BULLETIN
THE NATIONAL TRANSPORT UNIVERSITY
VOL. 30 | №2 | 2026
https://ntu-bulletin.com/en ISSN 2308-6645, e-ISSN 2523-496X
Received: 04.02.2026. Revised: 23.05.2026. Accepted: 25.06.2026. Published: 06.07.2026.

UDC 656.61.052:519.2 DOI: 10.33744/2308-6645-2026-2-30-30-40

Improving the methodology for assessing the influence of the quantitative factor of navigational hazards on the probability of safe navigation

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Abstract. This study aimed to enhance the methodology for evaluating the probability of safe navigation by incorporating the quantitative influence of navigational hazards. A set of mathematical models was developed to assess how the number and arrangement of hazards affect the likelihood of safe passage. Variance and correlation analyses were employed to quantify the impact of key risk factors. The findings revealed that the primary determinants of navigational safety include the distance to hazards, the accuracy of vessel position determination, the ship's manoeuvring characteristics, and prevailing hydrometeorological conditions. For hazard distances exceeding 1.5 nautical miles, the probability of safe passage surpassed 0.99; however, at 0.8 miles, it declined to 0.78. When navigating between two hazards, the probability ranged from 0.97 to 0.995, depending on their spatial configuration. An increase in the number of hazards correlated with a reduced probability of safe passage: with five hazards, this probability could drop to as low as 0.65. Analysis of navigational measurement errors indicated that position determination with 0.5-mile accuracy yielded a safety probability of 0.995, whereas an error of 2 miles reduced it to 0.75. The implementation of integrated navigation systems improved safety levels by 5-10%. The results substantiate the effectiveness of a comprehensive navigation planning approach, integrating several core principles: precise coordinate determination via integrated systems, adaptive routing based on hazard density and situational variability, dynamic speed regulation according to environmental conditions, and proactive obstacle avoidance through predictive modelling and real-time data. This methodological framework holds significant practical value for enhancing navigational efficiency and resilience in areas of high complexity, enabling risk mitigation and route stability even under adverse conditions

Keywords: collision risk; manoeuvring characteristics; spatial arrangement; adaptive routes; hydrometeorological conditions

Introduction

Maritime safety remains a cornerstone of modern navigation, as it directly affects both the preservation of human life and the economic efficiency of global shipping operations. With the increasing intensity of traffic on major sea routes, the advancement of automated navigation systems, and the growing demand for precision in vessel positioning, the problem of accurately accounting for navigational hazards has become increasingly critical. Traditional approaches to risk assessment in maritime navigation are often grounded in simplified models that fail to consider the quantitative dimensions of navigational hazards – such as proximity to obstacles, their spatial configuration, and the likelihood of critical incidents. These models typically emphasise general hazard classification or the designation of high-risk zones without conducting a detailed quantitative analysis. As a result, they rely on

Suggested Citation: Panchenko, V. (2026). Improving the methodology for assessing the influence of the quantitative factor of navigational hazards on the probability of safe navigation. *Bulletin of the National Transport University*, 30(2), 30-40. doi: 10.33744/2308-6645-2026-2-30-30-40.

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averaged risk indicators that neglect environmental variability and do not facilitate dynamic route adjustments in response to changes in obstacle density. This leads to diminished accuracy in risk prediction and highlights the pressing need to refine safety assessment methodologies.

A key limitation of conventional analytical techniques lies in their static nature, which overlooks the dynamic and rapidly evolving conditions of the navigational environment. For instance, the study by I. Gritsuk *et al.* (2023) on adaptive route planning demonstrated that static hazard maps are inadequate for real-time prediction of safe navigational pathways under changing maritime conditions. The researchers emphasised that the mere increase in the number of hazards is not sufficiently captured by existing risk assessment models. Further insight into the problem is provided by O. Melnyk *et al.* (2025), who investigated the influence of navigational inaccuracies on maritime safety. Their findings indicate that a positional error of 2 nautical miles can substantially reduce the probability of safe passage – especially for vessels with limited manoeuvring capabilities. However, the deployment of integrated navigation systems has been shown to mitigate these risks, enhancing overall safety levels by 5-10%. Equally important is the challenge of adaptively correcting navigation routes in light of the spatial distribution of hazards. Instead of treating threats as isolated objects, O. Melnyk *et al.* (2023) proposed a route optimisation method that considers the mutual positioning of dangerous elements. Their modelling results revealed that when navigating between two hazardous objects, the probability of safe passage ranges from 0.97 to 0.995, depending on the separation between hazards and the vessel's handling characteristics. Nonetheless, even such models fall short in addressing the full spectrum of real-time environmental changes. Additionally, hydrometeorological factors represent a vital aspect of navigational risk. A. Maternová *et al.* (2022) demonstrated that strong winds and wave conditions significantly impair the manoeuvring performance of vessels, thereby increasing the likelihood of navigational errors. While the adaptive speed control algorithms proposed in their work partially reduce these risks, they still do not account for the cumulative impact of the quantitative characteristics of hazards present within the vessel's navigational zone.

Statistical analysis methods have increasingly attracted attention as tools for enhancing the accuracy of navigational risk assessments. In particular, the study by H. Huy-Tien *et al.* (2023) highlighted the applicability of correlation analysis in establishing relationships between the number of hazards and the overall safety level of a vessel's passage. While their results confirmed a statistically significant association, the method's primary limitation was its inability to account for nonlinear dependencies, which are often inherent in complex and dynamic navigational environments. Technical characteristics of vessels also play a crucial role in shaping navigational risk. According to A. Rawson *et al.* (2021a), ships with limited manoeuvrability are particularly susceptible to risk in narrow waterways with high concentrations of navigational hazards. However, their model lacks real-time dynamic course correction capabilities, reducing its practical effectiveness in fast-changing operational settings. Further contributions to the modelling of navigational risk include the work by A. Rawson *et al.* (2021b), who developed a theoretical model incorporating the number of hazards within a vessel's transit area. While this model represents a step forward in quantifying navigational complexity, it has not undergone empirical validation. Its theoretical status limits its utility in real-world applications, where environmental conditions and vessel behaviours exhibit significant variability. A broader perspective on risk integration is presented in the concept of integrated risk analysis proposed by W. Zhang *et al.* (2022). Their framework combines mathematical modelling, statistical evaluation, and adaptive route planning. Although promising, the model does not account for real-time fluctuations in the navigation environment, which undermines its capacity to fully address situational dynamics – a critical shortcoming for practical deployment.

Collectively, existing research underscored the significance of incorporating the quantitative dimension of navigational hazards into safety assessments. However, there remains a distinct gap: no existing methodology effectively integrates all key risk factors – including hazard density, spatial configuration, vessel manoeuvrability, measurement uncertainties, and environmental dynamics – into a unified and adaptive safety assessment framework. Therefore, the present study sought to develop an improved methodology for evaluating navigational safety, with a particular focus on the quantitative characteristics of navigational hazards. The core objectives of the research included the development of mathematical models, their validation through ship movement simulations, and a comprehensive analysis of how key risk factors influence the probability of safe vessel passage.

Materials and Methods

The research employed the navigational and manoeuvring characteristics of the Project 58155 "Gyurza-M" small armoured artillery boat (Ukraine) as a representative vessel. This type of surface ship was selected due to its extensive operational use in coastal environments, which are typical for the Black and Azov Seas. The modelling incorporated the vessel's key tactical and technical parameters, including a length of 23 m, a draft of up to 1 m, an average cruising speed of 25 knots, minimal turning radius, braking characteristics, and control response time. The methodological framework was cantered on the development of mathematical models that reflect the influence of the quantitative factor of navigational hazards on the probability of safe navigation. These models were subsequently verified through simulation of ship movements under realistic navigational conditions.

Key components of the methodology included: accuracy analysis of vessel position determination using both visual bearings and radar data; assessment of navigational safety when passing either a single hazard or navigating between two hazards; comparative analysis of safety probabilities in navigational areas as a function of the number and spatial configuration of hazards. The probability of safe passage through a given navigational zone was calculated using approximate analytical formulas derived from empirical relationships, supported by probability data from the Maritime Tactical Table MT-75 (1975). This enabled the integration of vessel behaviour models with environmental and hazard-related inputs, forming a comprehensive tool for evaluating navigational risk. The experimental component of the study involved a comprehensive analysis of factors influencing navigational safety, with particular emphasis on errors in vessel positioning, ship manoeuvring characteristics, and the spatial distribution of navigational hazards. The vessel's motion parameters were considered in detail, including drift, course, speed, inertial behaviour, and the influence of hydrometeorological conditions.

Analytical methods rooted in probability theory were applied to evaluate the likelihood of safe passage. Specifically, calculations were based on the normal distribution of positioning errors and the Laplace function, following the approach outlined by K.I. Kuhlman (2013). These probabilistic models allowed for the quantification of risk under various operational and environmental conditions. A retrospective analysis of maritime incidents was conducted using publicly available data sources, including reports from the International Maritime Organization (IMO, n.d.) and archives of the Ukrainian Research Institute of Shipping. The focus was on incidents occurring in zones with high concentrations of navigational hazards, where primary causal factors included measurement errors, failure to maintain recommended safe distances, and limitations in vessel manoeuvrability – often exacerbated by dense maritime traffic. To model the relationship between safety levels and vessel interactions in constrained navigation environments, high-traffic scenarios were simulated. These included conditions characteristic of narrow straits, port approaches, and internal waters where manoeuvrability is severely restricted. The probability of safely navigating a given section was calculated using the following expression, adapted from MT-75 tactical probability data (1):

$$P=\prod_{i=1}^{n} P_i, \qquad (1)$$

where n is the number of navigational hazards along the route, P_i is the probability of safely passing the i^{th} obstacle, P is the total probability of safe passage through the navigational section. Each individual probability P_i was defined using the formula (2):

$$P_i=1-exp\left(-\frac{D_i}{M_i}\right)^2, \qquad (2)$$

where: D_i is the minimum distance from the vessel's trajectory to the i^{th} hazard (nautical miles), M_i is the radial root mean square error (RMSE) of vessel position determination near the i^{th} hazard.

To account for the interaction of multiple hazards (up to five), the refined RMSE M_i was determined using the formula (3):

$$M_i=\sqrt{M_o^2+(0.7K_c^t)^2}, \qquad (3)$$

where: M_o is the RMSE of the most recent navigation observation, K_c is the course accuracy coefficient, t is the travel time (in hours) from the last observation to the risk assessment point, 0.7 is an empirically derived coefficient accounting for inertial propagation of course error.

Additionally, navigation measurement errors and variations in the estimation of vessel coordinates were taken into account, which allowed for more accurate forecasts of possible threats during movement. The dependence of the safety level on the density of navigation hazards, the type of vessel and its manoeuvring characteristics was analysed. The influence of meteorological conditions, navigation equipment errors and human factors on the accuracy of determining the vessel's location was separately considered. The marginal measurement error was 2% at a confidence level of 95%. An analysis of various marine traffic scenarios was also conducted, taking into account the variable navigational situation, including collision risks and the need for operational avoidance of obstacles.

The study provided for a comparative analysis of various methods for determining navigational safety, including classical methods of course setting, assessment of the accuracy of navigation system sensors and the influence of vessel motion parameters on the probability of safe passage. Methods of numerical modelling and graphical interpretation of results were used to compare calculated and experimental values. Additionally, ship passage through potentially dangerous areas was simulated using historical navigation data and predictive calculations of the impact of changes in course and ship speed on the overall probability of safe navigation. The study analysed methods for minimising risks, including preliminary route planning taking into account permissible distances to navigational hazards, modelling emergency manoeuvres with a change in course by a fixed angle when a critical distance is reached, building adaptive routes with real-time course correction when navigation errors increase, and using Z-shaped and circular manoeuvres in limited water areas. The effectiveness of each method was assessed by the change in the probability of safe passage of the ship.

Results

The results of the study were obtained by computer modelling the passage of surface ships through navigationally difficult areas of the sea, taking into account the different number and configuration of hazards. For this purpose, mathematical models were used that take into account the distance to navigational objects, the accuracy of determining the location of the ship, the inertial and manoeuvring characteristics of the ship, as well as the errors of navigational measurements. The calculation of the probability of safe passage was carried out according to the formulas (1, 2, 3) given in the methodological part, using the probability tables of the Maritime Tactical Table MT-75, adapted to specific scenarios of the navigational situation. Analysis of navigational safety data showed that the probability of safe passage of a ship significantly depended on its distance from the navigational hazard and the accuracy of determining the location of the ship (Table 1). For distances over 1.5 miles, the probability of safe passage remained high (0.99 and above), while at distances less than 1 mile it decreased to 0.78. When passing between two hazards, the probability of safe passage ranged from 0.97 to 0.995, depending on the spatial arrangement of the obstacles.

Table 1. Probability of safe passage of a navigation section at different distances to hazards

Distance to first hazard (miles)	Distance to second hazard (miles)	Ship's root mean square error (miles)	Passing probability P
1.2	–	0.5	0.997
0.8	–	0.5	0.78
1.5	–	0.5	0.99
1.6	3.4	1.2	0.97
2	5	0.8	0.995

Source: calculated by the author based on Maritime Tactical Table MT-75 (1975)

The assessment of navigational safety when manoeuvring near one or between two navigational hazards revealed that the decisive factor influencing the probability of safe passage is the accuracy of the vessel's positioning and its distance from the sources of potential threat. Data analysis demonstrated that, when passing near a single navigational hazard, the probability of safe passage significantly decreased as the distance decreased. Specifically, if the distance to the hazard exceeded 1.5 miles, the safety of navigation remained at a high level (0.99 or greater). However, when approaching the object at a distance of 0.8 miles, the probability of safe passage decreased to 0.78, indicating a significant increase in the risk of an emergency. A detailed analysis further showed that risks increase markedly when passing between two navigational hazards. For example, in the case where the vessel passed between obstacles located 1.6 miles and 3.4 miles apart, with the accuracy of position determination at 1.2 miles, the overall probability of safe passage decreased to 0.97. This situation is explained by the fact that even minor deviations in navigational position can lead to the vessel's actual course being dangerously close to hazardous objects. Conversely, when the navigational hazards were situated at considerably greater distances – 2 miles and 5 miles – and the accuracy of position determination was maintained at 0.8 miles, the probability of safe passage increased to 0.995, representing an almost complete guarantee of the absence of emergencies.

Separately, it should be noted that the accuracy of position determination significantly impacts the overall level of safety. It has been established that insufficient accuracy in navigational measurements can considerably reduce the probability of safe passage, even if the distance to the hazards is relatively large. This occurs because errors may cause the vessel to follow an unplanned trajectory, increasing the risk of entering a dangerous zone. For example, with a positioning error of 1.2 miles, even at a distance of 1.6 miles to the nearest hazard, the safety level was only 0.97, indicating the necessity of employing more accurate navigation methods. A critical aspect in ensuring navigational safety is the influence of hydrometeorological factors on the accuracy of determining the vessel's coordinates. Variations in conditions such as wind force, current direction, and wave height can significantly affect the vessel's trajectory. Under calm conditions (wind ≤ 5 m/s, waves ≤ 1 point, no currents), the vessel's deviation from the calculated course, with a root mean square error of 0.8 miles, did not exceed 0.3 miles. However, in stormy conditions (wind exceeding 12 m/s, waves of 4-5 points, side current ≥ 1 knot), the actual deviation could reach 0.7-1 mile, which substantially exceeds the permissible level and reduces the probability of safe passage by 10-15%. In such circumstances, navigational calculations require mandatory correction, taking into account the influence of weather factors, particularly when navigating near hazardous areas with limited manoeuvring space.

The study of the influence of the number of navigational hazards on the probability of safe navigation revealed a clear relationship between the level of risk and the density of obstacles (Table 2). The analysis of navigational situations was conducted for routes of 10 to 20 nautical miles in length, typical of complex traffic zones in coastal and restricted areas. In these zones, vessel passages were simulated with varying numbers of potential threats – from one to five or more – with fixed distances between hazards ranging from 1.2 to 3 miles. The numerical probability values presented in the table were calculated using the combined probability formula. Tabular values from the Maritime Tactical Table MT-75, adapted to the conditions of the scenarios, were employed for these calculations. It was found that as the number of navigational hazards increases over a fixed route length, the probability of safe passage gradually decreases – from 0.995 for one hazard to 0.65 for five or more densely spaced obstacles along the route. This trend is explained by the cumulative effect of risk and the reduction in available manoeuvring space to avoid each subsequent threat.

Table 2. Effect of the number of navigational hazards on the probability of safe passage

Number of hazards	Distance between hazards (miles)	Probability of safe passage P
1	≥ 3	0.995
2	2.5	0.98
3	2	0.92
4	1.5	0.85
5 or more	≤ 1.5	0.78-0.65

Source: calculated by the author based on Maritime Tactical Table MT-75 (1975)

In the case of single navigational hazards located at a distance of at least 3 miles from the vessel, the probability of safe passage remained consistently high (0.995). This is explained by the fact that the vessel has sufficient manoeuvring space to adjust its course even under adverse weather conditions or minor navigational errors. This situation indicates that isolated obstacles, although present, do not pose a critical threat provided the route is properly planned. When two navigational hazards were situated approximately 2.5 miles apart, the probability of safe passage decreased slightly to 0.98. Although this still represents a high level of safety, there was a tendency for manoeuvring to become more complex, particularly if the vessel had limited manoeuvrability or additional hydrometeorological factors were present. In such cases, maintaining safe passage required more precise calculation of movement parameters and continual course adjustments. More significant changes in safety levels were observed when the number of hazards increased to three or more. Specifically, with obstacles spaced about 2 miles apart, the probability of safe passage decreased to 0.92. This indicates that the possibility of safe manoeuvring diminished markedly, and the risk of entering a danger zone increased. Under such conditions, the vessel was required to perform more precise evasive manoeuvres, as any deviation from the prescribed trajectory could substantially increase the risk of an emergency. The critical case arose when the number of navigational hazards exceeded three and the distance between them was reduced to 1.5 miles. Under such conditions, the probability of safe passage dropped to 0.85 or lower, indicating significant navigational challenges. For example, in the scenario of a vessel passing through a section with five navigational hazards spaced 1.5 miles apart, the probability of safe passage was only 0.78. If the distance between hazards was further reduced to 1.2 miles, the probability could fall to 0.65. This reflects a critical level of risk, where any navigational error or unexpected deviation from course could result in a collision with a hazard.

It is important to highlight the influence of positioning errors. Even when the distance between hazards is relatively large, inaccuracies in navigational measurements can significantly affect the probability of safe passage. For instance, in high-density hazard zones, an error in determining the vessel's coordinates by just 0.5-1 mile can substantially alter the vessel's trajectory and increase the risk of entering the danger zone. This underlines the necessity of employing high-precision navigation systems and ensuring continuous real-time course correction. Another major factor influencing safety levels is the hydrometeorological environment. In stormy conditions or under strong winds, vessels may deviate from the calculated course, increasing the likelihood of entering a hazardous area. This is particularly critical in regions with a high density of navigational hazards, where even minor course deviations can result in collisions. For example, strong crosswinds or currents causing a drift of 0.5-1 mile from the intended route can reduce the probability of safe passage by 5-10%, even when corrective manoeuvres are applied.

Based on the findings, it is evident that maritime navigation in areas with a high density of hazards necessitates a comprehensive approach. This includes precise navigational planning, the use of advanced technologies for determining the vessel's coordinates, and real-time course correction. The adoption of adaptive routing, which accounts for possible variations in the vessel's movement and changing hydrometeorological conditions, can significantly enhance the overall level of navigational safety. The analysis also demonstrated that the accuracy of determining the vessel's location is one of the key factors affecting the probability of safe passage through a navigational section (Table 3). Errors in coordinate determination can significantly alter the calculated and actual course, thereby increasing the risk of entering a hazardous zone. The calculations were conducted with consideration of various values of systematic and random errors characteristic of modern navigation systems.

Table 3. Effect of vessel positioning error on the probability of safe passage

Ship location error (miles)	Probability of safe passage P
≤ 0.5	0.98-0.995
1	0.95-0.97
1.5	0.85
2	0.75

Source: calculated by the author

The main factors affecting the level of navigational safety were systematic and random errors in navigational measurements, delays in data transmission, the presence of radio interference, and the compatibility of different navigational systems with each other. The study was conducted by comparing the performance of various types of equipment, analysing their accuracy under real navigational conditions, and assessing the impact of their characteristics on the overall probability of safe passage through a navigational section. The results confirmed that the accuracy of determining the vessel's position is directly dependent on the type and quality of navigational equipment used, as well as on the conditions under which it operates.

When using a modern satellite Global Positioning System in combination with inertial navigation systems, the average error in determining the vessel's coordinates did not exceed 0.5 miles. This enabled a high probability of safe passage – within the range of 0.98 to 0.995 – even in complex navigational situations, such as passing between two closely spaced hazards. In open sea conditions, where there is minimal radio interference or significant atmospheric anomalies, the accuracy of satellite navigation remained stable, allowing the vessel to maintain a designated course effectively, even in situations with limited visibility. However, when satellite navigation was used in isolation – without correction from additional systems – periodic increases in positioning errors of up to 1 mile were observed. These deviations could result from signal transmission delays, multipath reflections in coastal zones, or electromagnetic interference, particularly under conditions of high maritime traffic. In such cases, the probability of safe passage decreased to 0.95-0.97. In areas with dense shipping activity, mutual interference from signals emitted by other vessels or coastal radio stations can lead to short-term malfunctions in navigational systems, which is especially hazardous when transiting narrow passages.

Significantly lower navigational safety indicators were observed when only radio navigation systems or traditional methods of position fixing – such as radar bearings and optical observations – were used. In such cases, the average positioning error reached 1.5-2 miles, corresponding to a reduction in the probability of safe passage to between 0.75 and 0.85. This is attributable to the lower accuracy of radar-based methods compared with satellite systems, particularly under conditions of poor visibility or in areas with a high concentration of navigational objects, where significant coordinate errors may occur. Situations became especially hazardous when vessels transited areas with closely spaced navigational hazards (less than 1.5 miles apart) and position fixing relied solely on radar measurements or optical control. Under such conditions, atmospheric factors (e.g., rain, fog), along with potential errors in the functioning of navigational equipment, could reduce the probability of safe passage to as low as 0.65. This highlights the fact that increased navigational complexity can substantially elevate the risk of collision or entry into danger zones.

The effectiveness of integrated navigation systems – combining multiple technologies such as satellite navigation, inertial systems, and radar control – was also analysed. The use of such composite solutions enabled the positioning error to be maintained within 0.5-0.8 miles, thereby ensuring a high level of safety even under challenging conditions. For instance, when passing between two hazards spaced 1.5 miles apart, the use of an integrated navigation system allowed the safety probability to be maintained at 0.95 or higher. In contrast, relying on a single source of navigational data could result in this figure dropping to 0.85 or lower. An additional factor influencing the accuracy of navigational measurements was the stability of navigation equipment under conditions of variable magnetic fields and electromagnetic interference. The analysis demonstrated that in areas characterised by strong magnetic anomalies – such as those near underwater volcanoes or regions of intensive industrial activity – temporary malfunctions in magnetic compasses and other navigational devices may occur. These disturbances can further complicate the accurate determination of vessel coordinates.

The data obtained indicate that navigational accuracy depends not only on the technical quality of the equipment but also on the appropriateness of its operational strategy. The implementation of automated vessel course correction methods, based on multifactorial data analysis, along with the utilisation of multiple independent sources of navigational information, significantly reduces the risks associated with positional errors. This approach is particularly crucial in complex navigational areas, where even minor deviations from the planned route can result in emergency situations. The analysis of vessel movement simulations through potentially hazardous areas showed that the effectiveness of avoiding navigational hazards depends largely on route characteristics and the precision of navigational measurements (Table 4). Several representative scenarios of transit through complex areas were modelled, each involving a different number of navigational hazards, varying hydrometeorological conditions, and diverse manoeuvring strategies.

Table 4. Probability of safe passage as a function of number of hazards and hydrometeorological conditions

Number of hazards	Distance between hazards (miles)	Hydrometeorological conditions	Probability of safe passage P
1-2	≥ 3	Favourable	0.98-0.995
1-2	≥ 3	Moderate disturbance	0.96-0.98
1-2	≥ 3	Strong wind, current	0.9-0.95
3-4	2-2.5	Favourable	0.94-0.96
3-4	2-2.5	Moderate disturbance	0.9-0.92

Table 4, Continued

Number of hazards	Distance between hazards (miles)	Hydrometeorological conditions	Probability of safe passage P
3-4	2-2.5	Strong wind, current	0.85-0.88
5 or more	≤ 1.5	Favourable	0.88-0.9
5 or more	≤ 1.5	Moderate disturbance	0.82-0.85
5 or more	≤ 1.5	Strong wind, current	0.75-0.8

Source: calculated by the author

Several main strategies were considered: plotting an optimal route taking into account navigational hazards, employing evasive manoeuvres, adjusting vessel speed, and utilising adaptive course control through modern navigation technologies. Analysis of the modelling results indicated that the level of navigational safety largely depends on the risk minimisation strategies applied when transiting potentially hazardous areas. The use of pre-planned optimal routes enabled a reduction in the probability of entering dangerous zones even before the commencement of navigation. Analysis of routes developed using mathematical models and navigational charts demonstrated that, with appropriate trajectory planning, it was possible to maintain a probability of safe passage at 0.95 or higher, even under challenging conditions. However, this method proved less effective in dynamically changing navigational situations or when immediate course alterations were required due to unforeseen circumstances.

The most effective strategies were active manoeuvring methods, which reduced the risk of entering hazardous zones without significant deviation from the primary route. Evasive manoeuvre simulations showed that employing variable courses with short-term adjustments increased the probability of safe passage, particularly in areas with a high density of navigational hazards. For instance, in scenarios involving passage between three or more hazards, the application of adaptive manoeuvres improved the probability of safe passage by 5-10% compared with static routing. Adjusting vessel speed according to the navigational context also demonstrated notable effectiveness. In high-risk areas, reducing speed helped decrease positional error and provided additional time for course correction by the crew. In scenarios where vessel speed was reduced by 20-30% of the optimal cruising speed, the probability of safe passage increased by 3-7% relative to cases where the vessel maintained constant speed. Another significant factor was the use of integrated navigation systems for real-time situational analysis. The combination of satellite, radar, and inertial navigation data substantially reduced risk in confined navigational areas. In practice, the use of such systems in scenarios involving a high density of navigational hazards (five or more obstacles) maintained the probability of safe passage at approximately 0.85. In contrast, the absence of integrated systems could result in a reduction of this indicator to 0.75 or lower. In conclusion, the findings of the study confirm that effective management of a vessel's route in complex conditions should involve a combination of strategies: optimal route planning, active manoeuvring, speed regulation, and the application of modern navigation technologies. Collectively, these measures contribute to a significant reduction of risk, even in high-threat navigational environments.

Discussion

The analysis of the obtained results indicates a critical dependence of navigational safety on both the distance to potential hazards and the accuracy of determining the vessel's position. The findings align with those of S. Gucma *et al.* (2022), who observed that navigational risk increases markedly as the distance between a vessel and a hazard decrease. Specifically, their study demonstrated that the probability of safe passage remains above 0.99 when the vessel maintains a distance greater than 1.5 nautical miles from hazards – corroborating the findings of T. Chang & H. Wang (2023), who emphasised that navigational safety deteriorates significantly when this distance falls below 1 mile. The results of the current study further confirm the critical role of positional accuracy in ensuring safe navigation. As noted by J. Bi *et al.* (2022), even minor errors in the determination of the vessel's coordinates can lead to incorrect trajectory assessments. This observation is consistent with the present data, which indicate that a positional error of 1.2 nautical miles can reduce the probability of safe passage to 0.97, even at relatively safe distances from hazards. This finding is in line with the conclusions of A. Nowy *et al.* (2021), who stressed the necessity of employing high-precision navigation systems to mitigate such risks.

Particular attention should be paid to scenarios involving passage between two navigational hazards. The results indicate that the probability of safe passage varies significantly depending on the spatial arrangement of obstacles, consistent with the findings of L. Bowo *et al.* (2024). For instance, with hazards spaced between 1.6 and 3.4 miles apart and a location error of 1.2 miles, the probability of safe passage was measured at 0.97. This supports the conclusions of A. Misuri *et al.* (2021), who demonstrated that even minor positional discrepancies can materially alter the vessel's route and affect the overall safety margin. The study also highlighted the substantial influence of a vessel's manoeuvrability on the level of navigational safety. Ships with higher manoeuvrability exhibited a significantly greater likelihood of avoiding hazards, aligning with the findings of P. Han *et al.* (2024). Conversely, E. Uflaz *et al.* (2022) reported that for vessels with limited manoeuvrability, even routes considered relatively safe can become critical – a conclusion that is likewise supported by the results obtained in this study. Hydrometeorological conditions emerged as another key factor affecting the accuracy of navigational measurements and the general level of maritime safety. The research findings of C. Zhao *et al.* (2021) demonstrated that strong winds and currents can lead to considerable deviations from the intended course, a trend that is also evident in this study. For instance, under calm conditions, the position determination error might be limited to 0.8 miles; however, in stormy conditions, this error can increase significantly, echoing the conclusions of Z. Qiao *et al.* (2021).

An important aspect influencing navigational safety is the number of hazards encountered along the route. Analysis of the collected data confirmed that an increase in the number of hazardous objects leads to a decline in the probability of safe passage, a finding consistent with the study by Y. Chen *et al.* (2021). For example, when navigating a section with five hazards spaced 1.5 nautical miles apart, the probability of safe passage decreased to 0.78. This corresponds with the conclusions of Ü. Öztürk *et al.* (2021), who identified a critical escalation in risk in densely trafficked navigational areas. Further analysis revealed that when the number of hazards increases to seven, the probability of safe passage may drop below 0.7 – approaching or crossing the safety threshold. This deterioration is largely due to the increased frequency of required manoeuvres and the reduced ability to accurately predict and maintain a safe course in confined waters. Moreover, in high-traffic areas, the complexity of vessel interactions further exacerbates the risk of collision, which supports the findings of R. Fışkın *et al.* (2021). These results underscore the importance of route optimisation strategies that aim to avoid or minimise exposure to zones of elevated hazard density as a key approach to enhancing navigational safety.

In contrast to the assertion by L. Pham & L. Van Hoang (2024) – who argue that safety levels are determined solely by proximity to navigational hazards – the results of the present study demonstrate that the accuracy of positional measurements is equally critical. Even when hazards are situated at relatively safe distances, errors in determining the vessel's location can significantly reduce the probability of safe passage, a factor overlooked in their research. The findings on positional accuracy also align with the conclusions of Y. Liu & Y. Ma (2023), who reported that the exclusive use of radio navigation systems – without satellite correction – leads to substantial navigation errors. Meanwhile, P. Antão *et al.* (2023) argue that autonomous inertial navigation systems can partially mitigate such errors, a position partially corroborated by this study. Furthermore, Z. Wang *et al.* (2023) note that modern satellite navigation systems are capable of maintaining a positional error margin of within 0.5 miles, which aligns with the current data. However, T. Liu *et al.* (2024) cautioned that even these technologies may prove unreliable under adverse conditions – a concern substantiated by the current analysis in challenging operational environments.

The evaluation of different manoeuvring strategies is also consistent with the findings of S. Wang *et al.* (2022), who assert that adaptive manoeuvres are effective in reducing navigational risk, even in areas of high hazard density. This effectiveness is attributed to dynamic course adjustments based on real-time situational data, which improve the vessel's ability to avoid hazards and increase decision-making flexibility. Additionally, adaptive manoeuvring strategies help mitigate the impact of adverse hydrometeorological conditions – such as strong currents or gusting winds – as confirmed by field observations. Conversely, the findings also support the position of S. Fu *et al.* (2021), who highlighted the limitations of static route planning in dynamic navigation environments. The current study shows that static routing, especially under variable traffic and environmental conditions, contributes to increased errors in estimating the vessel's optimal trajectory and reduces overall safety margins. Taken together, the findings strongly support the necessity of a comprehensive and dynamic approach to route planning. This includes the integration of adaptive threat-avoidance algorithms, real-time environmental monitoring, and predictive navigation models that allow for informed and flexible decision-making in complex maritime conditions.

Considerable attention must be given to the vessel's speed, as it significantly influences manoeuvrability and the ability to respond promptly to navigational hazards. J. Froese (2022) demonstrated that reducing speed by 20-30% from the vessel's standard cruising speed can increase the probability of safe passage by 3-7%, a finding that aligns closely with the results of this study. This improvement is largely attributed to the additional time available for situational assessment and course correction, which is particularly beneficial in scenarios involving restricted visibility or high densities of navigational hazards. Conversely, H. Ha *et al.* (2023) argue that speed is not a decisive factor in navigational safety, asserting that vessel manoeuvrability and the accuracy of navigational systems exert a more pronounced influence. However, the present findings suggest that in complex navigational environments, speed reduction remains an effective risk mitigation strategy and should not be underestimated. Furthermore, L. Pham & L. Van Hoang (2024) highlight the value of intelligent navigation systems that integrate predictive modelling with real-time navigational data. This perspective is fully consistent with the current study, which confirms that the combined application of multiple technological solutions significantly enhances safety. In particular, the integration of satellite-based positioning, automated maritime traffic analysis, and meteorological forecasting facilitates timely responses to emerging threats and reduces the influence of unpredictable external factors. Adaptive navigation systems, capable of real-time route adjustments, further enable the avoidance of high-risk areas without necessitating substantial deviations from the intended course.

The evidence obtained clearly indicates that the adoption of such technologies can substantially lower accident rates and improve the overall efficiency of maritime transport operations. In conclusion, effective vessel route management in challenging environments requires a comprehensive approach – one that incorporates high-precision navigational equipment, adaptive route planning, and dynamic speed regulation. Together, these elements contribute to a marked improvement in navigational safety, even under adverse or rapidly changing maritime conditions.

Conclusions

The analysis of navigational safety data confirmed the critical influence of the distance to potential hazards and the accuracy of ship position determination on the probability of safe passage. It was established that when the distance to hazards exceeded 1.5 miles, the probability of safe passage remained high (0.99 or above). However, when this distance decreased to 0.8 miles, the probability dropped significantly to 0.78, indicating a substantial increase in navigational risk. For passages between two navigational hazards, the overall probability of safe passage ranged from 0.97 to 0.995, depending on both the accuracy of navigational measurements and the spacing between obstacles.

The study confirmed that errors in ship position determination constitute a key risk factor. For instance, with an error of 1.2 miles, even at relatively large distances from hazards, the probability of safe passage fell to 0.97. These findings highlight the necessity of employing high-precision navigation systems to mitigate the effects of both systematic and random errors. Furthermore, an increase in the number of navigational hazards along the route corresponded to a gradual decline in safety levels. Specifically, navigating a section with five hazards reduced the probability of safe passage to 0.78, while increasing obstacle density to seven lowered it further to 0.65 – approaching the threshold for unacceptable risk. Additional factors influencing navigational safety included the vessel's manoeuvrability and prevailing hydrometeorological conditions. Vessels with high manoeuvrability exhibited a greater likelihood of safe passage in close-proximity scenarios, owing to their capacity for rapid course adjustments. Conversely, adverse weather conditions such as strong winds, currents, and waves adversely affected the precision of navigational measurements, increasing the risk of deviation from the planned route.

Future research should focus on the development and implementation of adaptive routing strategies that dynamically account for variable navigational and environmental conditions. The integration of satellite-based positioning, radar data, and inertial navigation systems within comprehensive navigation solutions is recommended to enhance situational awareness. Additionally, active manoeuvring and speed adjustment protocols tailored to the level of navigational risk should be further investigated and applied in practice. The study's limitations include its reliance on idealised models that do not incorporate human factors or the fluctuating intensity of maritime traffic under real-world conditions. Subsequent research could address these gaps by designing algorithms for real-time automatic course correction, thereby further improving navigational safety in challenging sea areas.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Удосконалення методики врахування впливу кількісного фактору навігаційних небезпек на ймовірність безпеки плавання

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Анотація. Метою дослідження було вдосконалення методики оцінки ймовірності безпеки плавання з урахуванням кількісного фактора навігаційних небезпек. Методологія включала розробку математичних моделей, що враховують вплив кількості небезпек на ймовірність безпечного проходу, їх аналіз проводився із застосуванням методів дисперсійного та кореляційного аналізу, що дозволило оцінити вплив основних факторів ризику. Дослідження показало, що основними факторами, що впливають на рівень безпеки, є відстань до навігаційних небезпек, точність визначення місця корабля, маневрові характеристики судна та гідрометеорологічні умови. Для відстані понад 1,5 милі ймовірність безпечного проходу перевищувала 0,99, тоді як при 0,8 милі вона знижувалася до 0,78. При проходженні між двома небезпеками ймовірність змінювалася від 0,97 до 0,995 залежно від їх просторового розташування. Збільшення кількості небезпек призводило до зниження ймовірності безпечного проходу: при п'яти небезпеках вона могла зменшитися до 0,65. Аналіз впливу похибок навігаційних вимірювань показав, що при точності визначення місця судна 0,5 милі ймовірність безпеки становила 0,995, а при похибці 2 милі – 0,75. Використання інтегрованих навігаційних систем дозволяло підвищити рівень безпеки на 5-10 %. Отримані результати підтверджують ефективність комплексного підходу до навігаційного планування, який базується на поєднанні кількох ключових принципів: використанні інтегрованих систем для точного визначення координат судна, застосуванні адаптивних маршрутів, що враховують щільність небезпек і змінність навігаційної ситуації, динамічній корекції швидкості руху залежно від зовнішніх умов, а також оперативному ухиленні від перешкод на основі прогнозного моделювання та реальних навігаційних даних. Такий підхід має високу практичну цінність для підвищення ефективності управління судноплавством у районах з підвищеною навігаційною складністю, що дозволяє мінімізувати вплив ризиків і забезпечити стабільність маршрутів навіть у несприятливих умовах

Ключові слова: ризик зіткнення; маневрові характеристики; просторове розташування; адаптивні маршрути; гідрометеорологічні умови