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Assessment of the feasibility of vessel trains in the ocean shipping sector

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ABSTRACT

This paper introduces the concept of vessel train, a new mode in maritime transport offering both environmental and economic advantages. The study provides a framework for analyzing the economic feasibility of vessel train in ocean shipping, focusing on four different scenarios to evaluate its impact on navigation speed and productivity for both round-trip and year-long operations. Using the container ship route from Yangshan Port to the Port of Piraeus as a case study, the research compares vessel train with traditional shipping methods by categorizing shipping costs. It also includes a sensitivity analysis considering factors like route length, frictional resistance reduction, and variations in the container freight index, fuel prices, and carbon tax rates. The findings indicate that vessel train can reduce transportation costs and fuel emissions. The paper concludes that vessel train could significantly contribute to a competitive and sustainable future in shipping.

1. Introduction

According to the 2022 United Nations Conference on Trade and Development (UNCTD), maritime transport is responsible for over 80 % of global trade by volume. As a crucial element in connecting worldwide industrial chains, it faces significant challenges in various areas (Rigot-Müller et al., 2022; Sibul & Jin, 2021; Adland et al., 2018). Notably, maritime transport emits greenhouse gases equivalent to the world sixth-largest country emissions (Wang et al., 2021). Furthermore, the expanding global fleet is expected to necessitate an additional 32,000 officers by 2025 (Igbinosun et al., 2020). These challenges are prompting the shipping industry to explore solutions, such as navigating the Arctic route to achieve economic and environmental advantages (Theocharis et al., 2018). The concept of unmanned vessels represents a promising direction for future shipping, potentially addressing issues related to high crew costs and shortages (Munim, 2019). However, considering the average ship lifespan of around 20 years and the current pace of technological advancement, the widespread adoption of fully autonomous ships remains a distant prospect.

Compared to autonomous ships, the concept of Vessel Train (VT), also known as waterborne platooning, offers a more feasible short-term solution for shipping operations. This model, as outlined by Colling & Hekkenberg in 2020 and illustrated in Fig. 1, does not necessitate vessel reconstruction and is less technologically complex. VT involves a manned leader vessel (LV) and several minimally manned follower vessels (FVs) that can join or leave the formation as required. The earliest VT was formed by physical connections

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using chain and ropes while the advancement of technology realizes wireless connections, passing information between vessels to communicate to a control system and allows vessels to follow each other (Colling, 2021). To form a convoy, participating vessels converge in a designated area through coordinated departure times. The assembly can occur either in a port or during the journey, depending on whether the FVs have the capability for independent navigation. Following the developmental pattern ‘inland waterways-coastal shipping-ocean shipping’ of ship intelligent technology, the application of VT will gradually expand from VT transport involving homogeneous vessels in inland waterways to that involving heterogeneous vessels in ocean shipping sector.

Until now, VT has been implemented in surface ships through projects like NOVIMAR (2018) and the DARPA project (Nuss, 2020). The primary objectives of VT implementation include:

- Economic sustainability by keeping crew cost (Colling & Hekkenberg, 2020) and fuel cost lower (He et al., 2022),
- Environmental sustainability by reducing navigation resistance and thus reducing fuel consumption (Hult et al., 2019; Levander et al., 2015). It can be also speculated that the combination of VT and unmanned vessels will be an interesting and important research direction of maritime transport (Yang et al., 2023).

Assessing the feasibility of VT, which includes both technical and economic aspects, is crucial for its implementation. Technically, the cooperative control of multiple surface vessels has been a significant topic in the control community, as noted in works by Fahimi (2007), Jin (2016), and Xie et al. (2017). The leader–follower formation in shipping was practically demonstrated in the NOVIMAR project (2018). For formation organization, Chen et al., (2018, 2020) developed a framework for the cooperative scheduling and control of multi-vessel systems in urban waterway networks. Additionally, Yang et al. (2023) introduced a mixed integer programming model for VT scheduling in a hub-and-spoke network. Another technical challenge in implementing VT is cooperative scheduling. When vessels share the same routes, considerations extend beyond vessel size and navigation speed include making minor adjustments to the scheduling, typically within a few hours, to synchronize the departure times of all participating vessels (Yang et al., 2023). This implies that significant operational changes for the involved companies may not be necessary, and participation in VT might only require payment of organizational costs.

However, there has been limited focus on evaluating the economic viability of VT, with notable exceptions being the NOVIMAR project’s studies. These studies concentrated on VT in short-sea shipping and inland waterway transport, with a focus on crew size reduction. The proportion of crew costs to total costs significantly differs between ocean shipping (Kretschmann et al., 2017) and short-sea or inland waterway transport (Colling, 2021), making it challenging to extrapolate the viability of VT in ocean shipping from current studies. The lack of consideration for cost savings due to formation resistance reduction in these studies further complicates this assessment.

Therefore, this paper conducts a cost-benefit analysis to ascertain the economic feasibility of VT in the ocean shipping sector, building upon existing studies to develop formation resistance reduction models. The core research approach involves comparing the benefits and costs of conventional transport versus VT to determine if the economic advantages of VT can outweigh its economic drawbacks. To reflect the variety of potential vessel formation scenarios in reality, both homogeneous and mixed VT transport under different formation participation frequencies were designed and analyzed. This paper, going beyond the scope of Colling et al. (Colling & Hekkenberg, 2020), offers a more comprehensive understanding of VT feasibility in the ocean shipping sector by considering various aspects such as the sources of VT benefits, the design of VT compositions, and the requirements for VT participation. The Novelties and impact are summarized as follows:

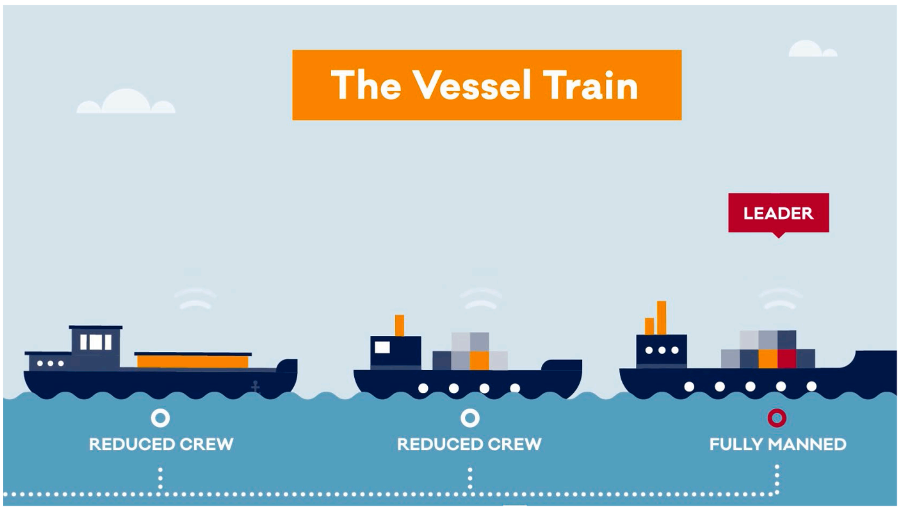

Fig. 1. The diagram of VT in ocean shipping (https://novimar.eu/).

- The concept of VT in ocean shipping is novel, offering a fresh perspective on maritime transport solutions.
- The research highlights the potential of VT to reduce transportation costs and fuel emissions, contributing to the growing body of literature on sustainable and efficient maritime transport. The findings could influence policy-making and operational decisions in the maritime industry, especially concerning sustainable practices and cost-efficiency.
- The study paves the way for future research in this area, encouraging more in-depth exploration of VT and its implications in different maritime contexts. If the VT model is adopted widely, it could lead to significant changes in maritime transport operations, enhancing efficiency, reducing environmental impact, and potentially reshaping global shipping practices.

The rest of paper is organized as follows: Section 2 analyzes the related literature on VT benefits. Section 3 introduces the framework for assessing VT feasibility, encompassing the determination of feasibility conditions, selection of cost items, and design of case studies. Section 4 presents the results of the case studies on the economic viability of VT. Section 5 offers the results of sensitivity analyses on critical factors. Finally, Section 6 presents conclusions drawn from the comparative cost-benefit analysis.

2. Literature review

This section highlights the role of VT technology in transforming maritime operations, focusing on crew reduction and sustainability. It positions our discussion at a crucial intersection, setting the stage for an in-depth exploration of VT models. This exploration aims to uncover how these models can improve operational efficiency and environmental sustainability in the shipping industry, bridging the gap between theoretical research and practical applications.

2.1. VT model for crew reduction

The most intuitive economic benefit of VT is reducing the crew cost of FVs by moving the situational awareness and navigational tasks and to the LV (Colling, 2021). Considering the minimum requirements for crew configuration for automated navigation tasks and automating mooring tasks (Kooij & Hekkenberg, 2020), Colling and Hekkenberg (2020) discovered that the benefits derived solely from automated navigational control were not sufficient for the short-sea sector's application of VT. Meersman et al. (2020) and Colling et al. (2021) further found that for VT to be economically viable in inland waterway transport in the Rhine River, specific requirements related to the number of participating vessels and route length needed to be met to achieve positive returns. Regarding the study on platooning in the Yangtze River in China, Jiao et al. (2024) found that under the current operational conditions, the reduction in crew costs brought by VT is still hardly able to significant lower transport costs.

2.2. VT model for sustainable maritime transportation

Another unique benefit of VT is the potential for resistance reduction. This concept is inspired by the observation that many animals in nature move in organized groups to conserve energy and enhance mobility, as noted in studies by Lissaman & Shollenberger (1970), Portugal et al. (2014), and Yuan et al. (2021). This principle is also applied in truck platoons to improve aerodynamics, thereby reducing fuel consumption and emissions (Alam et al., 2015; Bhoopalam et al., 2018). When applied to VT, there are two main implementation strategies. The first involves dividing the ship into a main hull and side hulls, arranged in a V-shape pattern, as suggested by Sulistyawati et al. (2018). The second approach focuses on formation transport for vessels with current hull designs, comparing resistance reduction in tandem, parallel, and triangle formations (He et al., 2022). He et al. (2023) further found that maintain specific longitudinal distances and operation at defined speeds in VT can effectively reduce the navigation resistance of FVs. Unfortunately, research on this subject is limited, and no studies have yet determined whether the resistance reduction achieved in actual formations can offset the potential drawbacks of formation transport.

Additionally, VT formed by both manned vessel and unmanned vessels can improve the safety and security of autonomous vessels during the transition from conventional vessels to unmanned ships (Yang et al., 2023). In polar navigation, VT generally comprises high-grade icebreaker serving as the LV and low-grade icebreakers as FVs. This configuration, utilizing vessels with different icebreaker capabilities, aims to maximize economic efficiency (Zhang et al., 2019; Liu et al., 2022; Liu et al., 2024).

2.3. Problem description and motivations

VT and a group of barges towed by a tug both involve the transportation of goods using multiple vessels, but they differ in fundamental ways. VT utilizes individual vessels with their own propulsion systems, offering flexibility, maneuverability, and potentially higher efficiency, albeit with higher initial costs. In contrast, a group of barges towed by a tug relies solely on the tugboat for propulsion, limiting maneuverability and speed to the capabilities of the tug, yet potentially reducing operational costs. The choice between VT and tug-towed barges depends on factors such as specific transportation needs, operational preferences, and economic considerations.

The current research on VT predominantly focuses on the economic benefits derived from crew costs reduction in inland and coastal waters. There is a significant gap in research regarding VT application in ocean shipping, which is attributed to distinctive motivations for VT transport across diverse scenarios. In inland water transport, crew costs account for about 30 %-40 %, while in ocean shipping, crew costs are less than 10 %. This difference diminishes the benefits of VT in ocean shipping from the perspective of crew cost reduction. However, since there is burgeoning research exploring the resistance reduction effect, a critical facet is amiss—incorporating this effect into VT assessments to holistically evaluate its feasibility. The omission of this consideration renders the current VT feasibility assessments incomplete, lacking a comprehensive analysis that incorporates the distinct challenges and opportunities presented by ocean-going VT transport. By addressing the dearth of research on ocean shipping scenarios and integrating the resistance reduction effects, our study seeks to provide a more comprehensive understanding of VT's feasibility, filling crucial voids in current research.

3. Methodology

3.1. Framework for cost-benefit analysis of VT

Shipping cost-benefit analysis primarily relies on the shipping case-flow model (Stopford, 2009), which describes the sources of shipping revenues, the components of operating and capital payments, and the net profit retained by the ship owner. When assessing the benefits of a new shipping route or shipping mode, the desired outcome is an increase in transport revenue with a decrease in transport cost compared to traditional routes or modes. Consequently, existing related studies conduct shipping cost-benefit comparisons by analyzing variations in the shipping revenues and cost (Ding et al., 2020; Kretschmann et al., 2017).

The framework for analyzing the feasibility of VT is accordingly designed in Fig. 2. The process begins by a comprehensive analysis of the cost-benefit elements in VT shipping based on the recognition of the unique characteristics of VT transport. After establishing the estimation method for each selected cost element, the key performance indicators, VT mode, and the fundamental conditions for the economic viability of VT are determined based on predefined assumptions. Subsequently, an economic feasibility assessment and sensitivity analysis of key influencing factors within the case studies are conducted. The final step involves presenting conclusions and recommendations concerning the commercial viability of VT in the ocean shipping sector.

3.2. The analysis of cost components of VT

To accurately assess the cost-benefit differences between conventional transport and Vessel Train (VT) transport, it is essential to identify the characteristics of VT transport. These characteristics are summarized into four components (Colling, 2021; He et al., 2022):

- Crew manning reduction through transferring maneuvers from follower vessels (FVs) to the leader vessel (LV);
- Variations in shipping operations, where VT navigation speed is determined by the slowest vessel, and port time for participants may increase to join the VT;
- Navigation resistance reduction, potentially decreasing the navigation resistance of FVs in the VT;
- Application of the VT control system, including standard sensors and communication devices (e.g., AIS, radar), processing components (e.g., position estimator, multi-sensor tracker), and the human–machine interface and control components.

When combined with cash flow items (Stopford, 2009), changes in shipping revenues and costs due to VT include:

- Variations in port time and navigation speed affecting ship productivity;

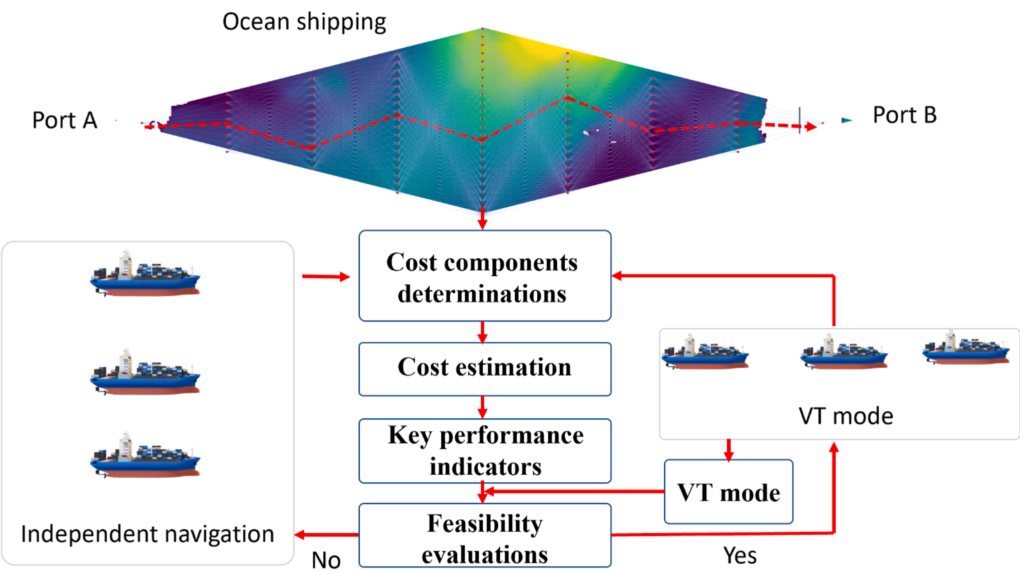

Fig. 2. The framework of a feasibility assessment for VT in ocean shipping.

- Operating costs, crew costs decrease, and insurance costs are correspondingly reduced (Colling, 2021), but time-related costs increase due to longer port and travel times;
- Voyage costs, VT transport reduces ship navigation speed and resistance, resulting in lower fuel and pollutant costs; d) depreciation, interest, and operating costs of the VT control system.

The assumptions for the research scenario are first provided as follows: (a) crew wages are assumed to remain unaffected by fluctuations in crew demand caused by VT, avoiding the complexity of evaluating the impact of crew requirements on crew wages; (b) freight charges are primarily influenced by cargo prices and are independent of the existence of VT, allowing for a comparative analysis between traditional and VT transportation under equivalent conditions. Based on these assumptions and abovementioned analysis, the revenue and cost analysis items for VT feasibility analysis in ocean shipping are determined, as presented in Table 1. For simplification, cargo costs only consider the cost of handling at the port (Ding et al., 2020; Furuichi & Otsuka, 2013). Since the IMO Marine Environment Protection Committee proposed new emission guidelines (International Maritime Organization, 2011), some countries have introduced or are considering carbon taxes (Ding et al., 2020; Kossoy et al., 2014), hence the inclusion of carbon tax costs. Finally, this paper does not consider shipping delay costs, as the scheduling plan already accounts for port waiting times, excluding delays during navigation.

3.3. Cost estimation of VT mode

For the various types of costs outlined in Table 1, the estimation methods for most costs are fundamentally similar in both the traditional model and the VT model. Therefore, this paper includes the detailed calculation processes and the used data in **Appendix A**. The primary focus of cost estimation here is on the changes resulting from the reduction in crew members and the decrease in navigation resistance of follower vessels (FVs) in VT.

- Crew cost estimation

Since crew cost in operating costs is mainly affected due to VT, crew cost is considered separately. Crewing varies in different transport scenarios. And the reduction of crew cost depends on the reduced crew role, the corresponding salary, and the number of reduced crew members. In addition to the crew's basic salary, crew cost also includes employment-related costs that can be calculated as a percentage of the basic salary. Equation (1) shows the calculation of annual crew costs.

$$C^{crew} = \sum_{j=1}^{r} (\eta_{c,j}(c_{w,j} + \frac{c_{w,j}{}^{*}p_{ex}}{1 - p_{ex}})) \tag{1}$$

where r represents different crew roles, $n_{c,j}$ and $c_{w,j}$ represents the number and the average wage of the j_{th} crew role, p_{ex} represents the percentage of employment-related costs to the basic salary. The crew configuration requirements for various types and sizes of vessels vary across different regions. In the case of China, for example, the crew complement for the largest level of ocean-shipping vessels is typically 7 individuals for both the deck department (1 master, 1 chief mate, 1 s office, 1 third office, 2 deck A.B rating, and 1 deck boy) and the engineering department (1 chief engineer office, 1 s officer, 1 third engineer officer, 1 forth engineer officer, 1 engine-room A.B rating, and 2 engine-room boys). On the other hand, it is also possible to obtain crew cost based on statistical data to avoid the impact of the differences in p_{ex} setting and crewing requirements in different countries (Igbinosun et al., 2020).

- Navigation resistance reduction estimation

VT affects fuel consumption costs through causing change in ship navigation resistance. The resistance reduction in VT mostly comes from the hydrodynamic interactions between the ships. Due to the wake of LV, the flow velocities relative to FVs are less than

Table 1
Revenue and cost analysis items for VT transport in ocean shipping.

Categories	Items	Explanation
Productivity revenue	operation speed	changes due to the speed-consistence requirement in VT
	port time	changes due to increasing waiting time for VT departure
Capital costs	description cost	changes due to variations in the port time and underway time for both ship and VT control system
	interest cost	
Operating costs	crew cost	changes due to variations in crew manning
	other ship operating costs	changes due to variations in the port time and underway time
	VT control system operating cost	changes due to the application of VT control system
Voyage costs	main engine fuel cost	changes due to variations in navigation speed and navigation resistance
	auxiliary engine fuel cost	changes due to variations in the port time and underway time
	canal navigation cost	changes in travel rounds due to variations in waiting time and underway time
	port charges	changes due to variations in productivity
Cargo cost	cargo handling costs	changes due to variations in productivity
Other costs	carbon tax cost	changes due to variations in fuel consumption

that in the far field, resulting in the reduction of the frictional resistance of FVs (He et al., 2022). Considering that the ships need to maintain at least one ship length apart (Colling, 2021), the percentage reduction of frictional resistance coefficient C_F for the three-ship tandem system is shown in Table 2, where *Fr* is the Froude number in Equation (2). When *Fr* is relatively small, the reduction in C_F of FVs is significant. However, *Fr* s in realistic sailing correspond to larger values and these calculation results cannot be used directly. Therefore, considering that the ship sails under displacement, i.e. $Fr < 1$, the following assumptions are given: a) the larger speed at which the ship sails, i.e. the greater the *Fr*, the less the reduction in C_F; b) the reduction of C_F becomes zero when the Froude number is large enough and the vessels maintain suitable positions.

$$F_r = \frac{v}{\sqrt{g^*L}} \tag{2}$$

where v and L represent the navigation speed and ship length, and g is gravitational acceleration.

Without considering the change in the resistance of LV, the C_F reduction percentage models of the FV-1 and FV-2 are constructed as shown in Equations (3) and (4), respectively. The corresponding model curves are displayed in Fig. 3, where y-axis represents the reduction percentage of frictional resistance coefficient and x-axis corresponds to *Fr*. This implies that as vessels become larger and slower in speed (resulting in a smaller Fr), the reduction in navigation resistance becomes more significant. Since it is not possible to obtain accurate information on the change in resistance reduction, sensitivity analysis will be conducted on the P_{rc}.

$$P_{rc}^2 = 0.0891504^*e^{-4.93129^*sin(-3.74824^*F_r-1.48759)} \tag{3}$$

$$P_{rc}^3 = 0.211683^*e^{-4.50171^*\sin(-3.24821^*F_r-1.50407)} \tag{4}$$

3.4. Key performance indicators

Whether productivity changes during the assessing phase determines whether shipping revenue is included in the performance indicators. In scenarios where productivity remains unchanged or changes are challenging to calculate, such as in a single round-trip participation, it is necessary to analyze only the difference in transport costs between VT and conventional transport. Given that the transport revenue remains constant, the total transport cost can be used to compare the economic gains between the reference vessel (RV), the LV and the FVs. Equations (5) and (6) represent conditions (1) and (2) (see section 3.6), respectively, for the feasibility of VT.

$$\sum_j^n C_r^{i,j} - \sum_j^n C_f^{i,j} \geq 0, \forall i \in Nandi \geq 1 \tag{5}$$

$$\sum_i^N \left(\sum_j^n C_r^{i,j} - \sum_j^n C_f^{i,j} \right) + \left(\sum_j^n C_r^j - \sum_j^n C_l^j \right) \geq C^S \tag{6}$$

where f, l, and r represent FV, LV, and RV; i and N represent i_{th} FV and FV set; j and n represent j_{th} cost and cost set {capital costs, operating costs, voyage costs, cargo cost, other costs}; C represents the shipping cost while C^S is the VT organization cost.

Considering the changes to shipping productivity brought by frequent or regular participation in VT transport, Equations (7) and (8) represent the two feasibility conditions including shipping costs and revenues.

$$\sum_T \left(R_f^i - \sum_j^n C_f^{i,j} \right) - \sum_T \left(R_r^i - \sum_j^n C_r^{i,j} \right) \geq 0, \forall i \in N \tag{7}$$

$$\sum_i^N \left(\sum_T \left(R_f^i - \sum_j^n C_r^{i,j} \right) - \sum_T \left(R_r^i - \sum_j^n C_r^{i,j} \right) \right) + \left(\sum_T \left(R_l^i - \sum_j^n C_l^{i,j} \right) - \sum_T \left(R_r^i - \sum_j^n C_r^{i,j} \right) \right) \geq C^S \tag{8}$$

where R and T represent the shipping revenue and the assessment phase, respectively.

3.5. VT mode design

The assessment timeframe encompasses the entire lifespan of ships (Kretschmann et al., 2017), one year of ship operation (Colling & Hekkenberg, 2020), and individual round trips (Ding et al., 2020). Since VT transport doesn't necessitate building new ships, assessing cost-effectiveness over the entire service life is unnecessary. Moreover, while vessels can join VT transport for individual

Table 2
Reduction percentage of frictional resistance coefficient for the three-ship tandem system with one ship length apart (He et al., 2022).

Fr	0.0479	0.0575	0.067	0.0766	0.0862	0.0958
LV	0.60	0.63	0.68	0.63	0.49	0.15
FV-1	12.08	11.82	11.52	11.17	10.72	10.25
FV-2	18.75	18.50	18.10	17.72	17.27	16.68

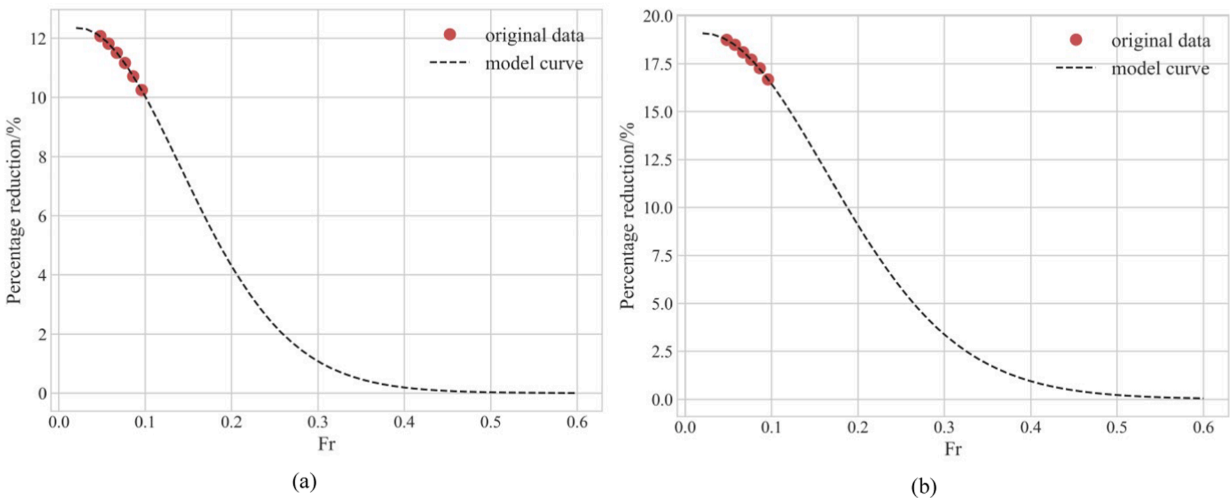

Fig. 3. Reduction percentage curves of the frictional resistance coefficient. (a) FV-1; (b) FV-2.

round trips based on their needs, they can also engage in VT transport for extended periods through commercial partnerships. Although individual round trips might take longer in VT mode, it doesn't affect the cargo-carrying capacity. Furthermore, if a vessel participates in VT transportation irregularly rather than continuously, the added time can be considered negligible over long-duration transport phases, making it challenging to estimate changes in ship productivity in this scenario. Therefore, for individual round-trip transport, a cost-benefit analysis can be conducted without accounting for productivity changes due to VT. However, for annual participation, the changes in productivity brought by VT should be considered. Accordingly, scenarios for both individual round-trip participation and annual participation are designed.

When defining the assessment timeframe, the composition of the VT also needs to be established. Since resistance reduction models are only developed for the first and second follower vessels according to He et al. (2022), a three-ship tandem VT system is constructed. Besides VT systems with the same type of vessel, the impact of different vessel types on the speed of the VT system is considered by designing VT systems consisting of diverse ship types. Consequently, four VT scenarios will be analyzed: round-trip VT systems for the same type of vessels, round-trip VT systems for different types of vessels, year-trip VT systems for the same type of vessels, and year-trip VT systems for different types of vessels.

For individual round-trip VT transportation, the total operating time t_{rv} includes the sailing time t_s and the port time t_p, where t_p consists of the cargo handling time t_o and the waiting time t_w for the departure of VT, as shown in Equations (9) and (10).

$$t_s = \frac{d_r}{v_r} \tag{9}$$

$$t_{rv} = 2^*(t_s + t_o + t_w) \tag{10}$$

where d_r is the route length and v_r is the navigation speed. For VT systems consisting of the same type of vessels, v_r is the designed speed; for VT systems consisting of different types of vessels, v_r is the smallest designed speed of all ships.

For year-trip VT transportation, to accurately assess changes in productivity, Equations (11) and (12) represent the operating time t_{sv} of one-way transport and the total year operating time O, respectively. Combined with cargo capacity V, the ship's productivity can be calculated using Equation (13).

$$t_{sv} = t_s + t_o + t_w \tag{11}$$

$$O = 24^*(D - r_h) \tag{12}$$

$$P = floor\left(\frac{O}{t_{sv}}\right)^*\mathrm{V} \tag{13}$$

where D is the total time a year and r_h is the holidays; *floor* denotes the downward rounding function.

3.6. *Feasibility evaluations*

The three business models for VT implementation are company-internal VT coordination, platform-based leading coordinated formations, and peer-to-peer VT services (Colling, 2021). In a scenario where VT technology is mature, a third-party platform-based organization mode can assemble VTs using ships from various companies, originating from different locations and heading to different destinations. This approach can effectively expand VT transportation services. In this paper, we assume the business model of third-party platform organization, which involves organization and coordination costs. In this model, VT transport includes both service organizers and users, with the users being primarily the FVs, as the LV does not reduce crew numbers and may even incur higher transport costs due to longer operation durations. According to the feasibility study of VT in the short-sea sector (Colling & Hekkenberg, 2020), the commercial viability of VT can be defined as follows:

- Condition (1): The cost of transport for FVs in VT mode should not be higher than in conventional mode.
- Condition (2): The total savings from FVs should not be lower than the sum of the VT organizer's service costs and the additional cost of the LV.

Condition (1) is a prerequisite for condition (2). VT is considered commercially viable when both conditions are satisfied. If only condition (1) is met, the implementation of VT may require external incentives, such as policy support, considering the environmental and other societal benefits that VT offers.

Finally, sensitivity analysis of key factors helps further clarify the feasibility of VT transport in specific scenarios, including: (a) external key factors such as freight charges, fuel prices, and carbon emission prices; and (b) key factors intrinsic to VT transport, which encompass route length, ship characteristics, resistance reduction effect, and the waiting time for the departure of VT. This process, by varying one or more of these factors while considering the abovementioned two conditions, can reveal the adaptability of VT transport in general deep-sea shipping.

4. Case study and results

4.1. VT scenario selection and parameter setting

The Maritime Silk Road (MSR) has been a crucial conduit for economic and cultural exchanges between the East and the West, emerging as one of the most significant channels for fostering coordinated interaction between related ports (Chang, 2018). Trade data shows that commodity trade along the MSR contributes to more than 35 % of global commodity trade and nearly 30 % of global GDP. It is projected to account for 80 % of global GDP growth by 2050 (Mou et al., 2022). This study selects the MSR route from Yangshan Port in Shanghai, China, to the Port of Piraeus in Greece as the case study, as illustrated in Fig. 4. The route covers approximately 7725 nautical miles (Lauron et al., 2019).

Container ships are chosen as the subject vessels for this study because they frequently stop at intermediate ports, offering more opportunities to participate in VT transport compared to tankers and bulk carriers. To understand the dynamics of container ships on the selected route, we analyzed 155 container ships corresponding to 909 trajectories from the AIS data of container ships in 2021 (Liu et al., 2023). Fig. 5 shows the distribution of ship attributes. The length of these ships primarily ranges from 340 m to 390 m, and their design speed is predominantly between 22 knots and 25 knots.

According to the above results, four different types of ships were chosen, and the parameters were displayed in Table 3. As the ships

Fig. 4. Case Route from the Yangshan Port to the Port of Piraeus.

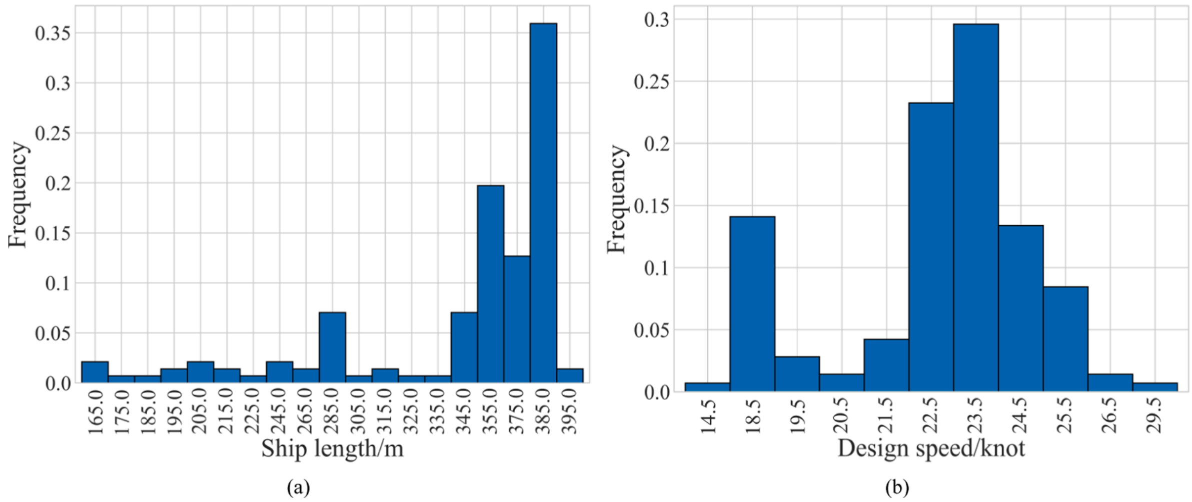

Fig. 5. The statistics of ship length and speed for container ships on the route using AIS data.

are container ships, the block coefficient, midship area coefficient, and waterplane area coefficient are 0.64, 0.98, and 0.7, respectively (see Tupper, 2004). The shipping operation conditions were set as followings:

- The ships were assumed to be fully loaded and to sail at their design speed.
- The operational schedule accounted for 365 days a year, with a total of 96 days off annually, considered as normal holidays.

The shipping scenario in 2020 was used as the case environment due to the data availability, and the median port time for container ships in 2020 was 0.71 days (United Nations Conference on Trade and Development, 2021).

To assess the changes in productivity and shipping revenues, the container freight rate on the case route in 2020 was collected and the median value of 676.65 $/TEU was used for subsequent cost-benefit analysis, followed by the sensitivity analysis on the container freight index. And the average price of marine diesel in 2020 was 436.5 $/t according to the statistics. In addition, the crew of FVs was reduced by a second officer and two deck boys (Colling & Hekkenberg, 2020; Kooij & Hekkenberg, 2020). The corresponding average salary of a second office and a deck boy in 2020 were 2700 $/month and 1550 $/month, respectively while p_{ex} was set at 0.3.

4.2. Cost analysis of reference vessels

The cost of independent navigation for container ships traveling from Yangshan Port in Shanghai, China, to the Port of Piraeus in Greece was evaluated. Fig. 6 illustrates the cost breakdown for each container on an individual round trip for the reference vessels (RVs) on this route. The analysis revealed:

- Cargo handling costs and the main propulsion engine fuel cost constitute a higher percentage of the total cost than other expenses for all four types of ships.
- As the size of the ship increases, the cost per Twenty-foot Equivalent Unit (TEU) decreases, and the proportion of cargo handling costs increases.

Table 3
Ship parameters for case study.

Parameters	Container ships			
	Small and slow (SS) vessel	Small and fast (SF) vessel	Large and slow (LS) vessel	Large and fast (LF) vessel
Overall length (m)	180	260.3	400	398
Perpendicular length (m)	169	247	383	381
Beam (m)	25	32.2	59	51
Draught (m)	9.5	11	16.0	16.0
GT (t)	17,068	42,112	193,489	168,423
DWT (t)	21,200	54,384	202,376	177,408
TEU capacity	1496	4380	19,200	13,892
MCR (kW)	9452	36,560	44,689	66,748
Design speed (knots)	18.5	24.37	19	23.2
Displacement (m^3)	27,360	59,006	241,664	207,851
Construction cost (million dollars)	22.714	72.27	142.6	135.046

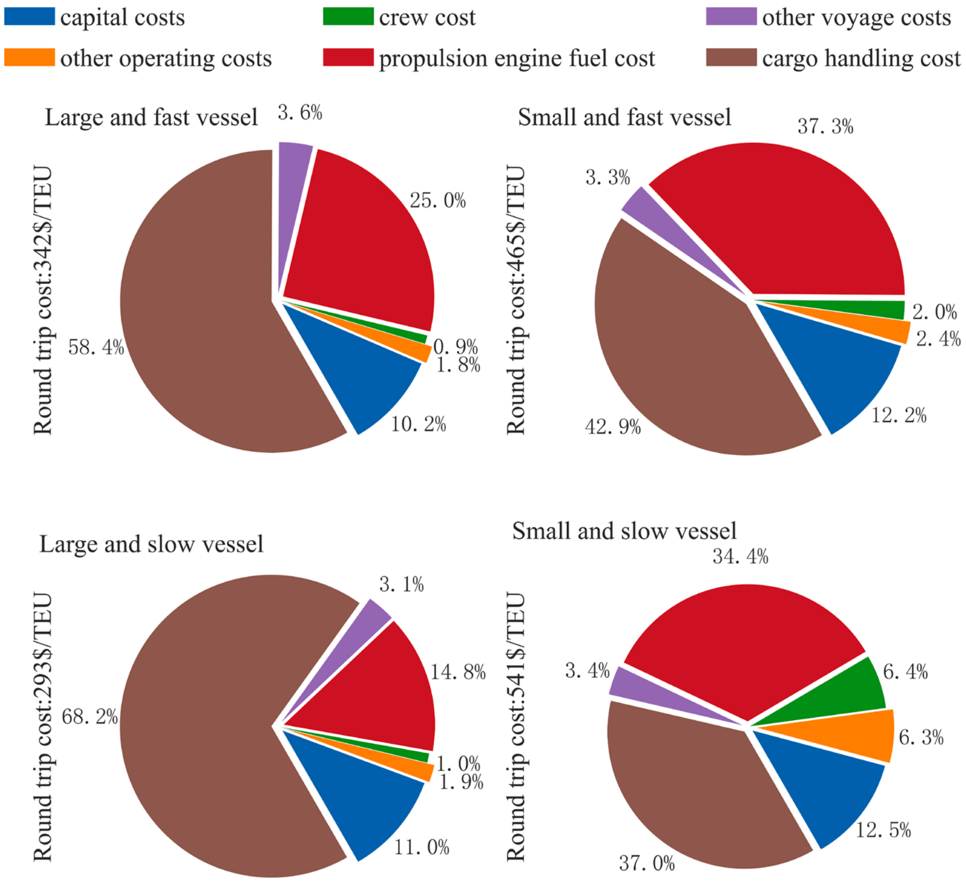

Fig. 6. Cost proportion per container for one round trip on the case route for the RVs.

- Crew costs in ocean shipping represent a smaller percentage of the total costs, significantly less than the 30 % to 40 % seen in short-sea shipping and inland waterway transport (Colling, 2021).

Generally, for vessels of the same size, a higher navigation speed results in increased transport costs. The reason the transport cost per TEU of the SF vessel depicted in Fig. 6 was lower than that of the SS vessel is due to the TEU capacity of the SF vessel being about three times that of the latter.

4.3. Round-trip transportation in VT systems involving ships of the same type

Based on the cost estimation method in Section 3, the initial focus on a three-ship VT system comprising vessels of the same type, it was found that all vessels would incur additional costs for the VT control system. Moreover, other operating costs would rise due to increased waiting times in port for VT departure. In contrast, fuel, crew, and insurance costs for the FVs would decrease. In this scenario, Fig. 7 illustrates the transport cost savings for the three ships in VT. It was observed that all leader vessels (LVs) experienced an increase in transport costs. Notably, the second follower vessel (FV-2) realized more significant savings compared to the first follower vessel (FV-1) due to more pronounced resistance reduction. Furthermore, the larger the vessel, the greater the potential savings in fuel costs and carbon tax expenses.

The comparison of Fig. 7(a) and (b) suggests that VT transport results in a decrease in carbon tax costs, indicating reduced fuel consumption. Consequently, fuel consumption for both VT and conventional transport was further calculated, as detailed in Table 4. The results show that the LS vessel achieved a significant fuel consumption reduction of 10.79 %, while the SS vessel had the lowest reduction, at 3.81 %. This finding implies that the VT model could potentially enhance the adoption of green shipping practices, provided that the resistance reduction effect is ultimately verified (see more in He et al. (2023)).

4.4. Round-trip transportation in VT systems involving ships of the different types

In scenarios where VT systems consist of ships of different types, the speed of all participating vessels is limited to the lowest speed among the ships in the VT system, leading to more significant changes in transport costs. When forming a VT system with a mix of

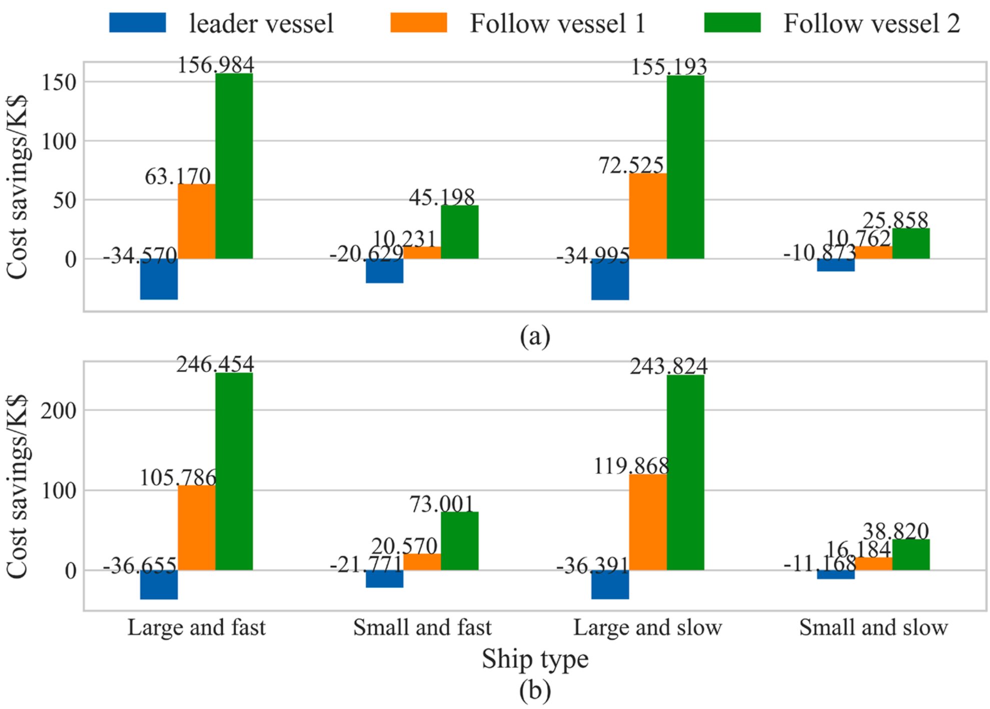

Fig. 7. Cost savings of round-trip VT systems for the same type of vessels. (a) without carbon tax cost; (b)with carbon tax cost.

Table 4
Fuel consumption of the conventional and VT transport in individual round trip.

Fuel consumption/t	LF vessel	SF vessel	LS vessel	SS vessel
Reference vessel	5455.45 t	3484.44 t	3826.03 t	1277.68 t
Follower vessel 1	5250.41 t	3431.78 t	3602.47 t	1251.46 t
Follower vessel 2	5035.49 t	3351.67 t	3413.08 t	1216.87 t

vessel types, the smaller vessels are typically designed to follow the larger one (Yuan et al., 2021). Four VT systems composed of different vessel types were constructed, as detailed in Table 5. To better understand the impact of VT on navigation duration, calculations were made for the VT round navigation duration and the additional time incurred due to speed reduction in some vessels. These calculations are crucial for assessing the changes in navigation duration caused by the implementation of VT. Based on the outlined design, the transport cost savings for the VT system involving 4 ships were illustrated in Fig. 8. The most notable observation was the significantly higher cost savings for the FVs in VT-2 and the LV in VT-3 compared to the other transport savings. These two VT systems involved combinations of fast and slow vessels, leading to considerable fuel cost reductions for the fast vessels that had to sail at reduced speeds. For the LVs in VT-2 and VT-4, their speeds remained unchanged relative to the RVs, resulting in increased costs solely due to the VT control system. In contrast, the LVs in VT-1 and VT-3 had to sail at reduced speeds, leading to longer sailing times and increased time-related costs. However, the decrease in fuel costs for the propulsion engine in these systems was greater than the increase in time-related costs. Regarding the FVs, in VT-1 and VT-3, the speed of the VT system depended on the FVs, so their cost savings were similar. On the other hand, in VT-2 and VT-4, the speed of the VT system was determined by the LVs, leading to different savings for the FVs. This analysis highlights the various impacts that different VT configurations can have on both the leader and follower vessels in terms of transport cost savings.

Additionally, Table 6 presents the cost savings for certain items for the FVs in the VT system. The time-related costs, which include

Table 5
Composition and speed setting of VT system for different types of vessels.

		VT-1	VT-2	VT-3	VT-4
VT composition	LV	LS vessel	LS vessel	LF vessel	LF vessel
	FV	SS vessel	SF vessel	SS vessel	SF vessel
VT Speed(knot)		18.5	19	18.5	23.2
VT round navigation duration(day)		34.8	33.8	34.8	27.8
Additional duration for speed-reducing vessels (days)		0.92	7.46	7.06	1.34

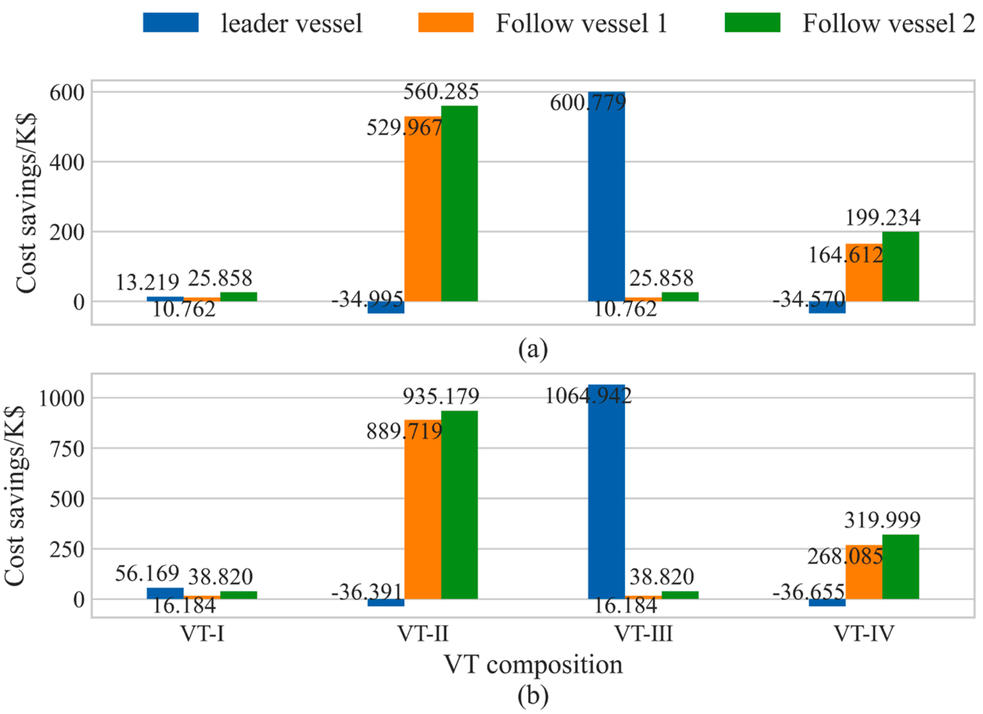

Fig. 8. Cost savings of round-trip VT systems for different types of vessels. (a) without carbon tax cost; (b)with carbon tax cost.

capital and operating expenses (excluding crew costs), were expected to increase with operating time. In three of the scenarios, a reduction in crew size led to lower crew costs. However, in the case of the SF vessel in VT-2, approximately an additional 7 days of sailing time was required, resulting in increased total crew costs.

Furthermore, the table reveals that even without taking into account the cost increases for the LVs, the reduction in crew costs alone is insufficient to offset the rise in the time-related costs for the FVs. This analysis indicates that while crew cost savings are a factor, they do not singularly balance out the increased expenses associated with extended operation times in VT systems.

4.5. Year trip transportation in VT systems involving ships of the same type

When ships engage in VT transport for an entire year, their shipping productivity is impacted by increased port and sailing times. According to the NOVIMAR project, the waiting time for large vessels in VT should not exceed 8 h. Table 7 displays the number of one-way transports completed by the RVs and VT systems over the total operating time. Notably, there was a reduction in the number of transports for the SF in VT system.

Based on the data in Table 7, the savings for the four types of VT systems, taking into account both shipping costs and revenues, were calculated and are presented in Fig. 9. For the VT systems involving LF, LS, and SS vessels, the annual savings were found to be positively proportional to the savings from round-trip transport, as there were no changes in productivity. However, for the SF vessel VT system, the cost savings achieved through VT transport were insufficient to offset the economic loss resulting from reduced productivity. This finding highlights the importance of considering productivity changes when evaluating the economic feasibility of VT systems over longer periods.

Table 6
Cost savings of partially items for FVs in four VT systems.

Cost savings/$		Time-related costs	Crew cost	Propulsion engine fuel cost	Auxiliary engine fuel cost	Carbon tax cost
VT-1	FV-1	−8803.3	8293.6	11447.4	−591.1	5422.2
	FV-2			26544.2		12962.1
VT-2	FV-1	−192463.0	−13977.7	742377.0	−22073.8	359752.0
	FV-2			772695.0		374895.0
VT-3	FV-1	−8803.3	8293.6	11447.4	−591.1	5422.2
	FV-2			26544.2		12962.1
VT-4	FV-1	−48885.7	2362.9	212994.0	−5817.1	103474.0
	FV-2			247616.0		120765.0

Table 7
Number of one-way transportations of RVs and homogeneous VT systems within the annual total operating time.

Number of round trips	LF vessel	SF vessel	LS vessel	SS vessel
Reference vessel	18	19	15	14
VT of the same type of vessel	18	18	15	14

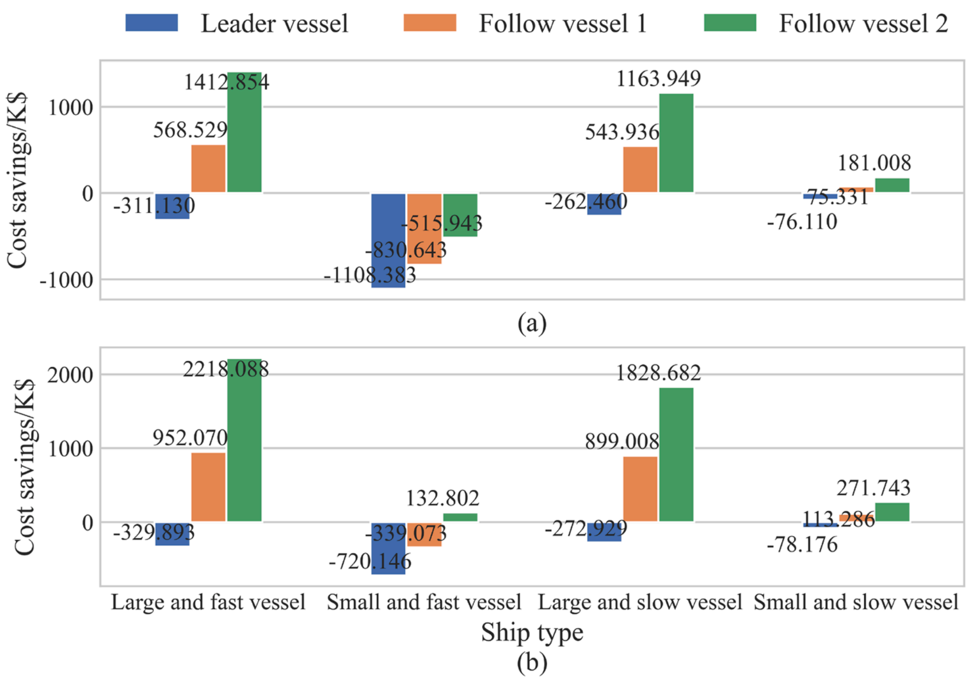

Fig. 9. Cost savings of year-trip VT systems for the same types of vessels. (a) without carbon tax cost; (b)with carbon tax cost.

4.6. Year trip transportation in VT system involving ships of the different types

Integrating the VT composition from Table 5 with the transport frequency data in Table 7, the annual transport for mixed VT systems is detailed in Table 8. Fig. 10 presents the cost savings of the four mixed VT systems over a year. For VT-1 and VT-3, the transport benefits provided by VT were insufficient to offset the loss in productivity. In the case of VT-2 and VT-4, while the transportation frequency of the LVs remained the same as that of the RFs, the costs related to VT control and increased operating time were higher. However, for the FVs in VT-2 and VT-4, the economic benefits from participating in VT transport exceeded the economic losses due to reduced productivity.

This does not mean that the cost per trip for smaller vessels exceeded the revenues. For instance, the net benefit per trip for the SF vessel was approximately 17,008,100 $ at design speed and without accounting for carbon tax costs. The results suggest that there is potential to enhance benefits by optimizing sailing times and operational conditions. It was observed that positive benefits for the VT system were only achieved when the speed of the small FVs was higher than that of the larger LVs, indicating a need for careful balancing in the VT system's composition and operation.

5. Sensitivity analysis and discussions

To ensure the generalizability of our findings for deep-sea shipping, we conducted a sensitivity analysis on key factors and engaged

Table 8
Number of one-way transportations of RVs and mixed VT systems throughout annual total operating time.

		VT-1		VT-2		VT-3		VT-4	
		LV	FV	LV	FV	LV	FV	LV	FV
VT composition		LS	SS	LS	SF	LF	SS	LF	SF
Number of round trips	Reference vessel	15	14	15	19	18	14	18	19
	VT system	14		15		14		18	

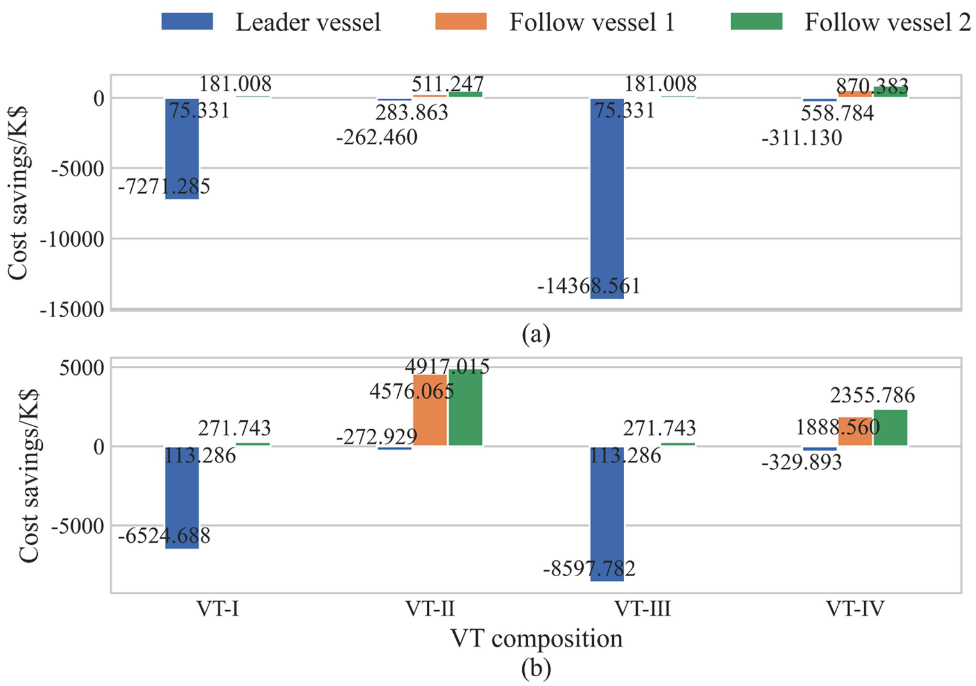

Fig. 10. Cost savings of year-trip VT systems for different types of vessels. (a) without carbon tax cost; (b)with carbon tax cost.

in discussions. The homogeneous vessel round-trip VT transportation was chosen as the experimental scenario for sensitivity analysis, as it allowed for a more intuitive assessment of how various factors impact shipping costs and benefits and the feasibility of annual participating in VT mode could be deduced from it.

It is worth noting that VT would increase the insurance cost by 5 % to 10 % due to the uncertainty of system functions in the initial stage, and then reduce the cost by 10 % as the technology matures and the number of potentially risky crew members on board decreases (Colling, 2021). However, in the case of a homogeneous three-ship VT system, the 10 % insurance cost for one round trip is less than 10,000$. Combined with Fig. 6, it becomes evident that the insurance cost would not exert a significant impact on the feasibility of the VT mode.

The sensitivity analysis factors are shown in Table 9. For P_{rc}, the ranges for the FV-1 and FV-2 were set at [0,0.12], corresponding to the no resistance reduction and the maximum values for the FV-1 in Table 2. And the container freight rate's range was set based on the Ningbo Containerized Freight Index in 2020. Additionally, for more general scenarios, different ships and routes need to be considered. However, the significant differences in basic parameters and costs among different ships make it challenging to collect an extensive dataset and conduct a feasibility assessment based on ship-related factors. As a result, we continued to use the ships introduced in Section 4.1 and only performed sensitivity analysis related to route length.

5.1. Sensitivity analysis on resistance reduction effect and route length

In this experiment, we did not consider the resistance reduction models constructed for FV1 and FV2 in Section 3.4. Instead, specified resistance reduction values was used for both follow vessels. Fig. 11 shows the cost savings of four VT systems with varying route lengths and reduction percentages of frictional resistance coefficient. When only the reduction in crew costs is taken into account without considering reducing frictional resistance, none of the four VT systems can achieve positive benefits. As the route length increases, the VT transportation model considering resistance reduction effect becomes increasingly economically feasible, even if this effect is relatively small. In this situation, larger and slower vessels require longer route lengths to achieve positive returns, as time-

Table 9
Sensitivity analysis factors and the value ranges.

Factors	Reason for sensitivity analysis	Ranges
P_{rc}	Related to fuel cost, carbon tax cost	[0,0.12]
t_w	Related to revenues, time-related costs	[0 h, 24 h]
container freight rate	Related to revenues	[574/TEU, 2574/TEU]
Fuel price	Related to fuel cost	[$268/t, $1068/t]
Carbon tax price	Related to carbon tax cost	[$68/t, $168/t]
Route length	Related to fuel cost and time-related costs	[2000 km, 20000 km]

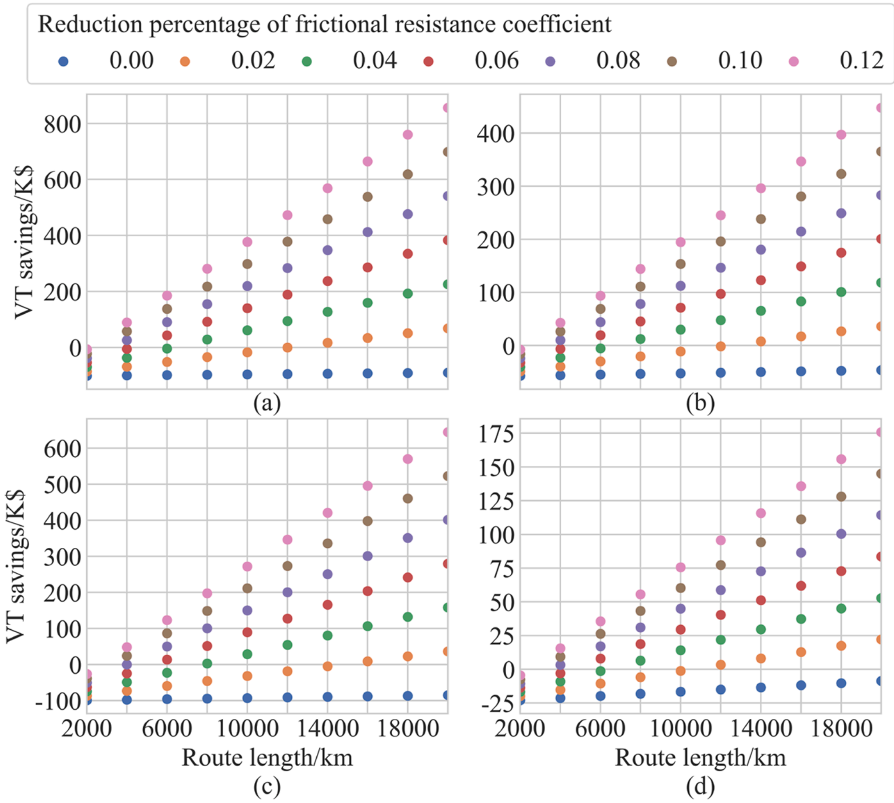

Fig. 11. Cost savings of four VT systems with varying route length and reduction percentages of frictional resistance coefficient. (a) LF vessel VT system; (b) SF vessel VT system; (c) LS vessel VT system; (d) SS vessel VT system.

related costs increase with the additional time required by VT and needs to be balanced by the more gains from the resistance reduction effect. In other words, under the same resistance reduction effect, smaller and faster vessels are more feasible for VT application. However, according to the paper's findings (He et al., 2022), slower vessel speeds result in more significant resistance reductions, implying the requirement of balancing ship size and sailing speed when using VT mode.

5.2. Sensitivity analysis on freight rate and waiting time

The increased waiting time for VT participation has a significant impact on the feasibility of VT transport due to reduced shipping revenues and increased time-related costs, as depicted in Fig. 9. Shipping revenues are directly correlated with the freight index and ship productivity. To estimate the impact of increased waiting time on the productivity of individual round-trip transportation, we introduced the productivity reduction percentage η in Equation (14).

$$\eta = \frac{\frac{O}{t_s+t_o}*\mathrm{V} - \frac{O}{t_s+t_o+t_w}*\mathrm{V}}{\frac{O}{t_s+t_o}*\mathrm{V}} = \frac{t_w}{t_s+t_o+t_w} \tag{14}$$

In this experiment, we continued to use the route and ships in Section 4.1. Fig. 12 displays the cost savings of four VT systems with varying waiting time and freight rate. When the waiting time is no less than 8 h, VT mode fails to yield positive benefits. For slower vessels, the longer travel time mean that the increased waiting time has a lesser impact on overall productivity. Therefore, under the same freight rates, VT mode became more economically feasible for slower vessels. It is worth noting that we did not consider integer frequencies within a specified time frame but employed a productivity reduction percentage here. However, as indicated in Table 7, under the condition of an 8-hour waiting time, only SF vessel system experiences a reduction of one one-way transportation in a year. Consequently, for longer timeframes, occasional participation in VT transportation does not significantly impact productivity, suggesting that VT could be economically feasible.

5.3. Sensitivity analysis on fuel price and carbon tax price

VT transportation primarily achieves benefits through reducing fuel costs, which are directly related to fuel prices. Moreover, reducing fuel consumption can further decrease carbon emissions costs. We used the constructed resistance reduction models in Section 3.4 in this experiment, but VT transportation in the case route certainly yields positive returns within the parameter setting

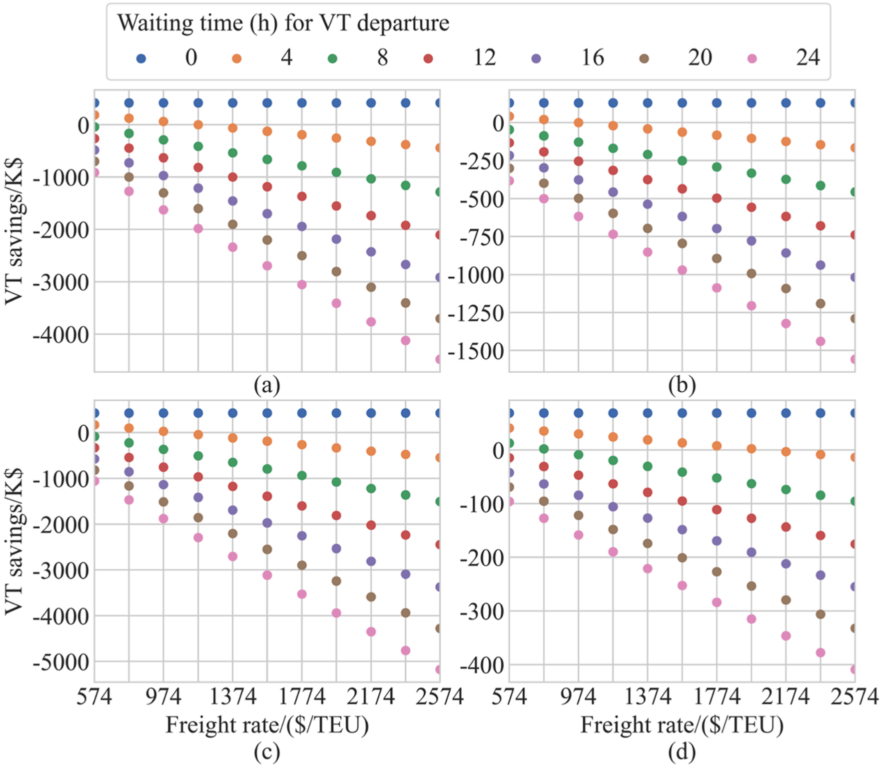

Fig. 12. Cost savings of four VT systems with varying waiting time and freight rate. (a) LF vessel VT system; (b) SF vessel VT system; (c) LS vessel VT system; (d) SS vessel VT system.

ranges. As a result, we set the route length to 7,000 km, as depicted in Fig. 11, where four VT systems start obtaining positive savings within the length range of 6,000 km to 8,000 km when the reduction percentages are at 0.04.

Fig. 13 shows the cost savings of four VT systems with varying fuel price and carbon tax price (including no carbon tax). When not considering the carbon tax cost, larger ships are more economically feasible for VT transportation since they achieve positive returns with lower fuel prices, as depicted in Fig. 13. When taking the cost of carbon tax into account, only the SF vessel VT system does not yield positive benefits under the current minimum parameter setting. This is due to the faster speed and smaller size, resulting in a lower resistance reduction effect.

While a detailed analysis of the feasibility of ocean-shipping VT was conducted, it is important to note that the practical implementation of such a transport mode might face operational and regulatory challenges. Compared to vessels in inland and coastal shipping, there are fewer ocean-shipping vessels, necessitating a clear understanding of the feasibility of VT transport organization. In the specific scheduling process, the organization of VT transport requires well-coordinated timing among all participants. However, the uncertainty in the travel time due to factors such weather, especially with longer journeys exhibiting higher uncertainties, coupled with the limited waiting time of FVs for VT arrival, results in the failure of planned scheduling. In addition, port operations and global shipping regulations could impact the seamless coordination required for VT.

6. Conclusions

This paper presents a comprehensive analysis of the economic feasibility of VT in the ocean shipping sector. It encompasses the design of four distinct VT transport scenarios, taking into account the effects of VT on navigation speed and the productivity differences between round-trip and year-long VT operations. The study focuses on the route from Yangshan Port to the Port of Piraeus, utilizing container ships as a case study. The methodology involves categorizing shipping cost items, selecting appropriate estimation methods, and comparing the transport costs between VT participants and conventional reference vessels. Additionally, a sensitivity analysis is conducted, considering various factors such as route length, frictional resistance reduction, waiting times for VT departure, and fluctuations in container freight index, fuel price, and carbon tax price. Key findings indicate that for individual round trips, VT can achieve lower total transportation costs and reduced fuel emissions, with its economic feasibility largely dependent on the costs of organizing VT. However, for annual participation, the economic benefits of VT vary depending on the composition of the vessel types within the VT. The study suggests that VT is more economically viable with a mix of different vessel types, especially when the speed of smaller follower vessels is higher than that of the larger leader vessels.

The paper also highlights that focusing solely on crew cost reduction in VT does not lead to significant economic benefits for deep-

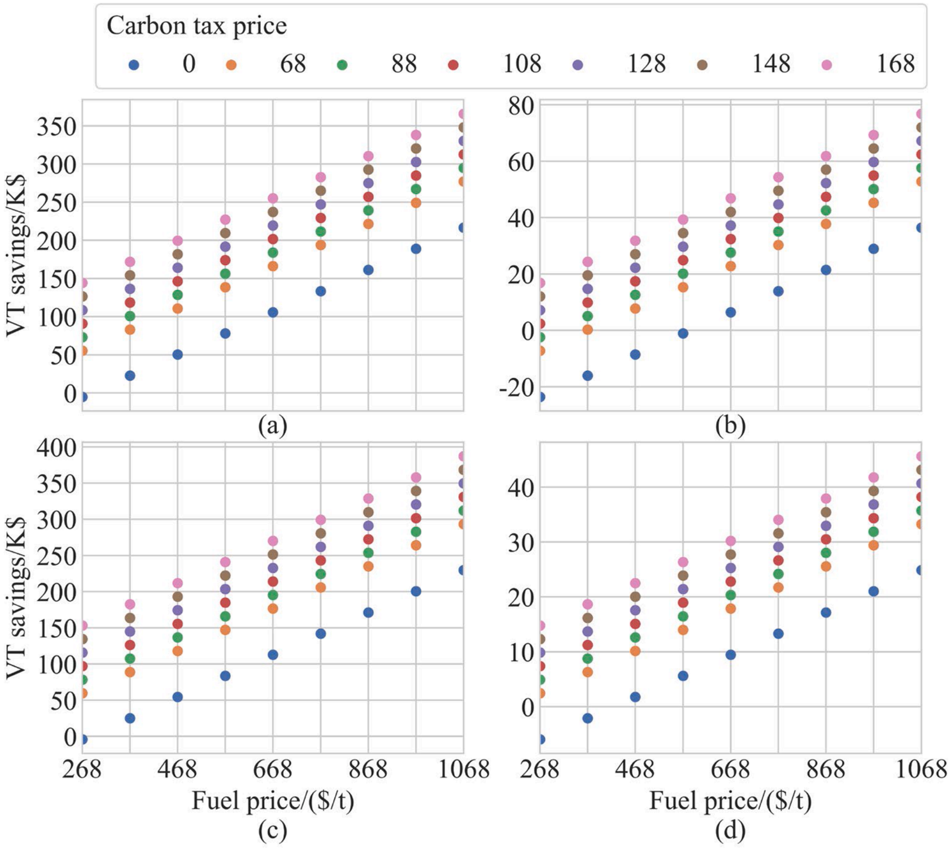

Fig. 13. Cost savings of four VT systems with varying fuel price and carbon tax price. (a) LF vessel VT system; (b) SF vessel VT system; (c) LS vessel VT system; (d) SS vessel VT system.

sea shipping. However, the feasibility improves with longer routes, occasional participation with controlled waiting times, and in the context of rising carbon tax and fuel prices. The resistance reduction model, a key element in the analysis, requires further empirical validation, especially regarding fuel cost savings. The study acknowledges the potential for increased shipping delay costs, particularly in scenarios like ship chartering when participating in VT.

The practical implications of these findings in real-world shipping scenarios are manifold. The third-party organizations, armed with insights from this paper, can develop strategies for more effective coordination and deployment of VT. These findings also aid ship owners in making informed decisions regarding their participation in VT transport. They provide clarity on whether to engage in VT transport and guides them in determining the most effective frequency of involvement. Furthermore, regulatory authorities may find value in understanding the potential impact of VT on shipping practices, helping them make informed decisions regarding policy and standards.

In conclusion, the paper finds that VT transport can offer significant economic advantages, outweighing the associated increased costs, under the condition of maintained shipping productivity. Future research directions include addressing the challenges identified in this study, verifying the feasibility of VT, and exploring its practical implementation in real-world shipping scenarios and scheduling studies. Exploring the feasibility and adaptive strategies for VT organization in response to dynamic factors like weather conditions and unforeseen disruptions would be instrumental. Moreover, investigating the scalability of VT from a regional to a global context and understanding its implications on international shipping could be a promising avenue for further exploration.

CRediT authorship contribution statement

Lei Liu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kaiyuan Liu:** Writing – review & editing, Conceptualization. **Ryuichi Shibasaki:** Validation, Investigation, Data curation, Conceptualization, Writing – review & editing. **Yong Zhang:** Conceptualization, Investigation, Project administration, Supervision, Writing – review & editing. **Mingyang Zhang:** Conceptualization, Data curation, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Cost estimation methods

A1 capital cost estimation

The capital cost includes the depreciation cost and the interest cost, and the estimation of a ship's capital cost is based on the construction cost of the ship. This paper adopts linear regression to calculate the construction cost of ships (Azhar & Kristiyono, 2022; Shetelig, 2013). The shipbuilding transactions for container ships from 2019 to 2022 were collected to construct the construction cost model for estimating the building costs of target ships, as shown in Equation (A.1).

$$C_{construciton} = 0.0000284965*\text{TEU}^3 - 1.41712*\text{TEU}^2 + 24713.1*\text{TEU} - 11180478.6946 \tag{A.1}$$

The depreciation cost of a ship needs to take the service life of the ship into account. The general service life of a ship is assumed to be 25 years, indicating that the annual depreciation of a ship is 4 % of the construction cost. The interest cost are calculated based on the total funds borrowed from the bank and are typically 4.5 % to 5 % of the total cost (Verberght, 2019).

A2 operating cost estimation

Operating cost estimation in this paper rely on statistics on the actual operating costs of ships, as shown in Table A1. Notably, the overall crew cost would be calculated based on the statistical results while the reduction in three crew cost is calculated using Equation (5) and p_{ex} is set at 0.3.

Table A1
Operating costs per day for target vessels with an age of 10 years (Igbinosun et al., 2020).

Costs($/day)	Container ships			
	SS vessel	SF vessel	LS vessel	LF vessel
Insurance cost	220	540	1150	1250
Maintenance cost	250	220	260	430
Crew cost	2840	2940	3160	2990
Administration cost	790	1110	1500	1410
Stores cost	250	250	600	510
Spare cost	250	230	500	470
Lubricating oils cost	490	570	910	910
Dry docking cost	560	610	990	950

A3 Voyage cost estimation

Voyage costs include propulsion engine fuel cost, auxiliary engine fuel cost, canal navigation cost, and port charges.

- Propulsion engine fuel cost estimation

Equation (A.2) illustrates the calculation of propulsion engine fuel cost for one-round trips.

$$C^{fuel} = f_c * t_v * p_{fuel} \tag{A.2}$$

Where f_c is the fuel consumption rate, t_v represents the sailing duration, p_{fuel} represents the fuel price. The calculation of a ship's sailing resistance is shown in Equation (A.3) (Holtrop & Mennen, 1982).

$$R_{total} = R_F*(1+k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \tag{A.3}$$

where R_F is frictional resistance; $1+k_1$ is the form factor describing the viscous resistance of the hull form in relation to R_F; R_{APP} is the resistance of appendages; R_W is wave-making and wave-breaking resistance; R_B is additional pressure resistance of bulbous bow near the water surface; R_{TR} is the additional pressure resistance of immersed transom stern; R_A is the model-ship correlation resistance. For the specific calculation, it is referred to Holtrop & Mennen (Holtrop & Mennen, 1982).

After obtaining the total resistance R_{total} and navigation speed v, the effective propulsion power P_E, the propulsion power P_p, the effective shaft power P_s, and the effective breaking power P_b are calculated sequentially.

$$P_E = R_{total}*v \tag{A.4}$$

$$P_p = \frac{P_E}{\eta_H} \tag{A.5}$$

$$P_s = \frac{P_p}{\eta_p} \tag{A.6}$$

$$P_b = P_s/\eta_d \tag{A.7}$$

where η_H is the hull factor; η_p and η_d represent the propeller efficiency and the transmission efficiency. With an operating point at 80 %-85 % Maximum Continuous Rating (MCR) at the given service speed and loaded, the fuel consumption rate is obtained based P_b and the specific fuel consumption (*SFC*), as shown in Equation (A.8).

$$f_c = P_b*(SFC/1,000,000) \tag{A.8}$$

- Auxiliary engine fuel cost estimation

According to the ship emission report, for general cargo ships, the loading factors for auxiliary engines at cruise, deceleration, maneuvering, and mooring are 0.17, 0.27, 0.45, and 0.22 respectively, while the average power provided by the auxiliary engines is approximately 0.191 in relation to the average power of the propulsion engines (Lindhjem & Browning, 2007). Consequently, the power of the auxiliary engine can be estimated with the power of the main propulsion engine, as shown in Equation (A.9). And the *SFC* of the auxiliary engine is set to 213.1 g/kWh (Kretschmann et al., 2017).

$$P_{auxi} = P_{main}*0.191*\gamma_{status} \tag{A.9}$$

where P_{main} and P_{auxi} represent the MCR of the main propulsion engine and the auxiliary engine; γ_{status} indicates the loading factor in different states.

- Canal cost

Ships passing through canals are required to pay the toll charge. Some websites provide the charge calculation based on ship parameters for different ships, such as Suez Canal navigation fees.

- Port costs

In port costs, the port entry and berthing fee and the route-handling charge are set at 0.092 ($/GT/call) and 0.244 ($/GT/call). In addition, the cost of cargo handling is set at 100($/TEU) (Furuichi & Otsuka, 2013).

A4 Carbon tax cost estimation

Carbon tax cost C^{carbon} is modeled as the product of unit price p_{co_2} of carbon dioxide equivalent multiplied by CO2 emission volume E (Ding et al., 2020), as shown in Equation (A.10) and (A.11).

$$C^{carbon} = p_{co_2}*E \tag{A.10}$$

$$E = Q_{fuel}*C_F \tag{A.11}$$

where Q_{fuel} is the fuel consumption and C_F is the corresponding parameter.

A5 Cost of VT control system

The costs of VT control system are shown in Table A2.

Table A2
Related annual costs of VT control system (Colling, 2021).

	Depreciation	Interest	Insurance	Maintenance	Management	Total
Rate	20 %	5 %	0.75 %	2 %	2.5 %	
Cost($/year)	18196.8	4549.2	682.4	1819.7	2274.6	27522.7

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