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Abstract. The paper is devoted to the problem of ensuring the safe movement of ships. The problem of assessing the safety of a traffic pattern implemented in a specific water area is considered. Five different safety metrics are introduced. The first metric - "traffic intensity" - the traditionally used traffic density estimate, is calculated as the number of vessels passing through a particular section of the water area per unit time. It is supplemented by the metrics "intensity and speed" (second) and "intensity and size of ships" (third). When calculating them, respectively, the speed of the vessels and their length, which determine the "weight" of each vessel, are taken into account. The fourth metric - "stability of traffic parameters" - takes into account the nature of the movement of ships in terms of the regularity of their courses and speeds. The paper discusses various options for the metric, to illustrate the simplest of them is implemented - an estimate of the standard deviation of the ship's course. The fifth metric - "traffic saturation" - characterizes the density of movement of ships in terms of the possibility of their maneuvers. The metric appeals to the traditional model representations of the collective motion parameters of the vessels in the form of a "speed-course" diagram and makes it possible to indirectly assess the difficulty of decision-making by skippers and the emotional burden on traffic participants. In the discussion of the results of the work, the option of integrating the five proposed metrics in the form of a system of rules giving an integrated assessment of traffic safety in a particular section of the water area is considered. The work is accompanied by the results of calculations of the proposed metrics on real data on the movement of ships in the Tsugaru Strait and their discussion. It is shown that the proposed system of metrics allows you to create a systematic idea of the degree of danger of traffic implemented in the water area.

1. Introduction

Navigation safety is a central issue in organizing maritime traffic. The increase in shipping intensity necessitates continuous improvement of instruments to ensure traffic safety [1]. So, recently the interpretation of the provisions of the International Rules for the Prevention of Collisions at Sea (COLREG) has been expanding; the integration of airborne and coastal navigation aids with information systems of related services (e-Navigation) is deepening; the automation and intellectualization of airborne and coastal decision support tools is being strengthened; qualitatively new approaches to traffic management are being formed, focused on the introduction of unmanned water vehicles in the future.

Two aspects of ensuring navigational safety should be distinguished from the point of view of the specifics of the tasks being solved. The first is associated with traffic from the port of departure to the port of destination along a given route, when the number of vessels simultaneously present in the current section of the water area is small. In this case, the tasks of risk assessment and prevention of dangerous proximity with a greater or lesser degree of automation of this process are solved on board the vessel [2]. The second aspect is related to movement in the local water area in the conditions of intense multidirectional ship flows. In this case, skippers additionally solve the problems of route planning, including considering the restrictions imposed by a certain traffic pattern [3].

The task of developing such traffic patterns was finally formed in the mid-50s [2]. At this time, a civilian fleet was massively introduced radar technology, which made it possible to accurately determine the location of the vessel. In relation to traffic patterns, the term "system for establishing ship traffic routes" has been established in navigational practice. The purpose of such a system is to eliminate uncertainties or the mistakes possibility of shipmasters.

The generation of traffic patterns and the selection of a specific option from the many possible ones are carried out taking into account the geography of the water area, traffic features and various practical aspects of navigation. The following factors can be distinguished that determine the navigation safety of the water area from the point of view of the trajectory properties of the vessels located on it [8]:
• density of vessels in the water area;
• characteristic ship speed;
• characteristic sizes of ships;
• stability of motion parameters;
• saturation of ship traffic.

As a tool for ensuring safety, the assessment of the traffic pattern implemented in the water area allows to identify its most problematic areas ("bottlenecks"). This serves as a signal for regulatory services about the need to change traffic rules and optimize ship traffic in one or another part of the water area.

Evaluation of the current version of the movement pattern is possible in several ways. The first is an expert method, focusing on traffic parameters and regulatory framework. The second method is the analysis of real ship traffic. In the latter case, a promising way is to access the data provided by the Automatic Identification System (AIS). Integration with its services serving this or that local water area allows you to obtain up-to-date information about the location, speed and course (also a set of other data) of the vessels located on it. It is also possible to access current and retrospective AIS data available on open Internet resources of the type [4].

In this paper, we consider model representations of the problem of assessing the navigational safety of the water area based on the trajectory properties of the vessels on it. The metrics (measure) of such safety are the traffic intensity of the ships, their size and speed, the degree of randomness of the traffic parameters, the degree of traffic completeness. Model representations are adapted to the specifics of the initial data on the movement of ships provided by AIS services.

2. Method and materials

The Automatic Identification System is based on automatic dependent surveillance technology in broadcasting mode (ADS - B) and multilateration (MLAT) [5]. As a result, it is possible to obtain a large data set for each vessel in the zone of responsibility of the system. This is primarily the geographic coordinates and registration data of the vessel, as well as its course, speed, geometric dimensions, displacement, class (tanker, dry cargo ship, steam, etc.), maneuver rate and a number of other parameters [3].

To solve the problem of assessing the safety of the water area under consideration, we assume that many tuples of the form are given:

$$\{SID, LAT, LON, SPEED, COURSE, TIME, AGE\} \qquad (1)$$

Here SID is the identifier of the vessel, LAT and LON are the latitude and longitude of the vessel, $SPEED$ and $COURSE$ are its speed and course, $TIME$ and AGE are the data arrival time and age. In

addition, the length and width of each ship are considered known. When accessing the data provided by resources of the type [4], discreteness of the *TIME* parameter should be taken into account (the usual data update period is 60 seconds). When modeling the movement of ships in the local water area, it is advisable to move from the geographical coordinates of the vessel to the local rectangular. The characteristic dimensions of such water areas do not exceed hundreds of kilometers, so the errors due to the sphericity of the Earth will be insignificant. Coordinates are converted by the rule

$$x = R \cos(LAT) \sin(LON - LON^*),$$
$$y = R \sin(LAT - LAT^*).$$

Here R is the average radius of the Earth when represented by its sphere; $LAT*$ and $LON*$ are the latitude and longitude of the point, taken as the beginning of the local rectangular coordinate system.

We will consider five metrics characterizing traffic safety in the water area.

1. *Metric "traffic intensity"*. The metric characterizes the number of vessels passing through a particular section of the water area per unit time. It can be evaluated for all vessels, or only for vessels of certain classes. The water area is divided into polygonal sections (for example, squares) to calculate the metric value. Next, it is determined how many points corresponding to different vessels from the set of tuples (1) are inside a polygon. The result obtained is normalized to the time interval for which the data are taken (1).

2. *Metric "intensity and speed"*. The metric allows you to identify those areas of the water area where the speed of the vessels is the highest. It is calculated similarly to the first metric, but "weight" is assigned to each vessel, depending on its speed. Thus, faster vessels make a greater contribution to the metric (sum) for each polygon. An informative result gives a linear dependence of the "weight" of the vessel on speed, for example, by a unit for every 10 m / s.

3. *Metric "intensity and size of ships."* The metric reveals those areas of the water area where the largest vessels are moving. It is calculated similarly to the second metric. The "weight" of a ship depends on its length, and longer ships have more weight. The linear dependence of the "weight" of the vessel on the length can be expressed, for example, by a ratio of one for every 100 meters of length.

4. *Metric "stability of motion parameters"*. The metric characterizes the variability of speeds and courses of movement of a particular section of the water area. As in previous cases, the water area is divided into polygonal sections. The metric can be evaluated in various ways. The first is an estimate of the standard deviation of the velocity vector of objects inside the selected polygon. Both a vector quantity and a set of scalar quantities can be estimated (i.e., the standard deviation of the velocity and course individually). The second method is more complex and informative. It is associated with the identification of clusters - the set of characteristic values of the speeds and courses of ships. In this case, clustering can be both vector and scalar. In the first case, the high relative value of the standard deviation indicates a "chaotic" nature of the movement in the selected area of the water area. In the second case, the number of identified clusters of motion parameters, their "width", and "spread" of values relative to the centers of the clusters are important. If 1-2 "narrow" clusters are detected at the heading, this indicates a regular, stable traffic flow in the area. A greater number of clusters at the exchange rate indicates multidirectional intersecting traffic flows. The large relative width of the clusters means irregular movement.

5. *Metric "traffic saturation"*. The metric characterizes the density of vessels located in a section of the water area in terms of their ability to perform maneuvers. We will divide the water area into polygonal sections. Suppose there are two vessels, the first of which ("managed") is inside the selected section, the second ("target vessel") can either be inside the section or be located outside it. The following equations of motion of two vessels hold:

$$x_1(t) = x_1(t_1^0) + SPEED_1 * \sin(COURSE_1) * (t - t_1^0),$$
$$y_1(t) = y_1(t_1^0) + SPEED_1 * \cos(COURSE_1) * (t - t_1^0),$$
$$x_2(t) = x_2(t_2^0) + SPEED_2 * \sin(COURSE_2) * (t - t_2^0),$$
$$y_2(t) = y_2(t_2^0) + SPEED_2 * \cos(COURSE_2) * (t - t_2^0),$$

where $x_1(t)$, $y_1(t)$, $x_2(t)$, $y_2(t)$ are the coordinates of the first and second vessel at time t, $SPEED_1$, $COURSE_1$, $SPEED_2$, $COURSE_2$ are the speeds and courses of the first and second vessel, t_1^0, t_2^0 are the time points corresponding to the age of the data of each vessel, $t_i^0 = TIME_i - AGE_i$. With this model of movement, the distance between the vessels at time t will be equal to:

$$r(t) = \sqrt{(x_1(t) - x_2(t))^2 + (y_1(t) - y_2(t))^2}$$

Solving the equation $dr(t)/dt = 0$ with respect to t, we obtain the value of the shortest approximation time for vessels t_{CPA} and the corresponding value $r(t_{CPA})$. $r(t_{CPA})$ is the shortest distance between the vessels, as well as the coordinates of the vessels at the moment of their closest approximation. If $t_{CPA} > t_1^0$ and $t_{CPA} > t_2^0$ (vessels approach each other) and $r(t_{CPA})$ is less than the minimum permissible distance between vessels, then their movement is considered dangerous. It is possible to estimate the fraction of the possible courses and speeds of the first vessel, leading to a dangerous approach with other vessels, sorting out the set of possible courses and speeds of the first ("managed") vessel and calculating $r(t_{CPA})$ relative to all vessels in the water area. Solving this problem for all vessels located inside the selected section of the water area, it is possible to determine the average value of such a share for this section. If the proportion of hazardous speeds and driving courses is high, this indicates a limited ability for the skipper to change the parameters of the traffic without interfering with other traffic participants. Indirectly, this indicates a "saturation" of traffic throughput in the selected area of the water area.

A geometric interpretation of the metric "traffic saturation" is possible [6, 7]. In this case, the dangerous and safe values of the vessel motion parameters are represented by the well-known "speed-course" diagram (diagram of the "maneuver area" of Degre and Lefevre [8, 9]).

3. Results

The proposed navigation safety assessment metrics have been tested using data from a number of characteristic marine areas. As an example, the results for the water area of the Tsugaru Strait are presented below. Analyzed data on the movement of ships during the day, collected from the resource [4] using a special software system [10]. The water area was divided into squares of 1 km in size.

Figure 1 shows the result of evaluating the values of the metric "Traffic intensity". Pale green color shows areas with an intensity of 0.2 ships per hour, bright green - more than 1 vessel per hour. The metric shows well the main routes along which the movement occurs in the strait: the north-south and west-east directions. The figure shows that the traffic intensity in the strait is low.

Figure 1. The results of the calculation of the metric "Traffic intensity" in the Tsugaru Strait.

Figure 2 shows the calculated values of the metric "Intensity and speed". The weight of the vessel increased by 1 for every 10 m / s speed. Areas where the proportion of vessels moving at a high speed is high are clearly visible (yellow dots correspond to metric values from 1 to 3 "high-speed" vessels per hour). This is the "Sea of Japan - Pacific Ocean" route and the water area near the port of Hakodate.
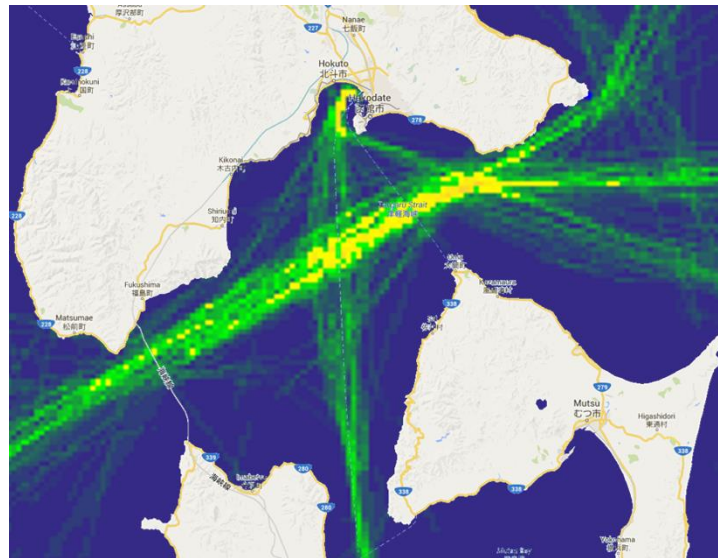

Figure 2. The results of the calculation of the "Intensity and speed" metric in the Tsugaru Strait.
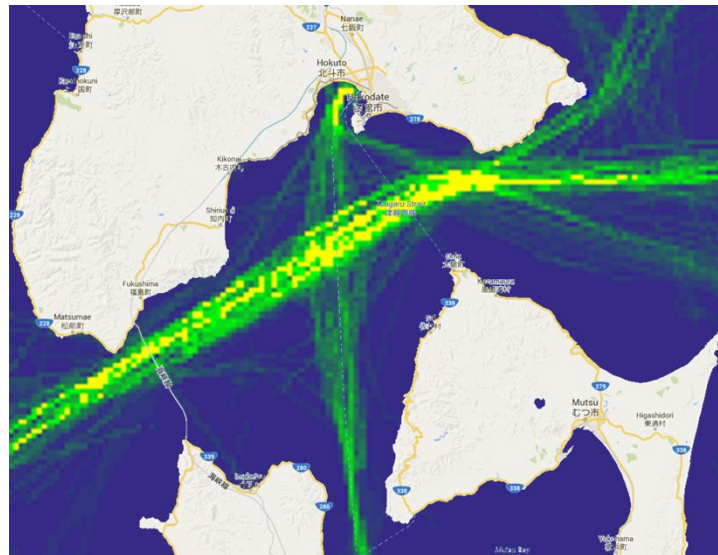

Figure 3. The results of the calculation of the metric "Intensity and ship dimensions" in the Tsugaru Strait.

Figure 3 shows the calculated values of the metric "Intensity and ship dimensions". The weight of the vessel increased by 1 for every 100 m of length. Areas where the proportion of large-sized vessels are high are clearly visible (yellow dots correspond to metric values from 1 to 3 "large" vessels per hour). They mainly move along the "Sea of Japan - Pacific Ocean" highway and in the waters of the port of Hakodate. An obvious correlation of Figure 2 and 3. This means that on the chosen trajectory the largest vessels are simultaneously the fastest.

Figure 4 shows the calculated values of the metric "Stability of motion parameters". The simplest version of the metric was chosen - the standard deviation of the ship rates was estimated. The colour indicates the points at which the number of different vessels per day was at least 3. Pale green colour corresponds to the standard deviation of the ship rates less than 10°, bright green - from 20° to 30°, yellow - more than 30°. Figure 4 shows a large "spread" of ship rates taking place in the zone of intersection of ship flows (in the centre of the figure) and in the turning areas of ships in the east of the strait.

Figure 4. Values of the metric "Stability of motion parameters"

Figure 5 shows the calculated values of the "Traffic saturation" metric. It shows the values of the share of dangerous values of speeds and courses of ships. Green colour corresponds to values from 20% to 50%, yellow - from 50% to 80%, orange - from 80% to 90%, red - over 100%. The figure also shows that in general the water area is characterized by low traffic saturation, orange and red sections are available only near the port water area. This suggests that the Tsugaru Strait is relatively "easy" for navigation.

Figure 5. Values of the metric "Traffic Saturation".

4. Conclusion
1. The generation of traffic patterns in offshore areas as a system for establishing ship traffic routes is an important part of measures to ensure the safety of ship traffic in areas of heavy shipping. This activity is related to solving the specific task of assessing the navigational safety of the existing traffic pattern

in order to develop recommendations for its change. Due to the multidimensionality of the very concept of traffic safety, it can be estimated by various metrics (measures). In this paper, we consider 5 such various metrics that complement each other, as well as a comprehensive safety assessment based on them.

2. The data source provided by the services of the Automatic Identification System can serve as a data source for assessing the safety of traffic patterns in the sea. The paper shows the promise of using not only primary AIS data, but also their options available on specialized Internet resources. Despite the strong "sparseness" of this version of the data, they adequately represent the summary features of the traffic.

3. To evaluate the metrics considered in the work, data on the movement of ships from several tens of hours to several days are needed. Arrays of 300 thousand records of the form (1) were processed to form Fig. 1-5. High-loaded water areas are characterized by data volumes of 1-50 million records. Assessing traffic safety in such areas requires the development of special software systems and algorithms based on supercomputer technologies and big data.

4. Conducted studies of the considered approach to safety assessment on real data on ship traffic confirmed its promise. It is possible to build a stable picture of areas of marine water areas characterized by increased load on shipmasters based on the created system of metrics. This information is of great value when implementing measures to ensure traffic safety.

5. References

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