**Feasibility of the Northern Sea Route for oil shipping from the economic and environmental perspective and its influence on China’s oil imports**

# Abstract

The Northern Sea Route (NSR) has the potential to become a key oil shipping route due to its shorter distance and abundant oil resources in the Arctic. This paper puts forward a model to calculate the Required Freight Rate of the NSR and China’s other oil import shipping routes, which includes both the shipping cost and the environmental cost. The calculation is undertaken in the context of IMO Sulfur 2020 limit, and the Very Low Sulfur Fuel oil (VLSFO) is chosen as marine oil. The vessel speed in this study varies with ice thickness in different route segments; the environmental cost in the model has considered emissions from all main air pollutants in addition to CO2. The results show that the NSR has the potential to carry some of China’s oil import volume; internalizing the environmental cost has improved the competitiveness of NSR; ice breaking fee and VLSFO price have a significant influence on the attractiveness of NSR, but the price (tax) of CO2 has no obvious impact.

***Keywords:*** Northern Sea Route; oil shipping; Required Freight Rate; environmental cost; global warming potential

# Introduction

With the impacts of global warming and the rapid melting of ice in the Arctic region, the potential of the Northern Sea Route (NSR) has been discussed by many scholars. The shorter distance of the NSR effectively reduces the shipping cost, especially when fuel prices are high, even though it includes the additional cost of being escorted by icebreakers ([1]). And increased accessibility brought by the NSR could facilitate shorter transit time, lower fuel and overall costs, improve network connectivity and lower carbon dioxide (CO2) and other [greenhouse gas](https://www-sciencedirect-com-s.svpn.dlmu.edu.cn:8118/topics/earth-and-planetary-sciences/greenhouse-gas) (GHG) emissions ([2]).

Most experts have compared the economic feasibility of the NSR and the Suez Canal Route (SCR) in container transportation ([3-7]). However, due to limits imposed by port facilities, climatic conditions, and the natural environment, the NSR is not suitable for liner shipping in the short term ([8]), but is more favorable for bulk cargo (dry and liquid) and LNG transport ([9,10]).

The Arctic region contains more than 22% of the world's unexplored oil and gas energy ([11])，and from the historical NSR traffic data, most of the transit vessels are tankers ([8,10]). With the development of Russian Arctic hydrocarbon projects, the volume of crude oil transportation through the NSR will further increase ([12]). So coupled with the distance advantage, the NSR may become an important channel for crude oil transport in the future ([13]).

On the other hand, oil is China's second energy source. China's dependence on oil imports reached 70.9% in 2018 ([14]) owing to its limited production of 170-200 million tons per year (see Fig. 1). With the continuous and rapid development of the economy, China's dependence on oil imports will continue to increase in the foreseeable future ([15]). In addition, except for some transported by rail and pipeline, more than 80% of China's imported oil is done by shipping. The Middle East and Africa account for about 80% of China's total oil imports from shipping, and almost all the oil from the two regions needs to pass through the Malacca Strait, which further enhanced the oil import risk and caused the “Malacca Dilemma” of China.

Therefore, China has sourced – and will continue to source – energy globally, including in the Arctic ([16]). In recent years, China's oil imports from Russia have grown rapidly. Since 2016, Russia has replaced Saudi Arabia as China's largest crude oil importer. And among these import volumes, most are transported by the pipeline ([14,15]). So if the NSR could be used to import crude oil from the Arctic, it can play a role in diversifying the source and shipping routes, and then improve the national security of China. In view of the fact that China has become a major energy consumer in the world, the utilization of sea routes and the exploration of the resources in the Arctic may not only have a huge impact on the energy strategy and economic development of China, but also will significantly impact global shipping, international trade and energy pattern ([13]).

**--- Insert Fig.1 about here ---**

A few studies have discussed the feasibility of the NSR in oil transportation: Faury et al. (2016)[17] proposed a model that considers the cost and time of oil transportation affected by the thickness of sea ice, and the results show that even in the most severe ice conditions, the NSR was still commercially feasible from July to November; however the capital cost of ships was not considered in this model. Zhanget al. (2016b) [18] established a cost model for tanker shipping, and the results show that the NSR is attractive to small- and medium-sized oil tanker transportation companies, but it has not considered the environmental cost.

The growing shipping activities in the Arctic will impose a great burden on the local fragile ecological environment as a result of the black carbon (BC) and other pollutant emissions from heavy fuel oil (HFO) combustion ([19]). Just as Corbett et al. (2010)[20] pointed out that although increased Arctic shipping may provide commercial and social development opportunities, the associated increased environmental burdens are also of great concern. Ships contribute significantly to global climate change and health impacts through emission of many air pollutants such as carbon dioxide (CO2), methane (CH4), nitrogen oxides (NOx), sulphur oxides (SOx), carbon monoxide (CO) and various species of particulate matter (PM) including organic carbon (OC) and black carbon (BC) ([21]).The IMO Sulfur 2020 legislation has limited the use of HFO, the current alternative fuels comprising 0.5% sulfur still have a high level of BC emission ([20]). Therefore, in addition to the economic concerns, the environmental effect on the Arctic from oil shipping should also be taken into account.

Lindstad et al. (2016)[22] indicated that the increase in climate impacts is much larger in Arctic than in non-Arctic areas when the ship is at low power. Zhu et al. (2018)[23] found that the environmental costs of the NSR tend to be higher than those of the SCR due to small ship size and low load factor in the present, but this is based on the analysis of container shipping. Theochariset al. (2019)[10] focused their discussion on oil shipping and calculated the RFR of the NSR and the SCR which includes CO2 tax. The results show that ship owners who will opt for the use of the expensive MGO will benefit from using the NSR. However, except for CO2, all other emissions and the corresponding environmental costs are not considered in their research.

With the fast development of China’s international trade, its emission problem is increasing prominent. China’s Ministry of Transport (MOT) has released a plan to set the sulfur limit in the region of Yangtze River Delta, Pearl River Delta and Bo Sea Region to 0.5% from 1 Jan, 2016. The coastal area of Hainan Island has been added into the Chinese Ship Emission Control Zones (ECZs) from 1 Jan, 2019, where the sulfur limit is tightened to 0.1%. On the other hand, The IMO Sulfur 2020 limit has been in place since its implementation on 1 January 2020. These policies will not only greatly affect the fuel cost, but will also further affect the environmental impact and the feasibility of the NSR and the other routes, because cleaner fuels can result in significant reductions in pollutants ([24]). In addition, given the huge impact of other emissions, particularly BC, on the Arctic environment ([20,21]), it is essential to consider all the emissions costs in addition to CO2 tax.

To summarize, most of the existing studies discussed the cost attractiveness of the NSR from the container shipping point of view; or only focused on the comparison of shipping cost, ignoring the environmental cost; or failed to consider the emission cost from other pollutants except CO2. While urgent action is required to mitigate global warming, the traditional ‘CO2 only’ approach should be replaced by the global warming potential (GWP) concept to ensure that the best climate mitigation options are selected ([22]). Thus this paper aims to fill the gap in the literature through comparing the total cost and Required Freight Rate (RFR) between the NSR and traditional routes in the context of the IMO Sulfur 2020 limit and Chinese oil import, which includes both the shipping cost and the environmental cost, and aims to further explain the impact of the NSR on China's crude oil import. The environmental cost in the paper is calculated on the basis of the emission from all the main air pollutants (SOx, NOx, NMVOC, PM, CO2, BC, CH4, CO, N2O, OC), and the calculation of NSR's fuel cost reflects the influence of sea ice thickness on the vessel speed.

This paper is organized as follows: The model is presented in Section 2, followed by the data in Section 3. The sensitivity analysis and discussion is provided in Section 4, and conclusions are drawn in Section 5.

# 2. Model

The model in this paper is based on RFR which takes into account shipping cost and environmental cost. The shipping cost includes capital cost, operating cost and voyage cost; and the environmental cost consists of air pollution cost and global warming cost. Thus, the RFR is a function of distance, speed, fuel price, operating cost, capital cost, port charges, toll fee (or ice breaking fee for the NSR), air pollution cost and global warming cost of a particular vessel size for each voyage (formulae (1-7)).

The major differences between this model and the former ones are the following two aspects: first, the calculation has contained the total environmental cost which includes all types of air pollutants, but the previous studies usually only include CO2 cost; and second, the vessel speed in the model is not set as a fixed value, but varies with the thickness of ice, which is a reflection of the reality.

The parameters are shown in Table 1.

(1)

(2)

(3)

(4)

(5)

(6)

(7)

**--- Insert Table 1 about here ---**

The details of the RFR calculation process are shown in Fig.2.

**--- Insert Fig.2 about here ---**

# 3. Data analysis

## *3.1 Investigated vessels and routes*

At present, the main origins of China's oil imports are the Middle East, Africa, South America and Southeast Asia，which account for 56.43%, 23.71%, 15.75% and 2.42% of import volume from 2009 to 2018 respectively (see Table 2).

**--- Insert Table 2 about here ---**

So in this article, the RFR is analyzed based on four types of vessels and seven different routes, which include the main oil source of China in addition to the Arctic. There is a representative oil loading port in each route, and Ningbo is chosen as the unloading port because it is located on the coast of central China and has the country’s largest oil terminal. The details of vessels and routes are show in Table 3, Table 4, and Fig. 3.

**--- Insert Table 3 about here ---**

On the NSR, ships normally need to cross through the Sannikov Strait with a draught limit of 13 m ([23]), so in this study we take ice class 1A (Arc4) Aframax as the normal vessel sailing via the NSR. Panamax is applied on the route of Southeast Asia for its short distance. On the other routes, Aframax, Suezmax and VLCC are selected for calculation and comparison.

**--- Insert Table 4 about here ---**

**--- Insert Fig.3 about here ---**

## *3.2 Shipping cost*

### *3.2.1 Capital cost*

The capital cost of vessels is calculated by formula (2), and we assume that the service life of a vessel is 20 years, the annual interest rate is 5%, and residual value is equal to 10% of the new building price. The price of the ice-strengthened ship is supposed to be 20% higher than that of the ordinary ship ([3,9,27]). After calculation, the capital cost of the Panamax is US$ 9,550 per day, the cost of the Aframax is US$ 11,140 per day, that of the Arc4 Aframax is US$ 13,400 per day, and the cost of the Suezmax is US$ 13,070 per day.

### *3.2.2 Operating cost*

Operating cost of tankers includes Manning, Insurance, Repairs & Maintenance (R&M), Stores/suppliers/spares, and Administration. The various cost of each vessel type is listed in Table 5, which is obtained from Drewry (2019)[28].

**--- Insert Table 5 about here ---**

### *3.2.3 Voyage cost*

1. Fuel cost

According to the IMO Sulfur 2020 limit, from 1 January 2020, the maximum sulfur content in marine fuels outside ECAs will be significantly reduced from 3.5% to 0.5% m/m (mass by mass). Thus in this paper, the Very Low Sulfur Fuel oil (VLSFO) is used for calculations, and we set the price of VLSFO as US$ 700 per ton according to the average cost of global 20 ports on 8 January 2020 (US$ 693 per ton; Ship and Bunker, <https://shipandbunker.com/>).

In the traditional routes, the total fuel consumption and fuel cost are calculated by formulae (3) and (4).When the situation of the NSR is considered, the dynamic consideration of sea ice extent is more reasonable for the assessment of Arctic shipping, because fuel consumption is highly related to ship speed, while ship speed is determined by the relative distance of ice-covered and ice-free stages ([6]). According to Faury et al. (2016)[17], for the vessel with a maximum speed of 15 kts, the relationship between the actual speed on ice and the ice condition could be expressed by formula (8). Thus the fuel consumption in each segment on the NSR is obtained by the speed which varies with ice conditions (formula (3)). We take the ice condition of November 2020 (which is calculated based on [17]) as standard to calculate the vessel speed, fuel consumption and total fuel cost of the NSR (details in Table 6).

(8)

**--- Insert Table 6 about here ---**

1. Port charges

The port charge only accounts for a very small portion of the total shipping cost, so in this paper we do not calculate it according to the due of each port, but simplify it: assume the cost of calling at a port is approximately US$ 20,000 ([18]), and the port fee for a round voyage is US$ 40,000.

1. Transit fee/Ice breaking fee

When sailing on some traditional routes, ships need to pay the canal toll. The Suez toll depends on the ship type, Suez Net Registered Tonnage (SCNT), full load orin ballast, sailing direction (southbound or northbound), and other factors. The parameters of each vessel type are as Table 7 shows. The online calculator (http://lethagencies.com/) provided by Leth agencies is used to calculate the Suez Canal Toll for each type of vessel.

**--- Insert Table 7 about here ---**

Ice breaking assitant has not been mandatory on the NSR since 2012, but ice breaking assistant is still assumed to be needed due to variability of ice conditions, and for safety and marine insurance reasons ([10]). According to the tariff regulation of the Northern Sea Route Administration (NSRA), the ice breaking fee depends on the sailing season, ice class of ships, gross tonnage, and escorting zones. In this paper, the ice breaking fee of Arc4 Aframax(57589GT) is calculated by the calculator provided by the NSRA (http://www.nsra.ru/en/contact.html). At the USD/Rb exchange rate of 62.59 in January 2020, the ice breaking fee of Arc4 Aframax in November is US$ 822,000.

### *3.2.4 The total shipping cost*

**--- Insert Fig.4 about here ---**

If we add the capital cost, operating cost and voyage cost together, we get the total shipping cost. And we get the unit shipping cost if the total shipping cost is divided by deadweight of cargo on the vessel. From Fig. 4, we can see that the unit shipping cost of the NSR is only lower than NAa, which means that for China’s oil import shipping, the NSR has no obvious competitiveness than other routes if only the shipping cost is considered.

## *3.3 Environmental cost*

Even though maritime shipping is the world's most carbon-efficient form of transporting goods, the industry's impact on the environment may still be mitigated. In April 2018, IMO adopted an initial strategy aimed at reducing the total annual greenhouse gas (GHG) emissions by at least 50% by 2050 compared to the 2008 level ([29]).

Traditionally, assessment of environmental performance of marine transport and ships has been based on fuel consumption converted to amount of CO2, while other trace emissions in the exhaust gas have been ignored ([22]). We address this gap in the literature by calculating the total environmental cost from the main air pollutants.The main air pollutants emitted by ships include CO2, SOx, NOx, PM, CO, CH4, N2O, NMVOC, BC and OC. The emission factors of VLSFO are adopted from the studies of Corbett et al. (2010)[20] and Smith et al. (2014)[30] (see Table 8). Following the study of Zhu et al. (2018)[23], we divide the environmental cost into air pollution cost and global warming cost.

**--- Insert Table 8 about here ---**

### *3.3.1 Air pollution cost*

SOx, NOx, NMVOC and PM are used to calculate the air pollution cost, which is based on formula (6).The air pollution cost is usually positively correlated with the economic development in the coastal area, so the Arctic sea and other areas have differrent levels of pollution cost ([20]) as shown in Table 9.

**--- Insert Table 9 about here ---**

### *3.3.2 Global warming cost*

Global warming potential (GWP) is an index of the greenhouse effect, which takes CO2 as a reference gas because it has the greatest impact on global warming. GWP20 and GWP100 are the greenhouse effect caused by various gases equivalent to the mass of CO2 with the same effect over 20 or 100 years. Assessments based on the 20 years’ time horizon are most relevant if the focus is on the climate impact within the next decades ([22]), so in this paper, GWP20 (see Table 10) is used to calculate the global warming cost, which is based on formula (7).

**--- Insert Table 10 about here ---**

### *3.3.3 Total environmental cost*

**--- Insert Fig.5 about here ---**

The total environmental cost is calculated by formula (5) (see A.1), and the unit environmental cost is shown in Fig. 5. Except for SEAp, MEv and EAv, the unit environmental cost of the NSR is the lowest among all the remaining 14 cases, thus the economic efficiency of the NSR has been improved after taking the environmental cost into account. The low level of the NSR’s environmental cost is mainly attributed to its lower vessel speed on ice and lower fuel consumption incurred. Another reason is that the economic development of Arctic areas is lower than the other areas, so the unit air pollution cost of the NSR is lower as well.

## *3.4 Total cost and RFR*

**--- Insert Fig.6 about here ---**

Under the given situation of the above analysis (seven escorting zones on NSR, 700 US$/t for VLSFO, and 25 US$/t for CO2), we obtain the total cost and RFR of each route (see A.1 and Fig. 6), and we find NSRa is lower than SAa, WAa, WAs, NAa, NAs,and NAv, which indicates that the NSR has some degree of substitution for the routes of South America, West Africa and North Africa.

# 4. Sensitivity analysis and discussion

This section carries out further sensitivity analysis on the ice breaking fee, fuel price, vessel speed on ice, CO2 price, and environmental cost in order to identify the important factors for comparison.

## *4.1 Ice breaking fee*

**--- Insert Table 11 about here ---**

**--- Insert Table 12 about here ---**

When the escorting zone is 6 or 7, NSRa is only lower than SAa, WAa, WAs NAa, NAs and NAv, but when the escorting zone is decreased to 0 (sailing independently), NSRa is only higher than MEa, MEs, MEv, EAs, EAv, SEAp and SAv (see Table 11 and A.1). The situation is similar when the NSR tariff is discounted (see Table 12 and A.1). So the ice breaking fee has an important influence on the viability of NSR. However, the current status of the Middle East line is that it has not been challenged whether the ship navigates independently or not. This result is in line with previous studies ([3,23,32]), which also reveal that the ice breaking fee/NSR Tariff plays a vital role in the potential of the NSR. In the research of Theocharis et al. (2019)[10], the NSR is always more competitive than the SCR when independent navigation is assumed, which proves that ice breaking fee is a crucial factor.

## *4.2 Fuel price*

**--- Insert Table 13 about here ---**

If the VLSFO price is cut down to 560 US$/t (-20%), the NSR is only more competitive than WAa, NAa and NAv; but if it is increased to 980 US$/t (+40%), the NSR will be more cost effective than SAa, SAs, WAa, WAs, NAa, NAs and NAv. So the price of VLSFO also has an obvious impact on the competitiveness of different routes – that is, the higher the VLSFO price, the more attractive the NSR. Similar to the circumstances of escorting zones, the changes of VLSFO price will not alter the dominance of the Middle East route. While the situation of East Africa does not change with the increase of VLSFO price, which is different with the situation of escorting zones. Furthermore, the interval between 560 US$/t and 700 US$/t is more decisive (see Table 13), which will transform the comparing results of SAa, WAa, WAs, and NAs. If we further increase the price from 700 US$/t to 980 US$/t, only the sequence of SAs has been changed. Therefore, we can conclude that compared with the influence of ice breaking fees, the impact of fuel price is relatively limited. This finding agrees with the research of Lasserre (2014)[5] and Theocharis et al. (2019)[10], which argues that high fuel prices are important, but fuel cost savings alone cannot determine the competitiveness of the NSR.

In the future, if a more strict environmental policy relating to the use of fuel oil, such as banning the use of Heavy Fuel Oil (HFO) and VLSFO, is implemented in the Arctic for the sake of BC reduction ([19, 33]), then the fuel cost of shipping on NSR will increase and the cost viability of NSR will be lowered for higher fuel cost (such as MGO) and enhanced capital cost for the vessel ([34]). At the same time, compared with marine fuel oil, LNG can reduce missions of PM and SOx by approximately 100%, NOx by 85%, and CO2 by 20-25%, and it is expected to be less costly than MGO([35]), so the feasibility for future use of LNG in the Arctic area is full of potential.

## *4.3 Vessel speed on ice*

In this study, the vessel speed on the NSR varies with the ice thickness which will decrease over time. The above analyses of vessel speed and fuel cost are done according to the situation of 2020. If we further make the calculation based on the ice thickness of 10 years later (2030) and 20 years later (2040), we can see that the RFR of the NSR will increase to 38.46 and 39.94, respectively (see Table 14).So the attractiveness of the NSR will reduce over time for the higher fuel cost caused by faster speed on thinner ice and the higher environmental cost incurred. However, this conclusion is based on the single change of vessel speed on ice. If we also take the decrease of ice breaking fee with ice melting into consideration at the same time, the potential of the NSR will not diminish over time (see Table 15).

In the former studies, the lower speed of the NSR is often seen as a negative factor for its potential ([3,5]), because their comparisons are drawn on container shipping which focuses on the fixed schedule and is only based on the total shipping cost, without considering the environmental cost. In the research of Theocharis et al. (2019)[10], the oil shipping is the discussion focus, and they conclude that reduction in speed through ice significantly reduces the potential of the NSR, particularly over the long-haul. However, in their research, the speed on ice water is fixed at 10.5 knots and only the CO2 cost is calculated, so their result does not reflect the benefit of lower fuel cost and environmental cost brought by lower speed on ice.

**--- Insert Table 14 about here ---**

**--- Insert Table 15 about here ---**

## *4.4 CO2 price on global warming cost*

**--- Insert Fig.7 about here ----**

The global warming cost is calculated based on GWP, which is expressed as “CO2 equivalents” of various pollutants, so the change of CO2 price will bring the change of global warming cost and the RFR. In the above analysis, we set the price of CO2 as 25 US$/t, which is a relatively low level. In the previous studies ([23,32]), it is often set as 100 US$/t. If we increase the CO2 price to 50 US$/t, 100 US$/t, 150 US$/t, and 200 US$/t, we find that the RFR of each route has risen correspondingly (see A.2), but their orders show no significant change. Therefore, we can conclude that the price of CO2 has no obvious influences on the attractiveness of the NSR. The main reason is the lower ratio of global warming cost in the total environmental cost (see Fig.7), which means that the change of global warming cost has no visible impact on RFR.

Most previous studies have ignored the environmental cost, while only a few have included the CO2 tax into the total cost: in the study of Cariou et al. (2015)[32], if the price per CO2 is set at 100 USD per ton, then the NSR can represent significant savings; and in the research of Theocharis et al. (2019)[10], it was found that a tax on HFO globally favors low speeds and the use of the shorter Arctic routes. Both these studies have not involved the emission cost from other air pollutants except for CO2, so the influence of CO2 has been magnified.

## *4.5 Environmental cost*

**--- Insert Fig.8 about here ---**

The environmental cost of most routes accounts for over 20% of the total cost (see A.1 and Fig.8), so the impact of the environment cost on the competitiveness of different routes is evident. As analyzed in section 4.3.3, the economic efficiency of the NSR has been improved after taking into account the environmental cost; if we cut off the environmental cost from the total cost, the RFR of NSR will only be slightly lower than the NAa.This result is in line with the research of Cariou et al. (2015)[32], which argues that internalizing the NSR environmental benefits marginally improves the attractiveness of the NSR, but is contrary to the study of Zhu et al. (2018)[23], which shows the total environmental cost in NSR is slightly higher. The main reason for this difference is because the influence of ice thickness on the vessel speed is not considered in their study, and their calculation is on the basis of IFO 380 but not VLSFO. Additionally, the global warming costs caused by NOx, SOx, and OC are not included in their calculation, which has some cooling effects, and has negative values in GWP.

# 5．Conclusions

Shorter distance is one of the drivers for utilizing Arctic routes, while exploration of oil and gas and other valuable minerals in the Arctic area is another ([22, 36]). The Arctic may become one of the main energy store bases and transport passages in the future ([13]). In addition, China's crude oil imports rank first in the world, and import dependence has continued to increase in recent years. Rapid growth in energy demand, particularly for liquid fuels, has made China extremely influential in world energy markets ([37]). So far the majority of China’s oil imports has to pass through Malacca Strait, so the feasibility analysis of NSR for oil shipping is not only significant for China's oil source diversification, but also meaningful for the global oil transport.

This paper introduces a model to compare the competitiveness of the NSR and traditional Chinese oil shipping routes. Similar to Schröder et al. (2017)[21], whose research underlined that ships contribute significantly to global climate change and health impacts through emission of many pollutants. Even though the increasing Arctic shipping may bring commercial and social development opportunities, the resulting environmental impacts need to be investigated and highlighted. The total environmental cost has been included in this research in the calculation of the total cost and RFR. From the results, we can obtain the following conclusions:

First, from the point of view of China’s oil imports, the Middle East route will not be substituted by the NSR and the East Africa route will not be replaced in most cases, but the North Africa route and West Africa route could be replaced by the NSR in most cases. Based on the ratio of oil shipping from North Africa and West Africa at present, we can conclude that about 20% of Chinese oil shipping is possible to be diverted to the NSR. So the NSR has the potential to become a new shipping route for China’s present oil imports, which could greatly relieve the “Malacca Dilemma” and diversify the oil import.

Second, ice breaking fee has the greatest influence on the potential of the NSR, followed by the fuel oil price, and vessel speed on ice. The price of CO2 has no significant impact. If the navigation on ice could be made independently without the escorting assistance from NSR Administration, the NSR will surpass most of the other routes for efficiency. As for the influence of VLSFO price, the relative potential of different routes is more sensitive at the interval between 560 US$/t and 700 US$/t. The vessel speed on ice will increase gradually, and the RFR of the NSR also will rise slightly over time, but it will not influence the comparison result if we also consider the decrease of ice breaking fee at the same time.

Third, if only the shipping cost is considered, the NSR has no obvious competitiveness than other routes in China’s oil import shipping. Adding the environmental cost to the total cost will enhance the potential of the NSR for its lower speed on ice, lower fuel costs, and lower environmental costs.

Although in the current situation, the environmental cost of the NSR is lower than that of traditional routes, this does not mean that oil transportation in the Arctic is more efficient than traditional routes, because there are some potential risks that have not been taken into account, such as the damage from oil leaking. Furthermore, the smaller environmental cost of the NSR is mainly attributed to its lower fuel consumption and lower unit air pollution cost, which is relative to the sparse population and lower level of economic development in the Arctic currently. As time goes by, if the HFO and VLSFO use is banned and replaced by "greener gas" such as MGO in the Arctic, the cost viability of the NSR will be decreased. In addition, the global warming potential caused by black carbon in the Arctic is much higher than the other areas, so we cannot blindly divert shipping to the Arctic. Future policy makers can take this into account and adopt measures to limit the large-scale movement of goods, such as enhancing the air pollution cost in the Arctic even though its economic development level is lower than other areas, or adding the oil leaking cost into their calculations, among other considerations. In this respect, we agree with the opinion of Zhu et al. (2018)[23], that shifting traffic volumes from SCR to the NSR, such as imposing higher canal fees on SCR, can be undesirable from the perspective of global environmental effects.

The main contributions of this paper are as follow. First, against the background of China’s oil import, we discuss the competitiveness of the NSR and other traditional routes for oil shipping. This indicates that about 20% of Chinese oil shipping is possible to be diverted to the NSR. Second, in the context of the IMO Sulfur 2020 limit, we analyzed the influence of ice breaking fee, VLSFO price, vessel speed on ice and CO2 price on tanker route selection. Last, a model to compare the RFR of different routes which contain the shipping cost and the complete environmental cost is put forward; this includes not only the emission from CO2 but also all the other main air pollutants, which is insightful for the environmental impacts on Arctic shipping.

The current emission regulations by the IMO provide limits for SOx and NOx for health and environmental reasons and for CO2 to mitigate global warming, while all other exhaust gas emissions are currently unregulated ([22]), so the discussion in this paper is helpful for understanding the complete environmental influence on the Arctic and other areas from shipping. In the future, the IMO extension of the limit on sulfur fuel content from the so-called Emission Control Areas (ECAs) currently at 0.1% to a global level is expected to have a significant impact on fuel costs, types of fuel used, and on capital expenses ([10]), and future research could shed light on these issues. On the other hand, the use of LNG as an alternative fuel seems to be a potentially good option in order to reduce shipping emissions, but its mitigation performance, the feasibility of application, and the cost effectiveness for Arctic shipping must be deeply analyzed and reviewed in advance ([33]). Furthermore, owing to the availability of data, some other environmental issues, such as shipping noise, waste water disposal, oil spill and others have not been considered in this paper, which can also be the focus of future research.

# Appendices

**Insert Appendix 1 about here.**

**Insert Appendix 2 about here.**

# References

[1] R. Shibasaki, K. Kanamoto, T. Suzuki, Estimating global pattern of LNG supply chain: a port-based approach by vessel movement database, Marit. Policy Manag. 47 (2) (2020) 143-171, <https://doi.org/10.1080/03088839.2019.1657974>.

[2] D. Theocharis, S. Pettit, V.S. Rodrigues, J. Haider, Arctic shipping: A systematic literature review of comparative studies, J. Transport Geogr. 69 (2018) 112-128, <https://doi.org/10.1016/j.jtrangeo.2018.04.010>.

[3] M. Liu, J. Kronbak, The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe, J. Transport Geogr. 18 (3) (2010) 434-444, <https://doi.org/10.1016/j.jtrangeo.2009.08.004>.

[4] H. Xu, Z. Yin, D. Jia, F. Jin, H. Ouyang, The potential seasonal alternative of Asia-Europe container service via Northern sea route under the Arctic sea ice retreat, Marit. Policy Manag. 38 (5) (2011) 541-560, <https://doi.org/10.1080/03088839.2011.597449>.

[5] F. Lasserre, Case studies of shipping along Arctic routes. Analysis and profitability perspectives for the container sector, Transport. Res. Part A 66 (2014) 144-161, <https://doi.org/10.1016/j.tra.2014.05.005>.

[6] H. Xu, D. Yang, J. Weng, Economic feasibility of an NSR/SCR-combined container service on the Asia-Europe lane: a new approach dynamically considering sea ice extent, [Marit. Policy Manag. 45 (4) (2018) 514-529,](https://www.tandfonline.com/toc/tmpm20/current)<https://doi.org/10.1080/03088839.2018.1443521>.

[7] M. Furuichi, N. Otsuka, Examining quick delivery at an affordable cost by the NSR/SCR-combined shipping in the age of Mega-ships, Marit. Policy Manag. 45 (8) (2018) 1057-1077, <https://doi.org/10.1080/03088839.2018.1473656>.

[8] Y. Zhang, Q. Meng, L. Zhang, Is Northern Sea Route attractive to shipping companies? Some insights from recent ship traffic data, Mar. Policy 73 (2016a) 53-60, <https://doi.org/10.1016/j.marpol.2016.07.030>.

[9] H. Schøyen, S. Bråthen, The Northern Sea Route versus the Suez Canal: cases from bulk shipping, J. Transport Geogr. 19 (4) (2011) 977-983, <https://doi.org/10.1016/j.jtrangeo.2011.03.003>.

[10] D. Theocharis, V.S. Rodrigues, S. Pettit, J. Haider, Feasibility of the Northern Sea Route: The role of distance, fuel prices, ice breaking fees and ship size for the product tanker market, Transport. Res. Part E 129 (2019) 111-135, <https://doi.org/10.1016/j.tre.2019.07.003>.

[11] D.L. Gautier, K.J. Bird, R.R. Charpentier, A. Grantz, D.W. Houseknecht, T.R. Klett, T.E. Moore, J.K. Pitman, C.J. Schenk, J.H. Schuenemeyer, Assessment of Undiscovered Oil and Gas in the Arctic, Science 324 (5931) (2009) 1175-1179, <https://science.sciencemag.org/content/324/5931/1175>. (Accessed 20 October 2019).

[12] B. Gunnarsson, Future Development of the Northern Sea Route, 2016. <https://www.maritime-executive.com/editorials/future-development-of-the-northern-sea-route>. (Accessed 8 January 2019).

[13] X. Ma, China's Arctic policy on the basis of international law: Identification, goals, principles and positions, Mar. Policy 100 (2019) 265-276, <https://doi.org/10.1016/j.marpol.2018.11.027>.

[14] China Energy Statistical Yearbook, 2019. [http://navi.cnki.net/KNavi/YearbookDetail?pcode=CYFD&pykm=YCXME&bh=](http://navi.cnki.net/KNavi/YearbookDetail?pcode=CYFD&pykm=YCXME&bh). (Accessed 8 July 2019).

[15] Chinese National Bureau of Statistics (CNBS), 2019. <http://www.stats.gov.cn/tjsj/>. (Accessed 8 July 2019).

[16] R.G. Bertelsen, V. Gallucci, The return of China, post-Cold War Russia, and the Arctic: Changes on land and at sea, Mar. Policy 72 (2016) 240-245, <https://doi.org/10.1016/j.marpol.2016.04.034>.

[17] O. Faury, P. Cariou, The northern sea route competitiveness for oil tankers, Transport. Res. Part A 94 (2016) 461-469, <https://doi.org/10.1016/j.tra.2016.09.026>.

[18] Y. Zhang, Q. Meng, S.H. Ng, Shipping efficiency comparison between Northern Sea Route and the conventional Asia-Europe shipping route via Suez Canal, J. Transport Geogr. 57 (2016b) 241-249, <https://doi.org/10.1016/j.jtrangeo.2016.09.008>.

[19] J. Han, Research on governance of HFO use and carriage on ships in accordance with the polar code, Adv. Polar Sci. 29 (04) (2018) 283-290, <https://pdfs.semanticscholar.org/d89a/9254d25fd5372081325258469804f10231e2.pdf>. (Accessed 10 October 2019).

[20] J.J. Corbett, D.A. Lack, J.J. Winebrake, S. Harder, J.A. Silberman, M. Gold, Arctic shipping emissions inventories and future scenarios, Atmos. Chem. Phys. 10 (19) (2010) 9689-9704, <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.948.7658&rep=rep1&type=pdf>. (Accessed 15 October 2019).

[21] C. [Schröder,](http://apps.webofknowledge.com/OutboundService.do?SID=8EH9ANJsi8MU4cmUOB6&mode=rrcAuthorRecordService&action=go&product=WOS&daisIds=735253) N. [Reimer,](http://apps.webofknowledge.com/OutboundService.do?SID=8EH9ANJsi8MU4cmUOB6&mode=rrcAuthorRecordService&action=go&product=WOS&daisIds=10112536) P. [Jochmann,](http://apps.webofknowledge.com/OutboundService.do?SID=8EH9ANJsi8MU4cmUOB6&mode=rrcAuthorRecordService&action=go&product=WOS&daisIds=2895959) Environmental impact of exhaust emissions by Arctic shipping, Ambio 46 (3) (2017) 400-409, <https://doi.org/10.1007/s13280-017-0956-0>.

[22] H. Lindstad, R.M. Bright, A.H. Strømman, Economic savings linked to future Arctic shipping trade are at odds with climate change mitigation, Transp. Policy 45 (2016) 24-30, <https://doi.org/10.1016/j.tranpol.2015.09.002>.

[23] S. Zhu, X. Fu, A.K.Y. Ng, M. Luo, Y.E. Ge, The environmental costs and economic implications of container shipping on the northern sea route, Marit. Policy Manag. 45 (4) (2018) 456-477, <https://doi.org/10.1080/03088839.2018.1443228>.

[24] Q. Zhang, Z. Wan, B. Hemmings, F. Abbasov, Reducing black carbon emissions from Arctic shipping: Solutions and policy implications, J. Cleaner Prod. 241 (2019) 1-9, <https://doi.org/10.1016/j.jclepro.2019.118261>.

[25] H. Lindstad, G.S. Eskeland, Low carbon maritime transport: How speed, size and slenderness amounts to substantial capital energy substitution, Transport. Res. Part D 41 (2015) 244-256, <https://doi.org/10.1016/j.trd.2015.10.006>.

[26] Clarksons, Clarksons Shipping Intelligence Network, 2019. <https://sin.clarksons.net/>. (Accessed 8 January 2020).

[27] F. Lasserre, Simulations of shipping along Arctic routes: comparison, analysis and economic perspectives, Polar Rec. 51 (03) (2015) 239-259, <https://doi.org/10.1017/S0032247413000958>.

[28] Drewry, Crude Tanker Forecaster (Annual Subscription), Maritime Research, 2019. <https://www.drewry.co.uk/maritime-research-products/crude-tanker-forecaster-annual-subscription>. (Accessed 10 January 2020).

[29] E.K. Hansen, H.B. Rasmussen, M. Lützen, Making shipping more carbon-friendly? Exploring ship energy efficiency management plans in legislation and practice, Energy Res. Soc. Sci. 65 (2020) 101459, <https://doi.org/10.1016/j.erss.2020.101459>.

[30] T.W.P. Smith, J.P. Jalkanen, B.A. Anderson, et al. Third IMO GHG Study, 2014. <https://www.cedelft.eu/publicatie/third_imo_ghg_study_2014/1525>. (Accessed 14 December 2019).

[31] A. Korzhenevych, N. Dehnen, J. Bröcker, M. Holtkamp, H. Meier, G. Gibson, A. Varma, V. Cox, Update of the Handbook on External Costs of Transport, European Commission: DG MOVE, 2014. <https://ec.europa.eu/transport/sites/transport/files/themes/sustainable/studies/doc/2014-handbook-external-costs-transport.pdf>. (Accessed 10 October 2019).

[32] P. Cariou, O. Faury, Relevance of the northern sea route (NSR) for bulk shipping, Transport. Res. Part A 78 (2015) 337-346, <https://doi.org/10.1016/j.tra.2015.05.020>.

[33] Q. Zhang, Z. Wan, B. Hemmings, F. Abbasov, Reducing black carbon emissions from Arctic shipping: Solutions and policy implications, J. Cleaner Prod. 241 (2019) 118261, <https://doi.org/10.1016/j.jclepro.2019.118261>.

[34] B. Roy, B. Comer, Alternatives to heavy fuel oil use in the Arctic: Economic and environmental tradeoffs, 2017. <https://theicct.org/sites/default/files/publications/Arctic-HFO-alternatives_ICCT_Working-Paper_04182017_vF.pdf>. (Accessed 25 January 2020).

[35] J. Hua, Y. Wu, H. Chen, Alternative fuel for sustainable shipping across the Taiwan Strait, Transport. Res. Part D 52 (2017) 254-276, <https://doi.org/10.1016/j.trd.2017.03.015>.

[36] Y. Zhang, H. Hu, L. Dai, Real-time assessment and prediction on maritime risk state on the Arctic Route, Marit. Policy Manag. 47 (3) (2019) 352-370, <https://doi.org/10.1080/03088839.2019.1693064>.

[37] T. Kompas, T.N. Che, A structural and stochastic optimal model for projections of LNG imports and exports in Asia-pacific, Heliyon. 2 (6) (2016) e00108, <https://doi.org/10.1016/j.heliyon.2016.e00108>.