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NSR TRANSIT SIMULATIONS BY THE VESSEL PERFORMANCE SIMULATOR "VESTA" PART 1 SPEED REDUCTION AND FUEL OIL CONSUMPTION IN THE SUMMER TRANSIT ALONG NSR

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ABSTRACT

The positive usage of the Northern Sea Route (NSR) is arising as a result of arctic ice melting in recent years. National Maritime Research Institute has developed an advanced vessel performance simulator in ice for accurate estimation of ship performance such as propulsion power, speed reduction and fuel consumption, taking the main engine characteristics into consideration.

The vessel performance simulator, "VESTA" has not originally developed in ice but in wave and wind. The authors incorporated two ice resistance models, Kashitelijan-Poznjok-Ryblin's (KPR) for small ice floes and Lindqvist's for large ice floes, in VESTA for performance calculation in ice.

The summer transit of ice-strengthened merchant vessel must be along marginal ice zone with pack ice rather than level ice. Thus we selected the KPR model, which requires ice concentration, thickness and floe size as input parameters of ice. Ice concentration of September from satellite observations was given to the simulator. Ice thickness and floe size were derived from the past onboard observation in the summer voyage along NSR. The ship-type virtually employed was a bulk carrier of 73,000 DWT with 9MW of M/E output.

Ship performance was estimated by VESTA along the seaway from Tokyo to Rotterdam via NSR. Several routing scenarios were simulated in order to investigate sensitivities of ice conditions for ship performance. Each route was selected so as to avoid severe ice with ice concentration. The mean ice concentration in the route was ranged from 8% to 33%. The calculation resulted in taking 3 weeks to transit from Tokyo to Rotterdam. The ship speed was up to 14 knots in open water and reduced to about 4 knots in ice. As a conclusion, the simulations showed that the NSR holds potential to reduce shipping cost of 35% as compared with Suez Canal route.

NOMENCLATURE

B :	Ship breadth
C :	Ice concentration
C_{WE} :	Waterline coefficient at the bow
F_L :	Froude number based on ship length
g :	Acceleration of gravity
h_i :	Thickness of ice
L :	Ship waterline length
L_H :	Length from stem to parallel part of the mid-body
r :	Floe size

V : Ship speed
α_0 : Waterline entrance angle
μ : Friction coefficient between ice and hull
ρ_i : Density of ice

INTRODUCTION

As is well known, the Northern Sea Route (NSR) is the shortest seaway to connect East Asia and Europe. Generally the Arctic sea ice extent has trended down in recent decades (e.g. Serreze et al. 2007,) and difficulties in using NSR as a seaway have been decreased prominently. It has a potential to reduce environmental impact in global maritime transport, such as GHG emission and fuel consumption. But the merit is greatly dependent on ice condition. Ship sometimes needs more engine power to overcome ice resistance in NSR. Consequently, precise performance estimation of NSR going ship is a critical issue.

There have been many estimation works from the viewpoint of cost. Ship speed reduction and fuel consumption are essential parameters for the fair estimation of shipping cost. Furuichi and Otsuka (2014) compared total cost of NSR and Suez Canal route (SCR), assuming the fixed ship speed as 20.0 knots in water and 14.1 knots in ice for summer transit of 6,500CEU container ship. Fuel consumption was assumed to decrease proportionally to the ship speed. Similar approach has been widely used in bulk cost estimations, but improving the accuracy is needed for the ship performance in the voyage simulation.

On the other hand, Kamesaki et al. (1999) estimated ship speed by a computer code according to ice condition. Engine power curve versus ship speed was assumed, thus fuel consumption was also computable. In this study, the route along NSR was divided into several segments and ice condition of each segment was obtained in advance. Reimer and Duong (2013) applied similar approach.

It is needless to say that the accurate cost estimation of realistic NSR transit requires an accurate simulation method of ship performance in ice. However the accuracy of ship performance estimation in ice-free water is also important because, even on NSR transit, ice-free water segment might be dominant in traveling distance. National Maritime Research Institute (NMRI) has developed a simulation program for ship performance, considering response to actual sea states such as wind and wave. The program has been enhanced to take ice resistance into consideration. In this paper, employing the enhanced program, the estimations of speed reduction and fuel consumption along three NSR transit scenarios are discussed.

COMPUTATION METHODS

Vessel Performance Simulator "VESTA"

The ship in actual sea meets wave, wind and their combination. They cause reduction of ship speed as well as increase of fuel consumption. Thus, taking them into consideration is necessary to evaluate ship's practical performance in actual sea. The "VESTA," Vessel Performance Evaluation Tool in Actual Seas, has been developed by NMRI as a computational program of ship performance in actual sea. (Tsujimoto et al. 2013)

VESTA can calculate added resistance due to waves, winds, drifting motion and rudder operation. It needs dimensions of target ship at least. User can add hull form and waterline data to execute more precise evaluation. In addition, main engine operation mode can be selectable in VESTA. The engine characteristics such as torque limit, over load protection limit and fuel index, can be taken into consideration.

VESTA has been validated by actual voyage of such as a container ship. (Sogihara et al. 2012)

Model of Ice Resistance

Sea ice affects on ship as an external force. VESTA can take added resistance by ice into account in evaluation of ship's performance. Several models of ice resistance have been proposed since 1900's. For ice-strengthened merchant ships, typical NSR voyages are in marginal ice zone where broken ice or ice floes are dominant condition. In this regard, Kashitelijan-Poznjok-Ryblin (KPR) model was selected in this study.

The KPR model has been introduced in many references. (e.g. Nozawa, 2006) This model adopts ice resistance in the area of rather small ice floes. The formulae are as follows; Total ice resistance R_{SF} is the sum of impact (R_{SF1}), dissipative (R_{SF2}), static (R_{SF3}) and hydrodynamic components (R_w).

$$R_{SF} = R_{SF1} + R_{SF2} + R_{SF3} + R_W \tag{1}$$

$$R_{SF1} = \bar{k}_3 \rho_i g r h_i L F_L^2 \tan^2 \alpha_o \tag{2}$$

$$R_{SF2} = \bar{k}_2 \rho_i g r h_i B F_L (\mu + C_{WE} \tan \alpha_o) \tag{3}$$

$$R_{SF3} = \bar{k}_1 \rho_i g \sqrt{r h_i} (\frac{B}{2})^2 (1 + 4\mu C_{WE} \frac{L_H}{B}) \tag{4}$$

Here, $\bar{k}_1$, $\bar{k}_2$ and $\bar{k}_3$ are empirical constants. $\bar{k}_1$ and $\bar{k}_2$ are the function of ice concentration. Details of ice resistance model and its validation is described in Uto et al. (to be published in 2015.)

PRECONDITIONS

Target Ship

Voyage simulations were executed on a typical ocean-going ship, Panamax bulk carrier of approx. 220m long. (Figure 1) Ice strengthen level was assumed as IMO Polar Class PC7, which is equivalent to Finnish-Swedish Ice Class 1A. In the present simulation, it is assumed that the ship independently transits NSR in summer light ice condition, whether or not the authorities' request to accept escorting by icebreaker.

Principal particulars are described in Table 1. Typical service speed in ice-free water is 14knots for Panamax bulk carriers.

Figure 1. Target ship: Panamax bulk carrier.

Table 1. Principal particulars of the target ship.

Length B.P.	217.34	m
Breadth molded	32.26	m
Draft	14.0	m
Dead Weight	73,000	MT
Engine Output	(MCR) 9,070	kW
Service Speed	14	knots

Route Selection

In the simulations, the ship was assumed to enter NSR from Bering Strait and to go westward. To calculate port-to-port cost, it was assumed that the departure port was Tokyo and the destination was Rotterdam. There could be choices of route in NSR corresponding to ice condition. In this study, three routes were selected according to the principles as follows.

(a) Shortest. Expecting ice concentration is less than 60%. Red line in Figure 2.
(b) Fair. Expecting ice concentration is less than 30%. Normal intention to find open lead. Blue line in Figure 2.
(c) Coastal. High intention to find open lead, thus the longest among these three routes. Mostly along to the traditional NSR. Green line in Figure 2.

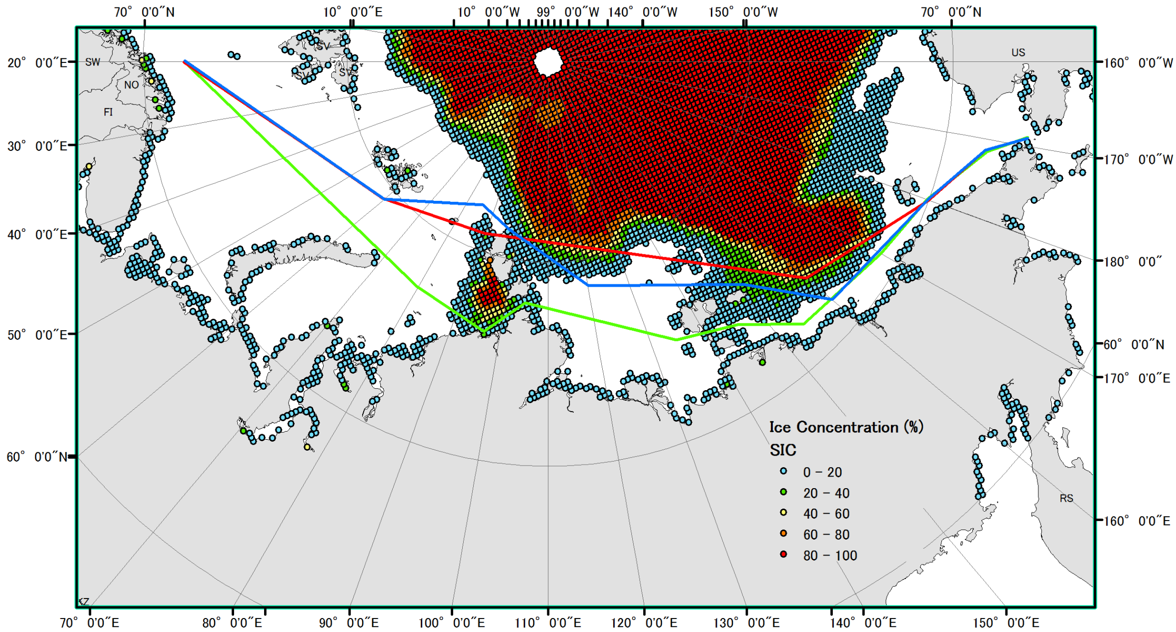


Figure 2. Assumed routes, NSR part, and ice distribution on Sep. 2013.

Ice Condition

Voyage period in the simulation was assumed as September 2013, in which actually 25 transits of ice class ships have been recorded. (Northern Sea Route Information Office, 2013) The KPR model input parameters to calculate ice resistance are: ice concentration, ice thickness and floe size. Ice concentration derived from AMSR2 satellite data, which was supplied by the GCOM-W1 data providing service, Japan Aerospace Exploration Agency. Monthly averaged ice concentration data was used as a representative ice condition of the month. The values are shown by the colored dots on the map in Figure 2.
Ice thickness was assumed as 1.0m. According to the onboard observation at the INSROP trial voyage, (Yamaguchi et al. 1995) both of first year ice of 0.3m to 2.0m thick and multi year ice of over 2.0m thick were seen evenly around the route. (See Table 2) In the area of low ice concentration, a ship is unlikely to encounter heavy ice. Then ice thickness of 1.0m is considered as a typical value for ships navigating marginal ice zone.
As in Table 2 ice floe diameter in the area of low ice concentration was less than 100m. In this study, typical size of ice floe was assumed as 20m.

Table 2. Stages of development and predominant form (floe size) of ice observed in the INSROP Trial Voyage. Calculated by authors from "egg code" in the published maps. The values indicate number of observation.

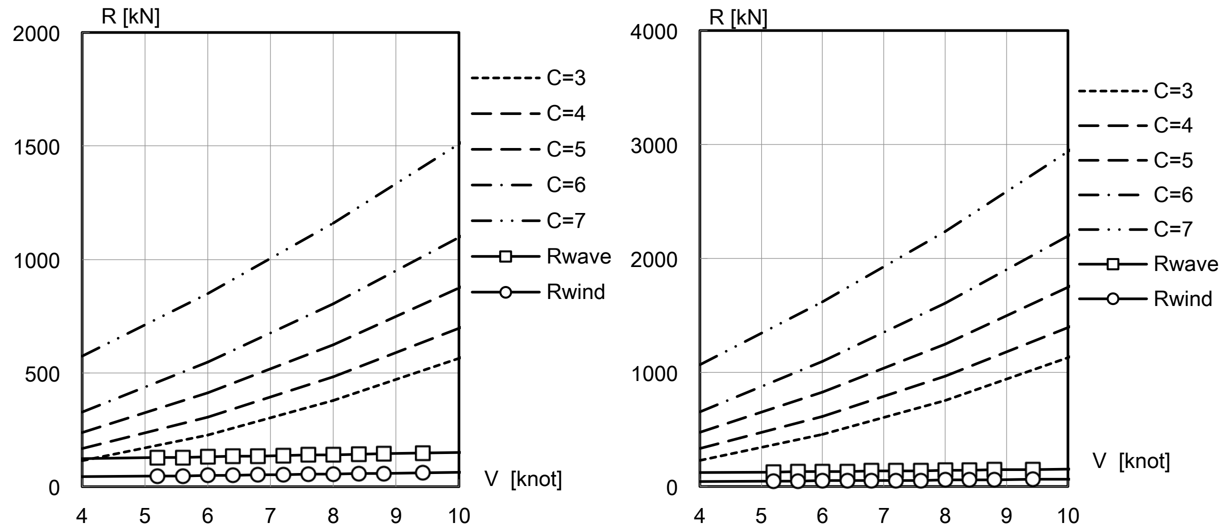
Category	Ice Concentration [%]								
	10	20	30	40	50	60	70	80	90
Stage 6	1	2	1	1	1	-	2	-	-
Stage 7*	1	2	1	-	-	1	2	1	-
Stage 8*	-	-	-	-	-	1	-	1	-
Form 1	1	1	-	-	-	-	-	-	-
Form 2	1	1	2	-	-	-	-	-	-
Form 3	1	3	1	1	1	2	1	1	-
Form 4	-	-	-	-	-	-	3	1	-

Stage 6: First Year (30-200cm thick)
Stage 7*: Old Ice (>2m thick)
Stage 8*: Second Year (>2m thick)
Form 1: Brash Ice (<2m dia.)
Form 2: Ice Cake (3-20m dia.)
Form 3: Small Ice Floe (20-100m dia.)
Form 4: Medium Ice Floe (100-500m dia.)

COMPUTATION

Added Resistance due to Sea Ice

Before the NSR transit simulation, a series of fundamental calculations was executed. Figure 3 shows the results of added resistance due to sea ice for the target ship. In the figure, resistance due to wave: R_{wave} and resistance due to wind R_{wind} are also drawn for reference. Wave and wind condition is Beaufort scale 6, for wind speed is 12.6m/s, significant wave height is 3.0m and wave period is 6.7s.



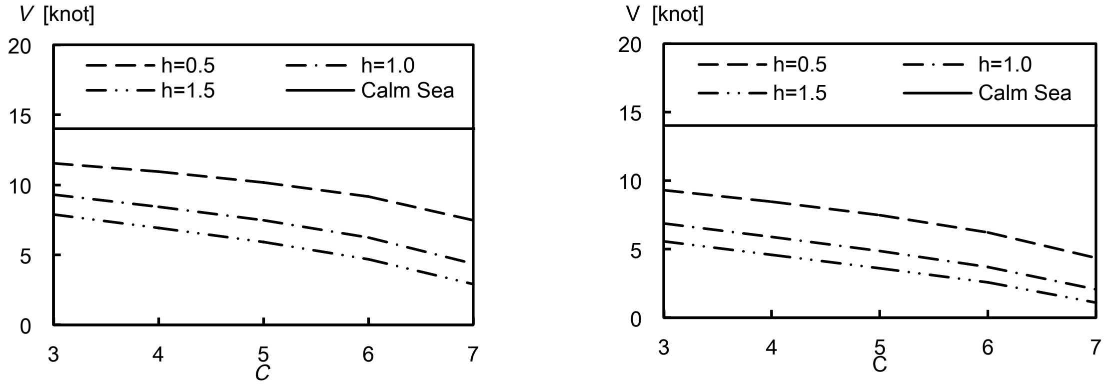
$h_i = 1.0, r = 10$ $h_i = 1.0, r = 20$

Figure 3. Calculated resistance versus ice concentration.

Speed Reduction and Fuel Consumption

As a result of additional resistance due to sea ice, ship speed decreases with the increasing of ice concentration. Figure 4 shows ship speed versus ice concentration computed by VESTA. Calm Sea in the figure means ice-free, no wind and no wave.

Fuel consumption is calculated from specific fuel oil consumption (SFOC), engine output (BHP) and running hours. SFOC is varied dependent on BHP. Figure 5 shows SFOC versus BHP and Figure 6 shows BHP curve for the range of ship speed. Both of them are computed results by VESTA, too. Note that O.P. in the figure means operation point of the engine.



h_i = 1.0, r = 10 h_i = 1.0, r = 20

Figure 4. Computed ship speed versus ice concentration.

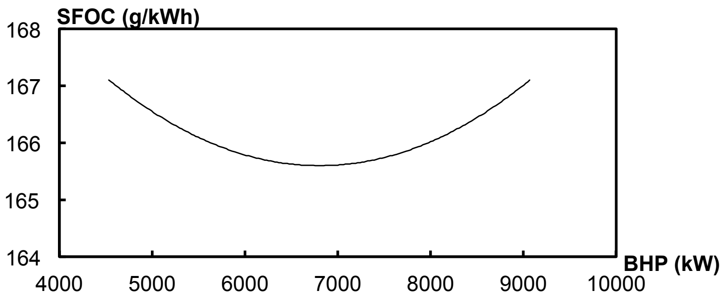
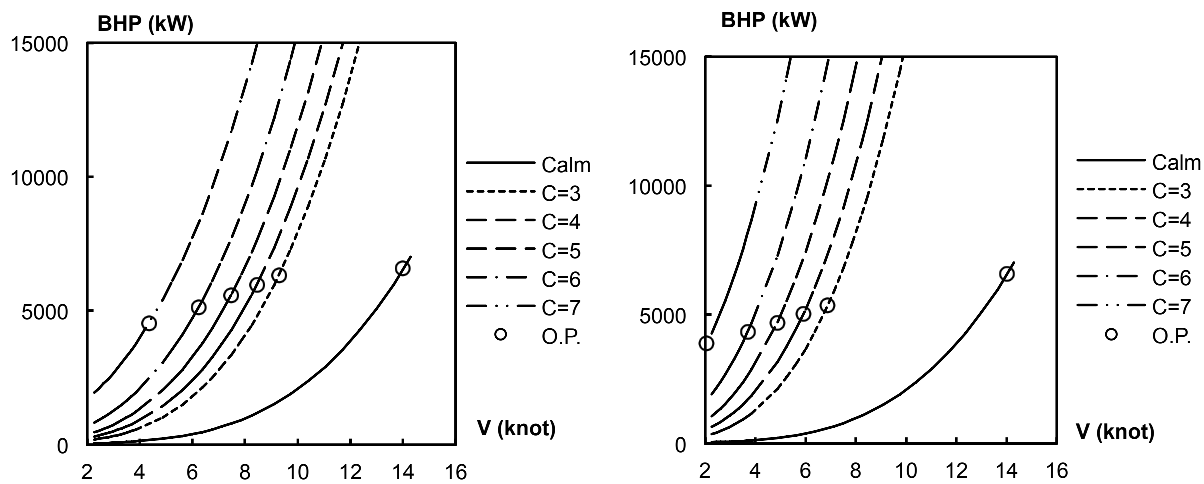


Figure 5. Computed specific fuel oil consumption.



h_i = 1.0, r = 10 h_i = 1.0, r = 20

Figure 6. Computed BHP curve.

Simulation of NSR transit
Ship performance simulations along the NSR were conducted. The target ship, route selection, ice condition are described in previous section. The simulation results were obtained for three routes as (a) Shortest, (b) Fair and (c) Coastal, respectively. Summarised data is presented here in Table 3, and Table A1-A3 at the end of this paper show the details of computed parameters. Figure 7 shows comparison of the length of the routes.
In all simulations, meridians stepping by 10 degrees divided the route throughout NSR (20E – 180E) into 16 computation segments. Ice condition was averaged in each segment. Then VESTA computed ship speed and FOC derived from ship's performance prediction.
Other parameters were post-processed. For example, the elapsed time is a fraction of length by ship speed. Note that the condition of ice-free water is calm sea. As a consequence, values in the SCR simulation are not of an actual voyage.

Table 3. Summary of simulation results.
SIC: Sea Ice Concentration
FPM: Fuel Per Mile

Segment	Length (NM)	Average SIC (%)	V (knots)	Elapsed Time	FOC (MT)	FPM (kg/NM)
(a) Shortest (Ice concentration is expected up to 60%)						
NSR (20E – 180E)	2,500	32.8	8.8	11d22h	263.1	105
Tokyo – Rotterdam	6,890	-	11.5	24d23h	606.0	88
(b) Fair (Ice concentration is expected up to 30%)						
NSR (20E – 180E)	2,610	13.7	12.6	8d16h	222.4	85
Tokyo – Rotterdam	7,000	-	13.4	21d18h	565.2	81
(c) Coastal						
NSR (20E – 180E)	2,810	8.3	13.5	8d16h	226.3	81
Tokyo – Rotterdam	7,200	-	13.8	21d18h	569.2	79
Suez Canal Route (Reference)						
Tokyo – Rotterdam	11,190	-	14.0	33d8h	872.8	-

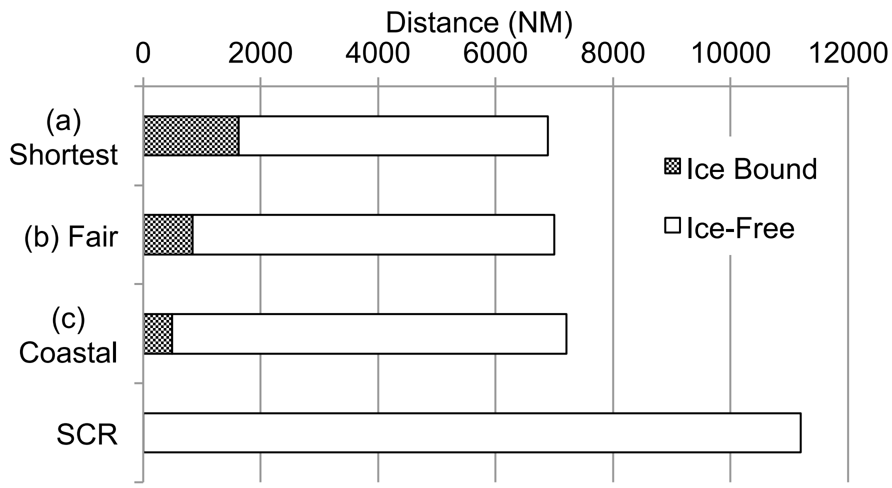


Figure 7. Comparison of the route length.

DISCUSSION

Influences of Ice in Total Ship Performance

In Figure 7, the fraction of ice bound length in whole route is generally small. Even in the most case of (a), the rate is 24%. Note that the Average SIC in Table 3 is calculated for ice bound area only. Therefore, accurate estimation of the ship performance in ice-free water plays important role for evaluation of the whole voyage. Since VESTA has been originally developed for ice-free actual sea, it has a potential to be a preferable tool for ship performance evaluation in NSR.

Speed reduction due to ice possibly influences averaged ship speed for the whole voyage. In the case of (a), the reduction of speed is 18% as a total and it definitely affect on the travel time, thus ice condition is critical information in the NSR transport.

Comparison among NSR Routes

Among three NSR lengths, (a) is shorter than the longest (c) by 11%, whereas (a) take 37% time more than (b) and (c). It indicates that the ice concentration significantly affects on the ship speed reduction, and that the ship navigating in NSR should avoid the area with high ice concentration in order to keep speed. The deviation in travel distance is within 10% around even if the ship chose the longest route, however speed penalty due to ice influences the cost greater than other factors.

On the other hand, there exists little differences between (b) and (c). FOC of (c) is slightly greater than that of (b). It means that length penalty exceeds speed and power penalty in the range of very light ice concentration. Consequently, the ship navigating in NSR could select shorter way if ice condition is low such as less than 10% around.

Comparison between NSR and SCR

According to the simulation results, usage of NSR has a concrete merit in travel distance, travel time and fuel consumption. Table 4 shows simple calculations of the reduction rates of these factors. Selected three routes could reduce about 35% of their fuel cost in general. Although the simulation in this study contains many assumptions, the values almost agree with actual voyage data in another year such as Sundnes (2014). But the case (a) indicates that the merits are greatly dependent on the ice condition. To develop practical evaluation tool of NSR navigation, validations on various conditions must be critical by using actual transit data and accurate ice data.

Table 4. Reduction rates of shipping factors for NSR against SCR.

	(a) Shortest	(b) Fair	(c) Coastal
Length	38%	37%	36%
Elapsed Time	25%	35%	35%
FOC	31%	35%	35%

CONCLUSION

The ship performance evaluation tool “VESTA”, which has been developed in National Maritime Research Institute, was enhanced to treat ice resistance and employed for simulation of NSR transit on September 2013. Three scenarios of voyage from Tokyo to Rotterdam via NSR were simulated and compared with each other in the viewpoints of such as ship speed reduction due to ice and fuel oil consumption. These factors were also compared with that of Suez Canal route. Discussed items from the simulation results are as follows.

- Estimation of ship performance in ice-free water must be accurate in the simulation of the whole voyage. Even in NSR, large proportion of the voyage is in ice-free water.
- Ship speed reduction due to ice greatly influences in the total fuel cost. The ship navigating in NSR should avoid ice with high concentration.
- In very light ice concentration, ship could choose shorter way because route length penalty due to ice possibly exceed speed and power penalties in such ice condition.
- The simulations showed that the NSR holds potential to reduce the fuel cost of 35% around as compared with Suez Canal route.
- Since the merits of NSR greatly dependent on the ice condition, ice observation and reasonable prediction is critical in NSR transport.

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Table A1. Computation results of the case (a) Shortest.

Segment	Length (NM)	Average SIC (%)	Vs (knots)	Elapsed Time	FOC (MT)	FPM (kg/NM)
Tokyo ～ 180E	3,060	0	14.0	9d2h37m	239.0	78
～170E	230	18.6	9.1	1d1h15m	25.3	110
～160E	200	36.9	6.2	1d8h7m	27.9	139
～150E	260	34.6	6.4	1d16h20m	35.3	136
～140E	180	2.7	13.2	13h39m	14.9	83
～130E	140	19.6	8.9	15h44m	15.6	112
～120E	120	55.8	4.2	1d4h29m	20.1	168
～110E	100	62.1	3.5	1d4h51m	17.6	176
～100E	90	40.9	5.8	15h26m	13.1	145
～90E	100	2.9	13.1	7h37m	8.3	83
～80E	100	2.6	13.2	7h34m	8.3	83
～70E	110	0.8	13.7	8h0m	8.7	80
～60E	130	0.0	14.0	9h17m	10.2	78
～50E	130	0	14.0	9h17m	10.2	78
～40E	150	0	14.0	10h42m	11.7	78
～30E	190	0	14.0	13h34m	14.8	78
～20E	270	0	14.0	19h17m	21.1	78
～Rotterdam	1,330	0	14.0	3d23h1m	103.9	78
NSR	**2,500**	**32.8**	**8.8**	**11d21h17m**	**263.1**	**105**
Total	**6,890**	**-**	**11.5**	**24d22h55m**	**606.0**	**88**

Table A2. Computation results of the case (b) Fair.

Segment	Length (NM)	Average SIC (%)	Vs (knots)	Elapsed Time	FOC (MT)	FPM (kg/NM)
Tokyo ～ 180E	3,060	0	14.0	9d2h37m	239.0	78
～170E	210	0.0	14.0	15h0m	16.4	78
～160E	200	0.0	14.0	14h17m	15.6	78
～150E	270	20.6	8.7	1d7h4m	30.6	113
～140E	200	12.6	10.5	19h4m	20.0	100
～130E	140	0.0	14.0	10h0m	10.9	78
～120E	140	0.0	14.0	10h0m	10.9	78
～110E	150	6.1	12.2	12h18m	13.3	89
～100E	110	12.7	10.5	10h30m	11.0	100
～90E	110	3.2	13.0	8h27m	9.2	84
～80E	90	0.0	14.0	6h25m	7.0	78
～70E	110	0.0	14.0	7h51m	8.6	78
～60E	140	0.0	14.0	10h0m	10.9	78
～50E	130	0	14.0	9h17m	10.2	78
～40E	150	0	14.0	10h42m	11.7	78
～30E	190	0	14.0	13h34m	14.8	78
～20E	270	0	14.0	19h17m	21.1	78
～Rotterdam	1,330	0	14.0	3d23h1m	103.9	78
NSR	**2,610**	**13.7**	**12.6**	**8d15h51m**	**222.4**	**85**
Total	**7,000**	**-**	**13.4**	**21d17h30m**	**565.2**	**81**

Table A3. Computation results of the case (c) Coastal.

Segment	**Length (NM)**	**Average SIC (%)**	**Vs (knots)**	**Elapsed Time**	**FOC (MT)**	**FPM (kg/NM)**
Tokyo ～ 180E	3,060	0	14.0	9d2h37m	239.0	78
～170E	220	0.0	14.0	15h43m	17.2	78
～160E	200	0.0	14.0	14h17m	15.6	78
～150E	220	0.0	14.0	15h43m	17.2	78
～140E	200	0.0	14.0	14h17m	15.6	78
～130E	180	0.0	14.0	12h51m	14.1	78
～120E	160	0.0	14.0	11h25m	12.5	78
～110E	150	0.0	14.0	10h42m	11.7	78
～100E	170	8.7	11.5	14h48m	15.9	93
～90E	170	11.0	10.9	15h36m	16.5	97
～80E	150	4.0	12.8	11h43m	12.8	85
～70E	140	0.0	14.0	10h0m	10.9	78
～60E	140	0.0	14.0	10h0m	10.9	78
～50E	140	0	14.0	10h0m	10.9	78
～40E	150	0	14.0	10h42m	11.7	78
～30E	190	0	14.0	13h34m	14.8	78
～20E	230	0	14.0	16h25m	18.0	78
～Rotterdam	1,330	0	14.0	3d23h1m	103.9	78
NSR	**2,810**	**8.3**	**13.5**	**8d15h53m**	**226.3**	**81**
Total	**7,200**	**-**	**13.8**	**21d17h31m**	**569.2**	**79**