Study of changes of vessel’s speed in ice conditions on the Northern Sea Route

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Abstract. Based on archive information of automatic identification system (AIS), studies of changes in the commercial speed of large-capacity ice-class vessels Arc7 along the route in the Kara Sea on the Northern Sea Route are carried out. To plan maritime traffic in the Arctic seas, it is necessary to have objective data on the influence of various factors on speed and time of transition. To ensure the safety of Arctic shipping, it is necessary to have objective data on the effect of ice on speed and maneuverability of vessels. It was proposed to use a geographic information system (GIS), the layers of which include data on the speeds and routes of vessels of various capacities and data on monitoring ice conditions. Detailed attention was paid to the route in the Kara Sea, as it the main entrance to the Northern Sea Route from the west, the movement of vessels was studied during the winter navigation period under the most severe ice conditions (March) and during the summer navigation period for clean water (September). It was found that in the dense stream of ships in summer navigation, the speed of ships varies slightly and depends on the density and intensity of traffic, and in winter navigation, the speed of ships has dramatic changes as ships go along the route with a large lateral deviation from the route. Research is performed at the Arctic Faculty of Admiral Makarov State University of Maritime and Inland Shipping. In future, all obtained relationships can be used for modeling the maritime traffic on the Northern Sea Route with an increase in the number of large-capacity vessels with Arc7 ice-class.

1. Introduction

Modern corporate traffic management strategies for sea transport vessels are aimed at increasing the commercial speed of vessels [1], ensuring a given frequency of navigation and consisting in solving a set of tasks that describe most transport processes at various levels of specification, from the micro to macro scale. For the Northern Sea Route (NSR), this task is the most topical, since the main cargo turnover is associated with the export of liquefied natural gas (LNG) and petroleum, the technological process of extraction of which does not provide for interruptions or downtime. The frequency of shuttle calls for tankers is planned for the year ahead with the accuracy of the vessel’s arrival of 2-3 hours.

The NSR is an intensively developing transport system, as evidenced by the sharp increase in cargo turnover over the past five years (according to preliminary data for 2018, it was 20 million tons) and the number of new large-capacity vessels of high ice class; since 2015, at least 15 new vessels of the Arc7 class have been put into operation. In 2021 their number will reach almost 30 units. At the same time, traffic management of sea transport on the NSR is reduced to local sections of approach channels and in-port water area and is limited to adaptive schemes, which are implemented in the form of vessel traffic service (VTS) with the ability to respond to different conditions during separation of ship traffic. The development of digital technologies and intellectual transport systems will allow one in the near future...
to implement the means of active management of marine traffic. This will require new strategies that can dynamically change the speed of ships, the geography of the route and the frequency of voyages in response to the predicted changes in navigation conditions, such as ice situation or hydrometeorological conditions for the NSR. The strategy of the scientific and technological development of the Russian Federation for the long term [2] considers the creation of intellectual transport systems for the mastering and use of the Arctic space as priorities of scientific and technological development. The scientific task of reliable and accurate forecasting of the dynamics of sea transport flows on the basis of the archived data of vessel traffic over past periods of time is new.

A large amount of literary data [3, 4] describing traffic flows uses unit unrelated and impersonal data, one-dimensional mathematical models for forecasting the number of vehicles on a route, their speed or travel time. Development of geographic information systems (GIS) tools [5] and Big Data processing, incl. the operational data of Earth remote sensing and satellite images [6], allow you to move to a new qualitative level of spatial analysis of sea transport flows based on actual data from past periods.

The task of this paper is a study the actual change of the passage time by the high ice class (Arc7) vessels of the traditional route in the Kara Sea, which is year-round used for movement in the western part of the NSR from the border of entry-exit to the NSR - the Kara Gates to Bely Island, where subsequently there is divergence of traffic routes. The purpose of the study is the development methodological foundations for the further assessment of the orderliness and workload of this route, since in the next few years the number of large-tonnage vessels may multiply due to the implementation of new projects in the Ob Bay and in the eastern part of the Kara Sea.

2. Methods and materials
The study of the actual parameters of the vessels traffic in the water area of the NSR is the basis for obtaining information about sea transport flows and developing mathematical models for their description. Ji, et al in [7] presented the complexity and laboriousness of studying actual data on sea transport flows using AIS data. Tezikov, et al in [8] used GIS as a tool for analysis of vessels traffic in various conditions for the NSR.

The western part of the NSR, the Kara Sea, which has two entrances: the Kara Gates and Cape Zhelaniya (it is not considered in this work) were chosen for analysis. Further the vessels move to the Gulf of Ob, Yenisei Bay or on the transit to the eastern part of the NSR, but the route always runs north of Bely Island, that was also chosen as the entry / exit zone. Two time periods in 2018 were chosen for the study, these are March, corresponding to the most severe ice navigation conditions, when the ice field is fully present in the Kara Sea, and September, corresponding to the period of clean water throughout the site.

The ice situation in the Kara Sea has been very unstable over the past 10 years. The period of full coverage by ice fields of the water area for shipping is from 6 to 8 months. Detailed information about the thickness of the ice is not available, we assume that it can be up to 1.5 meters in the most difficult conditions, and the distribution is uneven. The research group «REMOTE SENSING OF POLAR REGIONS» from University of Bremen [9, 10] provides detailed information on ice concentration. Data on ice concentration presented every day and reflect a picture in the Kara Sea and the Gulf of Ob with a grid size of 3.125 km.

In this paper, there was no goal of directly studying the effect of ice thickness on the speed of ships; data on ice concentration used only to determine the time and areas of ice formation.

The data from the ship’s satellite automatic identification system (AIS) contains detailed information about the vessel (name, IMO number, MMSI), such as the geographical vessel position, its speed and course, the draft, the end point of the route, etc. An example of data from the AIS for a group of selected ships of the ice class Arc7 is presented in Table 1. In total, more than 4000 thousand route positions with a geographical condition of the vessel position > 55°E and <70.7°E were selected. This approach is the most informative and is used by Zhang, et al in [11] and Le Tixerant, et al in [12] to study the vessels traffic on certain routes.
**Table 1.** An example of AIS data sample to study the time of the marine transition by high ice-class (Arc7) vessels

| ID | Vessel name          | Course, gr. | Date time   | Vessel type | IMO   | Speed, knots | Latitude, gr. | Longitude, gr. |
|----|----------------------|-------------|-------------|-------------|-------|--------------|----------------|----------------|
| 1  | SHTURMAN ALBANOV     | 42.0        | 01.08.1     | Tanker      | 975208| 10.0         | 71.93833       | 62.456666      |
|    |                      |             | 8 10:16     |             | 4     |              |                |                |
| 2  | MONCHEGORSK          | 227.4       | 02.08.1     | Cargo       | 940401| 13.2         | 72.18585       | 64.153556      |
|    |                      |             | 8 17:59     |             | 5     |              |                |                |
| 3  | BORIS VILKITSKY      | 65.0        | 10.08.1     | Tanker      | 976836| 16.0         | 73.59333       | 68.451666      |
|    |                      |             | 8 19:59     |             | 8     |              |                |                |
| 4  | FEDOR LITKE          | 179.6       | 13.08.1     | Tanker      | 976837| 17.5         | 73.40804       | 72.707838      |
|    |                      |             | 8 19:21     |             | 0     |              |                |                |
| 5  | CHRIS. DE MARGERIE   | 224.3       | 18.08.1     | Tanker      | 973718| 15.4         | 73.33925       | 66.561476      |
|    |                      |             | 8 5:17      |             | 7     |              |                |                |
| 6  | EDUARD TOLL          | 62.8        | 23.08.1     | Tanker      | 975069| 12.8         | 75.79652       | 53.382483      |
|    |                      |             | 8 2:43      |             | 6     |              |                |                |

Then all the data from Table 1 were entered into the GIS for analysis, where they were divided into separate layers for each vessel and, additionally, on the movement to the entrance or exit from the NSR. The final visualization of the GIS data set for September 2018 is presented in figure 1, for March - in Figure 2. To exclude errors, the routes on which the vessels stopped, dramatically changed the speed or course of movement, deviated from the general direction were not taken into account. Thus, all selected routes can be considered relevant, their mathematical analysis is possible.

**Figure 1.** The routes of the Arc7 ice-class vessels operating at the entry/exit from the NSR, September 2018.
To determine the exact time of crossing the border of the NSR, additional layers were introduced into the GIS as the lines. The intersection of which uniquely corresponded to the entrance-exit, for the Kara Gate these are the points coordinates: 70.50° N, 57.50° E; 70.37° N, 58.37° E (green line in Fig.1, 2), the border near the Bely island corresponded to the intersection by the vessel of longitude 70.7° E from west to east (blue line in Fig. 1, 2).

Figure 2. The routes of the Arc7 ice-class vessels operating at the entry/exit from the NSR, March 2018.

The number of vessels that during twenty-four hours was simultaneously within the boundaries of the studied route (the Kara Gates - Bely Island), had been fixing additionally (the data for September 2018 are presented in Figure 3). Only cargo ships with a capacity of more than 4 thousand tons were taken into account, since the other vessels (research, auxiliary fleet, tugs, etc.) do not have a significant effect on transport flow. Also, the vessels with a significant deviation of the route from the general direction (Figure 1) were not taken into account in the data in Figure 3.

The daily number of ships on the route was not calculated for the winter navigation period - March 2018 (Figure 2), since their number does not exceed 3 ÷ 5 entrances / exits from the NSR per day, which corresponds to the minimum value for summer navigation, and there are not affects on the speed of vessels.
3. Results

To analyze the transition speed from the Kara Gates to Bely Island, all vessels recorded in the GIS (Fig.1.2) were divided into three groups: LNG tankers of the YamalMax type, oil-loading Arctic shuttles of the 42K type and Arctic vessels of the Norilsk Nickel type, all vessels are Arc7 ice class, that allows them to navigate independently in the western zone of the NSR all year round. Such division into groups is necessary, since each type of vessel has its own tactical and technical characteristics, i.e. maximum speed, power, dimensions, ice passing, etc. The generalized results are presented in Table 2, where the transition time for the direction of movement to the entrance and exit from the NSR was calculated for each of the vessels. For the period of summer navigation, the vessels of YamalMax type move with the greatest accuracy, evaluation of standard deviation of the transition time is about 1 hour, for 42K tankers it is 4 hours, for Arctic container ships of the Norilsk Nickel type it is 1.4 hours.

| Vessel type | Date | Entry (exit) to the NSR | Transition time, hr |
|-------------|------|-------------------------|---------------------|
| Summer navigation, 2018 | | | |
| September 3, 2018 | Entry | 16,15 |
| September 7, 2018 | Exit | 19,25 |
| September 11, 2018 | Entry | 19,44 |
| September 11, 2018 | Exit | 18,68 |
| September 19, 2018 | Entry | 17,50 |
| September 22, 2018 | Exit | 16,98 |
| September 24, 2018 | Exit | 17,31 |
| September 28, 2018 | Entry | 18,00 |
| | | | Standard Deviation 1,07 |

Table 2. Transition time on the route of the Kara Gates - Bely Island (entrance / exit to the NSR)
| Vessel type | Date          | Entry (exit) to the NSR | Transition time, hr |
|-------------|---------------|-------------------------|---------------------|
| Arctic Shuttle Tanker of 42K type, Arc7 | September 2, 2018 | Exit | 22.51 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 2, 2018 | Entry | 31.29 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 4, 2018 | Entry | 28.11 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 5, 2018 | Exit | 21.03 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 8, 2018 | Entry | 30.30 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 9, 2018 | Exit | 24.35 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 11, 2018 | Entry | 30.36 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 12, 2018 | Entry | 34.75 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 15, 2018 | Entry | 21.90 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 17, 2018 | Entry | 22.50 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 18, 2018 | Entry | 30.53 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 19, 2018 | Exit | 26.45 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 22, 2018 | Exit | 27.31 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 23, 2018 | Entry | 24.33 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 25, 2018 | Entry | 28.80 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 30, 2018 | Entry | 22.49 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 6, 2018 | Exit | 25.49 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 9, 2018 | Entry | 25.55 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 15, 2018 | Exit | 24.58 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 21, 2018 | Entry | 21.78 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | September 23, 2018 | Entry | 24.02 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | Winter navigation, 2018 | Exit | 35.51 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | Winter navigation, 2018 | Entry | 38.04 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | Winter navigation, 2018 | Exit | 40.25 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | Winter navigation, 2018 | Entry | 36.50 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | Winter navigation, 2018 | Exit | 50.28 |
| Arctic container ships of the Norilsk Nickel type, Arc7 | Winter navigation, 2018 | Entry | 43.87 |

**Standard Deviation**

- Arctic Shuttle Tanker of 42K type, Arc7: 3.98
- Arctic container ships of the Norilsk Nickel type, Arc7: 1.38

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### Table 2. Ending

| Date          | Type   | Standard Deviation |
|---------------|--------|--------------------|
| March 5, 2018 | Entry  | 36.06              |
| March 13, 2018| Exit   | 49.69              |
| March 7, 2018 | Entry  | 44.01              |
| March 15, 2018| Exit   | 45.90              |
| March 7, 2018 | Exit   | 36.63              |
| March 15, 2018| Entry  | 42.02              |
| March 5, 2018 | Exit   | 35.80              |
| March 11, 2018| Entry  | 45.23              |
| March 19, 2018| Exit   | 51.45              |
| March 6, 2018 | Exit   | 32.72              |
| March 20, 2018| Exit   | 48.17              |
| March 27, 2018| Entry  | 54.41              |

For the period of winter navigation (March 2018), the average transition time increased 1.5 ÷ 2 times, which is explained by the presence of complex ice situation on the entire route. According to the GIS data (Figure 2) the vessels of the YamalMax type did not have a significant lateral deviation from the summer route, while the transition time almost doubled, the standard deviation was 5 hours. The Arctic Shuttles of the 42K type had a lateral deviation up to 70 km from the general direction during the transition, which is explained by the search for a route with the least ice thickness, which in turn increased the length of the route and the total transition time, the standard deviation was 6.6 hours. The Arctic container ships of the Norilsk Nickel type have the lowest power, and therefore the ice resistance has the greatest impact on the speed of this type vessels, the transition time for them has also been significantly increased, the standard deviation was 6.5 hours.

### 4. The discussion of the results

The density of sea transport flows in the NSR water area (the Kara Sea) is a reflection of the scale of vessels traffic, the size and power of their flow. Data on the vessels number in the surveyed area (Figure 3) indicate their orderliness as a whole, although there are sharp splashes that last for 2-3 days and can lead to the route congestion. For the period of winter navigation, the square of water area expands significantly [13], and the density of the vessels flow decreases proportionally.

The obtained results show that during the summer navigation period (Figure 1, Table 2), the vessels move in the common stream in one general direction with maximum speed, the deviations of the transition time are minimal and range from 1 to 4 hours.

The proposed methodology for studying the density of vessels can be extend to the high-latitude routes of the NSR [14] or other local area in Arctic.

The classical approach in describing the macroscopic transport model implies the obligatory presence of a monosemantic relation between the velocity \( v(x,t) \) and the density (linear) \( \rho(x,t) \) of the transport flow. At the same time, the speed \( v \) means the instantaneous vessel speed at the point with the \( x \) coordinate, which we determined according to the AIS data (Table 1), and the density \( \rho \) means the number of vessels per selected unit of the route length (Figure 3) at time \( t \) in neighborhood of point with
the \( x \) coordinate. For the period of summer navigation, it was found that vessels move within the boundaries of the general direction (Figure 1) without lateral deviation, therefore, the relationship between the flow velocity \( v(x,t) \) and its density \( \rho(x,t) \) can be obtained from the given actual data using the following functional dependency: \( v(x,t) = Z(\rho(x,t)) \).

For the period of winter navigation, this approach cannot be implemented, since vessels have significant lateral deviations from the general direction, and using the model of movement only on the \( x \) axis with a speed \( v(t) \) will lead to a significant error, even if there are actual instantaneous speeds on the route. Therefore, to study the functional dependence of the velocity of sea transport flow and its density, it is necessary to solve the task in a flat coordinate system, then \( v(x,y,t) \) is the average vessel speed in the water area of \( S(t) \) square at the point with \( x,y \) coordinates at the time \( t \). These schemes and their differences are illustrated in Figure 4.

![Figure 4. Model of maritime traffic flows in the NSR water area: a) – summer navigation; b) – winter navigation.](image)

5. Conclusion

The study of change in the passage time by vessels of the traditional route in the Kara Sea to entry and exit from the NSR was made on the basis of actual data on the traffic of large-capacity Arc7 ice class vessels in the period of summer and winter navigation. It is found that in the dense stream of ships in summer navigation, the speed of ships varies slightly and depends on the density and intensity of traffic, and in winter navigation, the speed of ships has dramatic changes as ships go along the route with a large lateral deviation from the route, which depends on the ice situation. The possible deviation of the transition time for the period of summer and winter navigation has been established. The number of vessels on the route of the Kara Gates - Bely Island for every twenty-four hours has been calculated, which allows to obtain a functional relationship between speed and density of the transport flow. For the period of winter navigation, a more complex model, taking into account the square of the water area, can describe this dependence.

The experience of year-round use of large-capacity ice class Arc7 vessels without icebreaker wiring is only developing, vessels of the YamalMax and 42K type have been in operation for only 2 years, which is still not enough to develop specific recommendations to the navigators.

In the future, the data volume on the temporal period of vessels navigation is planned to be expanded for a more detailed study of transport flows in the NSR water area and criteria for assessing orderliness and workload on the shipping routes of the Kara Sea are planned to be developed. All the accumulated information files will be used to develop the theoretical foundations of marine spatial planning, which will ensure more efficient navigation in the Arctic in the future.
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