# Generalized model of maritime transport of the Northern Sea Route

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## ABSTRACT

The work is devoted to the development of a generalized model of marine transport flows in the waters of the Northern Sea Route (NSR). The NSR is considered as a combination of many routes and many transport vessels. At the same time, all the main routes are only recommended. The main navigation characteristics of the routes and the associated characteristics of transport vessels are highlighted. The distribution of actual depths over the area of the arctic seas is presented, on coastal routes and for high-latitude routes. A rule has been developed that allows all general routes to be divided into routes suitable for navigation and routes that are unsuitable for navigation by vessels with certain characteristics. It is proposed to use the water area capacity indicator as a route classification criterion, which takes into account the ratio of the main navigation characteristics of ships and the conditions of the navigation situation in the water area. A method for calculating quantitative indicators of the actual water area capacity for transport flows in a state of dynamic equilibrium has been developed. The obtained models make it possible to formalize the problem of determining the throughput of shipping routes in the water area of the NSR, as well as to establish a set of throughput indicators on future. An example of a comparative assessment of the throughput capacity of the Sannikov Strait and the Dmitry Laptev Strait is given for vessels with a draft of less than 6 meters, from 7 to 12 and over 15 meters, which corresponds to different gross tonnage and ice class of sea vessels. The example uses data from field measurements of changes in shipping intensity parameters during 2019. In conclusion, the need to solve the problem of year-round navigation is formulated, which is of particular importance when the value of the seasonal unevenness of the density of traffic flows in the water area of the NSR will be the main obstacle to the development of the NSR and will have a direct impact on the safety of Arctic shipping. The directions of further research are determined.

KEY WORDS: Northern Sea Route; Shipping routes; Carrying capacity; Limiting depth; Ice permeability.

## INTRODUCTION

The Northern Sea Route (NSR) is a complex and developing transport system, which has undergone significant development and changes since 2013 (PAME, 2020). First of all, we are observing a sharp increase in the intensity of navigation, an increase in the share of large-tonnage vessels with a high ice class (Kondratenko, 2020), and secondly, there is an expansion of the network of shipping routes and the area of the water area where year-round navigation is used. These processes were mainly associated with the beginning of the development and export of oil and gas from the ports of the Ob Bay (Li, et al., 2020). According to the government plans, the volume of maritime cargo transportation from the Russian sector in 2020 exceeded 30 million tons, and by 2024 the volume of sea cargo transportation should reach 80 million tons, after 2035 - 160 million tons (Grigoryev, 2020). To ensure the safety of navigation and increase the volume of cargo turnover in the water area of the NSR, it is necessary to develop a network of routes (routes) on which vessels with a draft of up to 15 meters will be able to safely sail all year round (Pustoshny, 2017). Investigations of the regularities of the formation of sea traffic flows are being carried out (Afonin, et al., 2019. The organization of vessel traffic in the Arctic ice is being improved [6]. The theory and methods of controlling the parameters of the movement of ships and sea traffic flows are being developed, geographic information systems (Ol'khovik, et al., 2018 for studying the formation of waterways in ice. This work is devoted to the description of a generalized model of the formation of shipping routes in the Arctic seas and an assessment of their throughput.

## METHOD AND MATERIALS

The model is designed to assess the suitability of the water area of the NSR for year-round navigation. An integral part of the Arctic transport system is the network of shipping routes - *R*. Each route *R* is characterized by depths *Z* and ice conditions *H(T)*, which depend on the navigation period *T*. Shipping routes R pass through the Kara Sea, the Laptev Sea, the East Siberian Sea, and the Chukchi Sea. The routes include five main recommended sailing routes: two near-polar, two high-latitude, and a traditional coastal route. The total length of the shipping lanes exceeds 14 thousand miles. Table 1 shows the distribution of the depth over the area of the Arctic seas. The Laptev Sea and the East Siberian Sea are characterized by shallow depths. The share of the area with depths of less than 30 m in the Laptev Sea is 71.2 % and 86.5% in the East Siberian Sea. The Kara Sea and the Chukchi Sea are characterized by relatively large depths. The share of the area with a depth of 30 m in the Kara Sea and the Chukchi Sea is 81.1% and 93%.

Table 1. Depth distribution by area of the Arctic seas

| Depth range , m | Area share, % | | | |
|---|---|---|---|---|
| | Kara Sea | Laptev Sea | East Siberian Sea | Chukchi Sea |
| 0-10 | 3,5 | 11,1 | 14 | 1 |
| 10-20 | 5,3 | 37,4 | 47 | |
| 20-30 | 10,1 | 22,7 | 25,5 | 6 |
| > 30 | 81,1 | 28,8 | 13,5 | 93 |

The depth distribution on coastal routes is illustrated by the data in Table 2. In the Kara Sea and the Chukchi Sea, the depths on all coastal routes exceed 20 m. In the Kara Sea, half of the coastal routes pass through areas with depths of more than 50 m. In the Laptev Sea and in the East Siberian Sea, coastal routes mainly pass through areas with depths from 10 to 20 meters.

Table 2. Depth distribution on coastal routes

| Depth range, m | Percentage of route length, % | | | | |
|---|---|---|---|---|---|
| | Kara Sea | Laptev Sea | East Siberian Sea | Chukchi Sea | All seas |
| 9 - 10 | 0 | 0 | 2 | 0 | 2 |
| 10 - 20 | 0 | 55 | 49 | 0 | 29 |
| 20 - 50 | 51 | 43 | 49 | 100 | 51 |
| более 50 | 49 | 2 | 0 | 0 | 19 |

The depth distribution on high-latitude routes is illustrated by the data in Table 3. High-latitude routes have greater depths than coastal routes. There are no areas with a depth of less than 20 m. One third of the length of high-latitude routes passes through sections with depths of more than 50 m.

Table 3. Depth distribution on high-latitude routes

| Depth range, m | Percentage of route length, % | | | | |
|---|---|---|---|---|---|
| | Kara Sea | Laptev Sea | East Siberian Sea | Chukchi Sea | All seas |
| 10 - 20 | 0 | 0 | 0 | 0 | 0 |
| 20 - 50 | 44 | 59 | 100 | 100 | 68 |
| более 50 | 56 | 41 | 0 | 0 | 32 |

In Arctic waters, ice thickness - *H* varies from 0 to several meters depending on the navigation period - *T*. During the summer - autumn navigation period (mid - July-mid-November), navigation is carried out on all routes. During the winter - spring navigation period (from mid-November to mid-July), navigation in the Laptev Sea, the East Siberian Sea and the Chukchi Sea is almost stopped. The exception is the waterways of the Kara Sea, which are used all year round. The most difficult ice conditions in the NSR are observed in the winter - spring navigation period in March - April. In the summer - autumn navigation period in August - September, ice disappears over most of the water area. The repeatability of the types of ice conditions during the summer-autumn navigation is illustrated by the data given in table 4.

Table 4. Repeatability of ice conditions during summer and autumn navigation

| Type of ice conditions | Kara Sea | | Laptev Sea | | East Siberian and Chukchi Seas, % | Entire water area of the NSR |
|---|---|---|---|---|---|---|
| | South-western part, % | North-eastern part, % | Western part, % | Eastern part, % | | |
| Lungs | 58 | 39 | 29 | 61 | 54 | 48 |
| Medium | 33 | 37 | 39 | 22 | 16 | 30 |
| Heavy | 9 | 24 | 32 | 17 | 30 | 22 |

The Arctic fleet is represented by a variety of *V* vessels, each of which is characterized by a large set of characteristics. The main characteristics are the draft of the vessel *d* and the ice possibility *h*. Every year, 600 to 800 permits are issued to work in the waters of the Northern Sea Route. All vessels are divided into three groups, depending on their ice capacity. The first group includes vessels with the Arc7 ice class. Such vessels are able to overcome ice up to 1.7 m thick. Arc 7 vessels have a draft of 10 to 12 m. The second group includes vessels with ice classes Arc 4 and Arc 5. Such vessels are able to overcome ice with a thickness of 0.6 to 1.0 m. Arc 7 vessels have a draft of 6 to 11.5 m. The third group includes vessels that do not have an ice class, as well as vessels with ice classes Ice 1, Ice 2 and Ice 3. Such vessels in the Arctic seas are allowed to sail only on clean water. Vessels of the third group include vessels with a draft of 1.5 m to 13 m. In the total number of vessels of the Arctic fleet, the vessels of group 1 make up 21.4%; the vessels of group 2 - 33.5%; the vessels of group 3-45.1%. In the total tonnage of vessels of the Arctic fleet, vessels of group 1 account for 64.74%; vessels of group 2 - 25.0%; vessels of group 3-10.3%. Then, the throughput *X(T,Q)* of routes on the NSR is determined by the possibility of their use by vessels of different types, the throughput is given by the following expression:

$$X(T,Q) = R\big(Z(Q), H(T)\big) \cap V(d,h), \qquad (1)$$

where $Z$ is the limiting depth in the region $Q$;

$H$ is the average ice thickness during the navigation period $T$. Depending on the capacity, all routes on the NSR are divided into routes with zero capacity, $X_1(T) = 0$, and routes with non-zero capacity, $X_2(T) \neq 0$. The rule allowing the division of shipping routes is established by the following relationships:

$$X(T,Q) = X_1(T,Q) \cap X_2(T,Q) \qquad (2)$$

$$X_1(T,Q) = 0, \qquad if\ \{x \in X : (Z < d) \cup (H > h\} \qquad (3)$$

$$X_2(T,Q) \neq 0, \qquad if\ \{x \in X : (Z > d) \cap (H < h\} \qquad (4)$$

Relation (2) establishes that the sets $X_1(T,Q)$ and $X_2(T,Q)$ belong to the general set $X(T,Q)$. Rule (3) indicates that the route cannot be used by vessels if the vessel's draft d exceeds the depth $Z$ or the ice thickness $H$ on the route exceeds the vessel's ice capacity $h$. Rule (4) shows that a route can be used by vessels if the depth $Z$ along the entire route exceeds the vessel's draft $d$, and the vessel's ice possibility $h$ throughout the route exceeds the ice thickness $H$. To estimate the theoretical throughput of routes that meet condition (4), use:

$$X_2(T,Q) = k\left(1 - \frac{d}{Z}\right)\left(1 - \frac{H}{h}\right), \qquad (5)$$

where $k$ is a coefficient that takes into account the maximum density of the flow of vessels and their speed in the section of the water area $Q$ during the navigation period $T$.
Expression (5) can be used to estimate the capacity of routes located in the waters of $Q_m$ and $Q_n$ in different time periods $T_i$ and $T_j$. The relative change in throughput is calculated using the formula:

$$\varepsilon(T_{ij}, Q_{mn}) = \left(\frac{Z_m}{Z_n}\right)\left(\frac{h_j}{h_i}\right)\left(\frac{Z_n - d_n}{Z_m - d_m}\right)\left(\frac{h_i - H_i}{h_j - H_j}\right) \qquad (6)$$

Formulas (5) and (6) are intended for a priori estimation of changes in the capacity of routes depending on changes in the characteristics of routes or the composition and structure of the fleet.

## RESULTS

To determine the throughput of the shipping routes of the NSR, relations (1-4) are used, while it is necessary to have actual data on the movement of ships, i.e. measured parameters of the section of the transport system. Depending on the navigation period $T$, the number of vessels on the NSR routes is described by the following expression:

$$N(\Delta T) = N_0 + \sum_{i=1}^{\Delta T}\left(N_i^{in} - N_i^{out}\right) = N_0 + N_{\Delta T}^{in} - N_{\Delta T}^{out}, \qquad (7)$$

where $N_0$ is the number of vessels on the route at the initial time moment $T = 0$;

$N_T^{in}$ and $N_T^{out}$- the total number of ships entering and leaving the route during the time $\Delta T$.

Depending on the ratio of $N_T^{in}$ and $N_T^{out}$, the flow of ships takes one of three states:

$N_T^{in} = N_T^{out}$ - steady stream;

$N_T^{in} > N_T^{out}$- increase in flux density;

$N_T^{in} < N_T^{out}$- decrease in flux density.

The capacity of a route is determined by the number of ships that entered and left the route during a certain period of time at a steady flow. Taking into account the fact that flows in the NSR water area come to a stable state twice a year, the throughput is separately determined for the winter navigation period $N_W^{in} = N_W^{out}$and the summer navigation period $N_S^{in} = N_S^{out}$. The resulting formulas (7) and ratios were used for a comparative assessment of the throughput capacity of the Sannikov Strait and the Dmitry Laptev Strait, connecting the Laptev Sea and the East Siberian Sea. The relative position of the straits is shown in the figure 1. The straits are located in the Eastern sector of the NSR, which is illustrated on a fragment of a geographic map located in the upper left corner of the figure 1.

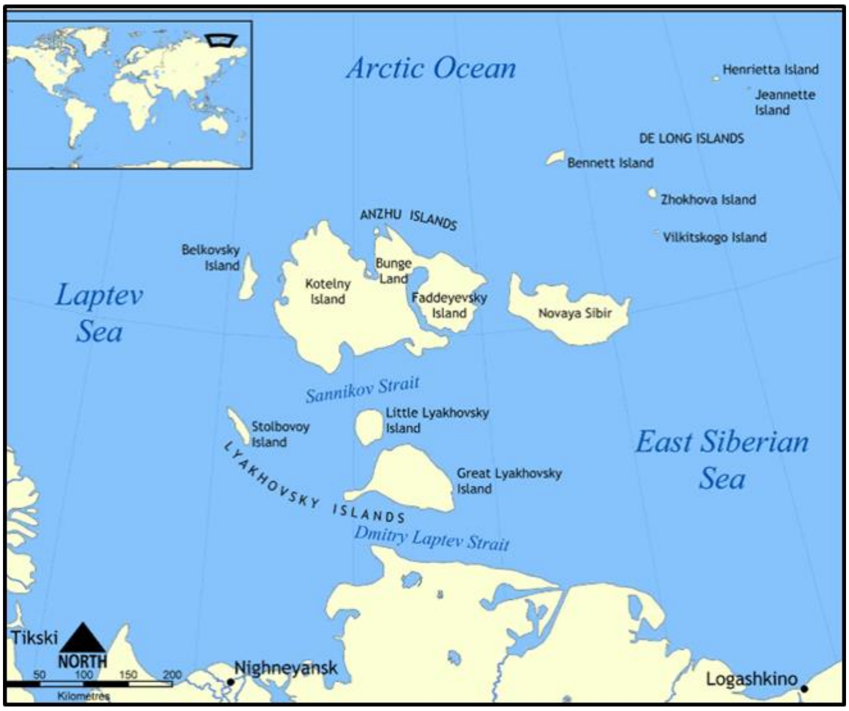


Figure 1. Mutual location of the Sannikov Strait and Dmitry Laptev Strait

The trajectories of the actual movement of ships in the Sannikov Strait and the Dmitry Laptev Strait are shown in Figure 2. Transport vessels move along three routes. The southern route passes through the Dmitry Laptev Strait. The central route passes through the Sannikov Strait. The northern route passes to the north of the Novosibirsk Islands.


Figure 2. Actual routes of transport vessels

The results of the comparative assessment of the straits are shown in Table 5. The first column of the table contains the names of the characteristics. The second and third columns show the values of the quantitative indicators of the characteristics of the Sannikov Strait and the Dmitry Laptev Strait. The fourth column contains the row numbers of the table.

Table 5. Comparative characteristics of the carrying capacity of the straits

<table>
<tr><th colspan="2">Characteristics</th><th>Sannikov Strait</th><th>Dmitry Laptev Strait</th><th>Line no.</th></tr>
<tr><td colspan="2">Fairway length, km</td><td>238</td><td>115</td><td>1</td></tr>
<tr><td colspan="2">Fairway width, km</td><td>55</td><td>50 - 60</td><td>2</td></tr>
<tr><td colspan="2">Ice thickness (March-April), m</td><td>2.0</td><td>2.0</td><td>3</td></tr>
<tr><td colspan="2">Ice thickness (August-September)</td><td>0</td><td>0</td><td>4</td></tr>
<tr><td colspan="2">Limiting depth, m</td><td>12.8</td><td>6.8</td><td>5</td></tr>
<tr><td colspan="2">Depth range, m</td><td>15 - 17</td><td>10 - 14</td><td>6</td></tr>
<tr><td rowspan="4">Actual Throughput (per month, 2019)</td><td>H=0, d > 12 m</td><td>0</td><td>0</td><td>7</td></tr>
<tr><td>H=0, 7 < d < 12 m</td><td>20-30</td><td>0</td><td>8</td></tr>
<tr><td>H=0, d < 6 m</td><td>15-20</td><td>60-70</td><td>9</td></tr>
<tr><td>H=1.0 m, Arc7: h=1.4 m,<br>8 m< d< 12 m</td><td>4</td><td>0</td><td>10</td></tr>
</table>

The main advantage of the Dmitry Laptev Strait is the length of its channel, which is half the length of the channel of the Sannikov Strait (line 1). The straits do not differ significantly in the width of the fairways (line 2) and ice conditions (lines 3 and 4). The main advantage of the Sannikov Strait is its limiting depth, which exceeds the limiting depth of the Dmitry Laptev

Strait by 6.0 m (line 5). The depths in the Sannikov Strait are also relatively large (line 6). The results of the actual use of the straits by vessels of different types are shown in lines 7 - 10. The Dmitry Laptev Strait is used by vessels with a draft of less than 6 m only during the summer-autumn navigation period, when there was no ice in the fairway (line 9). Under such conditions, from 60 to 70 ships passed through the strait per month. In the absence of ice, from 20 to 30 vessels with a draft of 7 to 12 m (line 8) and from 15 to 20 vessels with a draft of less than 6 m (line 9) passed through the Sannikov Strait every month. With an ice thickness of 1 m, 4 vessels of the high ice class Arc7 with a draft of 8 to 12 m passed through the Sannikov Strait (line 10). When the ice is thicker, navigation in the strait stops completely. The intensity of sea crossings of vessels along the entire route of the NSR is determined by the intensity of the use of the Vilkitsky Strait, which has no depth restrictions. With using geoinformation modeling technologies and according to AIS data and (7), we conducted direct research on the number of transitions for the period 2019-2020, which are presented in Figure 3, the data were recalculated for 10 days' period.

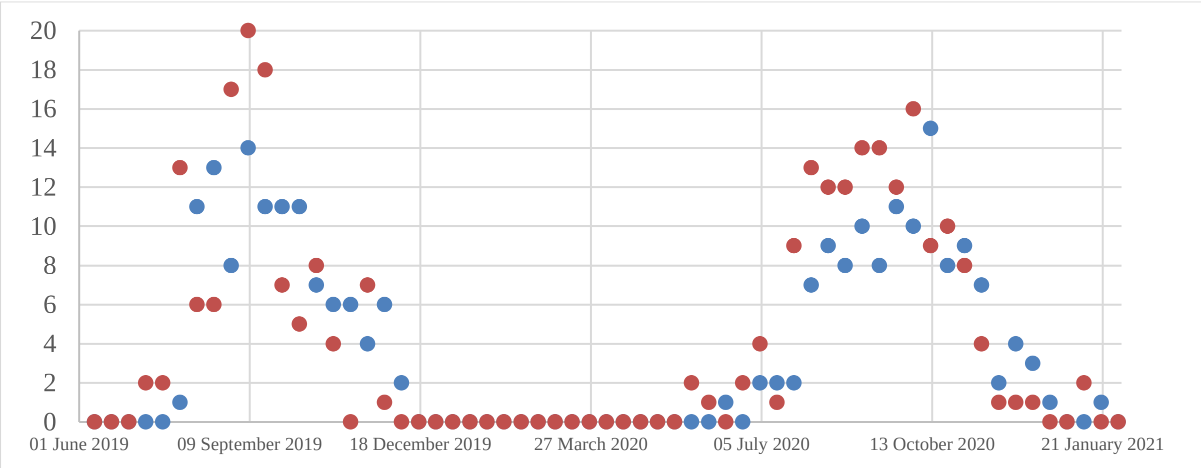


Figure 3. The number of ships crossing the internal border of the NSR for the period 2019-20 year, ● – from East to West, ● – from West to East (across the Vilkitsky Strait)

The general picture of the intensity remains, there is a tendency for the expansion of the navigation period in recent years, while the average number of ships remains at the same level.

## CONCLUSIONS

The obtained models make it possible to formalize the problem of determining the throughput of shipping routes in the water area of the NSR, as well as to establish a set of throughput indicators. An example is given based on real field data on the Vilkitsky Strait in both directions for the last two years, which in the future can be taken as a basis for building more accurate models. Generalized model of maritime transport for the NSR differ significantly from non-freezing seas, where the intensity of navigation is much higher, however, difficult natural conditions require updating the navigation and hydrographic support and information support to extend the navigation period and maintain the level of safety. The navigation uses of the Sannikov Strait and the Dmitry Laptev Strait is limited to shallow depths and severe ice conditions, which coincides with the opinion of Melia (2016) and Humpert (2012). The duration of the navigation use of the Dmitry Laptev Strait is currently 4 months. Navigation in the strait is mainly performed by vessels with a draft of 2 to 5 m, which are not able to overcome the Arctic ice. The use of nuclear powered icebreakers in the strait is limited to shallow depths. The duration of the navigation use of the Sannikov Strait is currently 6-7 months (Tezikov, et al., 2021). In the absence of ice, navigation in the strait is carried out by any vessel with a draft of less than 12 m. In the presence of ice up to 1 m thick, navigation is carried out by vessels with a draft of 8 to 12 m, having a high category of ice reinforcement. An increase in the duration of the navigation period in the strait is possible with the use of icebreakers, as well as large-capacity transport vessels Arc7-8 with the required draft. Real field data and calculations showed that the seasonal intensity in the straits of the NSR is low compared to shipping in non-freezing seas, but due to insufficient navigation and hydrographic support and the presence of dangerous depths, it requires additional study and a decision support system. In general, a high level of safety of navigation remains in the entire water area of the NSR.

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