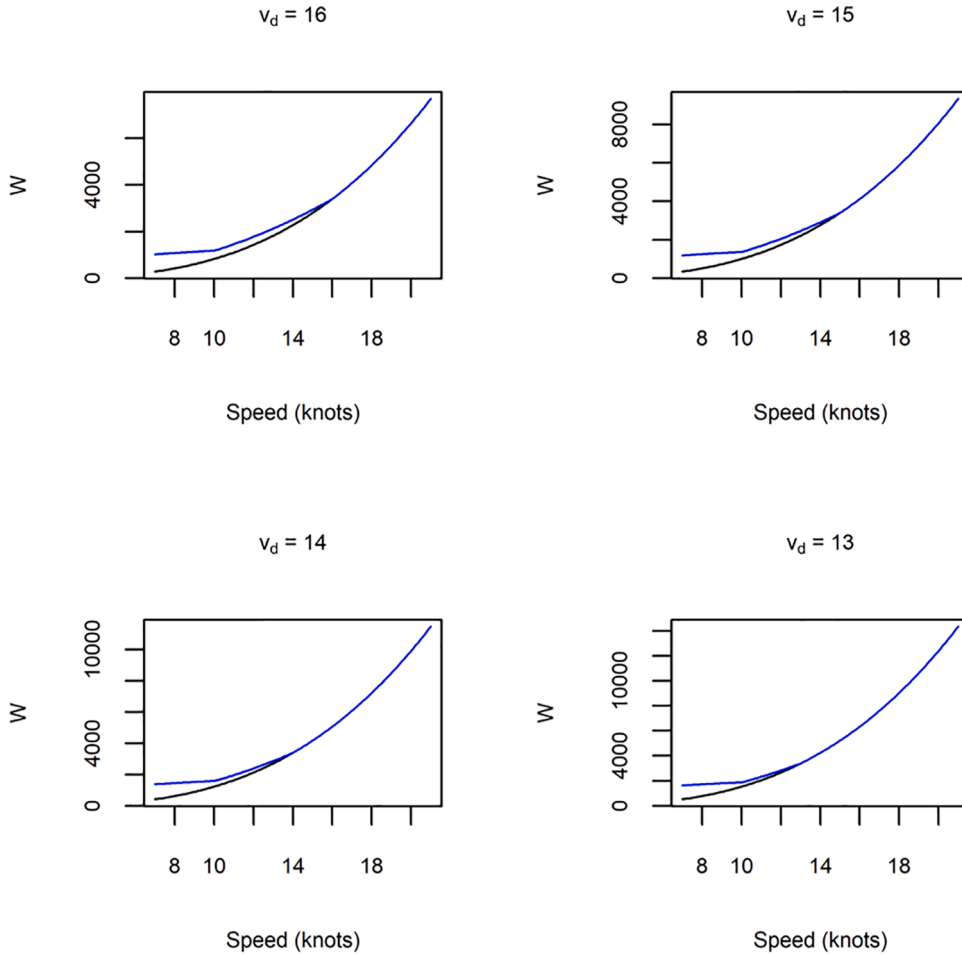
$v_d = 16$

$v_d = 15$

$v_d = 14$

$v_d = 13$

Fig. 4. Modelled speed-power relationship for different vessel design speeds. Blue line illustrates speed-power curve under a speed-dependent relationship with two threshold values. Black line illustrates cubic speed-power curve.

$$\Delta CO2_i = \Delta FC_i * EF_i \qquad (6)$$

We can also compute the share of fuel/emissions saved as a proportion of the estimated total fuel/emissions for the entire voyage. Using information from the SMA's port call records regarding each voyage's port of origin/destination and a port-to-port distance matrix developed by Eurostat, we estimate according to the methodology outlined above the total amount of fuel consumption and CO_2 emissions for the entire voyage.[7] Since we do not have information regarding voyage speed beyond the boundaries of our AIS data, we assume that the average recorded speed per vessel prior to anchorage ($v_{o,i}$) is representative for the voyage.[8]

4. Results

The results of applying the outlined methodology in terms of reduced fuel consumption on aggregate, reduced CO_2 emissions on aggregate and average fuel savings as a share of total voyage fuel consumption are shown in Table 2, Table 3 and Table 4 below. The results are structured according to operational and technical assumptions, where operational assumptions regard the assumed time beforehand when vessels can adjust speed downward in response to information regarding berth availability (*h* in Eq. (4)). Technical

---

[7] We match voyages' origin and destination ports with Eurostat's port distance matrix tool to compute total fuel consumption per voyage. However, for some 15 % of voyages in our dataset distances between ports could not be found due to unknown origin/destination or lacking coverage in the Eurostat matrix. Our subsequent calculation of fuel/emissions saved as a proportion of total voyage fuel/emissions leaves out this subset of voyages for which voyage distance could not be identified.

[8] It is possible that this assumption leads to an underestimation of average speeds for whole voyages if for instance vessels tend to slow down during the last few days prior to arrival. The consequence of this would be an underestimation of fuel consumption for entire voyages and thus an overestimation of the calculated savings as a proportion of total voyage consumption. We can however argue that this is unlikely to be an important problem since the majority of identified voyages are relatively short (see Figure 2).

Table 2

Results from Eq. (4), summed for all sampled voyages. The figures show total fuel savings (tonnes) under varying operational and technical assumptions. The variable h refers as in Eq. (4) to the number of hours in advance ships are assumed to adjust speed and n refers to the appearance of the exponent in the speed-fuel consumption curve.

	$\sum \Delta FC_i$ for $h = 12$	$\sum \Delta FC_i$ for $h = 8$	$\sum \Delta FC_i$ for $h = 4$
$n = 3$	6 940	4 564	2 363
$n = f(v)$	1 962	1 312	663

Table 3

Total CO_2 savings (tonnes) for the sample under varying operational and technical assumptions. As described by Eq. (6), emission savings per vessel are found by multiplying fuel savings by a fuel type-specific emission factor.

	$\sum \Delta CO2_i$ for $h = 12$	$\sum \Delta CO2_i$ for $h = 8$	$\sum \Delta CO2_i$ for $h = 4$
$n = 3$	21 505	14 143	7 324
$n = f(v)$	6 076	4 061	2 052

Table 4

Relative fuel savings for the sample under varying operational and technical assumptions. Expressed as the share of fuel savings in relation to fuel consumption for the entire voyage. Calculated only for cases where potential savings are greater than zero.

	$\sum \Delta FC_i / \sum FC_i$ for $h = 12$	$\sum \Delta FC_i / \sum FC_i$ for $h = 8$	$\sum \Delta FC_i / \sum FC_i$ for $h = 4$
$n = 3$	15.31%	9.89%	5.12%
$n = f(v)$	4.68%	3.27%	1.65%

assumptions regard the assumed form of the speed-fuel consumption curve (the exponent n in Eq. (2)), which is modelled either as a cubic relationship or using speed-dependent elasticities as outlined in the previous section.

It is shown in Table 2 that the range of fuel savings estimates under the assumption that vessels can reduce speed 4 h prior to original arrival varies from around 700 tonnes to around 2 400 tonnes. The higher value is reached when the speed-fuel consumption relationship is approximated using the cubic rule. This leads to a fuel savings estimate that is more than 3 times greater than the corresponding estimate using speed-dependent elasticities. The same factor of difference holds when assuming vessels can adjust speed 8 or 12 h prior to original arrival. Assuming vessels can adjust speed 8 or 12 h rather than 4 h prior to arrival naturally leads to higher fuel savings potential, as we allow for a longer period of time during which vessels can operate at reduced speeds.

As shown in Fig. 3, a small share (around 2 percent) of voyages operated at a speed of below 7 knots, which constitutes the assumed technical lower bound for feasible sailing speeds. This results in positive fuel savings (calculated as shown in Eq. (4)) being possible for 98% of voyages when using the cubic approximation for speed-fuel consumption relationship. Using the speed-dependent approach to model fuel savings, only 60% of vessels are revealed to have a positive fuel savings potential from speed adjustment. This is because 40 percent of voyages were already operating at initial speeds at or below 10 knots, below which the elasticity of fuel consumption with respect to speed is assumed to be so low that no further downward adjustment of speed is beneficial in order to save fuel. This is also visible in Fig. 3.

The CO_2 savings described in Table 3 follow the same pattern as the results in Table 2. Approximating emission savings from reduced speeds using the cubic rule results in more than three times higher emission savings compared to the alternative approach which takes current speeds into account. Still, annual savings of 2 000 – 6 000 tonnes of CO_2 (assuming implementation of speed adjustment 4 – 12 h prior to arrival) represents a non-negligible potential for emissions reduction.

The results in Table 4 are useful to put the estimated fuel and emissions savings into context. Under the cubic rule approximation, we can see that the fuel savings from adjusted speed prior to arrival can amount to some 5 – 15% of voyage fuel consumption, depending on the timing of initial speed adjustment. Using instead the speed-dependent modeling approach, these relative fuel savings are estimated to be significantly smaller: around 1.7 – 4.7%, depending on when speed adjustment can be implemented.

5. Conclusion, discussion, and future research

Previous research and professional initiatives within the industry have identified PCO measures in general and VA in particular as holding significant promise for increased fuel efficiency and as a CO_2-abatement strategy for the tramp shipping sector, globally. VA has been evaluated as technically and operationally feasible, cost-effective and mutually beneficial for all key actors such as cargo owners, shipping companies and ports. Given these circumstances, the unrealized potential of VA could be described as an energy efficiency gap. However, recent evidence from among others Poulsen and Sampson (2019) and Adland et al. (2020) reveal that the potential of VA for substantively contributing to increased fuel efficiency might be overestimated in the previous accounts. Raising the question whether what looked like an energy efficiency gap in reality reflected an overly optimistic estimate of the potential of such interventions in the first place. In this paper, we revisit some of the modeling assumptions that evidently account for some of the potentially overly optimistic results of the past.

Our results presented above highlight some important aspects regarding the fuel efficiency potential of policy schemes which are intended to facilitate more optimized vessel speeds prior to arrival in port such as VA. The data collection procedure, which is designed to capture voyages where there is plausible room for reduced unproductive waiting time through adjusted speed, results in an annual figure of around 3 000 port calls in Sweden. This is in relation to roughly 19 000 port calls in the same vessel segments. It is noteworthy that no more than 15% of tramp voyages report spending significant times at anchor prior to calling at a Swedish port. Out of these roughly 3 000 port calls, some 60% are estimated to be able to benefit in terms of fuel consumption from speed reduction prior to arrival (assuming speed-dependent elasticities). The fact that this is not the case for all port calls is explained by initial speeds which are so low that there are unlikely to be any significant gains from further reduction.

For the 60% of sampled port calls where the fuel savings potential is estimated to be greater than zero, the fuel reduction potential (savings as a share of total voyage consumption) is roughly 1.7 – 4.7% if reduction can take place 4 – 12 h prior to planned arrival. It should be kept in mind that these figures represent a best case, and the savings potential cannot be generalized to the sector overall. The results are calculated from cases where there is waiting time prior to arrival in port and where the initial speed is such that reduction meaningfully impacts fuel consumption without altering the quality of the service in terms of increased travel time from quay-to-quay. Subsequently, the fuel efficiency improvement potential of VA as a share of total energy use, is substantially lower than the reported best case for voyages that are affected by its implementation. The assumed timing of speed reduction in response to information regarding terminal readiness (4 – 12 h prior to planned arrival) is considered relevant given that the sample of identified voyages is composed of mainly short routes, most of which have a sailing time of 1 – 2 days, which considerably limits the scope for earlier arrival planning.

An interesting aspect of the results concerns the sizeable differences in estimates between the two approaches to modeling fuel consumption. Under the typical cubic rule approximation, the results generated vastly exceed those generated using speed-dependent elasticities. The difference is large because vessels are overwhelmingly operating at lower-than-normal speeds, and the cubic approximation is best known to hold at design speeds. The difference in results highlights the inadequacy of applying cubic approximations to estimate the potential of speed-reducing measures in a market environment when operational speeds are low. The main contribution of this study consists of demonstrating the shortcomings of the Admiralty formula for estimating the fuel efficiency potential of speed reduction in low sailing speed markets. Furthermore, it is shown that, given the characteristics of the Swedish tramp shipping, the potential for fuel savings and reduction of CO_2-emissions from widespread adoption of VA is likely to be marginal at best.

Still, more detail into empirical speed-fuel curves for different vessel types would be useful in order to more accurately model the potential of speed adjustment without having to rely on exogenous assumptions regarding threshold values. This is a recommendable task for future research. Provided higher quality empirical data, other key nautical aspects such as weather effects and routing choices could also be considered in more sophisticated models. Finally, in order to obtain accurate estimates of feasible potential of PCO measures, as opposed to best case estimates such as those presented here, the sample of calls that are technically viable for VA intervention, should be analyzed with regards to operational and business model considerations. It is likely, given the results presented by Poulsen and Sampson (2019) that a consequential number of these voyages cannot realistically be expected to adjust their speed during the port call process, notwithstanding potential benefits of fuel savings, due to other reasonable consideration. To produce an accurate estimation of the size of this sub-category of voyages is likely to impact the final results in a significant way.

Declaration of interests

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.

References

Acciaro, M., Hoffman, P., Eide, M.S., 2013. The energy efficiency gap in maritime transport. J. Shipp. Ocean Eng. 3, 1–10.
Adland, R., Cariou, P., Wolf, F.C., 2020. Optimal ship speed and the cubic law revisited: empirical evidence from an oil tanker fleet. Transp. Res. E 140, 101972.
Adland, R., Jia, H., 2018. Contractual barriers and energy efficiency in the crude oil supply chain. In: 2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM).
Andersson, P., Ivehammar, P., 2017. Green approaches at sea: the benefits of adjusting speed instead of anchoring. Transp. Res. D 51, 240–249.
Berthelsen, F.H., Nielsen, U.D., 2021. Prediction of ships' speed-power relationship at speed intervals below the design speed. Transp. Res. D 99, 102996.
BIMCO, 2013. Virtual Arrival Clause for Voyage Charter parties, BIMCO Special Circular no.9, October 4, Bagsvaerd. BIMCO.
Bouman, E.A., Lindstad, E., Rialland, A.I., Strømman, A.H., 2017. State-of-the-art technologies, measures, and the potential for reducing GHG emissions from shipping – a review. Transp. Res. D 52, 408–421.
Büssow, T., 2020. The Future of Shipping: the positive impact of just-in-time port arrivals. Wärtsilä white paper. https://www.wartsila.com/insights/whitepaper/future-of-shipping. accessed May 20, 2021.
Clarkson, 2020. Interim results presentation, https://www.clarksons.com/media/1232279/20200807_-_2020_interim_presentation_final.pdf.
Dewan, M.H., Yaakoub, O., Suzana, A., 2018. Barriers for adoption of energy efficiency operational measures in shipping industry. WMU J. Marit. Affair. 17, 169–193.
Du, Y., Chen, Q., Lam, J.S.L., Xu, Y., Cao, J.X., 2015. Modeling the impacts of tides and virtual arrival policy in berth allocation. Transp. Sci. 49, 939–956.
Eide, M.S., Longva, T., Hoffman, P., Endresen, Ø., Dalsøren, S.B., 2011. Future cost scenarios for reduction of ship CO2 emissions. Maritime Policy Manag. 38 (1), 11–37.
GIOMEEP, 2018. IMO holds roundtable on just-in-time operations of ships, https://glomeep.imo.org/news/imo-holds-roundtable-on-just-in-time-operation-of-ships/, accessed on May 20, 2021.
IMO, 2014. Third IMO GreenHouse Gas Study 2014. International Maritime Organization (IMO), London, UK.
IMO, 2020a. Fourth IMO GreenHouse Gas Study. International Maritime Organization (IMO), London, UK.
IMO, 2020b. Just-In-Time Arrival Guide – Barriers and Potential Solutions. International Maritime Organization (IMO), London, UK.
Intertanko/OCIMF, 2011. Virtual Arrival: Optimising Voyage Management and Reducing Vessel Emissions – An Emissions Management Framework, 2nd Edition. Intertanko/Oil Companies International Marine Forum, London.

Jia, H., Adland, R., Prakash, V., Smith, T., 2017. Energy efficiency with the application of Virtual Arrival policy. Transp. Res. D 54, 50–60.

Johnson, H., Styhre, L., 2015. Increased energy efficiency in short sea shipping through decreased time in port. Transp. Res. A 71, 167–178.

Kontovas, C., Psaraftis, H.N., 2011. Reduction of emissions along the maritime intermodal container chain: operational models and policies. Maritime Policy Manag. 38 (4), 451–469.

Meng, Q., Du, Y., Yadong, W., 2016. Shipping log data based container ship fuel efficiency modeling. Transp. Res. B 83, 207–229.

Rehmatulla, N., Smith, T., 2015. Barriers to energy efficiency in shipping: a triangulated approach to investigate the principal agent problem. Energy Policy 84, 44–57.

Poulsen, R.T., Sampson, H., 2019. Swinging on the anchor': the difficulties in achieving greenhouse gas abatement in shipping via virtual arrival. Transp. Res. D 73, 230–244.

Poulsen, R.T., Sampson, H., 2020. A swift turnaround? Abating shipping greenhouse gas emissions via port call optimization. Transp. Res. D 86, 102460.

Poulsen, R.T., Ponte, S., Sornn-Friese, H., 2018. Environmental upgrading in global value chains: the potential and limitations of ports in the greening of maritime transport. Geoforum 89, 83–95.

Psaraftis, H.N., Kontovas, C.A., 2013. Speed models for energy-efficient maritime transportation: a tarxonomy and survey. Transp. Res. C 26, 331–351.

Psaraftis, H.N., Kontovas, C.A., 2014. Ship speed optimization: concepts, models and combined speed-routing scenarios. Transp. Res. C 44, 52–69.

Schwartz, H., Gustafsson, M., Spohr, J., 2020. Emission abatement in shipping – is it possible to reduce carbon dioxide emissions profitably? J. Clean. Prod. 254, 120069.

Song, D.W., Panayides, P.M., 2015. Maritime Logistics: a Guide to Contemporary Shipping and Port Management, 2nd edition. Kogan Page Limited, Great Britain.

Tongzon, J., 2009. Port choice and freight forwarders. Transp. Res. E 45, 186–195.

Venturini, G., Iris, C., Kontovas, C., Larsen, A., 2017. The multi-port berth allocation problem with speed optimization and emission considerations. Transp. Res. D 54, 142–159.

Wang, S., Meng, Q., 2012. Sailing speed optimization for container ships in a liner shipping network. Transp. Res. E 48, 701–714.

Yu, H., Fang, X., Liu, J., Chen, J., 2021. Literature review on emission control-based ship voyage optimization. Transp. Res. D 93, 102768.