RESEARCH ARTICLE | OCTOBER 13 2023

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AIP Conf. Proc. 2910, 020124 (2023)
https://doi.org/10.1063/5.0166951

Modelling of Safe Traffic Schema for Marine Area

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Abstract. This work is devoted to the problem of ensuring the safety of vessel traffic at marine areas. Navigation safety in conditions of heavy traffic can be ensured only if the vessels comply with a certain traffic pattern. The paper highlights the problem of planning a system of routes (traffic patterns) of vessels. This schema depends on the geography of the water area and the characteristics of traffic. The necessity to ensure the maximum safety of vessel traffic and practical considerations determine the choice of a specific variant for a traffic scheme. Modeling the vessels motion along a set of possible trajectories and evaluating the metric describing the degree of movement danger is the basis of the method for solving the problem. The frequency of dangerous approaches of vessels is proposed as a metric for assessing the danger of traffic, and the possibility of using other metrics is noted. The work demonstrates that the model representation of the problem based on a weighted graph does not allow its solution without the involvement of specialized computing resources. An alternative approach is motion construction of schemes in an expert way from typical structural elements (primitives). Simulation modeling of a problem becomes possible on available general-purpose computing and software platforms if it is isolated within a separate primitive. The paper con-siders four such primitives and estimates the average time between dangerous approaches of vessels for each of them. An example of using the obtained modeling results for planning safe ship traffic patterns is given.

INTRODUCTION

The traditional approach to ensuring the navigation safety of ships is to solve three tasks: assessing the risk of dangerous approach, preventing dangerous approach and planning the trajectory of safe ships movement [1]. These classic tasks in areas with heavy traffic are not always able to provide the necessary level of safety, and therefore additional coordination of the joint actions of traffic participants is necessary [2]. Including - in the form of following a safe traffic pattern defined in the water area (traffic rules). In shipmasters practice, the term “system for establishing ship traffic routes” has been established in relation to such a scheme [3].

Historically, the formation of the traffic pattern of a particular water area was based on the possibility of its implementation, taking into account the geography of the area and navigation practice. It was important to have convenient visual landmarks that allow the navigator to follow the established route [4]. If necessary, natural landmarks such as noticeable mountains, capes, islands, etc. supplemented with artificial beacons, for example, luminous signs, buoys, etc. This approach, correlated with the rules of navigation, led to the formation of a traffic pattern not so much safe as convenient for the daily work of shipmasters and dispatchers of coastal services in conditions of limited capabilities of navigation aids of the past years (before the digital era).

The limitations of the “old” schemes in terms of their capacity and safety are becoming apparent with the increasing intensity of navigation in recent years [5]. At the same time, the development of the E-navigation concept and the arrival of a new generation of navigation aids such as satellite positioning systems, automated routing systems, and an Automatic identification system made it possible to implement any routes of vessels permitted by the geography of the water area, not limited to visual observation capabilities [6], [7]. This determined the need and prospects for the development of new approaches to planning ship traffic patterns in the marine areas.

International Conference on SMART Automatics and Energy
AIP Conf. Proc. 2910, 020124-1–020124-9; https://doi.org/10.1063/5.0166951
Published by AIP Publishing. 978-0-7354-4687-8/$30.00

This work is devoted to the study of the problem of planning a ship traffic pattern that ensures safety in conditions of high traffic intensity. The method for solving the problem is based on the simulation of movement along a set of possible trajectories and the evaluation of a metric describing the degree of movement danger. The choice in favor of a specific variant of the traffic scheme is due to the need to ensure maximum safety of collective traffic and practical considerations. The topicality of the study is also due to the prospects for the development of unmanned navigation [8].

MATERIALS AND METHODS

Suppose there is a certain water area on which the areas allowed and prohibited for the movement of ships are allocated. Taking into account the small size of typical water area, which are usually no more than 100 kilometers, it is possible disregard the spherical shape of the Earth. To model them, we will use a rectangular Cartesian coordinate system. Let's assume that there are zones of entry of vessels to the water area акваторию IN_m ($m = \overline{1, M}$) and zones of exit of vessels from the water area OUT_n ($n = \overline{1, N}$) at the borders and inside the water area. Zones can be either disjoint or intersect. Let's take the known intensity of the traffic flow from the IN_m ($m = \overline{1, M}$) zone to the OUT_n ($n = \overline{1, N}$) zone, expressed, for example, by the number of outgoing vessels per unit time at given characteristic speeds, geometric dimensions and trajectory properties of the vessels. This representation allows you to simulate the flows of vessels passing through the water area [9].

Let the routes of ships from the entry zones to the exit zones be given. We will simulate the traffic of the water area at discrete points in time t_i. The motion model of a particular vessel is described by kinematic equations (1)

$$
\begin{aligned}
x_{i+1} &= x_i + v_i \sin K_i (t_{i+1} - t_i), \\
y_{i+1} &= y_i + v_i \cos K_i (t_{i+1} - t_i).
\end{aligned}
\tag{1}
$$

Here x_i, $y_i$are the Cartesian coordinates of the ship at time t_i. v_i and K_i are the speed and course of the vessel, respectively. Assume that the model of the vessel's speed and course includes a random component, so$v_{i+1} = v_i + \delta v_i$, where δv_i is a random variable with a known distribution. The course of the vessel K_i is selected at each step so as to ensure movement along a given route, so that $K_i = K_i^* + \delta K_i$ (where K_i^* is the trajectory-determined value of the vessel's course, $\delta K_i$is a random variable with a known distribution).

We will generate vessels in the IN_m zones according to the given intensity of the ship flow A_{mn} and simulate the movement of vessels to the OUT_n zones. Vessels will be removed from processing as they reach the OUT_n zones. Thus, we will obtain a simulation model of the movement of vessels in the water area.

As a metric characterizing the degree of danger of movement, we will choose the number of dangerous approaches of ships per unit of time [5]. We will consider the mutual position of vessels dangerous if the distance between them is less than some critical distance R^* depending on the geometric dimensions of the vessels. By implementing a simulation model of vessel traffic, it is possible to count dangerous approaches of vessels both in the entire water area and in its separate sections, thereby identifying the most problematic ones.

Thus, the task, which consists in choosing a set of vessel routes from the entry zones IN_m to the exit zones OUT_n so that they provide a minimum number of dangerous approaches of vessels within the described simulation model is formulated. The solution of this problem will allow planning a scheme of safe movement in the selected water area.

Let's consider the model of the task on the graph. Let a set of edges and a set of vertices be defined in the water area. The set of vertices of the graph is formed as a uniform square grid with a given distance between the vertices. The set of edges is set so that a segment to each connects each vertex. In order for the number of edges not to be excessive, their possible length is limited. The geography of the water area is taken into account: there are no vertices in areas prohibited for navigation; edges should not intersect such areas.

The starting and ending points of possible ship routes are the vertices located in the IN_m and OUT_n zones. Let P_{mn} be the set of possible paths on the graph leading from the IN_m zone to the OUT_nzone. It is advisable to introduce a number of restrictions to reduce the number of possible paths: by the length of the path, by the magnitude of the change in the ship's course at the top, to prohibit cyclic paths, etc. In the process of modeling the movement along possible paths, we will get the number of dangerous approaches of ships for each pair of paths. Those paths that provide a minimum of dangerous approaches provide the solution to the initial problem of planning traffic patterns.

In the case of considering real water areas, the choice of paths from the sets of P_{mn} leads to the need for simulation modeling of the problem for a very large number of vessels. The random nature of estimating the number of dangerous approaches for pairs of selected paths is another problem that arises when solving the described problem. This does not make it possible to consistently distinguish similar paths from the point of view of their security measures. Different implementations of the model give significantly different estimates of the routes of the vessel traffic scheme. It is possible to reduce the random component in the estimation of the number of dangerous approaches if the number of simulated vessels is increased by several orders of magnitude. However, this will require the use of specialized computing resources. In other words, the features of the described problem make it difficult to solve it directly for the water area as a whole by traditional methods and means.

An alternative approach is to construct possible traffic patterns in an expert way from structural elements (primitives) that represent typical configurations of trajectories accepted in the practice of navigation. The implementation of the described simulation model in isolation within a separate primitive is quite possible on available general-purpose computing and software platforms.

Consider the following primitives of ship trajectories:

- the intersection of one-way ship flows of the same intensity (Fig. 1a);
- the intersection of two-way ship flows of the same intensity (Fig. 1b);
- the intersection of two-way ship flows of different intensity (Fig. 1c);
- the intersection of two-way ship traffic with a circular traffic zone (Fig. 1d).

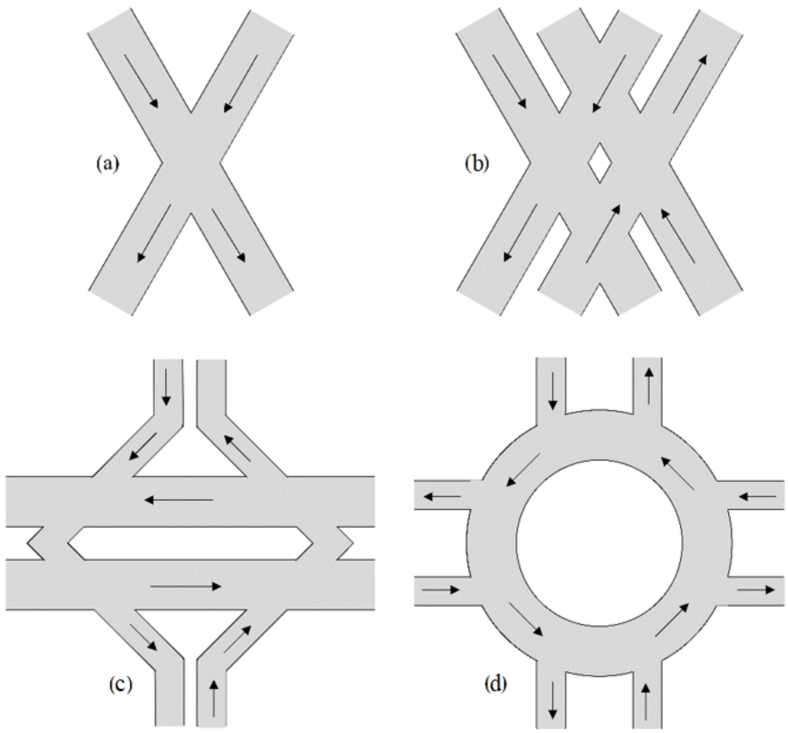

FIGURE 1. Models of vessels trajectory primitives.

In the first case (Fig. 1a), it is assumed that one-way ship flows of equal intensity intersect at some angle. The intensity of the flow is expressed in the number of vessels passing per unit of time at a given speed. It is required to estimate the characteristic number of dangerous approaches depending on the angle of intersection of ship flows, their intensity and the size of vessels (parameter values R^*).

In the second case (Fig. 1b), it is assumed that two-way ship flows of equal intensity intersect at some angle. This situation corresponds to the “summation” of the four primitives shown in Fig. 1a. In this case, it is also necessary to estimate the characteristic number of dangerous approaches depending on the angle of intersection of streams, their intensity and the size of vessels.

In the third case (Fig. 1c), it is assumed that a two-way ship traffic of high intensity is intersected by a two-way ship traffic of lower intensity. Vessels moving in a "large" stream maintain straight-line movement, and vessels moving in a "small" stream change course to cross a "large" stream at as small an angle as possible. It is required to estimate the characteristic number of dangerous approaches depending on the angle of intersection of flows, the size of vessels, the intensity of vessel flows and their speeds.

In the fourth case (Fig. 1d), it is assumed that two-way ship flows with the same traffic intensity intersect and circular traffic is organized to reduce the number of dangerous approaches. It is required to estimate the characteristic number of dangerous approaches depending on the size of vessels and the intensity of their flows.

RESULTS

Let's consider the intersection of one-way ship flows of the same intensity (Fig. 1a). Figure 2 shows the results of estimating the average number of dangerous ship approaches. On the abscissa axis, the angle of intersection of ship flows γ (in degrees) is postponed, on the ordinate axis – the average period between dangerous approaches τ (in minutes). The following parameter values were taken (see Table 1): R^* is 300, 600 and 900 meters; the time intervals between neighboring vessels moving in the stream are random values and are evenly distributed in the interval [1,10] and [1,20] minutes; the speed of the vessels was equal to 10 meters per second. Here and in the following examples, ship traffic modeling was carried out at an interval of 100 days.

It can be seen from Fig. 2 that there is a close to inverse linear dependence of the average intervals between dangerous approaches τ on the critical distance between ships R^*. This is clearly seen, for example, when comparing graphs 1 and 2, 4 and 5.

TABLE 1. Parameters of ship flows (one-sided of the same intensity)

The number of the graph on the diagram	Distance between vessels R^*, meters	Time interval between vessels, minutes
1	300	[1,20]
2	600	[1,20]
3	900	[1,20]
4	300	[1,10]
5	600	[1,10]
6	900	[1,10]

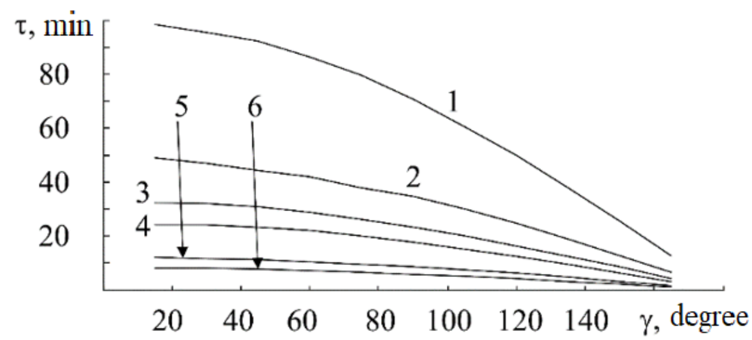

FIGURE 2. The average interval between dangerous approaches: the intersection of one-way ship flows of the same intensity.

A close to quadratic relationship is observed between the length of the time interval between neighboring vessels and τ. The latter is easy to assume, since as the time interval between ships decreases, the number of ships in each ship stream increases inversely. It can also be seen that the value of τ when crossing traffic flows at an acute angle is in several times higher than when crossing at "very obtuse" angles (greater than 135°). The difference in the value of τ for "very sharp" angles (smaller than 45°) is small (about 10%). Thus, it is necessary to strive to cross one-way traffic flows only at sharp angles when planning a traffic pattern. However, reducing the angles below 45° does not give a significant effect.

The intersection of two-way ship flows (Fig. 1b) is reduced to the integration of four primitives of one-way ship flows. Figure 3 shows the results of estimating the average number of dangerous ship approaches for the case of two-way ship flows of the same intensity and traffic parameters presented in Table 1. As in the previous example, the angle of intersection of ship flows γ (in degrees) is postponed along the abscissa axis, and the average period between dangerous approaches τ (in minutes) is on the ordinate axis.

It can be seen from Fig. 3 that, as can be assumed, the values of τ are symmetric with respect to the angle $\gamma = 90°$. At such values of γ, the values of τ are four times less than in the corresponding graphs of Fig. 2. Such as the maximum values of τ are reached at the point $\gamma = 90°$, when planning the traffic pattern, it is necessary to strive for the intersection of two-way ship flows at right angles.

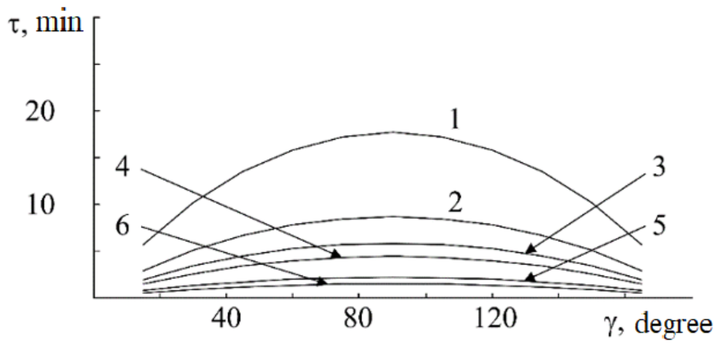

FIGURE 3. The average interval between dangerous approaches: the intersection of two-way ship flows of the same intensity.

Consider the intersection of two-way ship flows of different intensity (Fig. 1c). Figure 4 shows the results of estimating the average number of dangerous ship approaches. The following parameter values were accepted (see Table 2). As in the two examples earlier, the angle of intersection of ship flows γ (in degrees) is postponed along the abscissa axis, and the average period between dangerous approaches τ (in minutes) is postponed along the ordinate axis.

TABLE 2. Parameters of traffic flows (two-way traffic of different intensity).

The number of the graph on the diagram	Distance between vessels R^*, meters	Time interval between vessels, big flow, minutes	Time interval between vessels low flow, minutes	Vessel speed, high flow, m/s	Vessel speed, low flow, m/s
1	300	[1,10]	[1,40]	10	10
2	300	[1,10]	[1,40]	20	10
3	300	[1,10]	[1,20]	10	10
4	300	[1,10]	[1,20]	20	10
5	600	[1,10]	[1,40]	10	10
6	600	[1,10]	[1,40]	20	10
7	900	[1,10]	[1,40]	10	10
8	900	[1,10]	[1,40]	20	10
9	600	[1,10]	[1,20]	10	10
10	600	[1,10]	[1,20]	20	10
11	900	[1,10]	[1,20]	10	10
12	900	[1,10]	[1,20]	20	10

The following parameter values were adopted (see Table 2): R^* is equal to 300, 600 and 900 meters. The time intervals between neighboring vessels moving in the “big” stream are evenly distributed in the interval [1,10] minutes, in the "small" stream - in the segments [1,20] and [1,40] minutes. The speed of vessels in the “big” stream was equal to 10 meters per second (solid lines) and 20 meters per second (dotted line). The speed of vessels in a small stream was equal to 10 meters per second.

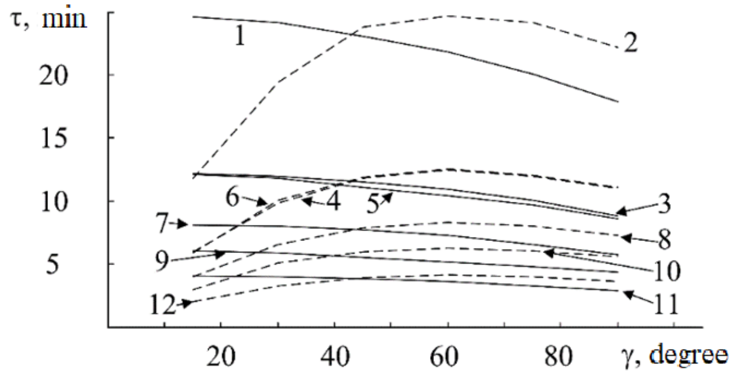

FIGURE 4. The average interval between dangerous approaches: the intersection of two-way ship flows of different intensity.

It can be seen from Fig. 4 that there is a close to inverse linear dependence of the average intervals between dangerous approaches τ on the critical distance between ships R^*. There is also a close to linear relationship between τ and the time interval between neighboring vessels in the "small" flow. This creates, for example, the effect of very close, almost identical graphs 3 and 5, 4 and 6. If the speeds of vessels in intersecting streams are not equal, the value of τ at sharp angles of their intersection decreases sharply (dotted graphs). This can be explained by the fact that the vessels of the "fast" flow are catching up with the vessels of the "slow" flow. The highest values of τ in the case of ship flows equal in speed are provided when their intersection angles are less than 45°, the difference between them in this case is insignificant (does not exceed 10%). Thus, the intersection of ship flows at an angle of 45 ° at close ship speeds is the most convenient for practice.

TABLE 3. Parameters of ship flows (bilateral with a circular traffic zone) and the average number of dangerous ship approaches.

The number of the graph on the diagram	Distance between vessels R^*, meters	Average period between dangerous approaches τ, minutes
1	300	[1,20]
2	600	[1,20]
3	900	[1,20]
4	300	[1,10]
5	600	[1,10]
6	900	[1,10]

Consider the intersection of two-way ship traffic with a circular traffic zone (Fig. 1d). Table 3 shows the result of the assessment of the average period between dangerous approaches of ships. Ship flows in the simulation have the same traffic intensity and move only in the directions "top-bottom", "bottom-top", "right-left", "left-right", which determines the intensity of traffic "on the circle". These assumptions were made for ease of modeling. All traffic flows were of equal width. The inner radius of the "circle" was assumed to be equal to two distances between opposite "straight" ship flows

Table 3 shows that in the case of circular motion there is also a close to inverse linear relationship between R^* and τ. As in the examples earlier, there is a close to quadratic relationship between τ and the length of the time interval between neighboring vessels. The data in Table 3 substantiate the advantage of a circular scheme when crossing two-way ship flows with heavy traffic. Thus, at R^*300 meters and a random time interval between vessels in the segment [1,20] (line 1), the values of τ for circular motion (24.6 minutes) are about a third higher than when crossing two-way ship flows at right angles (about 18 minutes, maximum of Graph 1, Fig. 3). A similar relationship can be seen for traffic flows with other parameters.

DISCUSSION

The results of modeling the movement of vessels on primitives give a representation of the characteristic number of dangerous approaches in a particular case. Taking into account these dependencies, this amount can be extrapolated to traffic flows with other parameters. The value of τ is the average time that passes between dangerous approaches of vessels in a small area of the water area. Taking into account the typical response time of navigators and coastal VTS operators responsible for the section to a warning about the risk of dangerous approach and to making a decision and performing an evasive maneuver, values of τ less than 10 minutes should be considered undesirable, and less than 5 minutes – dangerous [5]. For example, at R^*= 300 meters for one-way vessels flows, traffic is safe at sharp angles of their intersection if the length of the time interval between ships is both [1, 20] minutes and [1, 10] minutes. When crossing two-way ship flows of the same intensity, the movement of vessels with an interval of [1, 20] is safe (Fig. 3, Graph 1), and with an interval of [1, 10] is dangerous (Fig. 3, Graph 4). This gives a representation of the throughput capacity of this primitive of ship trajectories. When moving, as in Fig. 1c, the movement with the given intervals is safe. When moving, as in Fig. 1d, the interval [1, 20] is safe. The interval [1, 10] is also safe (unlike the primitive in Fig.1b), although it is located near the danger zone. A comparison of Fig. 4 and Table 3 gives a representation of the need to organize circular traffic with certain parameters of ship flows.

Let's consider the ship traffic flow diagram in Fig. 5a as an example of using the discussed modeling results for planning safe ship traffic patterns.

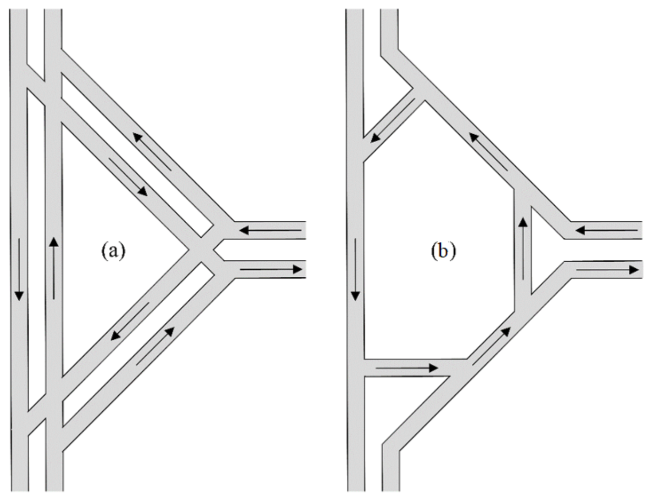

FIGURE 5. Variants of vessel traffic patterns.

Figure 5 shows the two-way movement of ships in the directions "north-south", "north-east" and "south-east" in such a way that a figure similar to a triangle is formed. Such an element of traffic occurs quite often in the water area. For example, it is present in the scheme of ship traffic in Nakhodka Bay. In the variant of Fig. 5a, there are 6 intersections of one-way ship streams: two intersections at angles of 45°, 135°, and 90°. If we turn to the data of the graphs in Fig. 2 and 3, we can determine that, for example, at R^* = 300 meters and a random time interval between ships in the interval [1, 10] minutes, we will have a value of τ = 2.85 minutes, which refers to the dangerous range.

Let's replace the diagram in Fig. 5a with the scheme of Fig. 5b equivalent to it in connectivity (similar to circular motion). In it we have only 3 intersections of one-way ship streams at an angle of 45°. This gives a value of τ = 8.33 minutes, which belongs to the safe range. The throughput capacity of the diagram in Fig. 5b is almost three times higher. Of course, we are talking about the ideal case. In order to draw conclusions about the danger and throughput of a specific traffic pattern of a real water area, it will be necessary to conduct a more capacious simulation. Nevertheless, the approach considered in this paper, based on the use of motion modeling data on primitives, gives quite informative results.

In addition to the number of dangerous approaches, other traffic hazard metrics can be used. Thus, in [10], the metrics "traffic intensity", "intensity plus speed of movement", "intensity plus size of vessels" are considered. The first metric characterizes the number of vessels passing through a certain area of the water area per unit of time. The second metric is similar to the first one, but the vessels have a "weight" that depends on the speed of movement. Thus, high-speed vessels make a greater contribution to the metric. Thus, the areas of the water area with the highest speed are identified. The third metric is similar to the second, but the "weight" of the vessel depends on its length. Longer vessels have more weight. The metric identifies the areas of the water area where the largest vessels are moving. Similar metrics related to traffic intensity are also considered in other studies [11, 12]. It should be noted that the intensity and danger of movement are implicitly, indirectly related. Traffic can be intense but safe, or sparse but dangerous.

In [10, 13], the metric "stability of motion parameters" is substantiated. This metric characterizes the variability of speeds and courses. It allows you to identify areas of the water area with stable or irregular, "chaotic" movement. In articles [10, 14], the metric "traffic saturation" is proposed, which characterizes the density of vessels located in the area of the water area in terms of their ability to maneuver.

CONCLUSION

The paper considers the task of planning a ship traffic scheme that ensures the safety of traffic in the marine water area. General model representations of the problem are formulated. It is noted that the search of possible routes of ships (including using various heuristics) does not make it possible to adequately assess the measure of their safety. As an alternative, it is proposed to construct possible motion schemes in an expert way from typical configurations of trajectories (primitives).

Four models of ship trajectories primitives are proposed: the intersection of one-way ship flows of the same intensity, two-way ship flows of the same intensity, two-way ship flows of different intensity and two-way ship flows with a circular traffic zone. It is noted that such structural elements of ship trajectories are widely used in navigation practice.

The results of statistical modeling of the vessels movement along the trajectories of the selected primitives give a representation of the characteristic number of dangerous approaches with certain characteristics of the ship flow. Taking into account the statistical nature of the problem, the magnitude characterizing the danger of a particular primitive of ships trajectories, it is convenient to choose the average time that passes between dangerous approaches. Other measures of traffic hazard assessment are also possible. The paper provides an example of using the obtained simulation results to plan safe vessel traffic patterns.

The proposed approach allows quite informative assessment of the degree of danger of the traffic pattern from a qualitative point of view. However, the traffic of real water areas is characterized by a variety of possible routes and trajectory properties of moving vessels. Often there are many vessels on them, the movement of which does not have the character of steady flows (pleasure boats and yachts, fishing vessels, coastal services watercraft, etc.), and their movement is characterized by a significant random component. In this case, a more capacious simulation of motion will be required to solve the problem. It may be necessary to use specialized software systems, to which the authors plan to devote a separate study.

ACKNOWLEDGMENTS

The reported study was funded by RFBR, project number 20-38-90018.

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