

Optimum routing for dry bulk voyages with the effect of an emission trading system: NSR vs SCR

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ABSTRACT

Concerning the significant environmental emissions from the maritime sector, an Emission Trading System (ETS) is an effective market-based emission control measure. This study analyses the effect of ETS on the optimum routing between the Northern Sea Route (NSR) and Suez Canal Route (SCR), considering 174 dry bulk voyages between Asia and Europe. First, cost-, emissions- and time-saving made by voyages via NSR compared to SCR are estimated, and marginal abatement costs are estimated to identify feasible NSR voyages with an ETS. Accordingly, nearly 35, 80, and 160 voyages were cost-saving with NSR if SCR speed equals 10, 15, and 20 knots, respectively. Although all voyages save emissions with NSR if SCR speed equals 15 or 20 knots, only limited voyages save emissions via NSR if SCR speed equals 10 knots. Moreover, a much faster voyage via NSR than SCR could save more voyage costs, although it could not save emissions. However, a much shorter voyage via NSR than SCR could save more emissions, although it could not save costs. The optimization model derives over 90 feasible voyages for NSR, varied based on the free-emissions quota, icebreaker availability, navigation month, fuel prices, and types. Some voyages that were environmentally feasible but economically infeasible via NSR without an ETS were both environmentally and economically feasible with an ETS. However, if vessels slow steam via SCR, ETS would not significantly enhance NSR's feasibility. Moreover, NSR is more feasible if the maritime industry uses expensive and cleaner fuel types.

1. Introduction

Maritime transport facilitates 80 % of the world's trade (UNCTAD, 2021), while the bulk shipping sector accounts for most of this volume. Dry bulk vessels mainly carry iron ore, coal, grain, and other industrial dry cargo, contributing to various industries and the world economy. However, due to extensive maritime transport activities, massive vessel-based emissions are released into the environment; thus, various international bodies highlight the importance of different emission control measures (ECMs). IMO's Fourth GHG (Green House Gas) study stated that the global shipping sector emitted 1056 million tons of carbon dioxide (CO₂), accounting for around 2.89 % of global anthropogenic CO₂ emissions. Therefore, a strategy to cut global GHG emissions from shipping by at least 50 % from 2008 to 2050 was formulated by IMO (Wang et al., 2021). Moreover, the European Union (EU) issued a regulation on monitoring, reporting, and verifying CO₂ emissions from ships in EU-related ports in 2018 and considered the possibility of including maritime transport in the EU Emissions Trading System (ETS)

in 2020. An ETS is regarded as a market-based ECM, encouraging market players to abate emission levels by providing monetary incentives. Maritime ETS is an incentive-based instrument to abate vessel emissions through allocating and auctioning GHG emission allowances among market players. These market-based ECMs decarbonize the shipping industry by internalizing externalities while generating funds to subsidize green technology investments (Cariou et al., 2021). However, due to the differences in costs and emissions related to voyages when using different maritime corridors, an ETS could significantly impact competing maritime corridors' feasibility and market share.

Considering the competing maritime corridors for cargo movement in Asia–Europe trade, the Suez Canal Route (SCR) is extensively used by shipping lines, although NSR has developed as an alternative maritime corridor with the deformation of Arctic Sea ice. NSR is a shipping lane between the Atlantic and the Pacific Oceans along the Russian coast of Siberia and the Far East (Liu and Kronbak, 2010), which demonstrates significant distance- and time-saving than SCR for Asia–Europe trade. According to Kavirathna and Shibasaki (2021), previous studies have

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derived various conclusions in analyzing the NSR feasibility over SCR, affected by various factors such as voyage-specific characteristics, ice conditions, load factor, vessel sizes and ice class, fuel price, and ice-breaking fees. Moreover, several studies analyzed environmental feasibility and ECMs on NSR vs SCR (Ding et al., 2020; Kavirathna et al., 2023; Theocharis et al., 2019). As ECMs, they focused on regulatory ECMs such as emission tax (Ding et al., 2020), bunker levy (Psarafitis, 2019), HFO-banned areas (Kavirathna et al., 2023), speed limits (Psarafitis, 2019), operational ECMs such as speed optimization (Kavirathna et al., 2023; Theocharis et al., 2019), and market-based ECMs such as ETS (Wang et al., 2020a). Compared to regulatory and operational ECMs, market-based ECMs such as ETS would incentivize vessel operators to abate the emissions because they can trade the excess emissions allowances in the market. Moreover, as previous studies highlighted both positive and negative cost- and emissions-saving with NSR navigation compared to SCR, an ETS would potentially impact the optimum routing between NSR and SCR. Considering the effectiveness of ETS in abating emission production, this study focuses on an ETS.

In the bulk shipping sector, point-to-point networks are considered; thus, voyages' economic and environmental feasibility are heavily influenced by the vessel's characteristics, shipping routes, voyage distances, and navigation speeds, among others. The ship routing behavior of bulk shipping vessels could be affected by the ECMs enforced on shipping routes. For instance, if a vessel sails from Singapore to Rotterdam via SCR in 21 days, burning 100 tons of fuel daily and producing 3.17 tons of CO₂ per each burned fuel ton. If the carbon price is 30 USD/ton, the voyage incurs over 200,000 USD of emission cost, while the SCR toll can be over 300,000 USD on average. This high voyage cost would encourage shipping companies to choose alternative routes, such as the route via the Cape of Good Hope at zero toll charge or NSR with a shorter voyage distance.

This study aims to analyze the optimum routing between NSR and SCR for dry bulk voyages between Asia and Europe, considering both the economic and environmental feasibility and the effect of an ETS. Therefore, as the first research objective, we analyze the economic and environmental feasibility of voyages by estimating the cost-, emission-, and time-saving of individual voyages by NSR over SCR without an ETS. Then, for the second objective, the feasible voyages via NSR with an ETS are analyzed by estimating the marginal abatement cost (MAC) of emissions. This study considers different ice-class vessels for NSR navigation and multiple average speeds for SCR navigation as alternative scenarios. Thereafter, as the third objective, the optimum numbers of voyages via NSR and SCR are estimated using an optimization model that minimizes the total cost of voyages. Since NSR's navigation speed is affected by the ice conditions (Stephenson et al., 2013), this study estimates the navigation speeds incorporating the IMO International Code for Ships Operating in Polar Waters (POLAR code), sea ice distribution, and the observed speeds from the automatic identification system (AIS) data. The analysis is done with different market prices of carbon allowance (CPs), free emission quotas (FEQs), fuel prices, and fuel types to discuss significant implications.

By analyzing optimum routing between NSR vs SCR for dry bulk shipping between Asia and Europe with an ETS, this study contributes to the literature, practitioners, and policymakers interested in Arctic shipping. The analysis relies on actual voyage data derived from the AXS Dry dataset and AIS, confirming its empirical novelty. Moreover, significant implications are discussed considering different ice classes, multiple speed scenarios, and spatial-temporal variation of NSR's speeds. Since the competition between maritime corridors is affected by the usage of different fuel types and variations of fuel prices, NSR's feasibility is analyzed with multiple fuel types and a range of fuel prices. Moreover, the NSR's navigation can be subject to the availability of icebreakers, especially during the winter-spring season. Therefore, the effect of ETS and NSR's feasibility is analyzed subject to the constraint of available icebreakers. The sensitivity analysis of these market-related factors provides more practical insights to the policymakers. As the

remainder of this paper, Section 2 provides a literature review, and Section 3 describes the model development, scenarios, and input data. Section 4 provides the analysis and discussion. Finally, Section 5 concludes the study.

2. Literature review

2.1. Route choice between NSR and SCR

Considering previous studies on route choice between NSR and SCR, several studies highlighted NSR's higher competitiveness over SCR with a longer navigable period of NSR (Liu and Kronbak, 2010; Zhao et al., 2016; Xiang et al., 2025). Also, voyages with specific O-D pairs chose NSR over SCR depending on the voyage-specific characteristics (Cariou et al., 2019; Dimitrios et al., 2019; Wang et al., 2020a) and especially, the voyage distance was considered a significant factor (Dimitrios et al., 2019; Zhang et al., 2016). Some studies highlighted NSR's feasibility over SCR concerning specific vessel sizes (Cheaitou et al., 2020; Dimitrios et al., 2019; Ding et al., 2020; Sibul and Jin, 2021; Stephenson et al., 2013; Yumashev et al., 2017; Zhang et al., 2016). Regarding route choice, several studies highlighted the significance of NSR's transit fees compared to the SCR's toll charges (Dimitrios et al., 2019; Liu and Kronbak, 2010; Liu et al., 2021; Wang et al., 2020b; Xu et al., 2018).

Apart from voyage- and vessel-related factors, several studies analyzed the effect of market-related factors on route choice between NSR and SCR. Among them, multiple studies highlighted NSR's higher feasibility over SCR at specific fuel prices (Cariou et al., 2019; Liu and Kronbak, 2010; Wang et al., 2020b; Xu et al., 2018). Since fuel price is an important component of voyage cost, it is reasonable to receive different feasibility results when changing fuel prices. Moreover, fuel type was considered a significant factor in route choice (Cariou et al., 2019; Cheaitou et al., 2022; Dai et al., 2021; Dimitrios et al., 2019). Different fuel types have different emission factors; thus, fuel type significantly impacts NSR's environmental feasibility. Furthermore, several studies have analyzed the effect of emissions cost on NSR vs SCR, which is also affected by the fuel types (Ding et al., 2020; Kavirathna et al., 2023). As stated by Xiang et al. (2025), the choice between NSR vs. SCR and the operational strategies of liner companies are directly affected by the black carbon tax rate because NSR may no longer be feasible with a very high carbon tax rate. Cheaitou et al. (2022) analyzed multiple logistic settings for NSR navigation and discussed that using hubs facilitates more container volume per year, enhances vessel productivity, and maximizes the number of journeys with short transit times, thus enabling time savings relative to the SCR.

Several studies also highlighted the disadvantage of using NSR over SCR due to NSR's high icebreaking and transit fees (Liu and Kronbak, 2010; Xu et al., 2018; Zhao et al., 2016). Moreover, NSR requires ice-class vessels for navigation, which are more expensive than the open-water vessels used via SCR (Solakivi et al., 2017; Zhao et al., 2016). Several studies found a lower popularity of NSR over SCR due to its inability to accommodate large-size vessels (Liu et al., 2021; Yumashev et al., 2017). In addition, Liu et al. (2021), Zhao et al. (2016), and Zhang et al. (2016) found low load factor and cargo unavailability as disadvantages of NSR compared to SCR. Furthermore, several studies found higher emissions levels of voyages via NSR compared to SCR due to various reasons, such as a gap between the vessel's operating speed and design speed (Cariou et al., 2019), and the higher negative impact of emissions, which is more than offsets the benefit of shorter voyages via NSR (Lindstad et al., 2016; Wang et al., 2020b). Supporting the same, Zhu et al. (2018a) highlighted higher environmental costs via NSR than SCR due to the small ship size and low load factor of NSR; thus, NSR would lead to severe environmental outcomes.

Accordingly, studies derived opposing conclusions from their analysis due to the differences in their modeling approaches. Regarding commodity types, numerous studies focused on container shipping via NSR over SCR (Liu et al., 2021; Zhang et al., 2016), while several studies

were on bulk shipping (Fauray and Cariou, 2016; Shibasaki et al., 2018). Apart from route choice, several studies focused on the combined use of NSR and SCR, assuming NSR's usage during its navigable period and SCR in the remaining months (Sibul and Jin, 2021; Liu et al., 2021). Also, studies considered the ice condition variation along the NSR in analyzing NSR's competitiveness over SCR (Cariou et al., 2019; Cheaitou et al., 2020; Fauray and Cariou, 2016; Stephenson et al., 2013; Yumashev et al., 2017).

2.2. Emission control measures for NSR

Concerning the environmental impacts, numerous previous studies discussed various ECMs on NSR navigation. By investigating navigation activities in the Arctic and their emissions production, Chen et al. (2024) highlighted the necessity of tightening the rules and regulations to govern Arctic shipping activities. As Zhu et al. (2018a) emphasized, despite the NSR's potential in Asia–Europe trade, the Arctic area is environmentally vulnerable; thus, a tradeoff between economic and environmental benefits must be considered. Regarding types of ECMs, most studies focused on regulatory ECMs such as emission tax, which encourages vessel operators to regulate emissions production using various mechanisms. For example, Ding et al. (2020) analyzed the effect of fixed vs. progressive carbon tax schemes for NSR's feasibility over SCR and found that NSR would be feasible if an emission tax were enforced or not enforced on both routes simultaneously, regardless of the tax schemes. Supporting the same, Kavirathna et al. (2023) found that enforcing an emission tax only for NSR would decrease its competitiveness if no emission tax were enforced for SCR's navigation. Xiang et al. (2025) investigated the challenges in designing liner shipping networks via NSR, considering its navigability, transit cost, and the environmental tax related to black carbon emissions. Moreover, they provided practical insights for shipping companies' daily operations along with policy formulation of sustainable green transport for countries along the NSR. Furthermore, Cheaitou et al. (2022) analyzed the effect of a carbon tax on NSR attractiveness, focusing on environmental, economic, and risk management perspectives, and highlighted that carbon tax is not antinomic with the NSR profit.

Although several studies analyzed NSR's feasibility with different fuel types and the transition from high- to low-sulfur fuels (Dai et al., 2021; Ding et al., 2020), Lindstad et al. (2016) stated that no general climate benefits would result from using NSR even with cleaner fuels because the impacts from emissions would more than offset the effect of shorter voyages. IMO Sulfur limit was incorporated for China's oil imports via NSR by Wang et al. (2020b) and highlighted the NSR's potential to carry some of the imported volumes. Kavirathna et al. (2023) analyzed the simultaneous effect of regulatory and operational ECMs, including speed optimization, HFO-banned areas, and emissions tax. They highlighted the NSR's feasibility with these ECMs over the NSR's status quo and SCR scenarios. Moreover, several studies considered speed optimization as an operational ECM (Ding et al., 2024; Kavirathna et al., 2023; Theocharis et al., 2019). According to a speed optimization with a tramp ship routing problem investigated by Li et al. (2022), the NSR indicates a high gross margin and fewer emissions with the effect of a carbon tax scheme. Moreover, limited studies focused on market-based ECMs such as ETS to decarbonize NSR navigation considering container shipping (Wang et al., 2020a), although a more detailed consideration of ice conditions is necessary.

2.3. Emission trading system and positioning this study

An ETS is a more market-oriented approach than a carbon tax and can have more potential participants. Both global and regional ETSs were considered in the literature regarding the implementation of an ETS. A global ETS can avoid carbon leakage from one sector to another and decrease MACs, while a regional ETS with incomplete coverage may lead to carbon leakage (Wu et al., 2022). For instance, with a regional

ETS, fossil fuel use and subsequent emissions could move from participating countries to non-participating countries due to the significant difference in their fuel prices while reallocating carbon-intensive activities such as changing navigation paths to avoid participating regions or increasing/decreasing vessel speeds within/outside participating regions. Moreover, the free emission quota (FEQ), a significant element of an ETS, implies the maximum amount of CO₂ that an entity could emit in a given period. Therefore, concerning the allocation of the FEQ percentage, different methods, such as benchmarking, grandfathering, and auctioning, were discussed (Huang et al., 2015). The benchmarking method allocates FEQ based on performance indicators, and the grandfathering method allocates FEQ proportionally to past emissions. Auctioning eliminates discriminative problems and generates funding to promote mitigation efforts (Wu et al., 2022). However, no consensus exists on which methods should be used in the carbon ETS for international shipping.

Since this study focused on ETS as an EMC, selected previous studies related to ETS are summarized in Table 1. Accordingly, several studies discussed the effect of ETS on the maritime industry in general (Cariou et al., 2021; Wang et al., 2021), while some studies focused on open-ETS and maritime-only ETS (Wang et al., 2015; Zhu et al., 2018b). The impacts of ETS on shipping companies' fleet composition and operations were analyzed by Gu et al. (2019) and Zhu et al. (2018b). Most previous studies focused on ETS on conventional shipping routes; however, the ETS's effect on NSR could differ from conventional routes due to the NSR's seasonality, ice conditions, ice-class vessels, and additional voyage costs, including icebreaking costs. Focusing on NSR, Wang et al. (2020a) examined the potential diversions of container shipping vessels to the *trans*-Arctic routes with an ETS and identified some potential diversions to achieve the GHG abatement goal. However, considering the complexity of NSR's navigation, a more detailed consideration of ice conditions is necessary. Besides, they did not consider the effect of ETS on bulk shipping voyages, which has more potential for diversion due to the point-to-point network.

In summary, it was noted that limited studies focused on the effect of ETS on the economic and environmental feasibility of competing maritime corridors, and no studies focused on optimum routing for dry bulk shipping voyages between SCR and NSR with an ETS.

3. Model development

3.1. Navigations paths via NSR and selected voyages

Unlike conventional shipping routes, NSR's navigation is heavily influenced by the ice conditions along the navigation paths and the seasonality. Thus, this study uses AIS vessel positioning data of previous vessel movements to obtain a representative navigation path for NSR (yellow track points in Fig. 1), and four main navigation paths (AB, AD, CB, and CD) were identified by connecting geographical points with high-density vessel positions as illustrated in Fig. 1. Considering the high density of vessel positions, only the path AB is selected for the analysis to maintain the brevity of this paper. Dry bulk voyages are considered for the analysis to derive implications on NSR's feasibility in the dry bulk sector because it is one of the potential cargo to be transported via NSR and considering data availability with the AXS Dry database. Hence, 174 dry bulk voyages navigated in 2018 were selected for analysis. Considering the applicability of both NSR and SCR routes, the voyages between North Europe and East Asia were selected, demonstrating distance-saving via NSR compared to SCR between the same Origin-Destination (O-D) pairs. The green points in Fig. 1 demonstrate the origins and destinations of 174 selected voyages. Most of these voyages carried iron ore pellets, iron ore concentrates, fertilizers, steels, and palm, while a few voyages transported coal, coke, cement, grain, alumina, and furnace slag, among others.

Table 1
A summary of selected previous studies on ETS.

Study	Objectives	Scope	Main Findings
Wang et al. (2020a)	Examine the potential for a general diversion pattern to the <i>trans</i> -Arctic routes of the global shipping traffic.	Container shipping	Identified some potential diversions to the NSR to achieve the GHG abatement goal.
Wang et al. (2021)	Discuss the implications for shipping companies from the EU's inclusion of maritime transport in the ETS.	SCR and the Cape route	Potential of redesigning services to include more ports in Asia instead of the EU and shifting between routes.
Zhu et al. (2018b)	Investigate the impact of an open maritime ETS on individual containership operators' fleet composition strategies and CO2 emissions levels.	Container shipping	ETS motivates operators to utilize new technologies, deploy more energy-carbon-efficient ships, and even lay up less energy-efficient ships. Bunker price has a larger effect on CO2 reduction than applying stricter CO2 allowance allocation, and the ETS is more efficient at high bunker prices.
Wang et al. (2015)	Analyze the monetary consequences of two ETS schemes: the open ETS and maritime-only ETS.	International shipping industry in general	Although both schemes reduce vessel speed, carrier outputs, and fuel usage, open ETS will cause a higher proportional reduction in the dry bulk sector than container shipping. In maritime-only ETS, the container sector will buy permits from dry bulk shipping.
Cariou et al. (2021)	Assess the impacts of including maritime transport in EU ETS.	Oil trade in Europe	Estimated 60 million tons of CO2 are generated by EU voyages. Even at a low price, ETS provides sufficient incentives for abatement measures, such as wind-assistance technologies.
Gu et al. (2019)	Study the impact of maritime ETS on fleet operations and CO2 emissions.	Global and regional ETS schemes	In the short term, ETS does not lead to emission reduction in most scenarios. However, at low bunker prices, high allowance costs, or global maritime ETS coverage, a more significant CO2 decrease can be expected in the short term.



Fig. 1. Navigation paths along the NSR.
Source: Made by authors

3.2. Navigation speeds via NSR

Due to the impacts of ice conditions, NSR's navigation speed has seasonal variations. Thus, this study estimates the navigation speeds incorporating the IMO POLAR code and considering the spatial-temporal variation of ice conditions. The entire navigation area is divided into numerous grids (70 grids with the dimension of 2° lat × 10° log), and daily ice thickness and concentration data of numerous geographical points along the navigation paths are obtained for each grid from the Arctic Data Archive (ADS)-TOPAZ4 system. Depending on the ice-thickness levels (cm) and the guidelines under the POLAR code, various ice types (i.e., ice-free (0 cm), new-ice (< 10 cm), grey-ice (10–15 cm), grey-white ice (15–30 cm),..., etc.) are identified along with their concentrations levels (%). Finally, Equation (1) estimates the monthly average risk index outcome (RIO) for each grid and each ice class separately.

$$RIO = (C_1 \times RIV_1) + (C_2 \times RIV_2) + (C_3 \times RIV_3) + \dots (C_x \times RIV_x) \quad (1)$$

where

- x Ice type;
- C_x Ice concentration (in tenths) of each ice type x ;
- RIV_x Risk index values (RIV) for each ice type x .

RIV changes based on the ice types and a vessel's ice class, as summarized in Table 2. Lower RIV values are given to the heavy and thick ice types; thus, a higher RIO implies a lower navigation risk, and a small or minus RIO indicates a higher navigation risk. This study considers two ice-class vessel types, PC7 and PC5, for the analysis. Therefore, Fig. 2 summarizes each month's estimated RIO related to the respective grids for PC7 and PC5 vessels, which are significantly different.

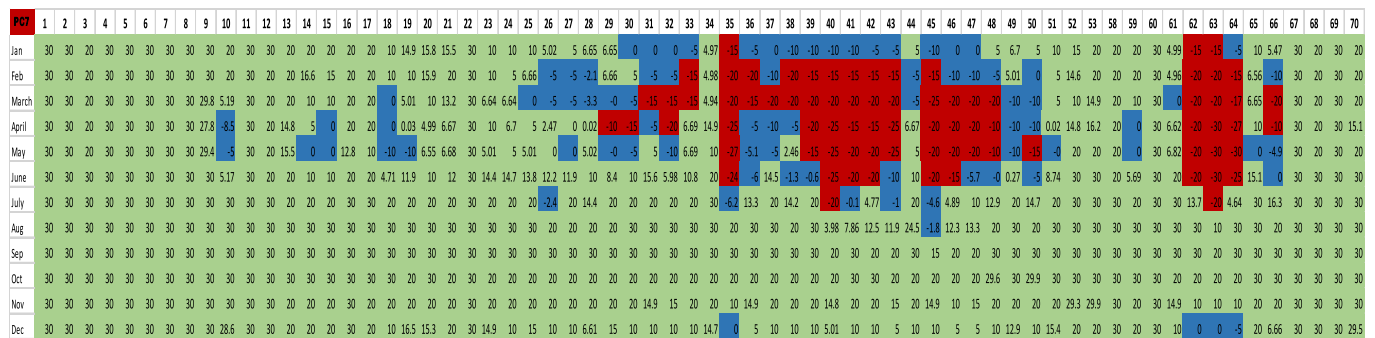
The NSR navigation speed is significantly affected by the respective ice conditions along the navigation path. To find the speeds associated

Table 2
RIVs for different ice-class vessels.

RIV	PC1	PC2	PC3	PC4	PC5	PC6	PC7	IA Super	IA	IB	IC	No ice class
Ice-Free	3	3	3	3	3	3	3	3	3	3	3	3
New ice	3	3	3	3	3	2	2	2	2	2	2	1
Grey ice	3	3	3	3	3	2	2	2	2	2	1	0
Grey white ice	3	3	3	3	3	2	2	2	2	1	0	-1
Thin first-year ice 1st stage	2	2	2	2	2	2	1	2	1	0	-1	-2
Thin first-year ice 2nd stage	2	2	2	2	2	1	1	1	0	-1	-2	-3
Medium first-year ice less than 1 m thick	2	2	2	2	1	1	0	0	-1	-2	-3	-4
Medium first-year ice	2	2	2	2	1	0	-1	-1	-2	-3	-4	-5
Thick first-year ice	2	2	2	1	0	-1	-2	-2	-3	-4	-5	-6
Second-year ice	2	1	1	0	-1	-2	-3	-3	-4	-5	-6	-7
Light multi-year ice, less than 2.5 m thick	1	1	0	-1	-2	-3	-3	-4	-5	-6	-7	-8
Heavy multi-year ice	1	0	-1	-2	-2	-3	-3	-4	-5	-6	-8	-8

Source: IMO (2016).

a. PC7 vessels



b. PC5 vessels

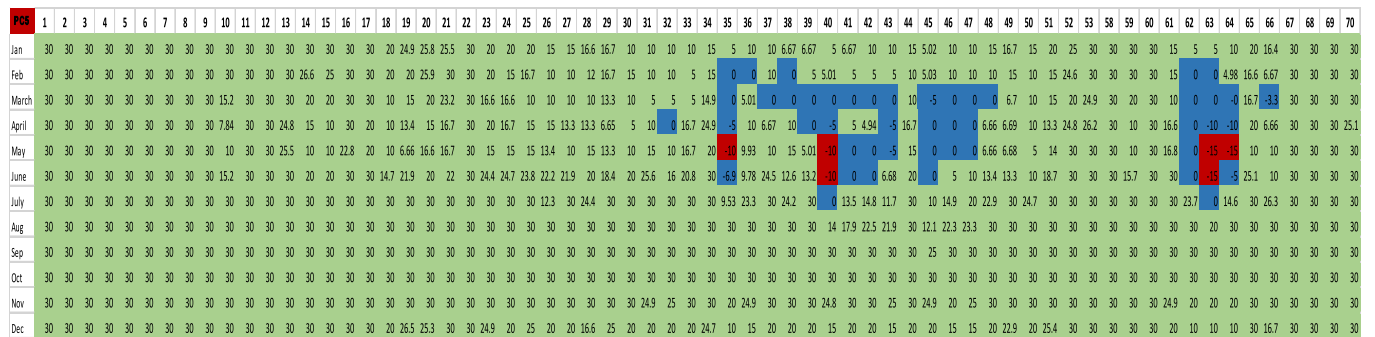


Fig. 2. RIO estimated for PC7 and PC5 vessels.

Source: Made by authors

with respective ice conditions, the observed speed data are then obtained for the different ranges of RIO from AIS, as summarized in Table 3, which are used for the cost and emission estimations via NSR.

Table 3
Average vessel speeds for different RIO.

Range of RIO Values	Average Vessel Speed (knots)
<(-10)	1.58
(-10)-(-5)	2.92
(-5)-0	3.70
0-5	7.30
5-10	6.53
10-15	7.16
15-20	10.69
20-25	10.85
25-30	11.30

Source: Estimated by authors.

These average speeds are calculated from the observed speeds of previous transit vessels via NSR if navigating inside grids with respective RIO. These average speed values in Table 3 are reasonable with the respective RIO. For instance, if RIO increases, the average speed also generally increases, which is sensible because a higher RIO implies a lighter ice condition. However, in some instances, the average vessel speed does not always increase as RIO increases; some lower RIO ranges could have slightly higher speeds due to the heavy usage of icebreaking assistance in navigation, resulting in higher average speeds. Moreover, observed speed could be affected by various other environmental and vessel-specific conditions. In any case, this study considers local ice conditions in small grids using RIO to find the speeds associated with respective ice conditions, which reasonably improves the model compared to most previous studies that used an average speed for the entire voyage. Notably, different ice-class vessels have different RIO inside a grid; thus, their speed varies spatially and temporally. However,

in the practical scenario, a more detailed consideration of the POLAR code should be given if navigating under heavy ice conditions with negative *RIO* because a vessel should follow special operation and safety measures, which will be considered in future studies.

3.3. Estimating the voyage costs and emissions

To analyze the optimum routing between NSR vs. SCR, costs and emissions of voyages are estimated. The list of notations used for the model is summarized in the Appendix. Equation (2) gives the NSR cost function, which has four components: capital, operating, fuel, and ice-breaking costs. Equation (3) gives the SCR cost function, which includes the SCR toll instead of icebreaking costs. Equation (4) estimates the capital cost of voyages (Xu et al., 2018), incorporating the new building price of vessels estimated with Equation (5), considering a vessel's deadweight tonnage (DWT) (Shibasaki et al., 2017). Operating cost is estimated with Equation (6) (Xu et al., 2018). For NSR, Equation (2) includes parameters σ and ρ to represent the premium for the new-building price and operating cost of an ice-class vessel compared to an open-water vessel.

Equation (7) estimates the fuel cost of voyages considering the total fuel consumption and fuel prices. To estimate the fuel consumption via NSR, Equation (8) considers the summation of fuel consumed at each navigation leg given as a function of the vessel's speed and DWT (Japan Shipping Exchange, 2021) because a vessel speed varies spatially based on the ice condition at the navigation time. However, Equation (9) estimates the fuel consumption of voyages via SCR by considering a vessel's DWT, navigation distance, and average speed because SCR's speed is the average speed for the entire voyage. According to the NSR's administration, the icebreaking fee for vessels is calculated based on a vessel's gross tonnage (GT) and the number of NSR's zones with icebreaker assistance, as given by Equation (10). Instead of the ice-breaking cost, SCR navigation requires a vessel to pay the Suez Canal Toll ($Toll_i$), which is the last component of the SCR cost function (Equation (3)). Equation (11) estimates the $Toll_i$ as a function of $scnr_t_i$, given by Equation (12) following Shibasaki et al. (2017). Duration of voyages via NSR and SCR are given by Equations (13) and (14), respectively. Finally, to analyze the environmental feasibility and to formulate the ETS mechanism, CO₂ emissions of each voyage via NSR and SCR are estimated by Equation (15) as a function of fuel consumption and emission factors.

$$Cost_{i,NSR,f} = \sigma \bullet K_{i,NSR} + \rho \bullet Oper_{i,NSR} + \gamma \bullet Fuel_{i,NSR,f} + IB_i \quad (2)$$

$$Cost_{i,SCR,f} = K_{i,SCR} + Oper_{i,SCR} + Fuel_{i,SCR,f} + Toll_i \quad (3)$$

$$K_{i,r} = \frac{T_{i,r} \times Price_i^{NB}}{LT_i \times 365 \times 24} \quad (4)$$

$$Price_i^{NB} = c_1 \times DWT_i + c_2 \quad (5)$$

$$Oper_{i,r} = 0.5 \times K_{i,r} \quad (6)$$

$$Fuel_{i,r,f} = FP_f \times FC_{i,r} \quad (7)$$

$$FC_{i,NSR} = \sum_{i_n}^N (c_3 \times DWT_i^{2/3} \times (S_{i_n}^{NSR})^3) \cdot ((D_i^n / (S_{i_n}^{NSR} \times 24))) \quad (8)$$

$$FC_{i,SCR} = (c_3 \times DWT_i^{2/3} \times (S_i^{SCR})^3) \cdot ((D_i^{SCR} / (S_i^{SCR} \times 24))) \quad (9)$$

$$IB_i = b_i \times B_n \times GT_i \quad (10)$$

$$Toll_i = SDR_{rate} \times (c_4 \times scnr_t_i + c_5) \quad (11)$$

$$scnr_t_i = 0.522 \times DWT_i \quad (12)$$

$$T_{i,NSR} = \sum_{i_n}^N (D_i^n / S_{i_n}^{NSR}) \quad (13)$$

$$T_{i,SCR} = D_i^{SCR} / S_i^{SCR} \quad (14)$$

$$Em_{i,r,f} = FC_{i,r} \times EF_{CO_2f} \quad (15)$$

3.4. Formulating ETS mechanism and optimum routing of voyages

This study formulates an ETS mechanism to analyze the effect of ETS on the optimum routing of voyages. However, considering the absence of an ETS in these routes in the real-world scenario, this study assumes an open ETS, allowing shipping companies to trade their excess allowances in the open market. Although the CP is decided based on the supply/demand mechanism in the ETS market, an average CP is assumed to be taken from the open market, considering the minor share of these two routes in the carbon market.

The feasibility of voyages via NSR and SCR could be affected by the presence or absence of an ETS. For instance, if a voyage has a higher cost and a lower emission via NSR than SCR ($Cost_{i,NSR,f} > Cost_{i,SCR,f}$ and $Em_{i,NSR,f} < Em_{i,SCR,f}$) at the status quo without an ETS, it may derive a lower cost via NSR than SCR with an ETS because that emission saving or excess carbon allowance can be traded in the ETS market. In the ETS market, a shipping company may minimize compliance costs and abate emissions until its marginal cost equals the CP. Therefore, even if a voyage cost via SCR is lower than NSR, a vessel may divert from SCR to NSR if the MAC by a route diversion is lower than the CP in the ETS market, thus enabling the shipping company to sell the abatement credits/excess allowances to the market (Wang et al., 2020a,b). The MAC of a route diversion from SCR to NSR for a voyage with higher cost but lower emissions via NSR than SCR is estimated with Equation (16), where $MAC_{i,f}$ calculates the cost of reducing a unit emission by diverting a voyage from SCR to NSR. A shipping company can benefit from this route diversion if the derived $MAC_{i,f}$ is lower than the CP. Therefore, the ETS mechanism considered in this study differs from a simple carbon tax scheme because ETS can convert an economically infeasible voyage to a feasible one if it demonstrates environmental feasibility, although an emission tax can be just an economic burden to the vessel operators.

A vessel routing optimization model is developed to understand the effect of ETS. Three scenarios (A to C) based on alternative FEQ definitions are assumed, as shown in Table 4. The model decides the route of individual voyages via NSR or SCR to minimize the total cost of all voyages. Equation (17) gives the total cost of voyages for scenario A, which considers an ETS if the FEQ is decided as the least emissions between the two routing options. In calculating the total cost of voyages with Equation (17), two instances are considered, such as the cost of voyages with lower emissions via NSR than SCR ($Em_{i,NSR,f} < Em_{i,SCR,f}$) and those with higher emissions via NSR than SCR ($Em_{i,NSR,f} > Em_{i,SCR,f}$), as given in Equations (18) and (19). Similarly, Equation (20) gives the total cost of voyages for scenario B, where the FEQ is assumed to have the highest emissions between the two routing options, and Equations (21) and (22) express the cost calculation for instances if voyages have lower or higher emissions via NSR than SCR, respectively. Finally, Equation (23) gives the total cost of voyages of scenario C, where the FEQ equals the average emissions produced by two routing options, while the average emissions of voyages via NSR and SCR are given with Equation (26). Similar to the previous scenarios, cost

Table 4
Scenarios for the FEQ.

Scenarios	Description
A	FEQ equals the least emissions between the two routing options.
B	FEQ equals the highest emissions between the two routing options.
C	FEQ equals the average emissions produced by the two routing options.

calculations with instances if voyages have lower or higher emissions via NSR than SCR are given with Equations (24) and (25), respectively.

$$MAC_{i,f} = (Cost_{i,NSR,f} - Cost_{i,SCR,f}) / (Em_{i,SCR,f} - Em_{i,NSR,f}) \quad (16)$$

TotalCost_A

$$= \sum_{i=1}^{174} \left[\theta_i \times Cost_{i,A,(Em_{i,NSR,f} < Em_{i,SCR,f})} + (1 - \theta_i) \times Cost_{i,A,(Em_{i,NSR,f} > Em_{i,SCR,f})} \right] \quad (17)$$

$$Cost_{i,A,(Em_{i,NSR,f} < Em_{i,SCR,f})} = \left[\delta_i^{NSR} \times Cost_{i,NSR,f} + (1 - \delta_i^{NSR}) \times [Cost_{i,SCR,f} + CP \times (Em_{i,SCR,f} - Em_{i,NSR,f})] \right] \quad (18)$$

$$Cost_{i,A,(Em_{i,NSR,f} > Em_{i,SCR,f})} = \left[\delta_i^{NSR} \times [Cost_{i,NSR,f} + CP \times (Em_{i,NSR,f} - Em_{i,SCR,f})] + (1 - \delta_i^{NSR}) \times Cost_{i,SCR,f} \right] \quad (19)$$

$$TotalCost_B = \sum_{i=1}^{174} \left[\theta_i \times Cost_{i,B,(Em_{i,NSR,f} < Em_{i,SCR,f})} + (1 - \theta_i) \times Cost_{i,B,(Em_{i,NSR,f} > Em_{i,SCR,f})} \right] \quad (20)$$

$$Cost_{i,B,(Em_{i,NSR,f} < Em_{i,SCR,f})} = \left[\delta_i^{NSR} \times [Cost_{i,NSR,f} - CP \times (Em_{i,SCR,f} - Em_{i,NSR,f})] + (1 - \delta_i^{NSR}) \times Cost_{i,SCR,f} \right] \quad (21)$$

$$Cost_{i,B,(Em_{i,NSR,f} > Em_{i,SCR,f})} = \left[\delta_i^{NSR} \times [Cost_{i,NSR,f} + (1 - \delta_i^{NSR}) \times [Cost_{i,SCR,f} - CP \times (Em_{i,NSR,f} - Em_{i,SCR,f})]] \right] \quad (22)$$

$$TotalCost_C = \sum_{i=1}^{174} \left[\theta_i \times Cost_{i,C,(Em_{i,NSR,f} < Em_{i,SCR,f})} + (1 - \theta_i) \times Cost_{i,C,(Em_{i,NSR,f} > Em_{i,SCR,f})} \right] \quad (23)$$

$$Cost_{i,C,(Em_{i,NSR,f} < Em_{i,SCR,f})} = \left[\delta_i^{NSR} \times [Cost_{i,NSR,f} - CP \times (Em_{i,Avg,f} - Em_{i,NSR,f})] + (1 - \delta_i^{NSR}) \times [Cost_{i,SCR,f} + CP \times (Em_{i,SCR,f} - Em_{i,Avg,f})] \right] \quad (24)$$

$$Cost_{i,C,(Em_{i,NSR,f} > Em_{i,SCR,f})} = \left[\delta_i^{NSR} \times [Cost_{i,NSR,f} + CP_f \times (Em_{i,NSR,f} - Em_{i,Avg,f})] + (1 - \delta_i^{NSR}) \times [Cost_{i,SCR,f} - CP \times (Em_{i,Avg,f} - Em_{i,NSR,f})] \right] \quad (25)$$

$$Em_{i,Avg,f} = (Em_{i,NSR,f} + Em_{i,SCR,f}) / 2 \quad (26)$$

These three alternative scenarios are assumed to understand their implications due to the challenges in deciding an exact value for the FEQ concerning the data unavailability. Therefore, Equation (27) gives the objective function of minimizing the total cost of voyages under a given scenario (S). The decision variable of the optimization model is whether a voyage i navigates via NSR or SCR; namely, $\delta_i^{NSR} = 1$ if a voyage navigates via NSR and $\delta_i^{NSR} = 0$ otherwise, as given in Equation (28). Since this study focuses on numerous vessels transit via NSR, the analysis is done with and without a constraint on the maximum number of transit voyages that can be accommodated via NSR each month due to the limited number of icebreakers available, given in Equation (29).

$$\min_{\delta_i^{NSR}} TotalCost_S \quad S = \{A, B, C\} \quad (27)$$

s.t.

$$\delta_i^{NSR} = \{0, 1\} \quad (28)$$

$$\sum_{i=1}^{V_m} \delta_i^{NSR} \leq V_{max,m} \quad \forall i \in V_m \quad (29)$$

The optimization model decides the route of each voyage to minimize the total cost. The problem is solved using the Frontline Solver 2020 version with its Evolutionary Solver feature, consisting of both Genetic Algorithms and Tabu/Scatter search methods.

3.5. Data and scenarios

As explained earlier, the analysis focuses on 174 dry bulk voyages. The navigation distances of individual voyages via SCR are estimated using the Marine traffic voyage planner application, considering their specific O-D pairs, while the distances via NSR are estimated with QGIS software. Moreover, voyage- and vessel-specific data, including vessel GT, DWT, and navigation month, are collected from the AXS Dry database and seasearcher.com. A ten-year lifetime is assumed for vessels to calculate capital cost (Otsuka et al., 2013). The fuel price and emission factor of CO₂ are taken as 600 USD/ton and 3.114 (g/gfuel). Moreover, the ice thickness and concentration data are gathered from the ADS-TOPAZ4 database. Tables 5, 6, and 7 summarize other model-specific parameters.

This study analyzes multiple scenarios, as summarized in Fig. 3. Since the navigation speed via NSR varies over months depending on the respective ice conditions, 174 voyages are grouped based on their actual navigation months. Unlike in NSR's navigation, a vessel can navigate through open water via SCR; thus, three average speeds (10, 15, and 20 knots) are assumed for SCR navigation as alternative scenarios. Hence, considering two ice classes via NSR (PC7 and PC5) and three alternative speeds via SCR, each voyage is analyzed with five alternative scenarios, totaling 870 voyage estimations.

4. Analysis and discussion

4.1. Feasibility of NSR over SCR without an ETS

Before analyzing the effect of an ETS, the NSR feasibility is compared to the SCR at the status quo without an ETS. The cost savings made by NSR with PC7 and PC5 vessels compared to the SCR with 10, 15, and 20 knots are estimated to analyze the economic feasibility, as summarized in Fig. 4, showing the distribution of voyages by the range of cost-saving percentages via NSR compared to SCR. The figure also indicates the total number of voyages with cost savings of positive (NSR feasibility) and negative (NSR infeasibility).

Accordingly, most voyages via NSR are economically infeasible (negative cost-saving) over SCR for each ice-class vessel if the SCR's speed equals 10 knots because slow steaming via SCR could significantly reduce vessels' fuel consumption. However, 37 voyages for PC7 vessels and 34 voyages for PC5 vessels indicate cost-saving with NSR because the reduction of fuel consumption with SCR's 10 knots cannot compensate for the SCR's higher capital and operating cost caused by the longer voyage duration with slow steaming. In contrast, most voyages via NSR are economically feasible for each ice-class vessel over SCR's 20 knots because of the SCR's higher fuel consumption with 20 knots speed. Compared to SCR's 10 and 20 knots, the case with SCR's 15 knots generates nearly equal feasible voyages for each ice-class vessel with both NSR and SCR, implying the higher competition between the

Table 5
Parameters for capital and operating cost estimation of bulk carriers.

Parameter	c_1	c_2	c_3
Value	2.42×10^2	1.64×10^7	8.97×10^{-6}
Source	Shibasaki et al. (2017)		Regression from the Japan Shipping Exchange (2021)

Table 6
Parameters for SCR toll estimation of bulk carriers.

	scrt _t range						
	0–5000	5000–10000	10000–20000	20000–40000	40000–70000	70000–120000	Over 120,000
c ₄	7.88	6.02	4.76	1.51	1.41	1.35	1.3
c ₅	0	39,400	69,500	117,100	147,300	189,600	257,100

Source: Shibasaki et al. (2017).

Table 7
Parameters for estimating ice-related costs.

		PC5	PC7	Source
Premium for ice-class vessels	σ	1.3	1.1	Kavirathna et al. (2021), Otsuka et al. (2013)
	ρ	1.25	1.25	Ding et al. (2020)
	γ	1.3	1.1	Kavirathna et al. (2021), Otsuka et al. (2013)
Number of NSR's zones with icebreaker assistance in different months	Jan–April	7	7	Assumed by authors based on ADS-TOPAZ4 system
	May–June	4	5	
	July	3	4	
	August–September	0	1	
	October–November	3	4	
December	4	7		

routes at SCR's 15 knots. These results are affected by various factors, including navigation lengths, navigation month, DWT, and GT of individual voyages. Moreover, the tradeoff between decreased fuel costs and increased capital and operating costs of voyages with SCR slow steaming could directly affect the NSR feasibility. Besides, using a higher ice-class (PC5) vessel via NSR could be more economical than using SCR with a higher speed because of its higher ice-strength level.

Besides, the voyage duration is a crucial factor influencing the competition between two routes because it affects the route choice decision of time-sensitive shippers or consignees. Fig. 5 summarizes the time-saving of voyages via NSR over SCR for each ice-class vessel. Accordingly, 137 voyages can save transit time via NSR with PC7 vessels than SCR's 10 knots, while all 174 voyages can save time with NSR's PC5 vessels because of the higher speed benefited from higher ice-strength level. Similar results could be obtained with SCR's 15 knots because 137 voyages can save time via NSR with PC5 vessels compared to only 80 voyages can save time with NSR's PC7 vessels. However, if SCR's speed equals 20 knots, very few voyages can save time with NSR, regardless of the ice class. Time-saving by voyages implies more benefits to the cargo owners because of lower depreciation costs and lower in-

transit inventory costs depending on the cargo value and time value. Despite the longer navigation distance of voyages via SCR, most voyages can save transit time with SCR's 20 knots. Thus, NSR is less attractive to time-sensitive shippers and consignees than SCR at a higher speed. Moreover, SCR is more attractive even with 15 knots than NSR with a lower ice-class vessel.

We also analyze the environmental feasibility of NSR for each ice-class vessel over SCR by estimating the emission-saving of voyages via NSR, as summarized in Fig. 6. Similar to the economic feasibility, limited voyages are environmentally feasible (positive emission-saving) of NSR for each ice-class vessel over SCR's 10 knots because slow steaming reduces the fuel consumption of SCR voyages. Moreover, more NSR voyages are environmentally feasible with a PC7 vessel than a PC5 vessel if SCR's speed equals 10 knots. Hence, a lower ice-class vessel is recommended to receive more environmental benefits with NSR. However, all 174 voyages demonstrate environmentally feasible via NSR for each ice class over SCR's 15 and 20 knots because of the SCR's higher fuel consumption caused by higher speed and comparatively longer navigation distances.

Since NSR's speed and costs are influenced by the ice condition at the time of navigation, the cost-, emissions- and time-savings of voyages via NSR could vary monthly. Fig. 7 summarizes the percentage of voyages with positive cost-, emissions-, and time-savings via NSR for each ice-class vessel out of the total number of voyages navigated each month. Accordingly, in SCR's 10- and 15-knot scenarios, NSR with PC7 vessels demonstrates cost-saving mainly between July and November, while PC5 vessels indicate cost-saving even during the winter and spring months. In the 20-knot scenarios, both NSR vessels can save costs in most voyages except February and March. The emission-saving via NSR is observed throughout the year in SCR's 15- and 20-knot scenarios, while time-saving is observed mainly in the summer and autumn months in these scenarios. Apart from ice condition variation, these results are affected by the origin–destination, navigation distance, and vessel specification of voyages navigated each month.

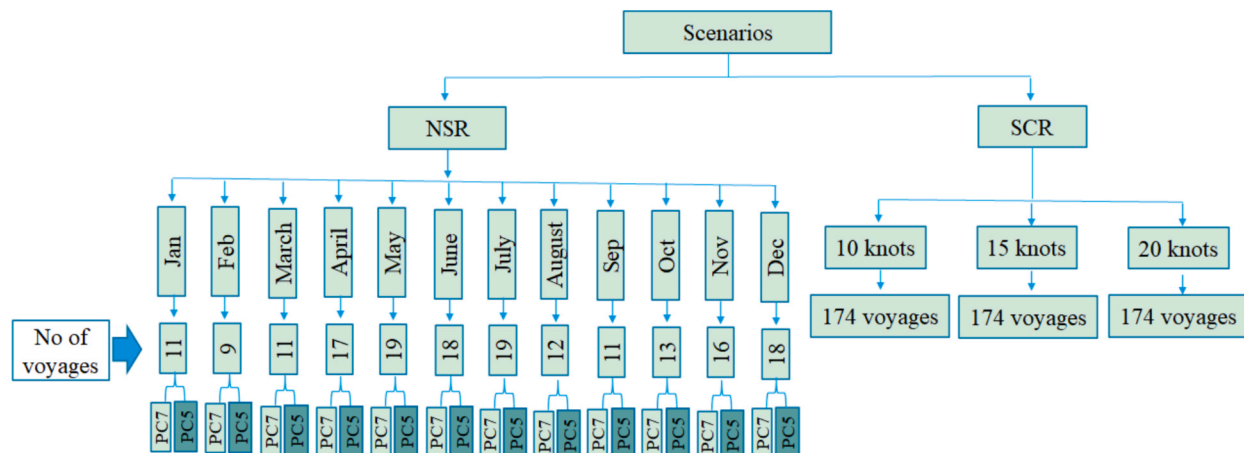


Fig. 3. Scenario analysis framework.

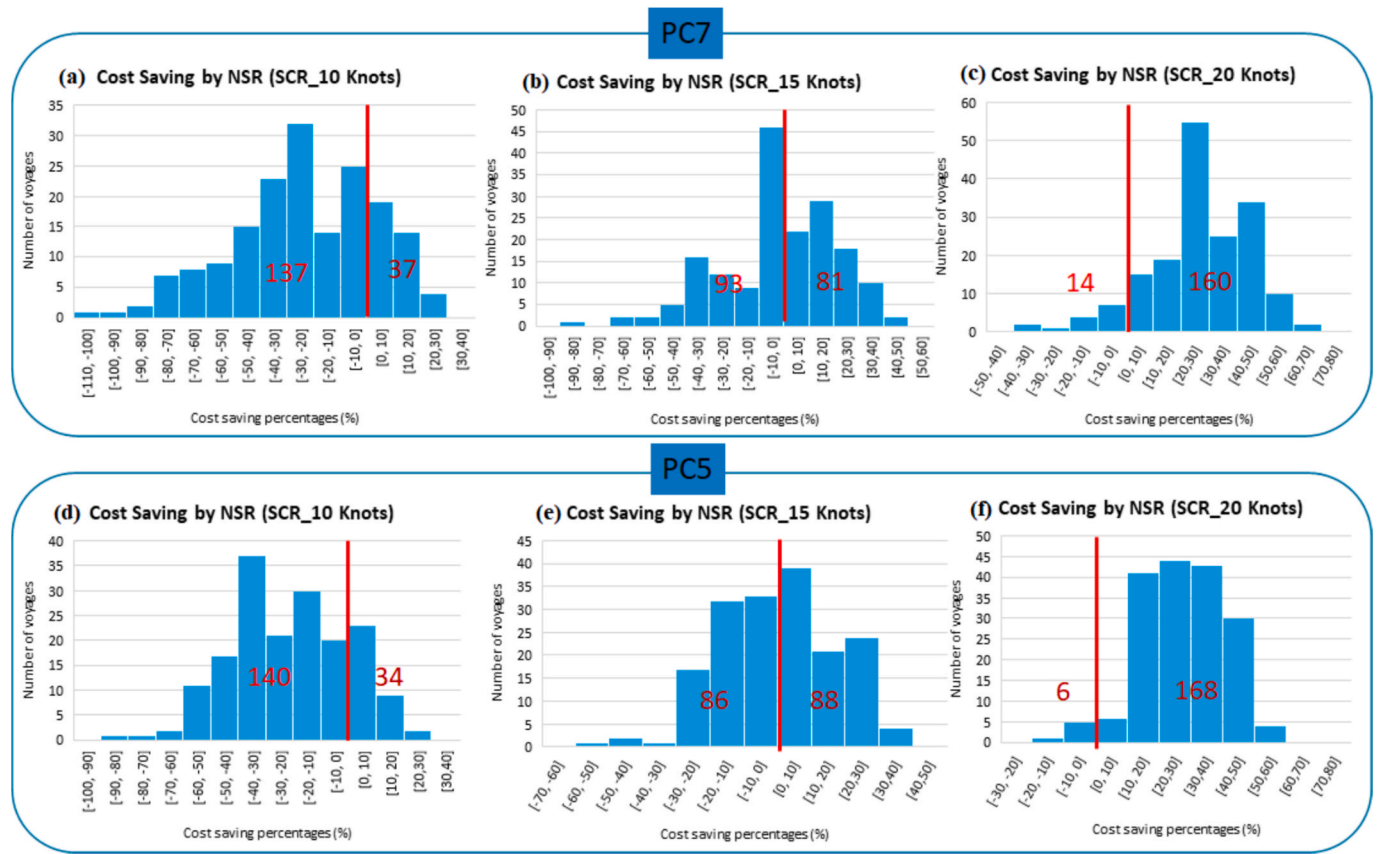


Fig. 4. Cost-saving by NSR over SCR with different ice-class vessels and SCR speeds.

4.2. Correlation analysis on NSR feasibility for justification of introducing an ETS

Based on the results shown in the previous subsection, the implications of NSR feasibility are discussed with several correlation analyses. Fig. 8 summarizes the results with SCR’s 15-knot scenarios because it derives nearly 50 % of feasible voyages for both routes, indicating that (a) the correlation between time- and cost-savings of voyages via NSR is high, especially with PC7 ice-class vessels. Moreover, both ice-class vessels demonstrate significantly high correlations (d) between distance- and emission-savings of voyages. However, (c) the correlation between time- and emission-savings is very weak, especially with PC7 vessels, although PC5 vessels demonstrate nearly 0.3 R-square value. Considering (b) distance- and cost-savings, although PC5 vessels demonstrate a minor correlation with a 0.44 R-square value, PC7 vessels do not demonstrate a correlation.

Accordingly, if NSR has a higher ability to save navigation time than SCR, it can also derive higher cost savings for voyages. Moreover, if NSR demonstrates higher distance-saving than SCR, it can also generate higher emission-saving. Therefore, a much faster voyage via NSR than SCR may not save emissions, although it can save voyage costs. Similarly, a much shorter voyage via NSR than SCR may not save voyage costs, although it can save emissions. Unlike in open-water navigation, higher distance-saving may not result in higher time-saving with NSR, depending on the ice condition. For instance, even a shorter voyage would take longer navigation time during winter and vice versa.

In addition, Fig. 9 justifies the analysis of the effect of an ETS on NSR and SCR in this study. Both positive and negative cost savings via NSR are observed with SCR’s 15-knot scenarios, as explained previously in Fig. 4, despite the positive emission-saving by NSR observed with many voyages, as shown in Fig. 6. Given the real world, NSR will not be attractive to vessel operators if it cannot save their voyage costs even if it

saves emissions. As illustrated in Fig. 9, no correlation is observed between cost-saving and emission-saving of voyages via NSR. Thus, emission-saving does not guarantee a cost-saving for voyages via NSR.

However, an ETS could change this situation because it allows a shipping company to trade its excess emission allowances earned by navigating via NSR at lower emissions to compensate for its higher cost. Therefore, a voyage that indicated negative cost-saving via NSR without an ETS could result in positive cost-savings via NSR with an ETS. Thus, although some voyages are environmentally feasible but economically infeasible via NSR in the absence of an ETS, they can be both environmentally and economically feasible with the presence of an ETS. Hence, an ETS would have different implications on the feasibility of voyages than an emission tax, which generally increases the voyage cost with additional tax expenses.

4.3. Feasibility of NSR over SCR with an ETS

This section analyzes the NSR’s feasibility over SCR with the effect of an ETS by estimating the MAC based on Equation (16). As we focus on NSR’s feasibility, voyages that demonstrated economically infeasible but environmentally feasible results without ETS are considered. The estimated MAC values (MAC_i) are compared with the CP value (CP) to decide the NSR’s feasibility; if the estimated MAC_i is lower than CP, navigating via NSR becomes feasible with an ETS. Five different CP s are assumed for the analysis, as summarized in Table 8.

Accordingly, most scenarios indicate more feasible voyages via NSR with an ETS than the status quo without an ETS, especially at a higher carbon price and faster speed via SCR. However, if SCR’s speed equals 10 knots, no additional voyages are feasible with NSR at lower carbon prices with both PC7 and PC5 vessels, except for two additional voyages feasible if the carbon price is 100 or 150 USD/MT CO₂e with PC7 vessels. At SCR’s 15-knot scenarios, the number of feasible voyages via NSR

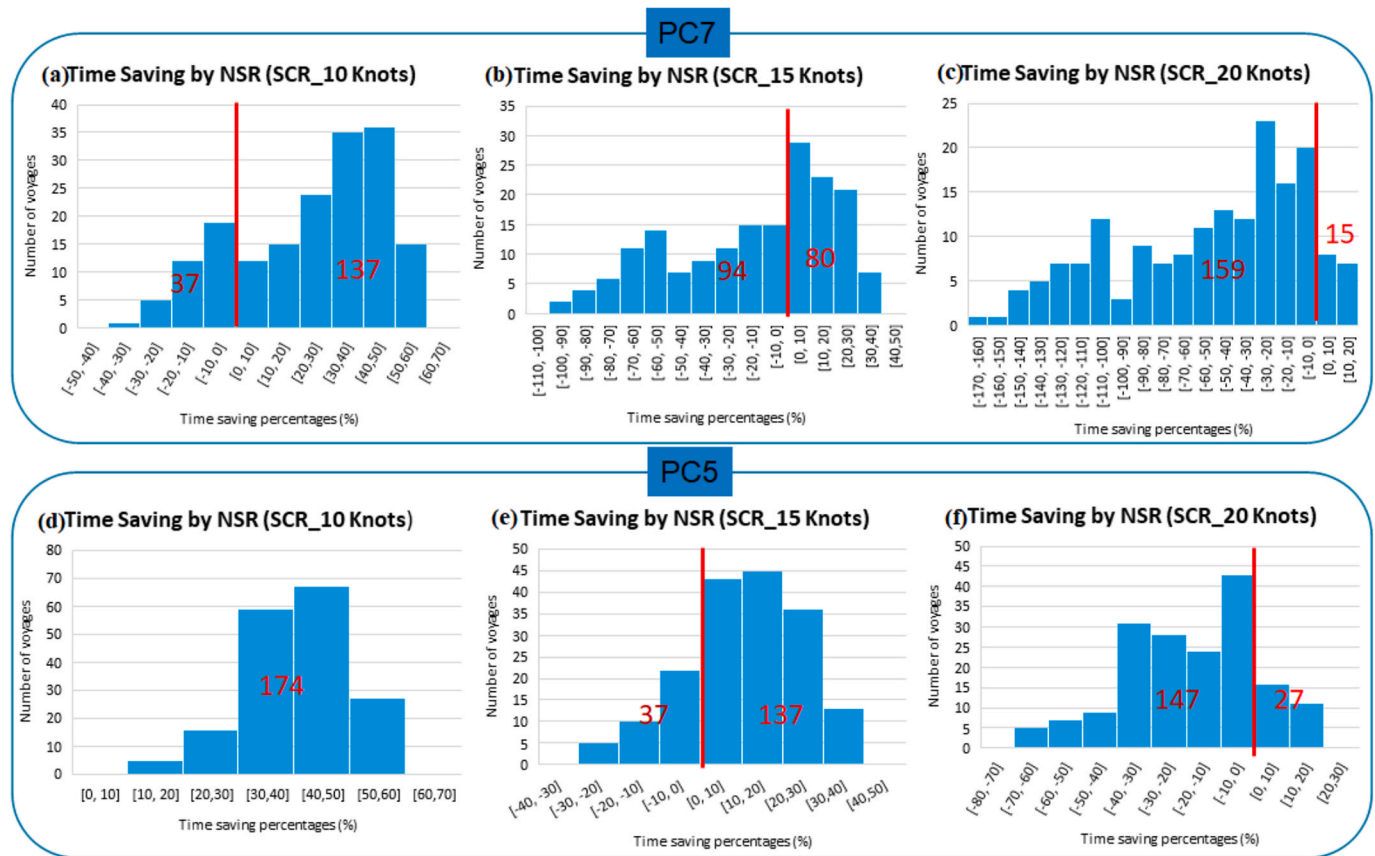


Fig. 5. Time-saving by NSR over SCR with different ice-class vessels and SCR speeds.

has increased significantly (from 89 to 138 voyages with PC7 vessels and from 90 to 124 voyages with PC5 vessels) if CP increases from 10 to 150 USD/MTCO_{2e}. If SCR’s speed equals 20 knots, many voyages are feasible with NSR even without an ETS, which increases further with an ETS. In extreme cases where CP equals 100 USD/MT CO_{2e} with SCR’s 20-knot scenarios and NSR’s PC5 vessels, all 174 voyages are feasible. In this way, if vessels slow steam via SCR, ETS would not significantly enhance NSR’s feasibility over SCR and vice versa. Although an emission tax would add additional costs to the vessel operators while reducing NSR feasibility, an ETS mechanism can enhance NSR feasibility, as reflected by additional voyages for NSR with an ETS.

To understand the variation of MACs estimated from voyages, the frequency distribution of estimated MAC values is illustrated in Fig. 10 for PC7 vessels. Here, the vertical axis represents the number of voyages in a given range of MAC values. Accordingly, at SCR’s 10-knot scenarios, most voyages have their MACs within 75–100 USD/MTCO_{2e}, and at SCR’s 15- and 20-knot scenarios, the highest frequency is received within 1–25 USD/MTCO_{2e} range. Considering the market average CP as 25 USD/MTCO_{2e} (Wang et al., 2020a), many voyages could choose NSR with an ETS scenario if SCR’s speed is above 15 knots. Meanwhile, MAC values of PC5 vessels are not summarized because they have a wider range (2–10148 USD/MTCO_{2e}), which is not meaningful enough to illustrate in a single graph.

4.4. Optimizing vessel routing with the effect of ETS

The following optimization results are based on the scenarios with the SCR’s 15 knots of PC7 vessels and 25 USD/MTCO_{2e} for CP. As explained in Table 4, three optimization scenarios (A, B, and C) are assumed based on the least, highest, and average emissions produced by two routing options. Moreover, reflecting that all transit voyages may not be accommodated in NSR due to the limited availability of

icebreakers, which is explained by the constraint on the maximum number of NSR voyages given with Equation (22), two sub-scenarios are analyzed with and without a limitation on available icebreakers. If limited icebreakers are available, the maximum limit on NSR voyages ($V_{max,m}$) is set for each month.

According to the results in Table 9, all three scenarios received 96 voyages via NSR despite their differences in FEQ if there were no limitations on the available icebreakers. However, with limited icebreakers, only 90 voyages use NSR in scenarios A and C, while 92 voyages use NSR in scenario B. The highest total cost is derived from scenario A, with limited icebreakers, while scenario B, with no limitation on icebreakers, received the lowest cost. Compared to the case with no limitation on icebreakers, the total cost and emissions are increased with limiting the icebreakers due to the inability to use NSR to its maximum potential.

Since NSR feasibility is significantly affected by the variation of ice conditions, this study considers these monthly variations. Table 10 summarizes the optimum NSR voyages monthly for scenario C, assuming the FEQ based on the average emissions from two routes. Accordingly, with both with and without limitation on icebreakers, the Feb–April season derives the least NSR voyages. This is reasonable due to the severe ice conditions for navigation in these months (Fig. 2), which results in higher icebreaking costs for NSR navigation. In August and September, all voyages use NSR because of the ice-free conditions along the navigation path, and July receives significantly larger NSR voyages. Compared with and without icebreaker limitation cases, the number of NSR voyages decreased in June and November due to the limited icebreakers. Fig. 11 visualizes the monthly variation of optimum routing between NSR and SCR, considering the percentages of voyages using each route. Accordingly, SCR receives significant high percentage of voyages from January to April; thus, even with an ETS, NSR is not an attractive routing option compared to SCR during the winter–spring months. In December, nearly an equal number of voyages uses NSR and

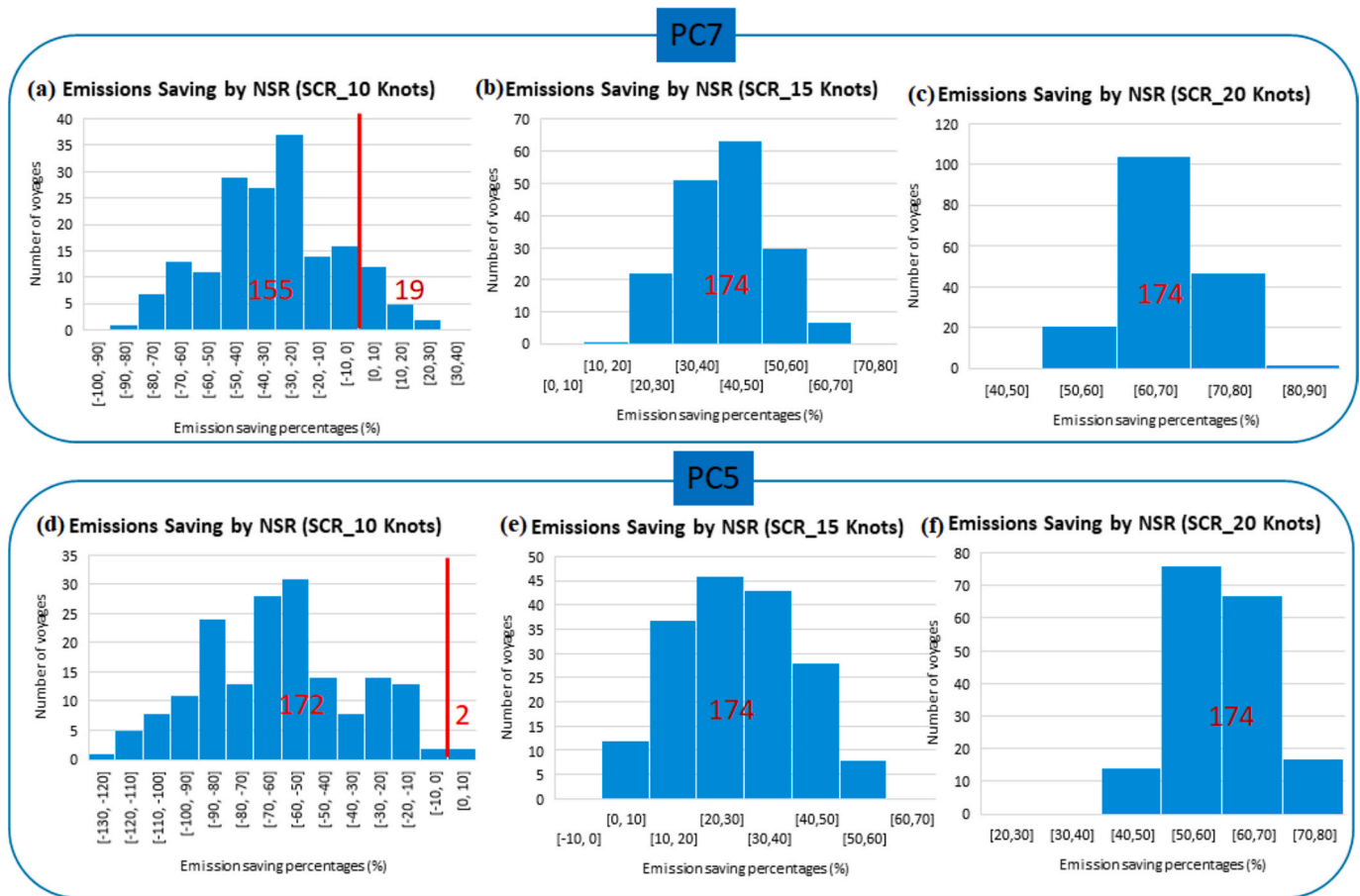


Fig. 6. Emission-saving by NSR over SCR with different ice-class vessels and SCR speeds.

SCR despite limited icebreakers. Because of the light ice conditions along the NSR in June and October, SCR receives fewer voyages in these months. Although over 50 % of voyages use NSR in June and November, SCR increases its market share slightly with NSR’s limited icebreaker scenario compared to the no limitation of icebreakers.

The above analysis assumes the fuel price to be 600 USD/ton, although the variation in fuel price significantly impacts the feasibility of maritime corridors. Therefore, the effects of different fuel prices on the optimum voyage routing between NSR and SCR with an ETS are examined, as shown in Fig. 12. Accordingly, if fuel prices increase, the number of NSR voyages increases, and the total emissions are reduced, although the total cost is increased significantly due to the higher fuel prices. In summary, NSR is more feasible with an ETS if the market fuel price increases because of its costs and emission-saving effect with shorter voyages. However, not many additional voyages are attracted by NSR at very high fuel prices (1500 USD/ton).

Fig. 13 illustrates the monthly variation of NSR voyages with different fuel prices. Accordingly, all voyages in August and September use NSR regardless of the fuel prices. From July to November, all voyages use NSR if the fuel price exceeds 800 USD/ton. However, from February to April, no voyages are feasible via NSR if the fuel price is 300 or 400 USD/ton, although many voyages use NSR at a very high fuel price. From December to January, over 90 % of voyages use NSR, with fuel prices over 1000 USD/ton. In summary, NSR is feasible for more months at expensive fuel prices.

Moreover, using different fuel types impacts route choice with the effect of ETS because of their different fuel prices and emission factors. Another sensitivity analysis is carried out on fuel types, as summarized in Fig. 14. Regarding fuel prices, 970, 600, 800, 700, and 750 USD/ton are assumed for MGO, HFO, LNG, LFO, and VLSFO, respectively. For the

emission factors of fuel types, 3.206, 3.114, 2.750, 3.151, and 3.188 g/gfuel are assumed for MGO, HFO, LNG, LFO, and VLSFO, respectively (IMO, 2020). Fig. 14(a) shows that the highest and lowest total costs are derived from MGO and HFO fuel types. Regarding total emissions, HFO and LNG derive the highest and lowest total emissions. The lowest number of NSR voyages with HFO indicates that using HFO in the maritime industry reduces the NSR’s feasibility. In other words, if ship operators can use a cheaper fuel type for navigation, their motivation to use NSR could be reduced even with an ETS because of insignificant fuel cost via SCR despite its longer navigation distance. However, if the maritime industry promotes the usage of MGO or LNG, more voyages would use NSR to reduce fuel costs. Regarding the monthly distribution of NSR voyages shown in Fig. 14(b), all voyages use NSR in August and September, regardless of the fuel type. From February to April, limited voyages use NSR even with expensive fuel types, and only about 10 % of voyages use NSR if they use HFO fuel. Although using cleaner fuel types with less emission factor reduces the emission production by voyages while reducing the magnitude of emissions-saving by NSR over SCR, these cleaner fuel types enhance the NSR’s economic feasibility due to their higher fuel prices.

5. Conclusions

This study analyzed the effect of ETS on the optimum voyage routing between NSR and SCR. The analysis was done with 174 dry bulk voyages between Europe and Asia, which indicated distance-saving via NSR over SCR. Initially, the cost-, emissions- and time-saving of voyages via NSR over SCR were analyzed considering 10-, 15-, and 20-knot alternative speeds via SCR and PC7 and PC5 ice-class vessels via NSR. Then, the MACs were estimated to formulate an ETS mechanism. Thereafter, the

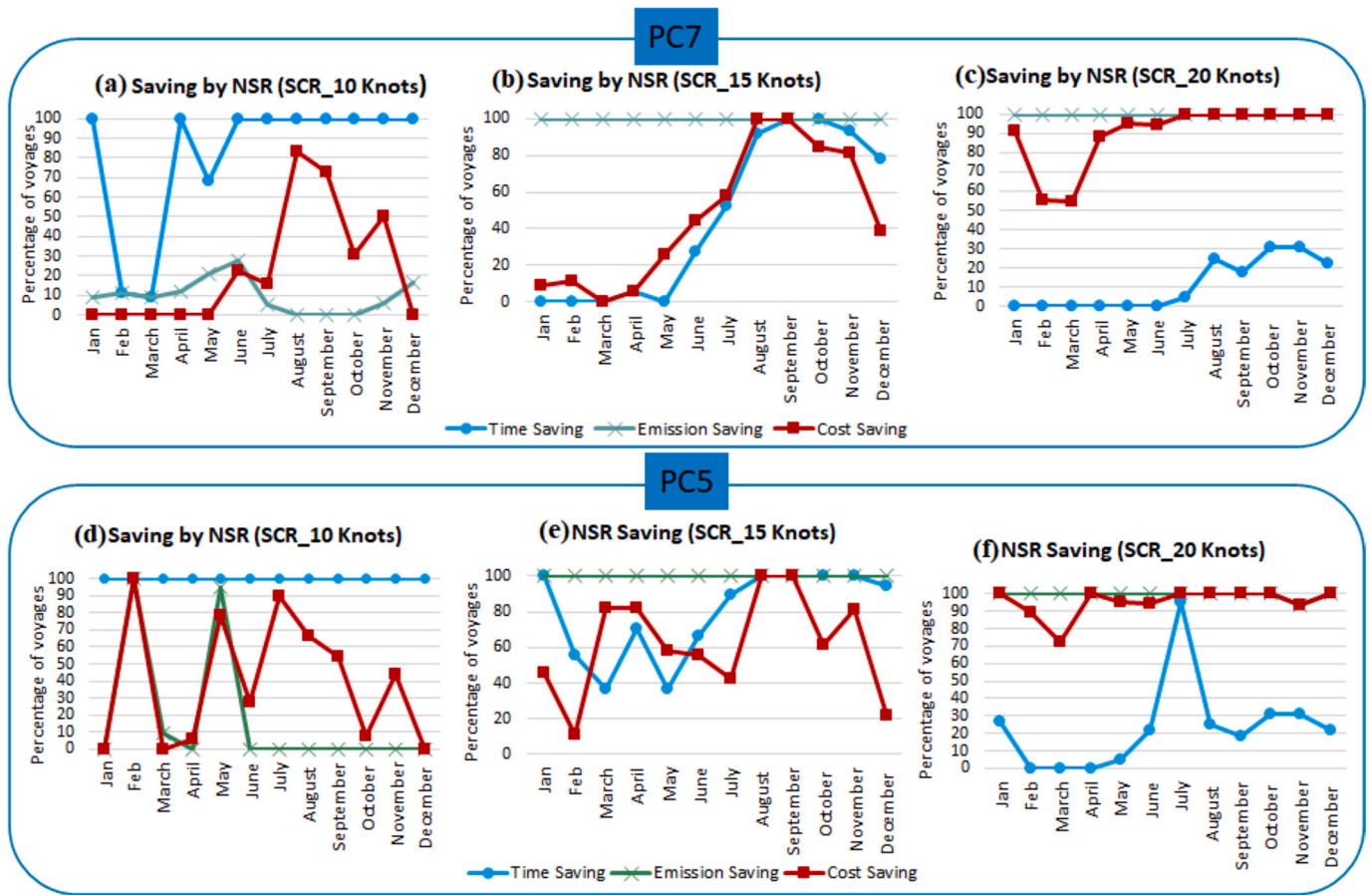


Fig. 7. NSR's feasibility from different viewpoints in different months.

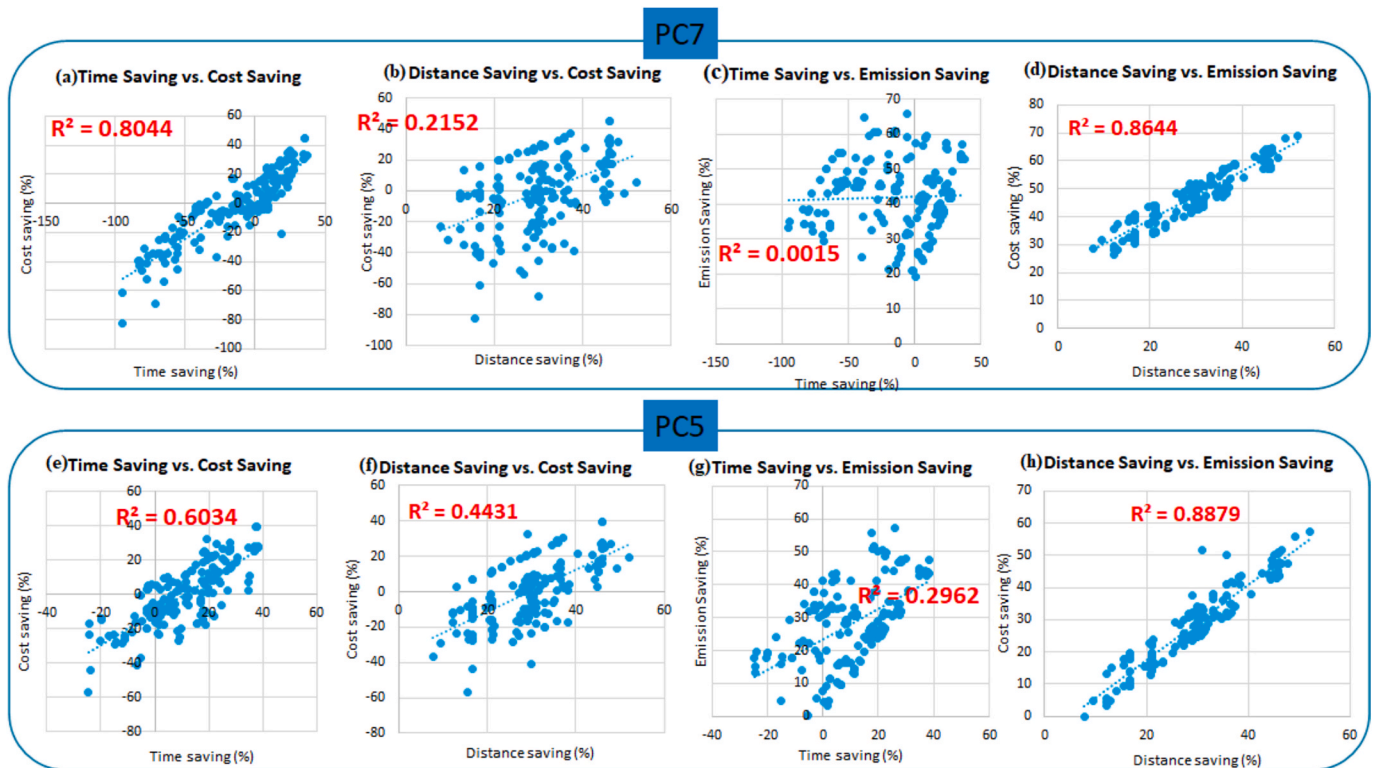


Fig. 8. Correlations analysis for NSR feasibility.

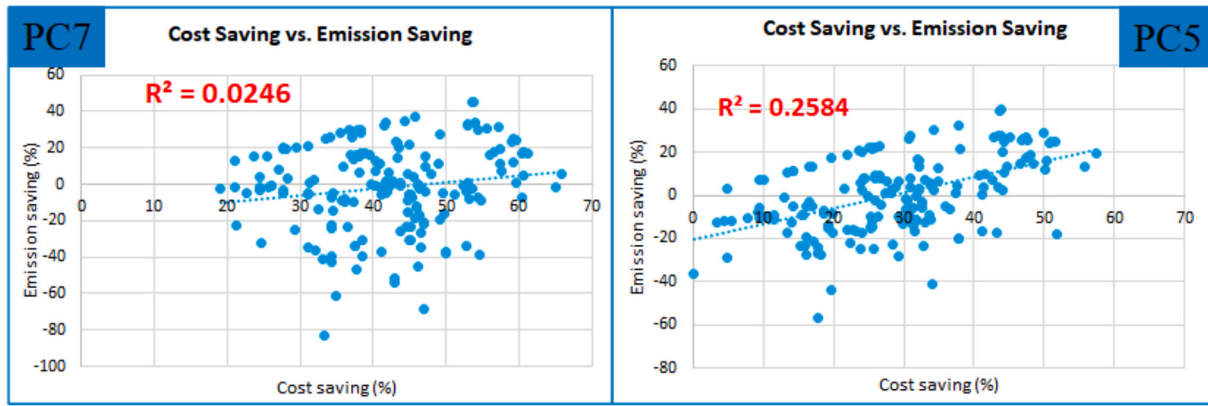


Fig. 9. Correlation between cost-saving and emission-saving of voyages via NSR.

Table 8
Number of feasible NSR voyages with different CP values.

Scenario	CP (USD/MT CO2e)	CP (USD/MT CO2e)					
		0 (without ETS)	10	25	50	100	150
SCR_10 Knots	PC7	37	37	37	37	39	39
	PC5	34	34	34	34	34	34
SCR_15 Knots	PC7	81	89	96	116	129	138
	PC5	88	90	92	96	104	124
SCR_20 Knots	PC7	160	163	168	168	171	173
	PC5	168	171	172	173	174	–

optimum routing of voyages was analyzed using a model that considers the effect of an ETS, and several scenarios were analyzed with different FEQs, fuel prices, and fuel types.

According to our main findings, slow-steaming via SCR is more cost-effective than NSR because voyages did not demonstrate significant cost-saving via NSR over SCR's 10-knot scenario. However, NSR is more feasible than SCR's 20-knot scenario due to the high fuel consumption at SCR's higher speed. Using a higher ice-class vessel (PC5) via NSR is more economical than using SCR at a higher speed. In addition, NSR is more environmentally friendly than navigating via SCR at higher speeds because all 174 voyages demonstrated emissions-saving via NSR over SCR's 15 and 20 knots, mainly because of NSR's slower speed and shorter distance than SCR. However, SCR's 10-knot scenario is more environmentally friendly than NSR. Regarding the time-saving of voyages, NSR will not be attractive to time-sensitive cargo owners over SCR's 20 knots, although it will be attractive over SCR's 10 knots. Moreover, NSR with PC7 vessels is feasible from July to November over SCR's 10 or 15 knots, and NSR with PC5 vessels is feasible even in winter-spring months. Compared to SCR's 20 knots, NSR is economically

Table 9
Optimization results by optimization scenarios.

Optimization scenario	Sub-scenarios	Cost (USD)	Emissions (MT)	NSR Voyages
A	No limitation on icebreakers	200,698,294	503,326.2	96
	Limited icebreakers	201,063,667	508,925.4	90
B	No limitation on icebreakers	193,207,095	503,326.2	96
	Limited icebreakers	193,566,041	506,534.1	92
C	No limitation on icebreakers	196,952,695	503,326.2	96
	Limited icebreakers	197,318,068	508,925.4	90

Table 10
Monthly distribution of NSR voyages.

Month	No limitation on icebreakers		Limited icebreakers	
	Total voyages	NSR voyages	Max limit on NSR voyages	NSR voyages
Jan	11	3	8	3
Feb	9	1	8	1
March	11	1	8	1
April	17	1	8	1
May	19	8	10	8
June	18	11	10	10
July	19	13	15	13
August	12	12	–	12
Sep	11	11	–	11
Oct	13	11	15	11
Nov	16	15	10	10
Dec	18	9	10	9

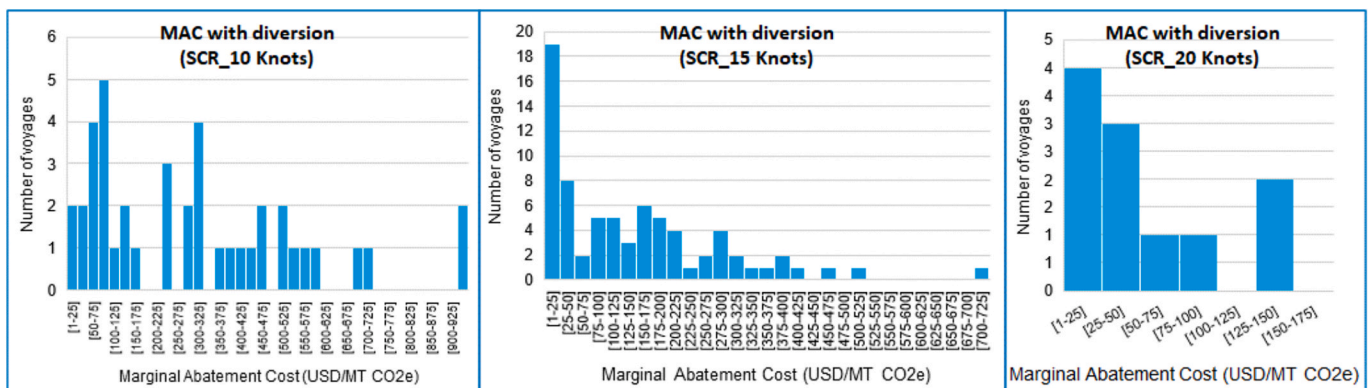


Fig. 10. Frequency distribution of MACs for PC7 vessels.

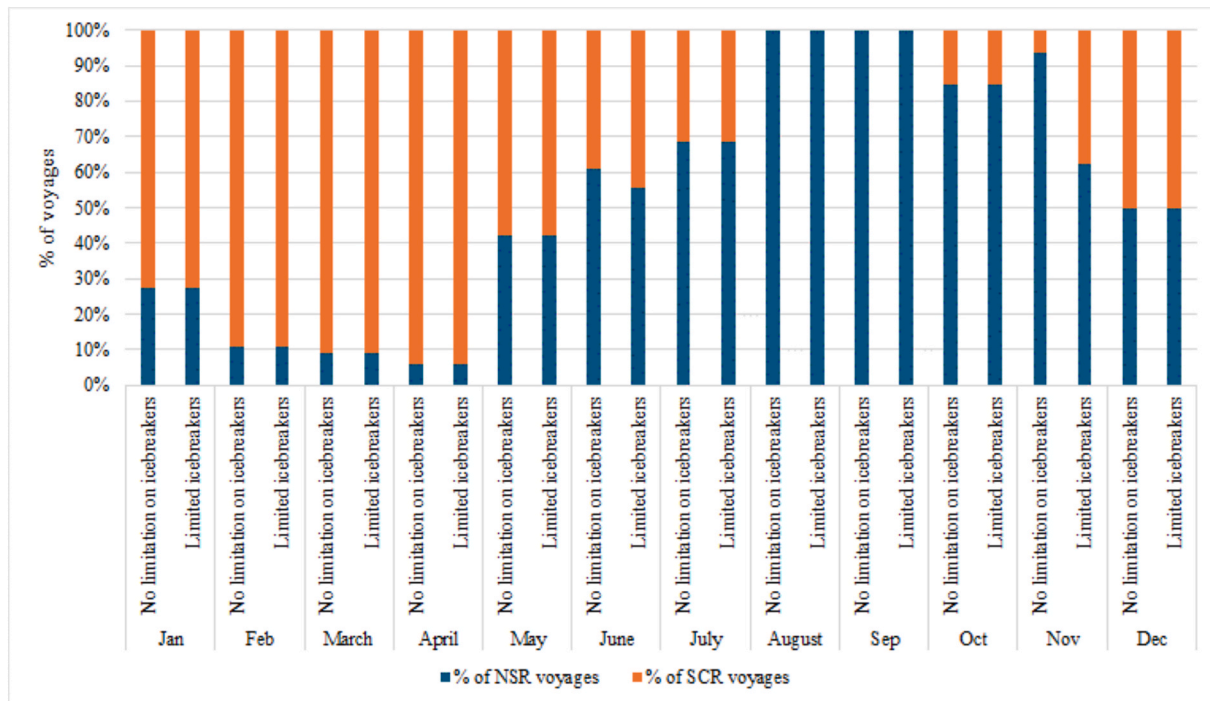


Fig. 11. Monthly variation of optimum vessel routing.

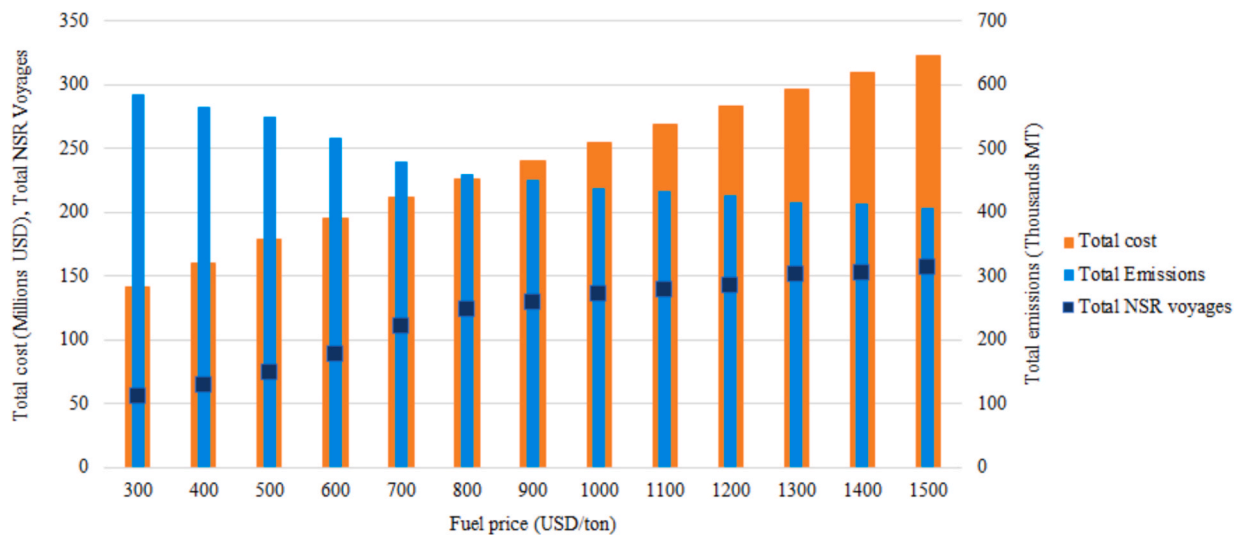


Fig. 12. Variation of total cost, emissions, and NSR voyages with different fuel prices.

feasible throughout the year, especially with PC5 vessels.

According to the results of correlation analysis, if a voyage is much faster via NSR than SCR, it also derives higher cost savings, although it may not save emissions. In contrast, if a voyage is much shorter via NSR than SCR, it also derives higher emission savings, although it may not save cost. Finally, a poor correlation between the cost-saving and emission-saving of voyages via NSR highlights that although NSR demonstrates environmentally feasible with most voyages, it may not guarantee economic feasibility. Therefore, the significance of an ETS is justified because of the potential of trading the emissions-saving benefits or excess emissions allowance to offset the higher voyage cost with an ETS.

Finally, the feasible NSR voyages with an ETS were analyzed by comparing the estimated MAC with the CP. Accordingly, NSR is more feasible at higher CP if SCR's speed is 15 knots or higher. However, an

ETS would not enhance NSR's feasibility significantly if SCR's speed is 10 knots. An ETS could convert economically infeasible NSR voyages to feasible ones, especially at higher CP and with higher speed of SCR, because of the comparatively higher emission saving of voyages via NSR. Therefore, market-based ECMs such as ETS could increase NSR's feasibility more effectively than regulatory ECMs such as emission tax, which add more economic burden to the vessel operators. Based on optimization results, about 96 voyages use NSR regardless of the FEQ if no limitation is considered with icebreakers' availability, while about 90 to 92 voyages use NSR if considering the limitation of icebreakers. Moreover, higher total costs and emissions are derived in the case of limited icebreakers due to the inability to use NSR at its maximum level. All voyages use NSR in August and September, while only limited voyages use NSR from February to April.

Besides, NSR is more feasible at higher fuel prices, reducing total

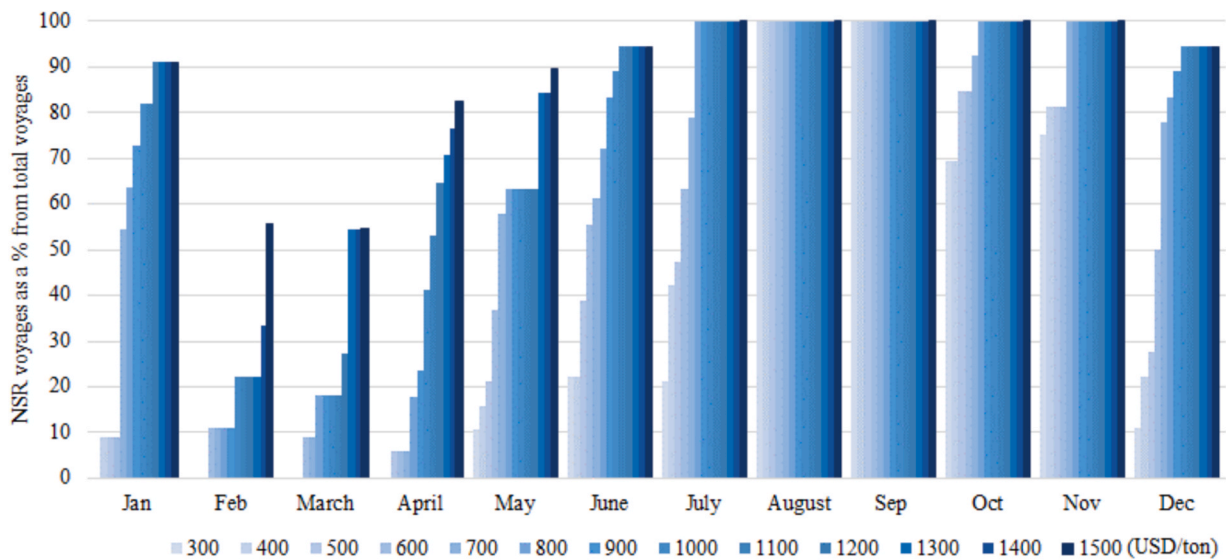


Fig. 13. Monthly variation of NSR voyages with different fuel prices.

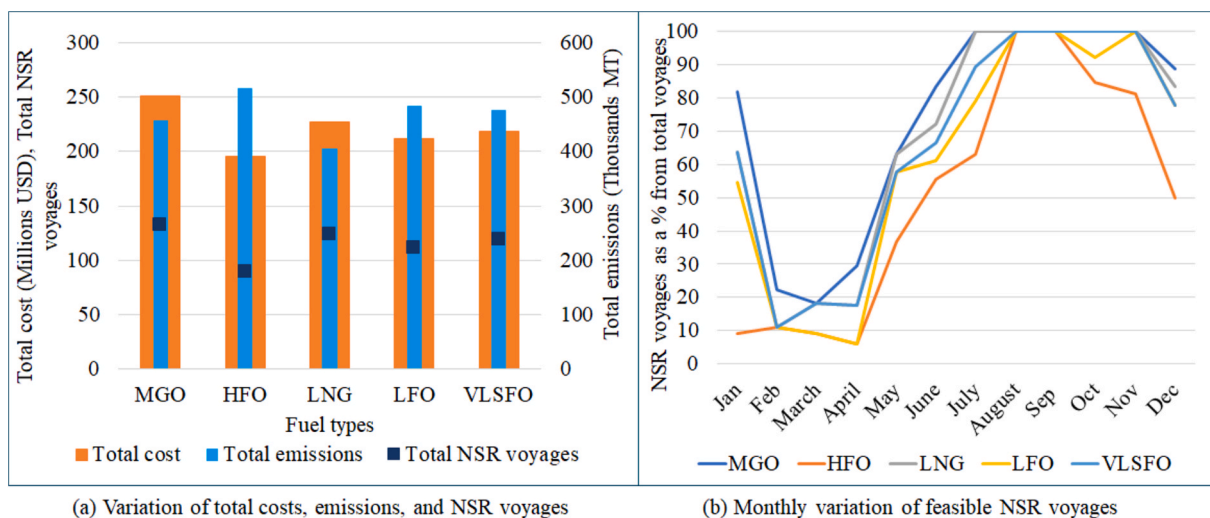


Fig. 14. Sensitivity analysis of fuel types on NSR feasibility.

emissions production. Most voyages use NSR from June to December, especially at higher fuel prices. Although a few voyages use NSR from February to April, no voyages use NSR if the fuel price is below 400 USD/ton. However, at very high fuel prices (1500 USD/ton), many voyages use NSR over SCR throughout the year. Moreover, limited NSR voyages received with HFO imply that using cheaper and high emissions fuel types in the maritime industry reduces the NSR's feasibility. Therefore, ship operators would choose to navigate via SCR with a cheaper fuel type regardless of its longer distances than NSR, even with an ETS, due to the insignificant fuel cost in total voyage cost. Conversely, if regulators promote using expensive and cleaner fuel types, more voyages would use NSR to reduce voyage costs. However, regardless of fuel type, all voyages use NSR in August and September, and limited voyages use NSR even with expensive fuel types from February to April.

Although this study derived significant implications if an ETS is introduced, the results could be influenced by vessel- and voyage-specific characteristics for individual voyages. Since this analysis was based on a given navigation path via NSR, future studies may consider alternative navigation paths via NSR. Although we analyzed multiple

scenarios with different CPs and FEQs, future studies may consider the market demand–supply mechanism to decide these parameters. Moreover, other modes of transport, including aviation and railways, can be considered in future studies while incorporating other commodity types.

CRedit authorship contribution statement

Chathumi Ayanthi Kavirathna: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ryuichi Shibasaki:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Wenyi Ding:** Investigation, Data curation.

Declaration of competing interest

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Appendix: List of notations

Sets	
i	A voyage ($i = 1, 2, \dots, 174$)
r	Shipping route of the voyage, $r = \{NSR, SCR\}$
f	Fuel type
l_n	Navigation leg via NSR (if SCR, $l_n = SCR$)
S	Scenario based on FEQ, $S = \{A, B, C\}$
V_m	The set of voyages navigated during month m
Parameters	
N	Total number of navigation legs via NSR
σ, ρ, γ	Premiums on new-building price, operation cost, and fuel consumption, respectively, for ice-class vessels, compared to an open-water vessel
c_1, c_2, c_3, c_4, c_5	Parameters for estimating voyage cost for bulk carriers
SDR_{rate}	SDR rate
B_n	Number of NSR zones that require icebreaker assistance
CP	The market price of a carbon allowance
$V_{max,m}$	A maximum number of voyages can be accommodated via NSR in a month m
FP_f	Fuel price (USD/ton) of fuel type f
Voyage dependent variables	
$Price_i^{NB}, LT_i$	New-building price (USD) and lifetime (years) of vessel navigating a voyage i
$scnr_{t_i}$	Suez Canal net tonnage for bulk carriers
DWT_i	Deadweight tonnage of a vessel navigating a voyage i
b_i	Icebreaking cost per NSR zone per unit GT
GT_i	Gross tonnage of vessel i
Intermediate variables	
$Cost_{i,r,f}$	Total cost of voyage i via route r of fuel type f
$K_{i,r}, Oper_{i,r}, Fuel_{i,r,f}$	Capital cost, operating cost, and fuel cost with fuel type f , respectively, of voyage i if using a normal vessel via route r
$IB_{i,r}, Toll_i$	Icebreaking cost via NSR or Suez Canal toll via SCR
$S_{l_n}^{NSR}, S_i^{SCR}$	A vessel speed via NSR at leg l_n or the average speed via SCR
D_i^n, D_i^{SCR}	Navigation distance within leg l_n of NSR or the navigation distance via SCR of voyage i
$T_{i,r}$	Duration of the voyage via route r
$FC_{i,r}$	Fuel consumption of voyage i when using route r
$Em_{i,r,f}$	Total emissions of voyage i via route r of fuel type f
$EF_{CO_2,f}$	Emission factor of CO ₂ with fuel type f
$MAC_{i,f}$	Marginal abatement cost of emissions by diverting to the NSR of fuel type f
$Cost_{i,s}(Em_{i,NSR,f} < Em_{i,SCR,f})$	Voyage cost if $Em_{i,NSR,f} < Em_{i,SCR,f}$ under scenario s
$Cost_{i,s}(Em_{i,NSR,f} > Em_{i,SCR,f})$	Voyage cost if $Em_{i,NSR,f} > Em_{i,SCR,f}$ under scenario s
θ_i	A dummy parameter $\theta_i = 1$ if $Em_{i,NSR,f} < Em_{i,SCR,f}$ and $\theta_i = 0$ otherwise
Decision Variables	
δ_i^{NSR}	Binary variable to decide whether voyage i follows NSR or not

Data availability

Data is available on <https://ads.nipr.ac.jp/dataset/A20250325-002>

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