Feasibility of the Northern Sea Route for seasonal transit navigation: The role of ship speed on ice and alternative fuel types for the oil product tanker market

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Abstract

The feasibility of the Northern Sea Route is assessed for seasonal operations of oil product tankers using alternative fuel types. A speed optimisation model is used that minimises the required freight rate (RFR) of a Long Range 2 (LR2) tanker against alternative routes. A cost model is developed that incorporates real hourly speed data from tanker voyages between the 2011 and 2019 summer/autumn seasons, and primary and secondary data regarding cost and operational factors. The analysis is based on naphtha and jet fuel/kerosene trades between Europe and Asia. A prospective ban on the use of High Sulphur Fuel Oil (HSFO) in the Arctic, and alternative fuels, such as the new Very Low Sulphur Fuel Oil (VLSFO) and Liquified Natural Gas (LNG) are included to take into account of the International Maritime Organisation (IMO) 2020 global sulphur limit and its long-term strategy towards the reduction of greenhouse gas emissions.

1. Introduction

The Northern Sea Route (NSR) stretches from Novaya Zemlya to the Bering Strait along the Russian Arctic coast and is part of the Northeast Passage (NEP). The route gained popularity during 2011-2013 due to an increase in transits between the Atlantic and the Pacific Oceans and destination voyages that either originated or ended from/to Arctic ports (CHNL, 2020). A growing number of voyages since 2007 (ARCTIS, 2013) led to a peak of 71 transit and destination voyages during the 2013 summer/autumn season followed by a decline in 2014 (NSRA, 2016, CHNL, 2020) owing to a number of factors including market conditions, geopolitics, and piracy incidents in the Gulf of Aden that increased piracy premiums (Platts, 2016, Tanker Company, 2019), drop in global oil prices during 2015, and shift of petroleum flows form the ports of Vitino and Murmansk located in the White and Barents Seas respectively to Baltic ports (Bambulyak et al., 2015, Tanker Company, 2019).

The NSR can potentially offer distance and time savings depending on origin-destination (OD) as well as prevailing market conditions and vessel positioning. However environmental factors largely determine the commercial viability of voyages through the Arctic. Variability in sea ice conditions (extent, thickness, and concentration), fog, darkness, harsh climate, and low temperatures (Stephenson et al., 2014, Faury and Cariou, 2016, Aksenov et al., 2017, Faury et al., 2020) make the NSR a very challenging environment to operate, where ice class ships, that is, ships with enhanced hulls and special equipment depending on the ice class level, are required as in the Baltic during the ice season. The use of ice class ships implies increased capital and operating costs whilst the risk of ice damage repairs can further increase costs and may render voyages unprofitable even if the NSR offers shorter distances (Tanker Company, 2019). Moreover, transit fees paid for icebreaking assistance is an additional cost factor, not least because of the uncertainty that the Northern Sea Route Administration (NSRA) exerts, underlining the unpredictability of tariff policy (Gritsenko and Kiiski, 2016; Moe and Brigham, 2016).

Research on commercial viability of the NSR has increased since 2011, with studies investigating liner and bulk shipping under various scenarios, and cost, profit, and operational factors (Lasserre, 2014, 2015, Meng et al., 2016, Theocharis et al., 2018, Theocharis, 2020). Bulk (dry and liquid) and specialised (e.g. LNG, LPG) shipping sectors are found to be more suitable for Arctic operations, mainly because of the less time sensitive cargoes than those carried by containerships (Theocharis et al., 2018). Notwithstanding the number of studies focused on seasonal and/or annual maritime operations on the NSR, these mainly examined liner shipping with the exception of four recent papers that focused on annual and/or prospective annual scenarios for tankers (Keltoo and Woo, 2020, Faury et al., 2020, Wang et al., 2020, Cheaitou et al., 2020). Although seasonal/annual planning and scheduling is more suitable to liner shipping due to the nature of this sector, seasonal/annual voyage opportunities for bulk shipping and more specifically for tankers may exist, especially in certain trade routes with established oil flows and/or frequent arbitrage opportunities.

This paper aims to examine seasonal transit navigation for oil product tanker voyages between ports in the Baltic, Northwest Europe, and Northeast Asia during the summer/autumn season. The analysis is undertaken on the strategic level (choice of oil products/commodities and routes as an expert-based scenario). Naphtha and jet fuel/kerosene voyages undertaken by Long Range 2 (LR2) tankers are chosen based on major oil product flows and historic NSR voyages between these regions. The NSR is compared with the Suez Canal route (SCR) between the Russian Baltic port of Ust-Luga, Rotterdam in the Netherlands and Ulsan in South Korea. A required freight rate (RFR) model is developed based on speed optimisation to assess the minimum cost per tonne from the shipowner's perspective. The model incorporates alternative fuel types and technologies to address current and future environmental policies pertaining to the prohibition of residual fuel oils in the Arctic, the IMO 2020 sulphur limit policy, and the long-term IMO GHG strategy to mitigate maritime transport emissions globally. Primary cost data are obtained from a tanker owner that operated on the NSR, as well as up to date cost and real secondary data. Moreover, real hourly speed data of historic NSR tanker transits were obtained from the Bloomberg vessel tracking platform to inform the models.

The remainder of this paper is organised as follows: A literature review is provided in Section 2, followed by the Methodology in Section 3 and the Analysis in Section 4. A discussion of the findings and conclusions are provided in Section 5 along with limitations and future research opportunities.

2. Literature review

Sea ice conditions along with the seasonal navigational window on the NSR largely determine the potential of the route to compete with the more established routes/canals such as the Suez and Panama Canals, and the Cape of Good Hope route. More specifically, sea ice exhibits inter-annual variability and uneven distribution along the NSR (Stephenson et al., 2014, Yumashev et al., 2017). Therefore, ship speed on ice is determined by local sea ice conditions, which vary within the same season, across different zones and the ice class of a vessel (Faury and Cariou, 2016, Cariou et al., 2019, Cariou and Faury, 2020, Faury et al., 2020, Cheaitou et al., 2020). Consequently, the impact of variable ship speed on ice means increased uncertainty of transit times and higher voyage and operating costs. Conversely, high speeds would increase voyage frequency and therefore profitability (Wergeland, 1991, Guy, 2006, Lasserre, 2014, 2015), albeit at the expense of safety depending on ice conditions (Lasserre and Pelletier, 2011).

Moreover, the use of ice class ships implies increased capital costs and fuel consumption depending on the ice class of the ship (Erikstad and Ehlers, 2012, von Bock und Polach et al., 2015, Faury et al., 2020, Cheaitou et al., 2020). Most importantly, icebreaking fees are found to have a big impact on voyage costs (Furuichi and Otsuka, 2015, Cariou and Faury, 2015, Gritsenko and Kiiski, 2016, Xu et al., 2018) and increase proportionally higher than Suez Canal Tolls with ship size (Theocharis et al., 2019). High fuel prices along with discounted icebreaking fees and an extended navigation season considerably increase the competitiveness of the NSR (Liu and Kronbak, 2010, Lasserre, 2014, 2015, Zhao et al., 2016). On the other hand, Shibashaki et al. (2019) first found that the inverse relationship between oil prices and the USD/RUB rate which determine official icebreaking fees, means that the NSR is still not competitive under high fuel prices. Theocharis et al. (2019) further investigated this relationship and found that under the official tariff structure the NSR is not competitive at either low or high fuel prices, which further explains the NSRA policy of discounted fees before 2014 (Gritsenko and Kiiski, 2016), when high fuel prices and competitive fees attracted shipowners and traders to use the NSR amongst others.

The small number of an ageing ice class tanker fleet globally (Solakivi et al. 2017, 2018, Gibson, 2018), combined with few transit voyages on the NSR when compared with the established routes/canals further increases the uncertainty of determining certain cost and operational factors (Lasserre, 2014, 2015, Meng et al., 2016, Fedi et al., 2018, Theocharis et al., 2018). Nevertheless, Solakivi et al. (2017, 2018) are the only studies to date that aim at statistically analysing capital costs and fuel consumption (on open water) for ice class tankers and dry bulk carriers, and containerships.

Notwithstanding the considerable number of studies focused on NSR operations against liner shipping, there has been a small but growing number of studies investigating the viability for tankers (Song and Zhang, 2013; Zhang et al., 2016; Faury and Cariou, 2016, Theocharis et al., 2019, Keltoo and Woo, 2020, Cariou and Faury, 2020, Faury et al., 2020, Wang et al., 2020, Cheaitou et al., 2020). The literature on the viability of the NSR for seasonal/annual operations has primarily focused on liner shipping, whereas only four studies investigated annual (Keltoo and Woo, 2020) and/or prospective annual (Faury et al., 2020, Wang et al., 2020, Cheaitou et al., 2020) tanker operations. Whilst the sea ice-ship speed dependency has been thoroughly investigated by employing historic sea ice thickness data to determine tanker speeds on the NSR (Faury and Cariou, 2016, Cariou and Faury, 2020, Faury et al., 2020, Cheaitou et al., 2020), there have not been any studies that used real data regarding ship speed on ice from actual NSR tanker transits, and therefore providing an alternative approach to the literature. Further, there have been only three studies that explored the impact of the IMO 2020 sulphur limit (Theocharis et al., 2019, Keltoo and Woo, 2020, Wang et al., 2020), and one study that included a future ban of heavy fuel oils in the Arctic (Theocharis et al., 2019). The main contributions of this study to the literature are as follows:

• Developing seasonal navigation scenarios for operations on the NSR drawing from major oil product flows and historic NSR voyages.

• Quantifying the competitiveness of the NSR by considering alternative fuel types so as to address current and future environmental regulations (ban of residuals in the Arctic, IMO 2020 sulphur limit, long-term IMO GHG strategy).

• Developing RFR minimisation and speed optimisation models to include dual-fuel engine set-ups.

• Employing real hourly speed data from historic NSR transits (2011-2019) to determine ship speed on ice obtained from the Bloomberg vessel tracking platform.

• Employing up to date primary and secondary data regarding cost and operational factors.

3. Methodology

3.1 Model

A cost minimisation model based on speed optimisation, which incorporates different fuel types and technologies is developed in this paper. The required freight rate (RFR) or minimum cost per tonne in US$ is determined at the optimal speed where costs equal revenue, that is, the long-run equilibrium point between supply and demand (Alderton, 1981).

The fuel types considered in this paper are: High Sulphur Fuel Oil (HSFO) with scrubber, Very Low Sulphur Fuel Oil (VLSFO) and Marine Gasoil (MGO) for oil-powered engines. As regards dual-fuel gas-oil powered engines, two modes are considered: LNG and pilot MGO (gas mode), and VLSFO (oil mode). The use of MGO is also considered for oil-powered engines following a ban of heavy fuels in the Arctic. The fuel consumption is a function of alternative fuels, speed, and displacement (Barrass, 2004, MAN Diesel and Turbo, 2013a, Psaraftis and Kontovas, 2013, Psaraftis and Kontovas, 2014, MAN Energy Solutions, 2020). When a dual-fuel diesel engine operates at gas mode, it also uses oil-based pilot consumption since LNG requires an ignition source to start the combustion process (MAN Energy Solutions, 2020, DNV GL, 2020). The oil pilot consumption is assumed to be MGO for compliance with the Emission Control Areas (ECA) regulations, given that LNG is assumed as an alternative fuel within ECAs amongst others (MAN Energy Solutions, 2020).

Table 1 reports the variables and parameters used in Equations 1-23.

The fuel consumption function of a ship using either of the oil-based fuels (HSFO, VLSFO, MGO) can be expressed as:

$$F_{FO}(v^*, \nabla) = F_{FO\ d} * \left(\frac{v^*_{FO}}{v_d}\right)^a * \left(\frac{P+L}{\nabla}\right)^{2/3} \quad (1)$$

The fuel consumption functions of a ship with a dual-fuel diesel engine that operates at LNG mode can be expressed as:

$$F_{DF\ LNG}(v^*, \nabla) = F_{DF\ LNG\ d} * \left(\frac{v^*_{DF\ LNG}}{v_d}\right)^a * \left(\frac{P+L}{\nabla}\right)^{2/3}, \text{ for the LNG consumption,} \quad (2)$$

and

$$F_{DF\ Pilot}(v^*, \nabla) = F_{DF\ Pilot\ d} * \left(\frac{v^*_{DF\ LNG}}{v_d}\right)^a * \left(\frac{P+L}{\nabla}\right)^{2/3}, \text{ for the fuel oil pilot consumption,} \quad (3)$$

whereas the fuel consumption function when the dual-fuel diesel engine operates at the oil mode can be expressed as:

$$F_{DF\ FO}(v^*, \nabla) = F_{DF\ FO\ d} * \left(\frac{v^*_{DF\ FO}}{v_d}\right)^a * \left(\frac{P+L}{\nabla}\right)^{2/3} \quad (4)$$

It can be seen that in the case of the pilot consumption, the function (Equation 3) follows the same exponential relationship between speed and consumption as in the other fuels. This can be explained by the fact that pilot consumption is proportional to the engine speed, which in turn is nearly proportional to the ship speed (MAN Energy Solutions, 2019a, 2020). This means that the pilot consumption varies nearly linearly with ship speed (MAN Energy Solutions, 2020). The exponent a ranges between 0.11 and 3.8 for LR2/Aframax tankers (Adland et al., 2020) and is approximated at three in this study (Psaraftis and Kontovas, 2013). All fuel consumption functions of this form depend on speed and payload (Psaraftis and Kontovas, 2013, Psaraftis and Kontovas, 2014).

The objective is to minimise the total RFR of all voyages of a route alternative (either RFR_{NSR} or RFR_{SCR}):

$$min \sum RFR + e * C_{IC} \tag{5}$$

The objective function also minimises the RFR of single voyages when these are not summed up. The term $\sum RFR$ denotes the sum of the RFR for each leg of a voyage in either of the two routes and/or the sum of the RFR of all voyages for seasonal round voyage operations. The term $e * C_{IC}$ denotes the additional costs of ice coating for ice class tankers to enhance the ship's hull and reduce the risk of ice damages. This option is considered when the strategy of the shipowner is to operate their tankers through the NSR for a whole ice season, in contrast to occasional single voyages through ice that do not necessitate such an investment (Tanker Company, 2020).

The RFR is a function of distance, fuel consumption, optimal speed, total cost inputs and cargo carrying capacity of a tanker for each leg and voyage. Equation 6 presents the RFR function for oil-based scenarios, whereas Equation 7 that of dual-fuel scenarios where LNG and pilot fuel oil are included. Equations 8 and 9 present the RFR for a ballast voyage between two ports that link seasonal voyage operations but is not a voyage between the Atlantic and the Pacific i.e. from Rotterdam to Ulsan (see Section 3.2), where only fuel, capital, and operating costs are included. Equation 8 refers to the use of either HSFO or MGO under the HSFO-Scrubber and VLSFO modes respectively, whereas Equation 9 refers to the use of LNG and pilot MGO under the LNG-VLSFO mode[1]. The number 24 denotes the hours per day, which is used in Equations 6-9 to obtain voyage legs in days. The RFR in this paper incorporates both the value of the ship and the value of the cargo on-board, that is, the in-transit inventory cost (Alderton, 1981). The latter is determined by the price of the total quantity of the cargo and a relevant interest rate for oil and petroleum products. The inclusion of in-transit inventory cost in an RFR model based on the shipowner's perspective is relevant, even if this is essentially a charterers' expense. The explanation is that a charterer will prefer a ship that delivers their cargo at the right time depending on market conditions, commodity prices and opportunity costs (Psaraftis and Kontovas, 2014).

$$RFR = \frac{1}{W}\left[\left(\frac{D_{SCR,NSR}}{v_{FO}^{*} * 24}\right) * \left(\left(F_{FO}(v_{FO}^{*}) * P_{FO}\right) + \left(C_o + C_c + g * C_s\right) + \left(W * P_C * \frac{r}{365}\right)\right) + C_{TI}\right]$$
(6)

[1] It is assumed that MGO is used in ballast voyages under the VLSFO option since these voyages occur within the North Sea and Baltic Sea ECA zones. LNG and pilot MGO are used only in this voyage as the fuel consumption requirements satisfy the voyage length and LNG is cheaper than VLSFO (see Section 3.2).

$$RFR = \frac{1}{W}\left[\left(\frac{D_{SCR,NSR}}{(v^*_{DF\ LNG}+v^*_{DF\ FO})*24}\right) * \left(b * \left((F_{DF\ LNG}(v^*_{DF\ LNG}) * P_{LNG} + F_{DF\ Pilot}(v^*_{DF\ LNG}) * P_{FO}\right)\right) + c * (F_{DF\ FO}(v^*_{DF\ FO}) * P_{FO}) + (C_o + C_c) + \left(W * P_C * \frac{r}{365}\right)\right) + C_{TI}\right] \quad (7)$$

$$RFR = \frac{1}{W}\left[\left(\frac{D_B}{v^*_{BFO}*24}\right) * \left((F_{FO}(v^*_{BFO}) * P_{FO}) + (C_o + C_c + g * C_s)\right)\right] \quad (8)$$

$$RFR = \frac{1}{W}\left[\left(\frac{D_B}{v^*_{BDF\ LNG}*24}\right) * \left((F_{DF\ LNG}(v^*_{BDF\ LNG}) * P_{LNG} + F_{DF\ Pilot}(v^*_{BDF\ LNG}) * P_{FO}) + (C_o + C_c)\right)\right] \quad (9)$$

subject to

$$\underline{V} \leq v^* \leq \overline{V} \quad (10)$$

and

$$b, c, e, g \in \{0,1\} \quad (11)$$

Table 1. Parameters and variables used in the model

Parameters:	
P	cargo weight including fuel, fresh water, stores, ballast water, baggage, and crew (m.t.)
W	average weight of cargo in metric tonnes (m.t.)
$\sum_{i=1}^{n} D_{SCR}$	total SCR distance (n.m.)
$\sum_{i=1}^{n} D_{NSR}$	total NSR distance (n.m.)
$D_{1,SCR}, \dots, D_{n,SCR}$	SCR distance legs (n.m.)
$D_{1,NSR}, \dots, D_{n,NSR}$	NSR distance legs (n.m.)
D_B	Distance for ballast leg between Rotterdam and Ust-Luga ports
$d_1, \dots, d_6$	NSR distance legs through ice (n.m.)
P_{FO}, P_{LNG}	fuel price in US$ per tonne for fuel oils (HSFO, VLSFO, MGO), and LNG respectively
P_C, r	Commodity price in US$ per tonne (here oil products), and interest rate
C_{IC}	cost of ice coating for seasonal operations scenarios in US$
$C_o,\ C_c$	operating costs in US$ per day, capital costs in US$ per day
C_{TI}	transit costs (canal tolls or icebreaking fees) and insurance premiums in US$
C_s	capital costs of exhaust cleaning systems (scrubber) in US$ per day
v_d	design speed in knots
$\overline{V}$	upper sailing speed in knots
$\underline{V}$	lower sailing speed in knots
$F_{FO\ d}$	fuel consumption for oil-based fuels (HSFO, VLSFO, MGO) at design speed

$F_{DF\ LNG\ d}$, $F_{DF\ Pilot\ d}$	fuel consumption for LNG and Pilot MGO at design speed
$F_{DF\ FO\ d}$	fuel consumption for dual-fuel engine when in oil-mode (VLSFO) at design speed
L	Lightweight of a product tanker in tonnes
∇	Displacement of a product tanker in tonnes
Variables:	
v^*_{FO}, v^*_{BFO}	single voyage optimal speed for oil powered (HSFO, VLSFO, MGO) engine in knots
$v^*_{DF\ LNG}$, $v^*_{BDF\ LNG}$	single voyage optimal speed for dual-fuel engine (LNG) in knots
$v^*_{DF\ FO}$	single voyage optimal speed for dual-fuel engine (oil-mode – VLSFO, MGO) in knots
b, c, e, g	Binary variables, equal to 1 when dual-fuel LNG mode, dual-fuel fuel oil mode, ice coating cost, and scrubber are considered respectively, and 0 otherwise
$\sum_{i=1}^{n} T_{SCR}$	total SCR transit time in days
$\sum_{i=1}^{n} T_{NSR}$	total NSR transit time in days
$T_{1,SCR}, \dots, T_{n,SCR}$	SCR transit time for each leg in days
$T_{1,NSR}, \dots, T_{n,NSR}$	NSR transit time for each leg in days
$t_1, \dots, t_6$	Transit time for each NSR leg through ice in days

The term $\frac{1}{W}$ transforms RFR to RFR in US$ per tonne, whilst the terms $\left(\frac{D_{SCR,NSR}}{v^*_{FO}*24}\right)$, $\left(\frac{D_{SCR,NSR}}{(v^*_{DF\ LNG}+v^*_{DF\ FO})*24}\right)$, $\left(\frac{D_B}{v^*_{BFO}*24}\right)$, $\left(\frac{D_B}{v^*_{BDF\ LNG}*24}\right)$ calculate the days at sea per voyage and leg for each of the fuel types/modes. The variable g denotes the use of a hybrid scrubber, based on assumptions from Lindstad et al. (2017), where $g = 1$ for the HSFO-Scrubber mode or $g = 0$ otherwise. The minimum speed is unrestricted when icebreaking assistance is assumed implying the possibility of blockage (Cariou et al., 2019), but a minimum of 5 knots is assumed for independent navigation of an ice class 1A ship (Trafi, 2017a) that cannot sail independently below this speed (MAN Diesel and Turbo, 2013b, Trafi, 2017b, Solakivi et al., 2017), and a maximum of 16 knots based on Lindstad et al. (2011), where the design speed falls between 90-95% of the maximum depending on ship size. The variable e equals 1 when special (ice) coating is included in the analysis for seasonal operations of consecutive round voyages or 0 otherwise. According to Tanker Company (2020), the use of ice coating depends on planning and the strategy of a shipowner. It is essential when operating on ice for a complete season as it can reduce the risk of ice damages and subsequent repairs. Thus, this cost is spread over the entire length of seasonal operations compared to single occasional voyages through ice that do not require such an investment. Additional costs such as port dues, cargo handling, and fuel cost in port are excluded from the cost analysis since these are assumed to be the same for either routeing alternative. Auxiliary fuel requirements are assumed to be satisfied by the use of the main engine, which depends on the ship and engine set up (Tanker Company, 2020).

The optimal speeds are obtained by partial differentiation of Equations (6), (7), (8), and (9) with respect to speeds v^*_{FO}, $v^*_{DF\ LNG}$, $v^*_{DF\ FO}$ v^*_{BFO}, and $v^*_{BDF\ LNG}$, which are set equal to zero, that is, $\frac{\partial RFR}{\partial_{v^*_{FO}}} = 0, \frac{\partial RFR}{\partial_{v^*_{DF\,LNG}}} = 0, \frac{\partial RFR}{\partial_{v^*_{DF\,FO}}} = 0, \frac{\partial RFR}{\partial_{v^*_{BFO}}} = 0, \frac{\partial RFR}{\partial_{v^*_{BDF\,LNG}}} = 0$, with all optimal speeds subject to lower, $\underline{V}$, (when independent navigation is assumed), and upper limits, $\overline{V}$. Equations 12, and 13-14 refer to optimal speeds of fuel oil and LNG-based modes respectively, and for laden legs of both Origin-Destinations (ODs), which minimise Equations 6 and 7, whereas Equations 15 and 16 minimise Equations 8 and 9.

$$v^*_{FO} = \sqrt[a]{\frac{\left(C_o+C_c+g*C_s+W*P_C*\frac{r}{365}\right)*v_d{}^a*\nabla^{2/3}}{((a-1)*(F_{FO\,d}*P_{FO}))*(P+L)^{2/3}}} \tag{12}$$

$$v^*_{DF\,LNG} = \sqrt[a]{\frac{\left(C_o+C_c+W*P_C*\frac{r}{365}\right)*v_d{}^a*\nabla^{2/3}}{\left((a-1)*\left(b*(F_{DF\,LNG\,d}*P_{LNG}+F_{DF\,Pilot\,d}*P_{FO})\right)\right)*(P+L)^{2/3}}} \tag{13}$$

$$v^*_{DF\,FO} = \sqrt[a]{\frac{\left(C_o+C_c+W*P_C*\frac{r}{365}\right)*v_d{}^a*\nabla^{2/3}}{\left((a-1)*\left(c*\left(F_{DF\,FO\,d}*P_{FO}\right)\right)\right)*(P+L)^{2/3}}} \tag{14}$$

$$v^*_{BFO} = \sqrt[a]{\frac{(C_o+C_c+g*C_s)*v_d{}^a*\nabla^{2/3}}{((a-1)*(F_{FO\,d}*P_{FO}))*(P+L)^{2/3}}} \tag{15}$$

$$v^*_{BDF\,LNG} = \sqrt[a]{\frac{(C_o+C_c)*v_d{}^a*\nabla^{2/3}}{((a-1)*(F_{DF\,LNG\,d}*P_{LNG}+F_{DF\,Pilot\,d}*P_{FO}))*(P+L)^{2/3}}} \tag{16}$$

The solution gives the optimal ship speeds for either leg/voyage, whilst the RFR is minimised by substituting them to the respective RFR equations.

These optimal speeds depend on fixed costs, including the capital cost of cargo on-board, that is, the in-transit inventory cost as well as the price of fuel, payload, and displacement. These optimal speeds are not affected by charterparty obligations or any other constraints (Psaraftis and Kontovas, 2014, Cariou and Faury, 2015). Optimal speeds obtained from Equations 12-14 refer to open water operations for both SCR and NSR, whereas the speeds through the ice legs on the NSR route are not necessarily optimised with respect to cost and market conditions. The reason is that speed through ice primarily depends on sea ice conditions and may not equal the optimal speed. Besides, increased capital and operating costs as well as higher fuel consumption for an ice class 1A tanker affect the open water optimal speeds and the costs in both open water and ice (see Sections 3.2.2 and 3.2.4 for assumptions on costs, fuel consumption and NSR speed).

The total distance and time of each individual leg for either SCR or NSR depends on a certain fuel type/technology, and can be expressed as:

$$\sum_{i=1}^{n} D_{SCR} = D_{1,SCR}+\ldots+D_{n,SCR} \tag{17}$$

$$\sum_{i=1}^{n} T_{SCR} = T_{1,SCR}+\ldots+T_{n,SCR} \tag{18}$$

And:

$$\sum_{i=1}^{n} D_{NSR} = D_{1,NSR} + D_{ICE} + \ldots + D_{n,NSR} \quad (19)$$

$$\sum_{i=1}^{n} T_{NSR} = T_{1,NSR} + T_{ICE} + \ldots + T_{n,NSR} \quad (20)$$

The total distance and time on ice water through the NSR can be similarly defined as:

$$\sum_{i=1}^{n} D_{ICE} = d_1 + d_2 + d_3 + d_4 + d_5 + d_6 \quad (21)$$

$$\sum_{i=1}^{n} T_{ICE} = t_1 + t_2 + t_3 + t_4 + t_5 + t_6 \quad (22)$$

where each of the distance and time legs refer to the East Kara, West and East Laptev, East Siberian West and East Siberian East, and Chukchi Seas, respectively.

A detailed analysis of the voyage itineraries, leg distances and fuel types are provided in Appendix B. Subsequently, the optimal speed for either mode/fuel type on a single voyage is defined as:

$$v_{FO}^{*}, v_{DF\ LNG}^{*}, v_{DF\ FO}^{*}, v_{BFO,}^{*}\ v_{BDF\ LNG,}^{*} = \frac{\sum_{i=1}^{n} D}{\sum_{i=1}^{n} T * 24} \quad (23)$$

The RFR differential between the Suez Canal route (SCR) and the Northern Sea Route (NSR) is then defined as:

$$\Delta RFR = RFR_{SCR} - RFR_{NSR} \quad (24)$$

3.2. Assumptions and data

3.2.1. Origin – Destinations

In general, two main operational patterns of tankers can be identified. The first one consists of loading cargo in one port, discharging in another port and then steaming in ballast either back to the loading port or to the next loading port, which can be located in a different geographic region. Alternatively, a tanker can load its next cargo either in the discharging port or in a port located relatively close to the discharging port, performing what is known as “triangulation”, and effectively reducing long ballast voyages. Various options of triangulated voyages exist in both the Atlantic and the Pacific Oceans for short, medium, or even longer oil product tanker voyages. In the Atlantic basin, a typical example is the front haul gasoline voyage from Northwest Europe to US Atlantic Coast, with the backhaul diesel/gasoil voyage from US Gulf to Northwest Europe (Clarksons, 2020). In the geographic region east of Suez, a naphtha voyage from Middle East Gulf (MEG) to South Korea/Japan is triangulated with a gasoil/diesel voyage from South Korea to Hong Kong followed by a gasoline/diesel voyage to Singapore, followed by either a ballast leg back to MEG or by a naphtha voyage back to Japan (Clarksons, 2020). It can be seen that in all cases the main aims are to reduce the time a ship spends in ballast voyages and increase earnings.

Table 2 shows historic seasonal tanker round voyages in either direction of the NSR between 2011 and 2019. It can be seen that some traders/operators explored the NSR for round voyages by aiming to exploit the seasonal window that the shorter NSR provides during the summer/autumn season. The number of seasonal round voyages between west and east varies from two to three and providing that some tankers did not perform some voyages outside the NSR (Bloomberg, 2020), they could use the NSR for up to four or five consecutive voyages during the summer/autumn season, depending on the month, distances between ODs, and ballast voyages linking loading ports, sea ice and as well as market conditions and employment opportunities. For example, Perseverance could perform another two voyages, in August and October respectively in between the period from July to November, whereas Propontis could perform four voyages between July and October, provided that its first voyage started in early July.

Table 2. Historic seasonal NSR tanker round voyages*

Year	Tanker	Size	Voyage	Period	Cargo	Mt
2011	Perseverance	LR1	Russia Arctic – China	June-July	Condensate	59,981
			South Korea – Netherlands	September	Jet Fuel/Kerosene	64,400
			Russia Arctic – China	November	Condensate	61,275
2012	Stena Poseidon	LR1	South Korea – Finland	July	Jet Fuel/Kerosene	66,416
			Russia Arctic – South Korea	September	Condensate	60,370
	Palva	LR1	Russia Arctic – South Korea	July-August	Condensate	60,310
			South Korea – Finland	September	Jet Fuel/Kerosene	66,275
	Marika	LR1	South Korea – Finland	August-September	Jet Fuel/Kerosene	66,552
			Russia Arctic – South Korea	October	Condensate	61,266
2013	Propontis	LR2	Norway – Japan	July-August	Naphtha	79,846
			South Korea – Netherlands	September-October	Gasoil	109,090
2014	Anichkov Bridge	MR	Russia Far East – Russia Baltic	July-August	Ballast	
			Russia Baltic – Russia Far East	September	Fuel Oil	44,175
			Russia Far East – Russia Baltic	October	Ballast	
	SCF Neva	MR	Russia Far East – Russia Baltic	August	Ballast	
			Russia Baltic – Russia Far East	September	Fuel Oil	44,050
	SCF Amur		Russia Far East – Russia Arctic	August	Ballast	
			Russia Arctic – Russia Far East	September	Fuel Oil	43,998
			Russia Far East – Russia Arctic	October	Ballast	
2019	Korolev Prospect	Aframax	Russia Arctic – China	August-September	Crude Oil	N.A.
			China – Russia Arctic	September-October	Ballast (?)	

Source: CHNL (2020). *Crude and fuel oil round voyages are also included. Some tankers listed may have changed names. MR: Medium Range, LR1: Long Range 1, LR2: Long Range 2.

The choice of seasonal multiple voyages for oil product tankers between Northwest Europe and Northeast Asia is based on the respective oil products trade flows and tanker routeing patterns, as well as considering historic voyages through the NSR. According to data from IEA (IEA, 2019), naphtha is the largest single oil product in volume (metric tonnes), shipped from Northwest Europe/Baltic to Northeast and Southeast Asia and Oceania between 2016 and 2018 (76-70%), with Russia being the biggest exporter (84-87%) and South Korea (72-79%) the biggest importer. On the other hand, jet fuel/kerosene is the dominant oil product from Northeast and Southeast Asia and Oceania to Northwest Europe – 56-65% of the volume between 2016 and 2018 respectively, with South Korea the biggest exporter (65-60%) and the Netherlands the biggest importer (57-56%) of the commodity. These statistics reflect the typical arbitrage oil product trades between the Far East, and the Baltic and Amsterdam-Rotterdam-Antwerp (ARA) regions, whilst this is also evident from the NSR seasonal single or round voyages between 2011 and 2019, where naphtha was shipped from the Baltic or Norway to the Far East and jet fuel/kerosene was transported from the Far East to the ARA region (CHNL, 2020). Besides, the re-direction of naphtha and condensate flows from Vitino to Ust-Luga since 2014, shifted Arctic-originated oil products to the Baltic for exports to the Far East (Bambulyak et al., 2015).

Therefore, the cost analysis in this paper is based on consecutive seasonal round voyages between Russia Baltic (Ust-Luga) and South Korea (Ulsan) for the front haul naphtha voyage, and between South Korea (Ulsan) and the Netherlands (Rotterdam) for the backhaul jet fuel/kerosene voyage, including a ballast leg between Rotterdam and Ust-Luga for the next front haul voyage to Ulsan. The choice of ports is based on fixtures from Clarksons (2020) for the respective commodities. Figure 1 shows the Origin-Destinations (ODs) and route alternatives chosen in this paper. Port characteristics and LNG bunkering infrastructure are presented in Appendices A1 and A2, respectively.

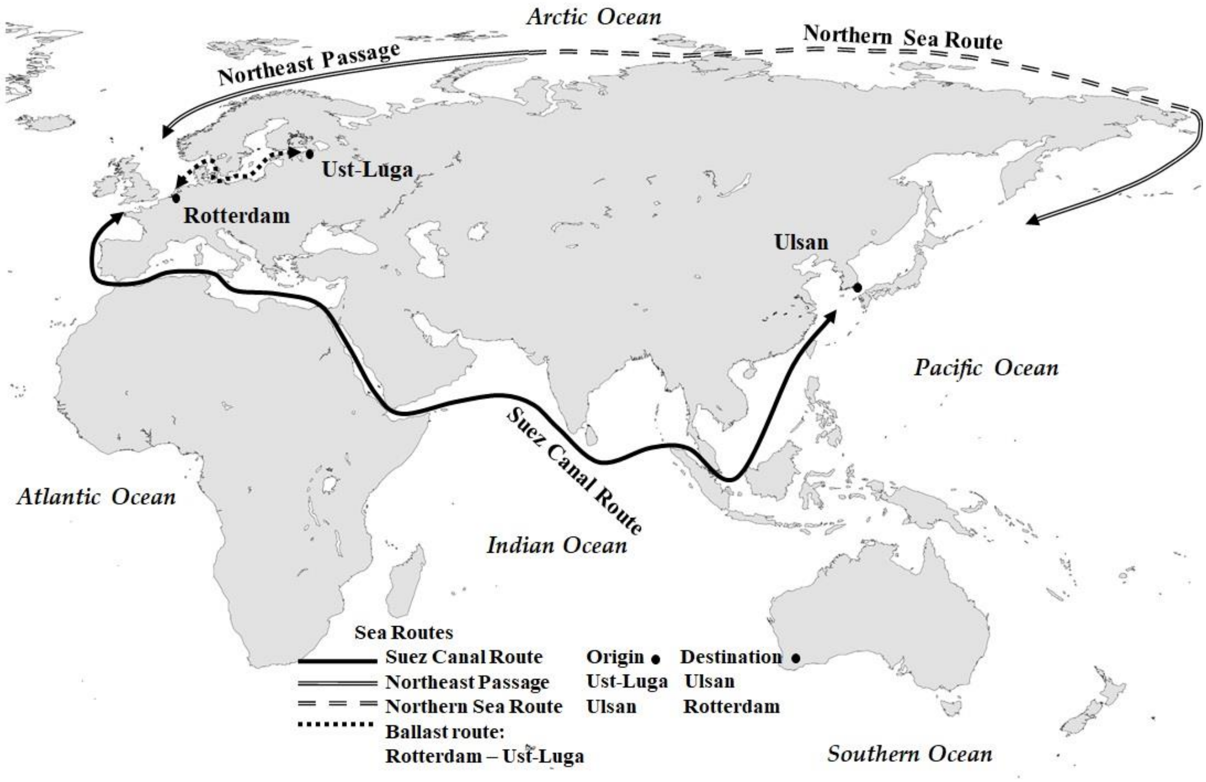


Figure 1. Origin-Destinations (ODs) and Route alternatives (Equirectangular projection map created with NASA GISS G.Projector tool).

3.2.2. Cost and operational factors

The ship size chosen in this paper is based on typical naphtha and jet fuel/kerosene quantities for long-haul voyages of Long Range 2 (LR2) tankers between Europe and the Far East. Naphtha is typically traded in quantities of 75-90,000 metric tonnes (m.t.) and jet fuel/kerosene is traded in quantities of 80-90,000 m.t. (Clarksons, 2020). These figures are also in line with NSR voyages between 2011 and 2019 (see Table 1, CHNL, 2020). The choice of cargo quantity also depends on port physical characteristics as well as any other logistical or physical constraints. The cost analysis is based on a comparison between an ordinary LR2 tanker and an ice class 1A (Arc4) LR2 tanker, both of 115,000 dwt, Length Overall (LOA) 250 metres, draught of 15 metres and beam of 44 metres, loaded with 80,000 m.t. of either naphtha or jet fuel/kerosene[2]. The majority of the tankers used the NSR from 2011 to 2019 fall under this ice class (NSRA, 2016, CHNL, 2020). In addition, Sovcomflot's LNG-powered Aframax tankers that have started using the NSR since 2018 are of ice class 1A/B, meaning that they have a hull

[2] The quantity of 80,000 tonnes of oil products on board correspond to a draught of 12 metres based on Tonnes per Centimetre Immersion (TPC) of 97.2 and ballast capacity of 41,400 tonnes which satisfy the port physical characteristics chosen for this study (MAN Diesel and Turbo, 2013c, MAN Diesel and Turbo, 2013a, Barrass, 2005, Clarksons, 2020).

that conforms to ice class 1A standards, whereas the rest of their specifications are equal to ice class 1B (Sovcomflot, 2020).

The technical characteristics of different fuel types and technologies for LR2 tankers are presented in Table 3. These refer to global average size and characteristics of Aframax/LR2 tankers and to those of Sovcomflot's LNG-powered ice class 1A/B Aframax series (MAN Diesel and Turbo, 2013a, 2013c, MAN Energy Solutions 2019a, 2019b, 2020, Sovcomflot, 2020).

The HSFO fuel gives a slightly higher fuel consumption at the design speed than the VLSFO fuel partly due to the lower energy density of the former and partly due to the additional consumption of the use of a scrubber. The lowest fuel consumption at the design speed is given by LNG, owing to its higher energy density compared to the other fuels. Moreover, the dual-fuel diesel engine gives a higher VLSFO consumption than an oil-powered diesel engine when operating on VLSFO mode, since restrictions on the design of the dual-fuel gas/oil engine means it cannot be as efficient as a fuel oil-based engine at both operational modes (MAN Energy Solutions, 2019b).

Table 3. LR2 tanker costs and technical characteristics for all fuels.

	HSFO-Scrubber	VLSFO	LNG	
			LNG mode	VLSFO mode
Design Speed (knots) [a]	15	15	15	15
Maximum Speed (knots)	16	16	16	16
Fuel Consumption (tonnes/day of non-ice/ice class)[b]	46.7/63.2	45.6/61.6	36.5/49.6	46.7/63.1
MGO Consumption (tonnes/day of non-ice/ice class)[b]	–	44/59.4	–	–
MGO Pilot Consumption (tonnes/day of non-ice/ice class)[b]	–	–	0.91/0.98	–
Fuel Tank Capacity (tonnes) [c]	2,415	2,415	773	1,700
Operating Costs (US$ per day) (non-ice/ice class)[d]	7,974/8,406	7,974/8,406	7,974/8,406	7,974/8,406
Capital Costs (US$ per day) (non-ice/ice class)[e]	13,056/16,861	12,296/16,033	12,827/16,562	12,827/16,562

Sources: [a]MAN Diesel and Turbo, 2013c, calculations based on MAN Energy Solutions, 2019b, [b]calculations based on MAN Energy Solutions, 2019b, email communication with MAN Energy Solutions, 2019a, 2020, IMO, 2016, Platts, 2017, [c]Clarksons, 2020, Platts, 2017, 2020, [d]average 2011-2018 from Moore Stephens OpCost Platform, [e]average newbuilding prices of LR2 tankers 2013-2019, Clarksons, 2020, average 12-month USD Libor 2011-2019, FED of St. Louis, 2020, + 3%, capital recovery factor of 12.5% over 10 years payment, ice class 1A premium: 30.4%, Solakivi et al., 2018, ice class 1A/B dual fuel premium 34.78%, based on Sovcomflot's contracted prices on 2017 compared to ordinary LR2 tankers, Sovcomflot, 2020, dual fuel 1A/B premium 4.38% assuming that 30.4% is for ice class specification, hybrid scrubber, Lindstad et al., 2017.

Additional costs related with operations on the NSR include a capital cost premium of 30.4% for a new ice class 1A LR2 tanker (Solakivi et al., 2018), fixed costs of US$ 50,000 and US$ 20,000 for insurance, and books and charts per voyage, respectively as well as a 10% premium in crew costs per day, whereas piloting is estimated at 1,000 US$ per day with travel expenses at US$ 5,000 per voyage (Tanker Company, 2019). In addition, the installed power of an ice class 1A tanker is assumed to be 30.8% higher than that of a non-ice class tanker (Solakivi et al., 2018), with increased fuel consumption at design speed for each engine set-up obtained from MAN Energy Solutions (MAN Energy Solutions, 2019a, MAN Energy Solutions, 2019b, Theocharis et al., 2019). Additional costs on ice-infested waters when a vessel performs several voyages on the NSR and/or for the whole summer/autumn season include ice coating in the hull for additional protection from ice estimated at 75,000 US$ (Tanker Company, 2020). Piracy insurance premiums for transits through the Gulf of Aden are estimated at 10,500 US$ currently (Tanker Company, 2019).

Voyages for each OD pair, including distances for each leg depending on the fuel type are included in Appendix B. It is assumed that the tanker uses HSFO during the whole voyage under the HSFO-Scrubber mode, at both ODs and route alternatives. The installed scrubber gives the option to remove the sulphur of the fuel before it is emitted in the atmosphere. The VLSFO option means that the ship uses MGO within the ECA zones of each OD and VLSFO for the rest of the voyage on both route alternatives. The LNG-VLSFO mode gives a dual-fuel LR2 tanker the option to use LNG for a certain distance (including within the ECA zones and within the NSR) depending on the range and LNG tank capacity, and VLSFO for the rest of the voyage. The current option for dual-fuel LNG powered LR2 tankers provides a maximum range of about 7,800 n.m., and 5,700 n.m. for an ordinary and ice class 1A/B dual-fuel LR2 tanker respectively at the maximum speed of 16 knots when they are loaded with 80,000 m.t. of oil products assumed in this paper. However, the daily LNG fuel consumption through ice corresponds at speeds well below 16 knots and as a consequence it would be lower than the consumption at the maximum speed even after considering increased fuel consumption for an ice class tanker. Thus, the actual LNG consumption for the ice class tanker before switching to oil mode ranges between 6,659 n.m. and 7,159 n.m. depending on the different speed regimes across the icy part of the NSR (Appendix B).

Fuel oil prices, either residuals (HSFO, VLSFO) or distillates (MGO), refer to an average of the prices in Rotterdam and Singapore in February 2020, that is 300, 480 and 500 US$ per tonne respectively (Clarksons, 2020). Equally, naphtha and jet fuel/kerosene spot prices refer to February 2020 averages in Rotterdam and Singapore, that is, 457 US$/t and 498 US$/t respectively (OPEC MOMR, 2020). The annual interest rate for the estimation of in-transit inventory cost is assumed 10% based on industry estimates for crude and oil products (McQuilling, 2012), which is slightly lower than the 15% assumed in Lindstad and Eskeland (2015). LNG price refers to an average of the Natural Gas Title Transfer Facility (TTF) (The Netherlands) and the spot delivered LNG price in Asia in February 2020, which was 250 US$ per tonne, including distribution costs (Clarksons, 2020, Capital IQ, 2020, DNV GL, 2020b).

3.2.3. Icebreaking assistance and transit fees

Icebreaking assistance is assumed for all zones of navigation across all base case scenarios in accordance with the NSRA rules for navigation and tariffs (NSRA, 2014). The fees depend on the number of escorting zones, navigation season, ice class, gross tonnage, and the value of Russian rouble (NSRA, 2014). Suez Canal Tolls depend on the type of ship, Suez Canal Net Tonnage (SCNT), routeing direction, laden/ballast condition, and specific drawing rights (SDR) rates. The latest SDR/US$ rates are used, based on July-November 2019 values, as well as the Leth agencies online calculator to calculate additional costs (tugs, mooring, disbursements, pilotage) (IMF, 2019, Leth Agencies, 2020).

3.2.4. Speed on the NSR and seasonal navigation planning.

Ice thickness and concentration, ridges, icebergs, and other physical factors largely influence the operational environment on the NSR (Löptien and Axell, 2014, Aksenov et al., 2017). Consequently, ship speed on ice can vary across the NSR depending on the season, month, navigation zone, local sea ice conditions and the ice class of a vessel (Stephenson et al., 2014, Faury and Cariou, 2016, Cariou et al., 2019, Faury et al., 2020, Cheaitou et al., 2020). AIS data were obtained from the Bloomberg vessel tracking platform to determine ship speed on ice across the NSR, given that speed optimisation with respect to cost and market factors may not be feasible when operating through ice in the Arctic. Ship speed data of 44 NSR tanker transits during the 2011-2019 summer/autumn seasons were retrieved with tanker sizes ranging from MR (47,000 dwt) to Suezmax/LR3 (162,000 dwt). The data comprise 29,964 observations of tanker speeds recorded per minute for every transit between Cape Zhelanya/Kara Strait and Cape Dezhnev from end of June (30th) to mid-November (17th). The average speeds in every Sea per month were then calculated by dividing the travelled distances by the time interval between the start and end points of each segment. The speed statistics are included in Appendix C1, whilst the start and end points of the AIS data for each Sea/Zone are reported in Appendix C2.

The statistics reported per month and across all Seas show that tanker speeds ranged from a minimum of 2 to a maximum of 16.9 knots. This highlights the uncertainty of operating across the NSR during the summer/autumn season. Whilst most of the times the mean speed for a certain zone across every month was between 10 and 11.8 knots, with higher speeds (10.9-13.2 knots) reported mostly in September, the standard deviation values indicate a large variability. The largest variability is found at the East Siberian Sea (East and West), where almost every month is subject to large departures from mean speeds that were amongst the lowest across every month compared to the other navigating zones.

The East Laptev and Chukchi Seas have the highest variability in July, whereas speeds at the Kara Sea are variable at every month with standard deviation values between 2.3 (September) and 3.2 (July). Speeds at the West Laptev Sea are found the least variable with August and October having the largest departures from the mean speed. Another important observation is the very low speeds, below 5 knots, at the East Siberian Sea (East) during July and August, and at the East Siberian Sea (West) and Chukchi Seas during July respectively, which shows that voyages at the opening of the navigation season still face severe ice conditions. Yet, the East Siberian (West) and East Kara Seas exhibit minimum speeds below 5 knots during October. The lowest variability in tanker speeds across every zone is found in September most of the times, the month which typically has the minimum sea ice extent every year and navigation season is the longest (Stephenson et al., 2014, NSIDC, 2020). The real speed data analysis is in line with Stephenson et al. (2014), who found that the Laptev, East Siberian, and eastern Kara Seas exhibit inter-annual variability and uneven distribution of sea ice conditions in the medium-term.

Figure 2 shows average transit time and speed for each month and Seas and for a whole season from west to east, which were calculated based on Equations (18) and (19) provided in Section 3.1 and using the mean speeds reported in Appendix C1. The distances for each Sea are: East Kara Sea: 468 n.m., West Laptev Sea: 265.5 n.m., East Laptev Sea: 265.5 n.m., East Siberian Sea (West): 345 n.m., East Siberian Sea (East): 345 n.m., Chukchi Sea: 370 n.m. (Dataloy

Distance Table, Mulherin, 1996). It should be noted that owing to the very low number of speed observations for November (n=87) , speeds for this month are assumed to be at least equal to those of October, although in reality speeds in November might be lower (Mulherin, 1996, Wergeland, 1992, Faury and Cariou, 2016). The entry/exit point of the NSR from the west is Cape Zhelanya , and therefore only the distance of East Kara Sea (between Cape Zhelanya and Vilkitsky Strait) is included in the analysis and not that of West Kara Sea.

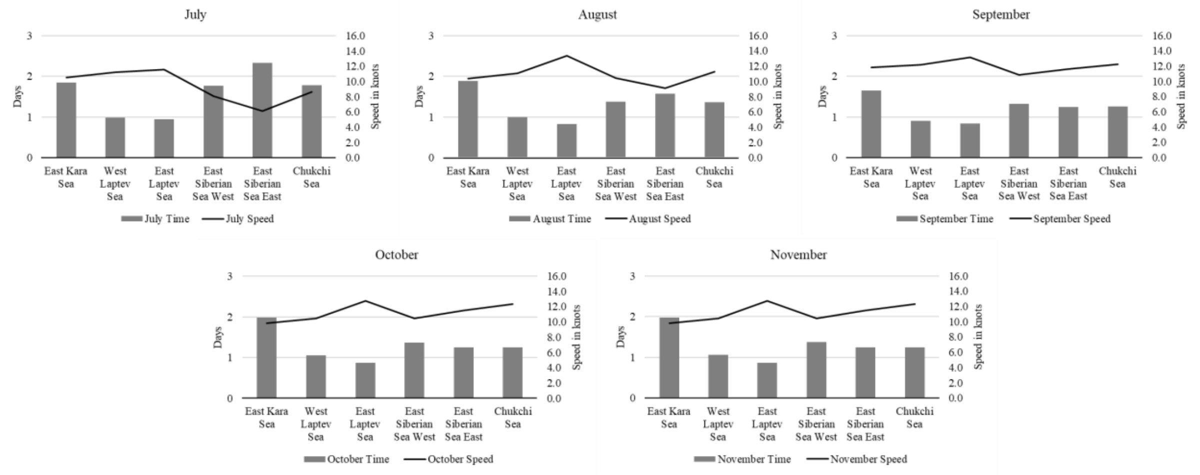
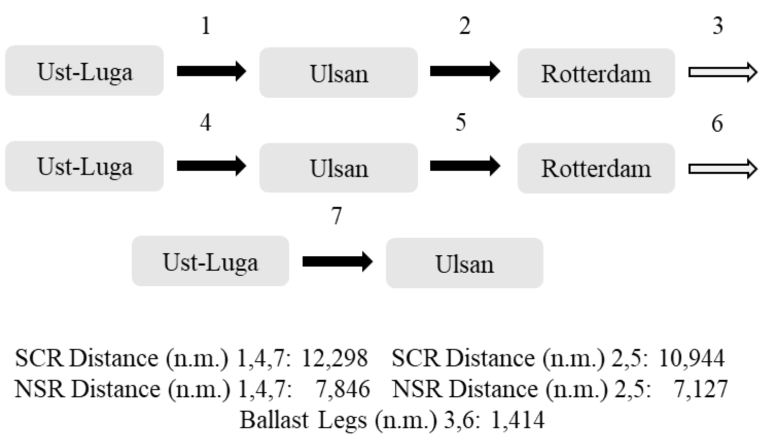


Figure 2. Speed, and time on the NSR

The planning for seasonal navigation of consecutive round voyages between Northwest Europe/Baltic and Northeast Asia is based on the following voyage pattern for both the SCR and NSR: the LR2 tanker departs on 1st July from Ust-Luga for its first naphtha voyage to Ulsan. Then, it is loaded with jet fuel/kerosene at Ulsan for the return (second) voyage in Rotterdam. The third voyage is a ballast one from Rotterdam to Ust-Luga to load naphtha and perform the fourth voyage to Ulsan, where the product is discharged, and is loaded with jet fuel/kerosene (fifth voyage) back to Rotterdam. Finally, the tanker steams to Ust-Luga (sixth voyage), where it is loaded with naphtha for its seventh voyage to Ulsan. Figure 3 shows the voyage itineraries and distances for the respective voyage legs. Seasonal round voyages via the NSR adhere to the period between early July and end-November (see Figure 2 for time and speed within NSR), which means that the tanker does not operate through ice beyond the end of November. Two days in port are assumed for either loading or unloading, and one day for a Suez Canal transit under the SCR route (Clarksons, 2020).



Source: Dataloy Distance Table. The distance on NSR is assumed to be 2,059 n.m., referring to the deep-water high-latitude route north of the New Siberian Islands, based on the majority of historic NSR voyages between 2011 and 2019. (Bloomberg, 2020).

Figure 3. Voyage itineraries and OD distances.

4. Analysis

Table 4 reports voyage SCR-NSR RFR differential results. The number of voyages on the NSR depend on several factors. First, the OD distance is very important, along with sea ice conditions, which affect the ship speed and time through ice. Second, the prices/costs of different fuels/technologies along with other fixed costs influence the optimal ship speed that minimises the NSR RFR, and therefore the transit time outside the NSR. Moreover, port and canal transit time, and potential delays also affect seasonal operations. The choice of VLSFO, including MGO within ECAs, gives the highest SCR-NSR RFR differentials for all voyages, whereas HSFO-Scrubber gives the lowest, with the differential for the LNG-VLSFO option found in between them since it is a combination of a low LNG price and a high VLSFO price. Ballast voyages between Rotterdam and Ust-Luga give a negative RFR differential. This is primarily the result of the higher fuel consumption of the ice class tanker on open water and in a lesser extent of the higher capital and operating costs than those of an ordinary tanker. The highest RFR differential between SCR and NSR across all fuel types is found on the 4th voyage of the Ust-Luga – Ulsan OD owing to higher distance savings than on the Ulsan – Rotterdam OD voyages, as well as to the highest speed on ice compared to all voyages.

Table 4. Voyage and Seasonal SCR-NSR RFR Differential in US$ per tonne.

OD	Fuel Type		
	HSFO-Scrubber*	VLSFO*	LNG-VLSFO
1. Ust-Luga - Ulsan	0.82 (0.59)	1.79 (1.78)	1.73
2. Ulsan - Rotterdam	0.75 (0.42)	1.51 (1.51)	1.47
3. Rotterdam - Ust-Luga	-0.36	-0.42	-0.31
4. Ust-Luga - Ulsan	1.62 (1.21)	2.38 (2.37)	2.37
5. Ulsan - Rotterdam	0.83 (0.47)	1.57 (1.56)	1.53
6. Rotterdam - Ust-Luga	-0.36	-0.42	-0.31
7. Ust-Luga - Ulsan	1.46 (1.11)	2.29 (2.28)	2.27
Seasonal Differential	0.95 (0.61)	1.74 (1.73)	1.75
Seasonal Differential incl. ice coating	0.76 (0.43)	1.55 (1.55)	1.56

*Differentials in parentheses refer to results when MGO is used in NSR.

Moreover, the use of multiple fuels has further implications for route competitiveness. The ratio of LNG/VLSFO mileage between the NSR and SCR varies in both ODs and it depends first on overall distance savings when comparing the two routes against a certain OD, and second on the LNG consumption through ice depending on the average speed per transit and ultimately on the month and prevailing sea ice conditions. Ratios of 91/9, 85/15, and 87/13 for the 1st, 4th, and 7th voyages of the NSR versus 63/37 for the SCR on the Ust-Luga – Ulsan OD pair, and ratios of 96/4 for the 2nd and 5th voyages of the NSR versus 71/29 for the SCR on the Ulsan – Rotterdam OD pair means that the shorter NSR benefits from the use of the cheaper LNG at longer distance legs compared to SCR (see Appendix B). This demonstrates that given the constraint of LNG tank capacity, the use of a cheaper fuel on the NSR, depending on mileage and OD distance, can offer a higher RFR differential than a relatively more expensive fuel (here HSFO), which is used for the entire length of both routes.

The use of MGO within the NSR, under the assumption that residual fuels will be prohibited in the Arctic even with the use of scrubbers, affect the RFR differentials mostly on the HSFO-Scrubber due to a 200 US$/t price difference between HSFO and MGO. The impact on the VLSFO mode is almost negligible owing to a price difference of 20 US$/t, and results in the same RFR differential for the two ODs.

Table 4 also shows the seasonal SCR-NSR RFR differentials with and without ice coating. It can be seen that results for the whole summer/autumn season reflect the impact that alternative fuels have on the economics of individual voyages albeit LNG-VLSFO is slightly more competitive than VLSFO. This is the result of using the cheaper LNG only at the ballast legs compared to VLSFO mode. The inclusion of ice coating which allows an ice class tanker to undertake consecutive voyages on icy waters for a complete season and further protecting the ice class hull, means an additional 0.2 US$/t cost across all options.

The RFR differential analysis per voyage is complemented by Figure 4, which illustrates ship speed on ice, optimal ship speed across a whole voyage and time within and outside icy waters depending on monthly ice conditions per zone and direction of transit (eastbound/westbound) (see Figure 2). The differences across SCR-NSR RFR differentials for a certain OD at different transits/months can then be explained by monthly sea ice conditions, which affect the optimal ship speed, transit time and ultimately the voyage minimum NSR RFR. The seasonal navigation allows three transits for the Ust-Luga – Ulsan OD, and it can be seen that July is the most challenging month with a ship speed on ice of 8.9 knots on an eastbound voyage, which gives the lowest NSR-SCR RFR differentials under fuel prices as of February 2020, and September being the best month with a speed on ice of 11.9 knots and the highest RFR differentials across all fuels. The Ulsan – Rotterdam OD transits occur in August and October, with the former providing the second lowest speed on ice after July at 10.7 knots and the latter a speed on ice of 11 knots which slightly increases the differential across all fuels. A lower speed on ice at a given month means a lower average speed for a whole voyage, therefore the longer the time spent within ice water, the longer the overall voyage transit time. Consequently, the minimum NSR RFR at a given transit gets higher when the speed on ice decreases, and vice versa. The lowest point for the minimum RFR NSR on the Ust-Luga – Ulsan OD is achieved in September, where the SCR-NSR RFR differential is also the highest across all fuel types/modes, and the difference between the speed on ice and optimal speed on open water being 2.5 knots compared to 4.1 in July and 3.0 knots in November. Equally, the minimum RFR NSR on the Ulsan – Rotterdam OD reaches its lowest point in October and the highest RFR differential across all fuel types with a difference of 2.9 knots between the optimal speed and speed on ice compared to a difference of 3.1 knots in the August transit.

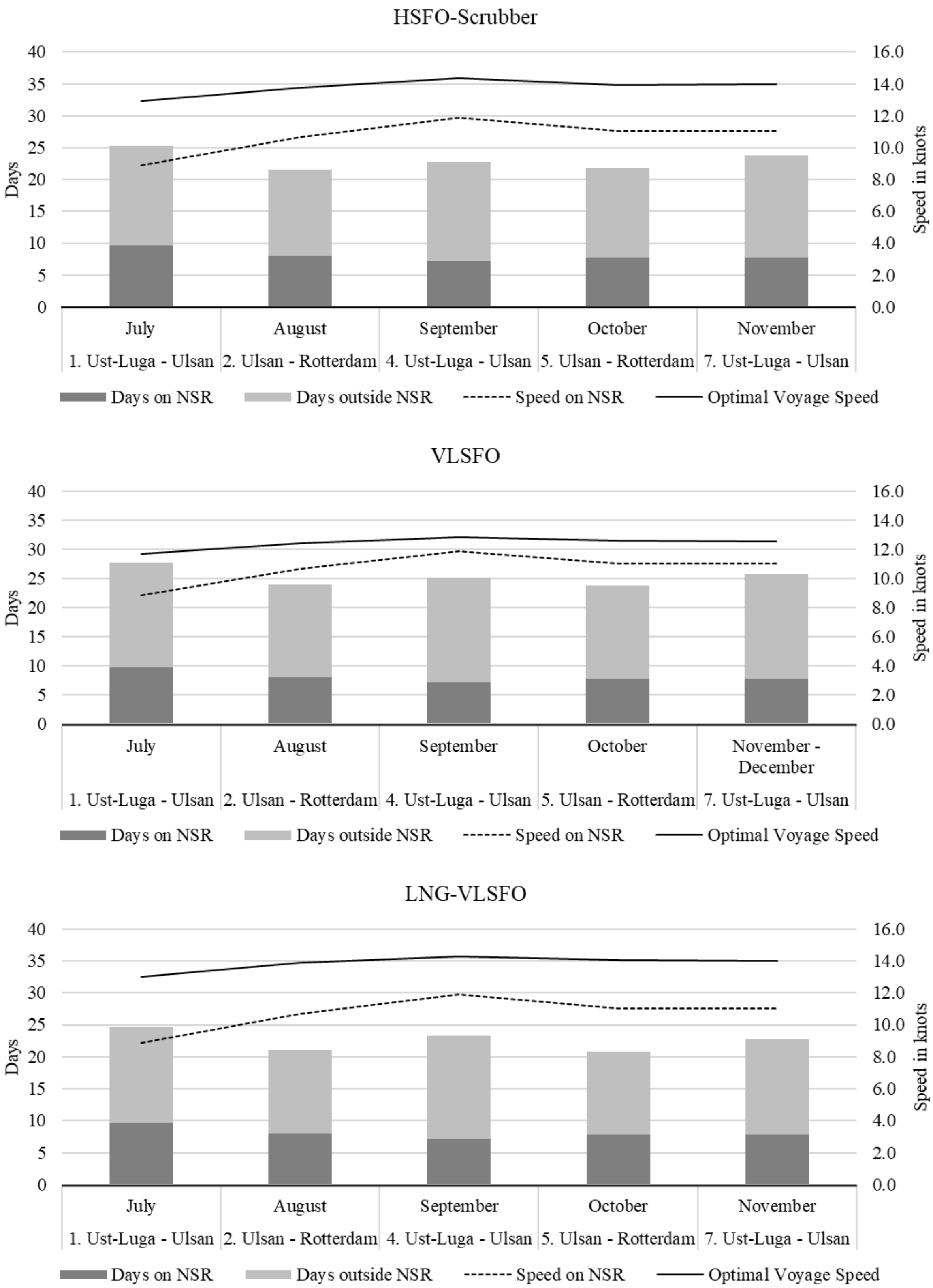


Figure 4. Speed – time relationship within and outside NSR across all laden voyages.

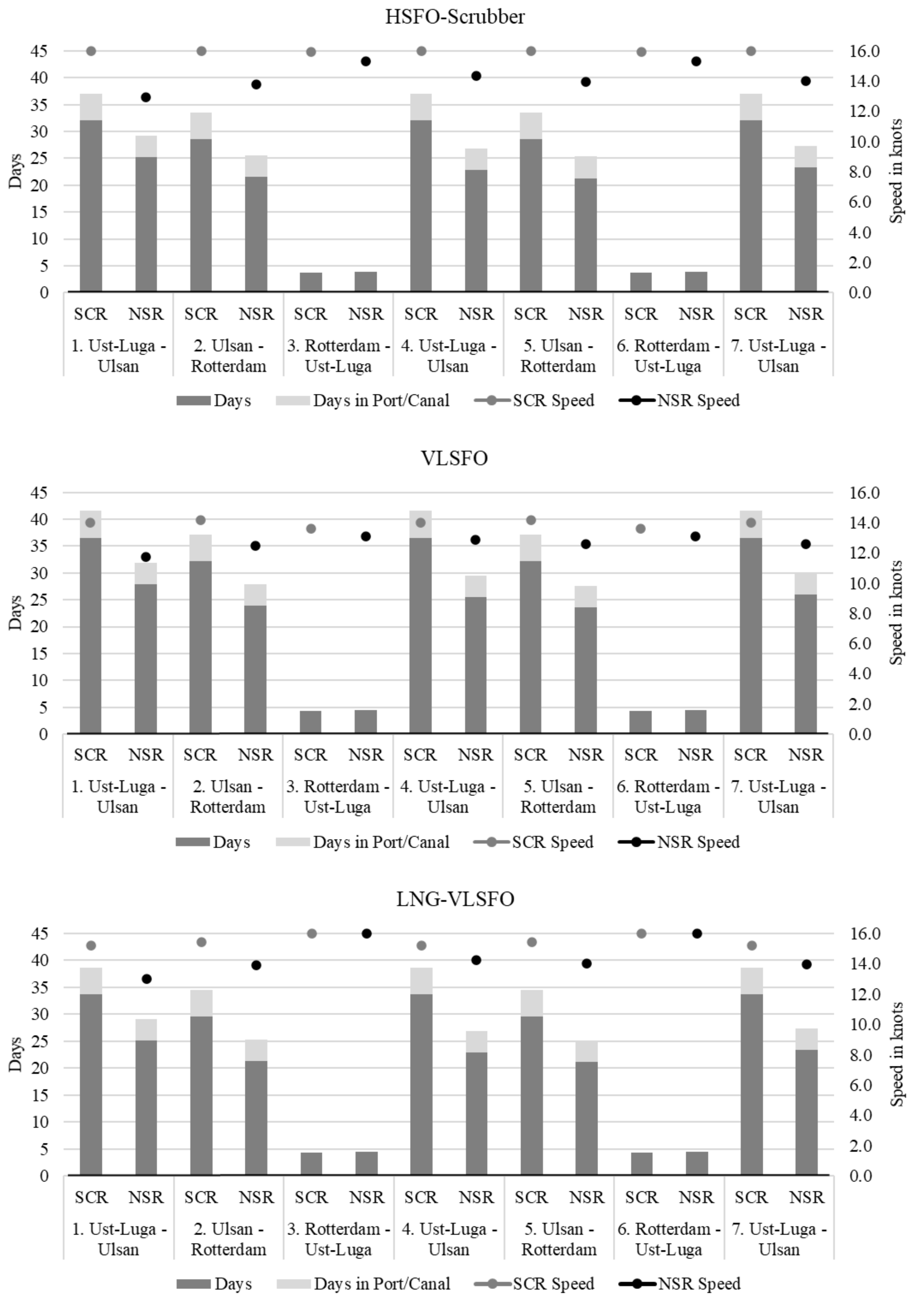


Figure 5. Voyage and seasonal time & speed analysis.

Figure 5 shows voyage transit times for all itineraries and fuel types. The transit time of NSR ballast voyages between Rotterdam and Ust-Luga (3 and 6) are slightly higher than those of the SCR, given the lower optimal speeds for ice class tankers. The use of the expensive VLSFO means lower optimal speeds, and as a consequence longer transit times in both routes, which in turn means greater time savings when using the shorter NSR, all else being equal. Conversely, the HSFO-Scrubber mode gives the shortest transit times as well as the least time savings when using the NSR, with LNG-VLSFO being in between them. Whilst transit times for a certain OD on the SCR route are the same across every fuel type, voyage times vary on the NSR owing to different sea ice regimes and speeds on icy waters. The least time savings occur during July, August, and October transits, whereas the highest during September and November across every fuel type/mode.

Figure 6 graphically illustrates the relationship between optimal ship speed and minimum RFR for both route alternatives and for all fuel types using voyages 4 (Ust-Luga – Ulsan in September) and 5 (Rotterdam – Ulsan in October) as examples. The top two graphs depict the optimal speed-minimum RFR relationship for the HSFO-Scrubber mode, with black dashed curves reflecting the SCR route and grey dashed curves the NSR route. The higher SCR RFR on the Ust-Luga – Ulsan OD is the result of a longer distance than on the Ulsan – Rotterdam OD, even after considering the higher in-transit inventory costs for jet fuel on the latter. Equally, the shorter OD distance albeit with a lower speed on ice than on voyage 4 is the main reason for the lower NSR RFR on the (5th) Ulsan – Rotterdam OD. Similar observations can be made for VLSFO and LNG-VLSFO options shown in the middle and bottom graphs, respectively. The lowest RFR for both route alternatives is given by the LNG-VLSFO mode, followed by HSFO-Scrubber and VLSFO options. Higher optimal speeds on the Ulsan – Rotterdam OD for SCR and across all fuels is the result of higher in-transit inventory costs due to a more expensive price of the jet fuel compared to that of naphtha, whereas the lower optimal speeds on NSR for the same OD are attributed to a lower speed through ice, which offsets the impact of the higher in-transit inventory cost of jet fuel.

The use of MGO within NSR, assuming a ban of residuals and reflected in the dotted curves at the top and middle graphs, would mean an increase of the NSR RFR of 0.41 and 0.35 US$/t for voyages 4 and 5 respectively on the HSFO-Scrubber option, whereas those on the VLSFO mode remain virtually the same due to a narrow difference between current VLSFO-MGO prices. It should be noted that the use of MGO within the NSR in either case does not affect optimal speeds, since speed on ice for each voyage is the same and determined by monthly sea ice conditions.

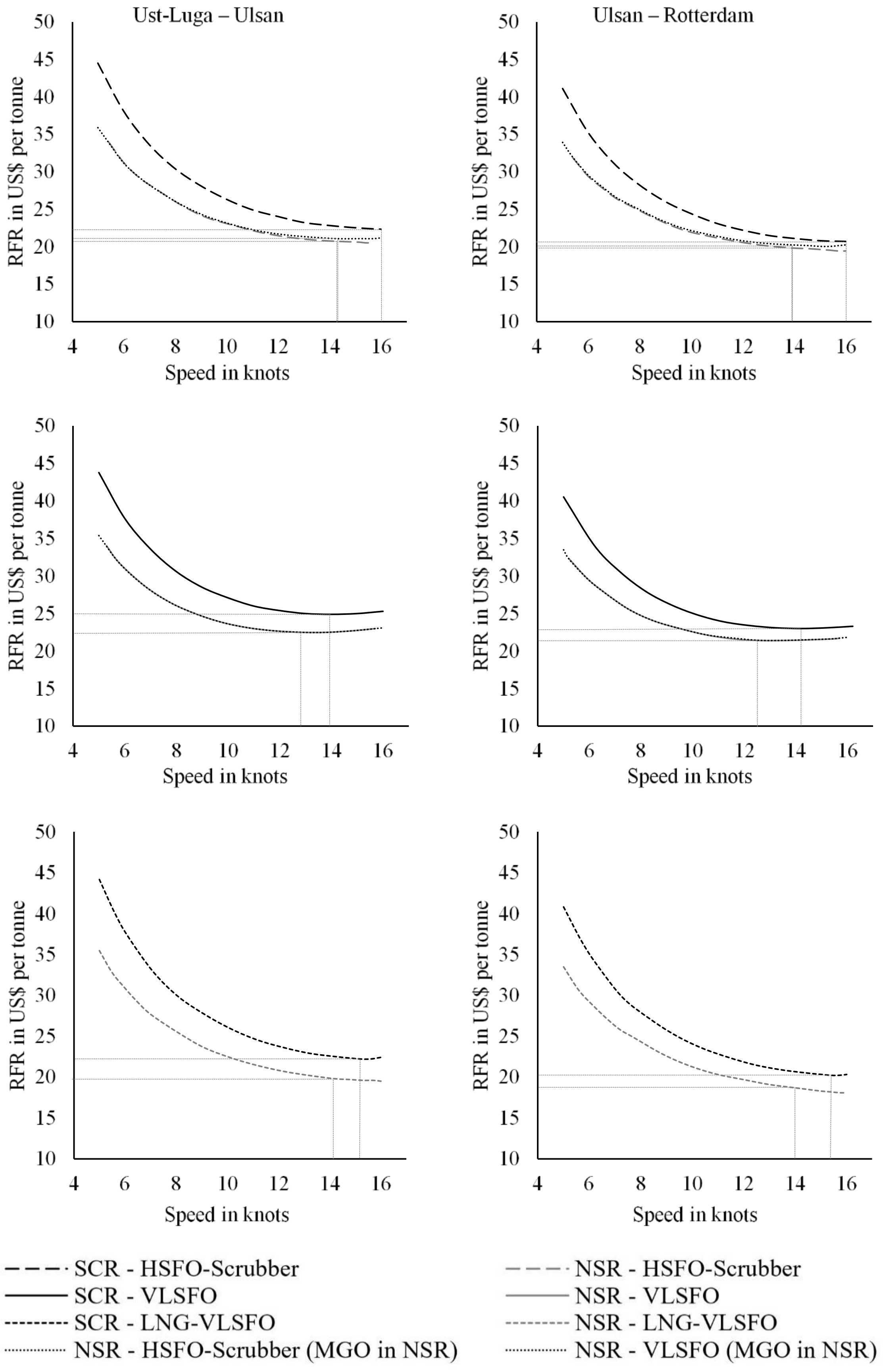


Figure 6. Relationship between round voyage optimal speed and minimum RFR for various operational modes for the fourth and fifth voyages, respectively.

Figure 7 illustrates a breakdown of fixed and variable costs for all itineraries and across all fuel types. Fuel and capital costs are the primary cost factors on the SCR route across all voyages and fuel types, followed by transit fees, in-transit inventory, and operating costs. In-transit inventory costs become more important on the VLSFO and LNG-VLSFO options (third cost factor after fuel and capital costs) due to longer transit times than on the HSFO-Scrubber option, whereas fuel costs come second under the LNG-VLSFO option. When it comes to the NSR, icebreaking fees are the most important cost factor across all fuel types. Capital costs are the second cost factor across all fuel options, followed by fuel, operating and in-transit inventory costs for HSFO-Scrubber and VLSFO. On the other hand, operating and in-transit inventory costs are the third and fourth factors followed by fuel costs under the LNG-VLSFO option, except for the 4th and 7th voyages where fuel costs are higher than in-transit inventory costs owing to higher speeds through ice. As regards ballast voyages, capital costs come first across all fuel types, followed by fuel and operating costs for HSFO-Scrubber and VLSFO, whereas fuel costs come third after operating costs under the LNG-VLSFO option. Figure 8 shows cost factors in US$/t from a seasonal point of view, which largely confirm the individual voyage cost analysis.

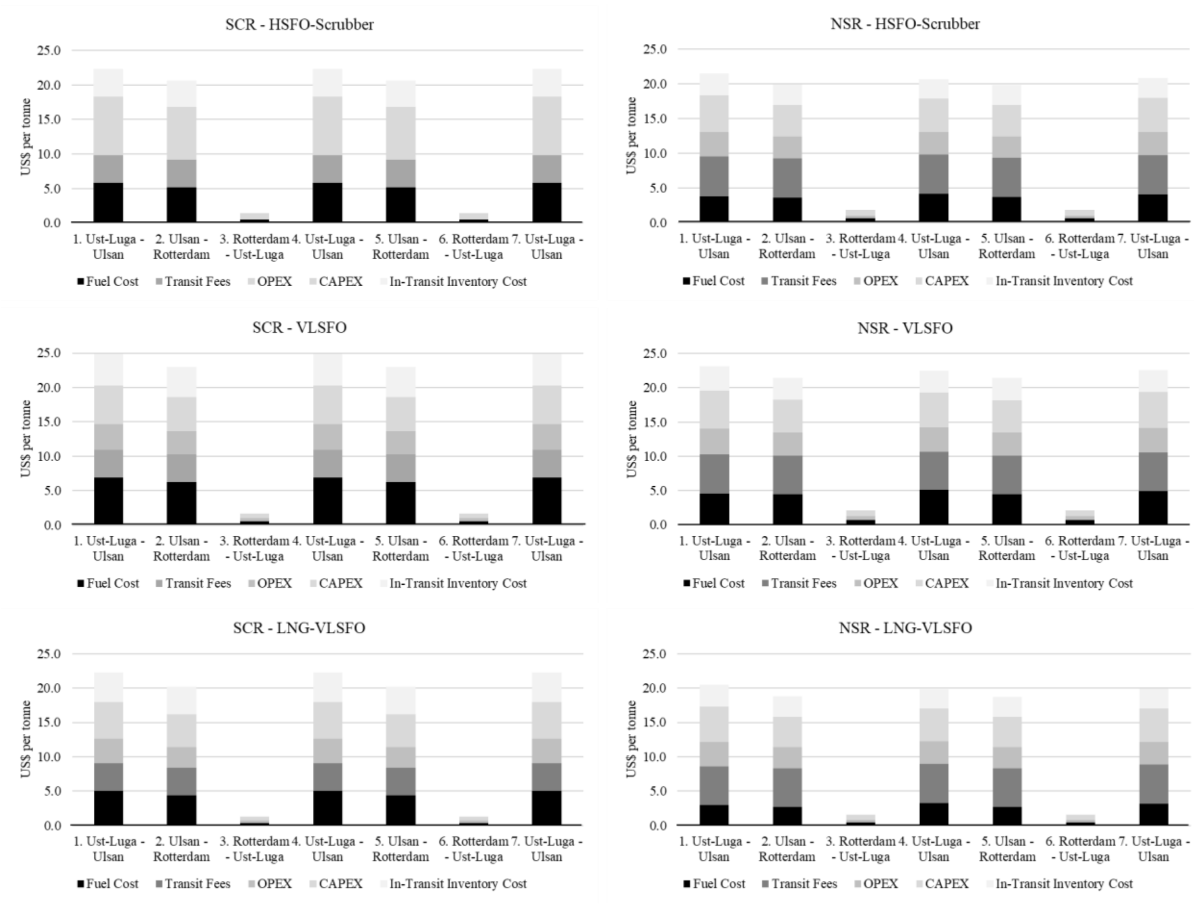


Figure 7. Voyage cost analysis

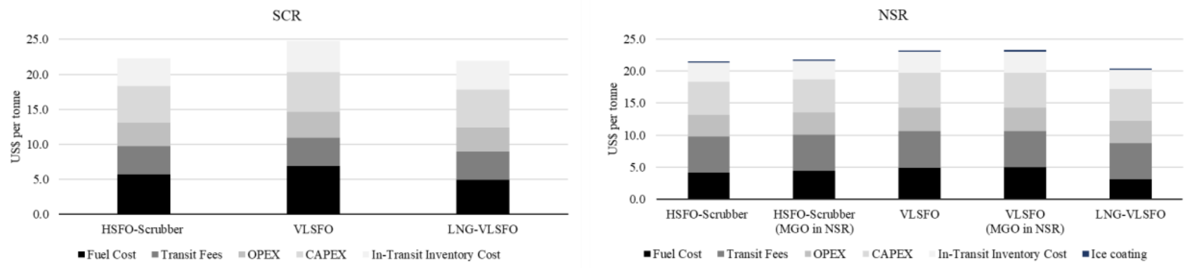


Figure 8. Seasonal cost analysis

5. Sensitivity Analysis

A sensitivity analysis is conducted to control for important cost and operational factors, such as fuel and commodity prices, icebreaking fees, USD/RUB rates, transit times, and speed on ice when operating without icebreaking assistance. The base case refers to prices as of February 2020 used in the main analysis. Residual fuels (HSFO, VLSFO), MGO, and naphtha/jet fuel prices are assumed at +/-50% compared to their base case value due to their interdependence and their long-term relationship with crude oil prices (Gjølberg and Johnsen, 1999, Lindstad and Eskeland, 2015). LNG prices are assumed at +/- 40% based on historic average LNG price movements of the TTF gas and Asian LNG spot prices. For instance, the LNG spot price in Asia dropped from a high of 818 US$/t during 2011-2014 by almost 50% to a low of 420 US$/t between 2015 and 2017, in line with a 52% drop of Brent price (from 785 to 376 US$/t), whereas TTF gas price which is less tightly coupled with oil prices (Fulwood, 2019) declined by 23% during the same periods (Clarksons, 2020, Capital IQ, 2020). Naphtha prices fell from 888 to 437 US$/t and jet fuel/kerosene from 986 to 491 US$/t, i.e. a 50% drop in Rotterdam and Singapore respectively (OPEC MOMR, 2011-2020). Marine fuels followed similar price movements between 2011 and 2017 in these regions, that is, a decline of 48% (MGO) and 53% (HSFO) (Clarksons, 2020). Moreover, the USD/RUB rate was 62.11 during 2011-2014 and fell to a low of 33.28 during 2015-2017 (Bank of Russia, 2020), indicating an inverse relationship between crude oil and USD/RUB rates (Beckmann and Czudaj, 2013, Yang et al., 2017, Shibashaki et al., 2018, Chuffart and Hooper, 2019). A low USD/RUB rate of 33.28 and a high of 64.41 are used in the sensitivity scenarios, assuming icebreaking assistance for all zones (NSRA, 2014). Discounted fees are included, reflecting the practice of negotiated icebreaking fees, that is 5 US$/t of cargo and 2.5 US$/displacement tonne (Falck, 2012, Lasserre, 2014, 2015, Gritsenko and Kiiski, 2016, Moe and Brigham, 2016, Tanker Company, 2019, Logistics Company, 2019), as well as independent navigation with the speed on ice the same as in the base case, albeit with a minimum constraint of 5 knots (MAN Diesel and Turbo, 2013b, Trafi, 2017b, Solakivi et al., 2017).

Table 5 (a-d) presents the abovementioned assumptions along with the voyage and seasonal time and SCR-NSR RFR differential sensitivity results. It can be seen that the NSR is not competitive when using the official NSRA fees at high fuel and commodity prices across all fuel types, whilst it is competitive at certain voyages across all fuel types, as well as marginally competitive on the first voyage under the LNG-VLSFO option at low fuel prices. This is largely due to different starting points (with same low commodity prices, low HSFO is assumed at 150 US$/t whereas low VLSFO and MGO prices are 240 and 250 US$/t, respectively), a higher LNG/VLSFO ration on the NSR, and higher speeds on ice on certain voyages in a lesser extent.

A low USD/RUB rate means that the NSR is even less competitive at high than at low fuel and commodity prices. The influence of high fuel prices is more prevalent at discounted fees scenarios, especially on the VLSFO option, as well as on independent navigation scenarios, where the NSR becomes competitive across all operational modes and even at low fuel and commodity prices. Ballast voyages against same distances are the exception, as higher fuel consumption and fixed costs for an ice class tanker mean that the result will always be negative regardless of price and commodity movements.

The results for seasonal operations largely reflect those of individual voyages, especially the influence of a low USD/RUB rate at high fuel prices (Table 5d). The NSR is mainly competitive at base case, high fuel prices and discounted fees, and under independent navigation. Transit time savings become larger with high fuel prices across all scenarios. However, transit time savings under high HSFO and naphtha/jet fuel prices and low USD/RUB rates are similar as in the HSFO low price-commodities/high exchange rate and base case scenarios due to very high optimal speeds on the SCR, which reduce the advantage of the shorter NSR.

Table 5a. Voyage SCR-NSR RFR Differential sensitivity of HSFO-Scrubber in US$ per tonne.

HSFO Price (US$ per tonne)	Commodity Price (US$ per tonne)	USD/RUB Exchange Rate	Voyage	Official Fees*	Discounted Fees*	Independent Navigation*	Time Differential
			1. Ust-Luga - Ulsan	-0.49 (-0.61)	0.01 (-0.12)	4.99 (4.88)	8
			2. Ulsan - Rotterdam	-0.42 (-0.59)	0.06 (-0.10)	5.06 (4.90)	8
			3. Rotterdam - Ust-Luga	-0.28	-0.28	-0.28	
150	Naphtha: 228, Jet Fuel: 249	64.41	4. Ust-Luga - Ulsan	0.31 (0.10)	0.79 (0.59)	5.79 (5.59)	11
			5. Ulsan - Rotterdam	-0.34 (-0.52)	0.14 (0.03)	5.14 (4.97)	9
			6. Rotterdam - Ust-Luga	-0.28	-0.28	-0.28	
			7. Ust-Luga - Ulsan	0.14 (0.04)	0.62 (0.45)	5.62 (5.45)	10
			1. Ust-Luga - Ulsan	0.82 (0.59)	1.30 (1.08)	6.30 (6.08)	8
			2. Ulsan - Rotterdam	0.75 (0.42)	1.23 (0.90)	6.23 (5.90)	8
			3. Rotterdam - Ust-Luga	-0.36	-0.36	-0.36	
300	Naphtha: 457, Jet Fuel: 498	64.41	4. Ust-Luga - Ulsan	1.6 2 (1.21)	2.10 (1.69)	7.10 (6.69)	10
			5. Ulsan - Rotterdam	0.83 (0.47)	1.31 (0.96)	6.31 (5.96)	8
			6. Rotterdam - Ust-Luga	-0.36	-0.36	-0.36	
			7. Ust-Luga - Ulsan	1.46 (1.11)	1.95 (1.59)	6.95 (6.59)	10
			1. Ust-Luga - Ulsan	-2.90 (-3.24)	2.72 (2.38)	7.72 (7.38)	8
			2. Ulsan - Rotterdam	-3.11 (-3.61)	2.50 (2.00)	7.50 (7.00)	8
			3. Rotterdam - Ust-Luga	-0.42	-0.42	-0.42	
450	Naphtha: 685, Jet Fuel: 747	33.28	4. Ust-Luga - Ulsan	-2.11 (-2.72)	3.51 (2.89)	8.51 (7.89)	11
			5. Ulsan - Rotterdam	-3.04 (-3.57)	2.57 (2.04)	7.57 (7.04)	8
			6. Rotterdam - Ust-Luga	-0.42	-0.42	-0.42	
			7. Ust-Luga - Ulsan	-2.25 (-2.77)	3.37 (2.84)	8.37 (7.84)	10

*Differentials in parentheses refer to results when MGO is used in NSR.

Table 5b. Voyage SCR-NSR RFR Differential sensitivity of VLSFO in US$ per tonne.

VLSFO/MGO (US$ per tonne)	Commodity Price (US$ per tonne)	USD/RUB Exchange Rate	Voyage	Official Fees*	Discounted Fees*	Independent Navigation*	Time Differential
			1. Ust-Luga - Ulsan	-0.07 (-0.07)	0.42 (0.42)	5.42 (5.42)	8
			2. Ulsan - Rotterdam	-0.10 (-0.10)	0.39 (0.38)	5.39 (5.38)	8
			3. Rotterdam - Ust-Luga	-0.33	-0.33	-0.33	
240/250	Naphtha: 228, Jet Fuel: 249	64.41	4. Ust-Luga - Ulsan	0.62 (0.62)	1.10 (1.10)	6.10 (6.10)	11
			5. Ulsan - Rotterdam	0.03 (0.03)	0.45 (0.45)	5.45 (5.45)	8
			6. Rotterdam - Ust-Luga	-0.33	-0.33	-0.33	
			7. Ust-Luga - Ulsan	0.48 (0.48)	0.97 (0.97)	5.97 (5.97)	10
			1. Ust-Luga - Ulsan	1.79 (1.78)	2.27 (2.27)	7.22 (7.27)	10
			2. Ulsan - Rotterdam	1.51 (1.51)	2.00 (1.99)	7.00 (6.99)	9
			3. Rotterdam - Ust-Luga	-0.42	-0.42	-0.42	
480/500	Naphtha: 457, Jet Fuel: 498	64.41	4. Ust-Luga - Ulsan	2.38 (2.37)	2.86 (2.86)	7.86 (7.86)	12
			5. Ulsan - Rotterdam	1.57 (1.56)	2.05 (2.05)	7.05 (7.05)	10
			6. Rotterdam - Ust-Luga	-0.42	-0.42	-0.42	
			7. Ust-Luga - Ulsan	2.29 (2.28)	2.77 (2.77)	7.77 (7.77)	12
			1. Ust-Luga - Ulsan	-1.69 (-1.69)	3.93 (3.92)	8.93 (8.92)	11
			2. Ulsan - Rotterdam	-2.17 (-2.18)	3.45 (3.44)	8.45 (8.44)	11
			3. Rotterdam - Ust-Luga	-0.48	-0.48	-0.48	
720/750	Naphtha: 685, Jet Fuel: 747	33.28	4. Ust-Luga - Ulsan	-1.19 (-1.20)	4.42 (4.41)	9.42 (9.41)	14
			5. Ulsan - Rotterdam	-2.13 (-2.14)	3.49 (3.48)	8.49 (8.48)	11
			6. Rotterdam - Ust-Luga	-0.48	-0.48	-0.48	
			7. Ust-Luga - Ulsan	-1.24 (-1.25)	4.37 (4.37)	9.37 (9.37)	13

*Differentials in parentheses refer to results when MGO is used in NSR.

Table 5c. Voyage SCR-NSR RFR Differential sensitivity of LNG-VLSFO in US$ per tonne.

LNG/VLSFO/MGO (US$ per tonne)	Commodity Price (US$ per tonne)	USD/RUB Exchange Rate	Voyage	Official Fees	Discounted Fees	Independent Navigation	Time Differential
			1. Ust-Luga - Ulsan	0.01	0.50	5.50	8
			2. Ulsan - Rotterdam	-0.02	0.46	5.46	8
			3. Rotterdam - Ust-Luga	-0.26	-0.26	-0.26	
150/240/250	Naphtha: 228, Jet Fuel: 249	64.41	4. Ust-Luga - Ulsan	0.71	1.19	6.19	11
			5. Ulsan - Rotterdam	0.04	0.53	5.53	9
			6. Rotterdam - Ust-Luga	-0.26	-0.26	-0.26	
			7. Ust-Luga - Ulsan	0.57	1.06	6.06	10
			1. Ust-Luga - Ulsan	1.73	2.21	7.21	10
			2. Ulsan - Rotterdam	1.47	1.95	6.95	9
			3. Rotterdam - Ust-Luga	-0.31	-0.31	-0.31	
250/480/500	Naphtha: 457, Jet Fuel: 498	64.41	4. Ust-Luga - Ulsan	2.37	2.85	7.85	12
			5. Ulsan - Rotterdam	1.53	2.01	7.01	9
			6. Rotterdam - Ust-Luga	-0.31	-0.31	-0.31	
			7. Ust-Luga - Ulsan	2.27	2.75	7.75	11
			1. Ust-Luga - Ulsan	-1.86	3.76	8.76	11
			2. Ulsan - Rotterdam	-2.30	3.31	8.31	10
			3. Rotterdam - Ust-Luga	-0.35	-0.35	-0.35	
350/720/750	Naphtha: 685, Jet Fuel: 747	33.28	4. Ust-Luga - Ulsan	-1.24	4.37	9.37	13
			5. Ulsan - Rotterdam	-2.24	3.37	8.37	10
			6. Rotterdam - Ust-Luga	-0.35	-0.35	-0.35	
			7. Ust-Luga - Ulsan	-1.32	4.29	9.29	12

Table 5d. Seasonal SCR-NSR RFR Differential sensitivity in US$ per tonne.

Fuel Type	Fuel Price (US$ per tonne)	Commodity Price (US$ per tonne)	USD/RUB Exchange Rate	Official Fees*	Discounted Fees*	Independent Navigation*	Time Differential
	150	Naphtha: 228, Jet Fuel: 249	64.41	-0.46 (-0.63)	0.02 (-0.14)	5.02 (4.86)	46
HSFO-Scrubber	300	Naphtha: 457, Jet Fuel: 498	64.41	0.76 (0.43)	1.25 (0.91)	6.25 (5.91)	43
	450	Naphtha: 685, Jet Fuel: 747	33.28	-3.04 (-3.54)	2.58 (2.08)	7.58 (7.08)	45
	240/250	Naphtha: 228, Jet Fuel: 249	64.41	-0.14 (-0.14)	0.35 (0.34)	5.34 (5.34)	47
VLSFO	480/500	Naphtha: 457, Jet Fuel: 498	64.41	1.55 (1.55)	2.04 (2.03)	7.03 (7.03)	53
	720/750	Naphtha: 685, Jet Fuel: 747	33.28	-2.07 (-2.06)	3.55 (3.54)	8.54 (8.54)	58
	150/240/250	Naphtha: 228, Jet Fuel: 249	64.41	-0.03	0.46	5.46	46
LNG-VLSFO**	250/480/500	Naphtha: 457, Jet Fuel: 498	64.41	1.56	2.05	7.05	51
	350/720/750	Naphtha: 685, Jet Fuel: 747	33.28	-2.12	3.49	8.49	55

*Results refer to both HSFO-Scrubber/VLSFO and HSFO-Scrubber/VLSFO (MGO in NSR). **The VLSFO and LNG-VLSFO options include MGO consumption (within ECAs for the VLSFO option and pilot MGO for the LNG option), hence the inclusion of MGO price sensitivity.

6. Discussion and conclusions

This paper examines the competitiveness of the NSR for oil product tankers at the strategic level for a shipowner who operates on the NSR during the summer/autumn season. The seasonal operations in this paper refer to arbitrage opportunities for commodities that may exist between Europe and the Far East, so that the shipowner could offer competitive freight rates to traders/charterers that want to exploit such opportunities from a seasonal navigation perspective. A cost model is developed which minimises the RFR with speed optimisation considering alternative fuel types including dual-fuel oil-gas engine set-ups, fuel consumption and costs. The main oil product trades between the Atlantic and the Pacific are identified and linked with historic seasonal operations on the NSR based on which seasonal navigation planning is conceptualised and real speed data from Bloomberg (2020) are employed along with up to date secondary and relevant primary data related to Arctic maritime operations.

Whilst there have been studies which explored ice thickness data to estimate speed on ice (von Bock und Polack et al., 2015, Faury and Cariou, 2016, Cariou et al., 2019, Cariou and Faury, 2020, Faury et al., 2020, Cheaitou et al., 2020), this is the first study that employs real hourly speed data from tanker voyages conducted on the NSR between 2011 and 2019 to inform the RFR and speed optimisation models. Thus, this paper offers a new approach to estimate speed within the NSR. Another novelty is the consideration of alternative fuel types with reference to the IMO 2020 sulphur limit, a prospective ban on the use of residual fuels in the Arctic and long-term environmental policy implications with respect to emissions abatement. These include the use of scrubber with HSFO, the new VLSFO and dual-fuel engine set ups with LNG and oil-based fuels. Moreover, the use of MGO within the NSR is considered, following a future ban on VLSFO and HSFO in the Arctic even with the use of scrubbers under only oil-powered engines.

Seasonal voyage planning and navigation for oil product tankers on the NSR, in a speed optimisation context aiming to minimise the RFR, depends on many factors which can affect the competitiveness of the route. The main factors that increase the competitiveness of the NSR are a combination of discounted icebreaking fees, higher fuel and commodity prices, shorter OD distances, and relatively high ship speed through ice. However, independent navigation significantly increases the competitiveness of the route even at low fuel and commodity prices, and across all fuel types.

The results show that July is the most challenging month when simulating voyages between Ust-Luga, Rotterdam and Ulsan for naphtha and jet fuel/kerosene trades. Ship speed on ice in September and November provide higher average speeds, bigger time savings, and as a result the SCR-NSR RFR differentials for the naphtha (Ust-Luga – Ulsan voyage 5) and jet fuel voyages (Ulsan – Rotterdam voyage 7) are the highest compared to the rest of the seasonal voyages.

Although VLSFO offers the biggest cost and time savings given its highest price amongst others, the LNG-VLSFO option can be an interesting alternative in terms of cost savings, compliance with ECAs and a ban on residual fuels in the Arctic as well as emissions reductions in the long-term. More specifically, a bigger LNG/VLSFO mileage ratio on the NSR compared to the SCR means that the route is more competitive compared to the latter even if LNG is the cheapest alternative fuel. This option becomes even more attractive compared to a HSFO-Scrubber option and including the use of MGO within NSR under a ban on residuals in the

Arctic. The ratio depends on OD distance and LNG tank capacity. The inclusion of in-transit inventory costs in the analysis increases the competitiveness of the NSR under high fuel and commodity price scenarios, as transit times via SCR become even longer. This is also evident from the SCR cost breakdown analysis at the base case, where they become the third cost factor after capital and fuel costs under the VLSFO and LNG-VLSFO options. The use of ice coating for seasonal operations reduces the potential cost savings that the NSR provides by 0.2 US$/t, but can be considered an essential measure to prevent damages in the hull of the ship when operating for more than one voyages on ice as in the Baltic ice season (Tanker Company, 2020).

The results from this study, which are based on real hourly speed data on ice of tanker transits between 2011 and 2019, are not directly comparable to other studies which investigated the NSR economics for tankers from a seasonal/annual approach using historic ice thickness data to determine the theoretical speed on ice. However, they are in line with Faury and Cariou (2016) and Cheaitou et al. (2020) when it comes to the cost competitiveness of an ice class 1A tanker between July and November. Both Faury and Cariou (2016) and this study found September to be the best month in terms of costs (here for the Ust-Luga – Ulsan OD), followed by October (here for the Ulsan – Rotterdam OD) and November (third transit for the Ust-Luga – Ulsan OD). Besides September and October generate the highest profits either by VLSFO or MGO (Cheaitou et al., 2020). Yet, the OD distance and initial date of a transit are important considerations when investigating the impact of speed on ice.

Fuel and commodity prices as of February 2020 and those of the sensitivity analysis can be compared to historic prices when the NSR was attractive for transit voyages between 2011-2013 due to high fuel prices and discounted fees (Theocharis et al., 2019). A HSFO price of 300 US$/t and a naphtha price of 458 US$/t result in a 1.62 US$/t differential for a cargo of 80,000 m.t. at the September voyage, that is 129,207 US$ savings from Ust-Luga to Ulsan, whereas a VLSFO price at 500 US$/t and a naphtha price of 458 US$/t give 2.38 US$/t savings, i.e. 190,249 US$ for the same voyage.

The equivalent differentials at high fuel and commodity prices, and discounted fees, that is, HSFO and VLSFO at 450 and 720 US$/t and a naphtha price of 685 US$/t respectively (section 5), give a 3.51 (280,571 US$) and 4.42 US$/t (353,884 US$) differential respectively. This high VLSFO price is relatively close to the HSFO price in Rotterdam between 2011-2013 i.e. an average of 600 US$/t (Clarksons, 2020) and given that spot naphtha prices in Rotterdam were 910 US$/t during the same period (OPEC, 2020), it can be argued that at 353,884 US$ savings per voyage, the NSR is an attractive choice for a shipowner who wants to offer a competitive freight rate even if including potential ice damage repairs (about 200,000 US$ in a dockyard at the Yangtse river, China – Tanker Company, 2019). However, at fuel prices used in the base case scenarios (as of February 2020), the potential is smaller, even if the differentials are positive at certain voyages and this is also reflected in the seasonal SCR-NSR RFR differentials. On the one hand, the inclusion of ice damage repairs and deviation of an ice class tanker from the seasonal schedule to visit a dockyard would give negative SCR-NSR RFR differentials at the base case scenarios. On the other hand, proceeding with slow speed within NSR and provided that ice coating is applied on the ice class tanker can reduce the possibility of ice damages (Tanker Company, 2020).

Both the cost breakdown and the sensitivity analysis confirm that first, icebreaking fees are the most important cost factor for the NSR route, and second that the inverse relationship between icebreaking fees, determined by USD/RUB rates, and fuel prices (Shibashaki et al., 2018) have had important implications for the potential of the NSR since the introduction of the latest official NSRA fees back in 2014 (NSRA, 2014). More specifically, the NSR is neither competitive at low fuel prices nor at high fuel prices given that fees increase at high crude oil prices in tandem with high fuel prices and a low USD/RUB rate (Lindstad and Eskeland, 2015, Shibashaki et al., 2018, Faury et al., 2020). Yet, discounted fees can still be offered since the NSRA explicitly refers to 'maximum rates', implying that these can be negotiated (NSRA, 2014).

Another important factor is the number of voyages an ice class 1A tanker can perform during the summer/autumn season. The seasonal navigation in this paper allowed for five laden voyages providing that these occur between Ust-Luga and Ulsan and between Ulsan and Rotterdam with additional time spent outside the NSR to allow the tanker to steam from Rotterdam to Ust-Luga for its next laden voyage. All else being equal, the impact of fuel prices in a speed optimisation context is evident. The last day through ice under the high fuel/commodity price scenarios in the sensitivity is 8 November on the LNG-VSLFO option, 16 November on the HSFO-Scrubber option, and 30 November on the VLSFO option.

Yet, different assumptions regarding the relationship between ship speed and fuel consumption could give very different results both in terms of the number of voyages in a speed optimisation context, as well as in terms of costs. Adland et al. (2020) recently found that for Aframax/LR2 tankers the cubic law between speed and fuel consumption holds only close to the design speed of a vessel with elasticities ranging from 3.8 to 0.7 for a speed range between 16 to 8.4 knots. On the one hand, this could mean significantly higher fuel consumption at very low speeds such as those when a tanker operates through ice, which can further increase depending on ice conditions (Solakivi et al., 2018). On the other hand, higher total fuel consumption and costs could occur for longer routes depending on the OD distances and optimal speeds. The relative difference for the SCR-NSR RFR differential would then depend on the speed through ice and the difference between the design speed and the optimal speed for a given route. The bigger the departure from the design speed, especially at low speeds, the higher the costs for a given route.

The round voyage scenarios are assumed only during the summer/autumn season rather than on annual operations and/or combined NSR/SCR annual voyages. The reason being that first, more than one strategy and routeing options may exist for oil product tankers depending on various trades and market conditions (fuel prices, freight rates, commodity prices in various geographic regions). Second that the arbitrage between two regions is not "open" every month or even week throughout the year reflecting the dynamics of commodity and spot markets, where tankers do not operate on fixed itineraries in general, except in some very specific trade routes. Thus, the seasonal NSR operations of five consecutive laden voyages assumed in this paper may not always materialise in practice. Moreover, the positioning of a tanker at the beginning of the season may not be such that can exploit the full summer/autumn navigation season or may not find sufficient employment opportunities to conduct all possible consecutive round voyages. Examples are the tankers listed in Table 2, where all except Anichkov Bridge could perform more voyages during the season, providing OD distances and sea ice conditions allowed them to do so. Besides, AIS data should be considered with caution, since reported speeds cannot always be defined and assigned to a specific state (e.g. drifting, stuck on ice etc) accurately. This uncertainty can have an impact on modelling of seasonal navigation and the total number of voyages.

Future research could include other OD pairs drawing on the same or other product trades to assess how distance, speed on ice, and alternative fuels affect the NSR economics. Fuel price differences, especially between HSFO and VLSFO could be further explored, given the volatility of the spread between the two. Moreover, the relationship between oil-based marine fuels and LNG could be further investigated. Asian spot LNG prices seem to follow closely the global oil prices, whereas TTF gas prices are less sensitive to oil price movements (Fulwood, 2019). Yet, the decoupling of the former from oil prices could mean a weaker relationship of both gas prices from oil price movements and therefore a different impact on route comparison.

Appendix A1. Port characteristics for LR2 tankers of 115,000 dwt, LOA: 250 m and loaded draught of 12 m.

Port	Tanker Terminals	Berths/Jetties	DWT	LOA (m)	Draught (m)
Ust-Luga	Oil Products Terminal Nos 1-3, Nos 4-5; SIBUR Terminal Nos 6-7	7	Up to 120,000	535-1,250	17.5
Rotterdam	11 terminals/berths for clean oil products		120,000-355,000	270-375	12.65-20.7
Ulsan	S-Oil 2-1; Sk Corp Sk8	2	120,000; 150,000	250; 280	13.5; 16.5

Sources: Ports and Terminals Guide 2015-2016, IHS Maritime (2015), DNV GL Veracity Platform (2020).

Appendix A2. LNG bunkering infrastructure/vessels.

Port	LNG infrastructure	LNG Tank Capacity (m^3)	Home port/Country	Operations
Ust-Luga	LNG Bunker Vessel LGC 6000 (Ice Class 1A) (to be delivered in September 2020)	6,000	Lithuania	Northeast Baltic Sea
	LNG Bunker Vessel Kairos (Ice Class 1A)	7,500	Lithuania	North Sea, Baltic Sea
	Gazpromneft LNG Bunker Vessel (to be delivered by the end of 2020)	5,800	Vyborg district (Russia Baltic)	Baltic Sea
Rotterdam, Ust-Luga	Coral Fraseri (Ice Class II)	10,000	Rotterdam (The Netherlands)	North Sea, Baltic Sea, West Mediterranean
	Coral Methane (Ice Class 1B)	7,551	Rotterdam (The Netherlands)	North Sea, Baltic Sea, West Mediterranean
	LNG Bunker Vessel Coralius (Ice Class 1A)	5,600	Risavika (Norway)	North Sea, Baltic Sea
	LNG Bunker Vessel Cardissa	6,500	Rotterdam (The Netherlands)	North Sea, Baltic Sea
Rotterdam	GATE Terminal Rotterdam	720,000	Rotterdam (The Netherlands)	Rotterdam

	Flexfueler 001	1,480	Amsterdam (The Netherlands)	ARA region
	LNG London	2,998	Rotterdam (The Netherlands)	Rotterdam
Ulsan	KOGAS LNG Bunker Vessel (to be delivered by the end of 2020)	7,500	Busan (South Korea)	Coastal in South Korea

Sources: Offshore Energy (2018), Lloyds List (2019), Argus (2019), DNV GL Veracity Platform (2020), Sumitomo (2020), Clarksons (2020).

Appendix B. Distance breakdown per operational mode and route.

Ust-Luga – Ulsan

Operational Mode	Fuel Type	Voyage Leg – Distance (n.m.)			
		SCR		NSR	
HSFO-Scrubber	HSFO-Scrubber*	Ust-Luga – Ulsan	12,298	Ust-Luga – Cape Zhelanya	2,848
				Cape Zhelanya – Cape Dezhnev (NSR)	2,059
				Cape Dezhnev – Ulsan	2,939
VLSFO	MGO	Ust-Luga – North Sea ECA	1,768	Ust-Luga – North Sea ECA	1,371
	VLSFO	North Sea ECA – Ulsan	10,530	North Sea ECA – Cape Zhelanya	1,477
	VLSFO*			Cape Zhelanya – Cape Dezhnev (NSR)	2,059
	VLSFO			Cape Dezhnev – Ulsan	2,939
LNG-VLSFO	LNG	Ust-Luga – Indian Ocean	7,800	Ust-Luga – Cape Zhelanya	1st, 4th, 7th voyages: 2,848
	LNG			Cape Zhelanya – Cape Dezhnev (NSR)	1st, 4th, 7th voyages: 2,059
	LNG			Cape Dezhnev – North Pacific Ocean	1st, 4th, 7th voyages: 2,252; 1,752; 1,917
	VLSFO	Indian Ocean – Ulsan	4,498	North Pacific Ocean – Ulsan	1st, 4th, 7th voyages: 687; 1,187; 1,022

Source: Dataloy Distance Table. *The use of MGO is assumed inside the NSR (2,059 n.m.) under the "MGO in NSR" variant.

Ulsan – Rotterdam

Operational Mode	Fuel Type	Voyage Leg – Distance (n.m.) SCR		NSR	
HSFO-Scrubber	HSFO-Scrubber*	Ulsan – Rotterdam	10,944	Ulsan – Cape Dezhnev	2,939
				Cape Dezhnev – Cape Zhelanya (NSR)	2,059
				Cape Zhelanya – Rotterdam	2,129
VLSFO	VLSFO		10,531	Ulsan – Cape Dezhnev	2,939
	VLSFO*			Cape Dezhnev – Cape Zhelanya (NSR)	2,059
	VLSFO			Cape Zhelanya – North Sea ECA	1,500
	MGO		413	North Sea ECA – Rotterdam	629
LNG-VLSFO	VLSFO	Ulsan – Indian Ocean	3,144	Ulsan – North Pacific Ocean	2nd, 5th voyages: 250; 303
	LNG	Indian Ocean – Rotterdam	7,800	North Pacific Ocean – Cape Dezhnev	2nd, 5th voyages: 2,689; 2,636
	LNG			Cape Dezhnev – Cape Zhelanya (NSR)	2nd, 5th voyages: 2,059
	LNG			Cape Zhelanya – Rotterdam	2nd, 5th voyages: 2,129

Source: Dataloy Distance Table. *The use of MGO is assumed inside the NSR (2,059 n.m.) under the “MGO in NSR” variant.

Appendix C1. Speed statistics for ice class 1A tankers during the 2011-2019 summer/autumn ice seasons.

Arctic Sea	Descriptive Statistics Speed (knots)	July	August	September	October	November
East Kara Sea	Minimum	6.1	5.8	6.5	4.7	12.6
	Mean	10.6	10.3	11.8	9.8	12.6
	Maximum	14.9	14.1	13.9	13.9	12.6
	Standard Deviation	3.2	3.1	2.3	2.9	N.A.
West Laptev Sea	Minimum	10.1	5.5	9.6	7.1	8.8
	Mean	11.2	11.1	12.2	10.5	8.8
	Maximum	12.6	14.4	14.3	13.7	8.8
	Standard Deviation	1.0	2.6	1.6	1.7	N.A.
East Laptev Sea	Minimum	8.9	11.0	10.9	9.4	5.1
	Mean	11.6	13.4	13.2	12.8	5.1
	Maximum	14.6	16.2	15.4	16.0	5.1
	Standard Deviation	2.3	1.5	1.3	1.9	N.A.
East Siberian Sea (West)	Minimum	2.6	7.0	5.1	2.0	7.1
	Mean	8.1	10.5	10.9	10.5	8.6
	Maximum	13.0	16.0	13.3	16.9	10.2
	Standard Deviation	3.8	2.2	2.3	4.5	2.2

East Siberian Sea (East)	Minimum	3.4	3.4	8.2	8.1	8.9
	Mean	6.2	9.1	11.6	11.5	9.5
	Maximum	10.5	14.0	14.8	15.9	10.2
	Standard Deviation	2.8	3.5	1.9	2.5	0.9
Chukchi Sea	Minimum	2.6	6.0	8.5	7.4	7.7
	Mean	8.6	11.3	12.3	12.3	11.2
	Maximum	14.0	15.7	15.9	15.9	14.8
	Standard Deviation	4.9	2.7	1.9	2.7	5.0

Source: Bloomberg (2020).

Appendix C2. Start and end points of AIS data.

Location	Longitude	Latitude
Cape Zhelanya	68° 19′ 38″	77° 14′ 51″
End of East Kara Sea (Vilkitsky Strait)	103° 24′ 18″	77° 53′ 51″
End of West Laptev Sea	128° 47′ 36″	77° 19′ 43″
Dmitry Laptev Strait	141° 59′ 11″	72° 59′ 05″
Sannikov Strait	140° 20′ 55″	74° 31′ 45″
End of East Laptev Sea (North of New Siberian Islands)	139° 45′ 43″	76° 55′ 17″
End of East Siberian Sea (West)	164° 47′ 09″	73° 55′ 35″
End of East Siberian Sea (East) Wrangel Island	178° 15′ 35″	70° 12′ 17″
Chukchi Sea Cape Dezhnev	-169° 14′ 17″	65° 55′ 07″

Source: Authors based on Bloomberg (2020).

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