

# CONCEPTUAL RISK ASSESSMENT OF NAVIGATIONAL SAFETY ON INLAND WATERWAYS USING THE AUTOMATIC IDENTIFICATION SYSTEM (AIS)

**Abstract.** Navigational safety on inland waterways depends on the ability to identify sections with an increased level of risk. Traditional risk assessment approaches are often based on empirical experience and do not fully reflect current operational conditions. The Automatic Identification System (AIS) provides data that enable the analysis of real vessel behaviour and the identification of hazardous sections based on collected operational data. A conceptual approach to the use of AIS data for navigational safety risk assessment through computational analysis may potentially be applied within vessel traffic management systems.

**Keywords:** Vessel operations, Safety of navigation, AIS data, Hazardous River sections

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## Introduction

Navigational safety on inland waterways is among the fundamental priorities of the transport policy of the European Union as well as the Slovak Republic. Increasing demands for efficiency, digitalisation, and environmental sustainability in transport create a need for new tools for risk assessment and risk management. Traditional approaches to the identification of high-risk sections rely primarily on expert experience, historical accident data, and visual assessments, which may lead to subjective decision-making and delayed responses to changing operational conditions (Demirci, Meltem, 2025). Safety and risk identification represent some of the most critical issues in navigation, as their consequences may be devastating to property, the environment, and human life (Bulut Ozan, Mehmet Serdar 2024).

The current high level of traffic intensity in inland waterway transport, together with its anticipated further growth, indicates an increasing likelihood and severity of potential accidents. Statistical analyses have shown that the most significant number of incidents occurs primarily on narrow waterways with a high density of vessels, where navigation and vessel manoeuvrability are particularly challenging, especially under adverse meteorological conditions (Karanović et al., 2024). In this context, safety and risk related terminology has gained increasing attention in numerous studies. Consequently, experts in inland waterway transport have recently applied various methodologies within the navigation industry that enable the analysis of failure modes and their consequences, reliability methods, fault analysis techniques, and related approaches (Abdullahi Abdulkarim et al., 2023).

In this regard, the Automatic Identification System (AIS) provide comprehensive and continuous real-data on vessel movements. These data enable the analysis of vessel

behaviour, traffic density and frequency, manoeuvring patterns, and speed profiles, thereby opening new possibilities for data-driven decision-making. The use of AIS data for the identification of high-risk section represents a modern approach that allows for objective and dynamic assessment of conditions on waterways and within navigation channels.

The conceptual assessment of navigational safety risk is based on analytical data processing combined with expert judgement, with the aim of demonstrating its applicability under the conditions of the international Danube waterways. The proposed approach relies on a combination of analytical data evaluation and expert assessment through the calculation of a risk index, which enables the classification of waterway section according to their risk level (Demirci, Meltem, 2025). Despite the growing focus on environmental impacts and compliance with international regulations, operational risks and the reliability of onboard systems remain insufficiently examined and modernised. Many studies primarily focus on environmental effects and regulatory effectiveness, often overlooking practical failures that occur in real operation situations. Risk assessment under conditions of uncertainty remains particularly challenging, especially when historical data are limited and expert judgement plays a central role in risk identification (Peide et al., 2024). The objective of conceptual risk assessment in navigation operations is to support stakeholders in decision-making processes situation.

## 1. Theoretical Background and Principles of Risk Index Development

The risk index represents a synthetic indicator that enables the quantitative assessment of navigational risk levels on inland waterways. This index integrates multiple

variables into a single numerical value, thereby providing a more objective perspective on operational safety compared to traditional empirical or qualitative approaches (Yuging et al., 2024). The underlying principle is based on the assumption that risk in vessel operations is not the result of a single factor, but rather a combination of multiple operational and dynamic influence that collectively affect the level of navigational safety. In the inland navigation environment, risk levels vary both spatially and temporally, depending primarily on traffic density, vessel type, hydrological and meteorological conditions, the geometry and parameters of the navigation channel, manoeuvrability, speed, and other variables that may significantly influence navigational safety.

These factors are often reflected in changes in vessel behaviour, such as variations in speed, manoeuvring patterns, or frequent close encounters with other vessels. The Automatic Identification System (AIS) enables the quantification of these characteristics by providing continuous data on vessels position, course, speed, and identity (Donghao et al., 2025). Based on these data, it is possible to construct a dynamic representation of vessel movements and to derive indicators that reflect current operational conditions and potential hazardous situation.

The concept of risk index calculation is inspired by the well-established analytical approach of Failure Mode and Effects Analysis (FMEA), which is widely applied in practice for the identification and quantification of risks in technical systems, industrial processes, and transport. In classical FMEA, risk is expressed as the product of three parameters-severity, occurrence probability, and detectability. The resulting value, known as the Risk Priority Number (RPN), allows risk factors to be ranked according to their relative importance. This approach is simple, systematic, and provides a structured framework for prioritising safety measures.

In recent literature, modern variants such as Fuzzy FMEA and Bayesian FMEA have increasingly emerged, addressing the uncertainty and imprecision of input data through the application of fuzzy logic or probabilistic models. These methods enable a more accurate assessment of risk in systems where parameters change dynamically or are not fully known. They are relatively frequently applied in the evaluation of environmental and operational risks in maritime transport, where individual factors are assigned weight according to their influence on overall system safety (Emre, Selcuk, 2025). This principle of weight and combining multiple variables also forms the basis for the development of the proposed conceptual risk index.

### 1.1 Use of Operational AIS Data in Risk Assessment

Within the presented approach, the described logic can also be transferred to the inland navigation environment, where subjective expert estimates are replaced by objective operational data obtained from the AIS system. Particular emphasis is placed on indicators that directly describe vessel behaviour and from which the level of risk in a selected waterway section can be derived.

Among the selected indicators, the following can be directly included:

- Traffic density (H) – the number of AIS messages or vessels passing through a given section within a specified time period, representing the level of traffic load,
- Speed variability (V) – the deviation from the average speed, indicating changes in navigational conditions (e.g., reduce visibility, manoeuvring in narrow sections),
- Manoeuvring frequency (M) – the number of changes in course or speed, signalling navigational complexity and potential conflicts between vessels,
- Relative vessel proximity (P) – the minimum distance between vessels, which is directly related to collision risk,
- Navigation channel curvature (K) – the geometric complexity of the navigation channel, influencing manoeuvring capability and situational awareness.

Each of the listed indicators represents a partial aspect of risk, while their combined analysis enables the development of a comprehensive picture of conditions on the waterway and within a specific section. Unlike the traditional FMEA approach, where all parameters are considered equivalent, the proposed methodology assigns a relative weight to each indicator based on its significance for navigational safety (Peide, et al., 2024). For example, traffic density has greater influence on risk than route geometry and is therefore assigned a higher weight in the risk index calculation.

The resulting risk index (R) is therefore a combination of these normalised indicators and their respective weights, enabling the transformation of large volumes of AIS data into a single interpretable metric. This index may serve as a tool for comparing temporal trends and supporting decision-making in the planning of preventive measures. Its key advantages lie in its universality and adaptability, allowing application across various types of waterways, with indicators and weights adjustable according to local conditions. From a methodological perspective, the risk index thus combines the strengths of quantitative models-such as accuracy and comparability-with practical applicability in safety management (Liu, et al., 2025). In this way, it establishes a link between theoretical risk assessment concepts and modern data-driven approaches enabled by the AIS system.

## 2. Calculation and Interpretation of Risk Index

### 2.1 Methodology of Risk Index Calculation

Based on the indicators derived from the AIS system, it is possible to determine the value of the risk index (R) for each waterway section. The objective of the calculation is to transform multiple factors influencing navigational safety into a single unified indicator that enables the comparison of individual sections in terms of their risk level. For each section, the value of each indicator  $X_{ij}$  is

first determined based on AIS data. As the indicators differ in units and magnitude, all values are normalised to a range between 0 and 1. Normalisation ensures data comparability and eliminates differences in measurement scales. The resulting risk index  $R_i$  is subsequently calculated using the following relationship:

$$R_i = \sum_{j=1}^n \omega_j \cdot X_{ij} \quad (1)$$

where:

- $R_i$  - the value of the risk index for section  $i$ ,
- $\omega_j$  - the weight of indicator  $j$ , representing its significance in the overall risk assessment,
- $X_{ij}$  - the normalised value of indicator  $j$  for section  $i$ ,
- $n$  - the number of indicators (in this case,  $n = 5$ ).

The sum of the weights of all indicators equals 1, which ensures that the risk index assumes values within the interval from 0 to 1. Higher values of the indicate a higher level of risk associated with respective waterways section.

## 2.2 Assignment of Weights to Indicators

The indicator weights are determined according to their assumed impact on navigational safety, primarily base on expert knowledge derived from the literature and professional judgement (Bläser, Búgyi, Fuentes, Hua, Reinhardt, 2024). The highest weight is assigned to traffic density, as a high concentration of vessels directly increases the probability of hazardous situation. The lowest weight is attributed to navigation channel curvature, which, although relevant for navigation, does not independently represent a dominant risk factor (Skupien, Tubis, 2018). The assignment of weight to individual indicators may vary depending on the geographical area, the characteristics of the navigation channel on the waterway, as well as other specific navigational and operational conditions.

**Table 1.** Assignment of Gradient Levels for Speed Classes

| Indicator | Description                  | Weight ( $\omega$ ) |
|-----------|------------------------------|---------------------|
| H         | Traffic density              | 0,30                |
| V         | Speed variability            | 0,25                |
| M         | Manoeuvring frequency        | 0,20                |
| P         | Relative vessel proximity    | 0,15                |
| K         | Navigation channel curvature | 0,10                |

Source: Bläser et al., 2024) (Ye et al., 2023

## 2.3 Risk Index Calculation

To illustrate the calculation of the risk index  $R_i$  a model example was developed consisting of three fictitious sections of the international Danube River:

- Section A – a port area with high traffic intensity,

- Section B – a navigation channel section with lower traffic intensity,
- Section C – a narrow section requiring frequent manoeuvring under higher traffic density.

For each section, values of the five indicators derived from AIS data were expressed within the range of 0 to 1. Subsequently, the risk was calculated for each section using the general equation:

$$R_i = \sum_{j=1}^n \omega_j \cdot X_{ij} = \omega_H \cdot H_i + \omega_V \cdot V_i + \omega_M \cdot M_i + \omega_P \cdot P_i + \omega_K \cdot K_i \quad (2)$$

where:

- $\omega_H, \omega_V, \omega_M, \omega_P, \omega_K$ , are the weights of the individual indicators,
- $H_i, V_i, M_i, P_i, K_i$ , represent the value of the respective indicators for section  $i$ .

All indicator values are hypothetical and are used solely for the purpose of demonstrating the calculation.

**Table 2.** Calculation of Indicator Values for Individual Sections of the Danube River

| Section | H   | V   | M   | P   | K   | Calculation                                                                                      | R     |
|---------|-----|-----|-----|-----|-----|--------------------------------------------------------------------------------------------------|-------|
| A       | 0,8 | 0,6 | 0,5 | 0,7 | 0,5 | $(0.3 \times 0.8) + (0.25 \times 0.6) + (0.2 \times 0.5) + (0.15 \times 0.7) + (0.1 \times 0.5)$ | 0,645 |
| B       | 0,5 | 0,4 | 0,3 | 0,4 | 0,2 | $(0.3 \times 0.5) + (0.25 \times 0.4) + (0.2 \times 0.3) + (0.15 \times 0.4) + (0.1 \times 0.2)$ | 0,365 |
| C       | 0,9 | 0,8 | 0,6 | 0,8 | 0,6 | $(0.3 \times 0.9) + (0.25 \times 0.8) + (0.2 \times 0.6) + (0.15 \times 0.8) + (0.1 \times 0.6)$ | 0,78  |

Source: Author's own processing

## 2.4 Interpretation of the Risk Index Results

The resulting risk index value can be classified into three categories, based on which the level of risk a given section is determined (Urgulu, 2025).

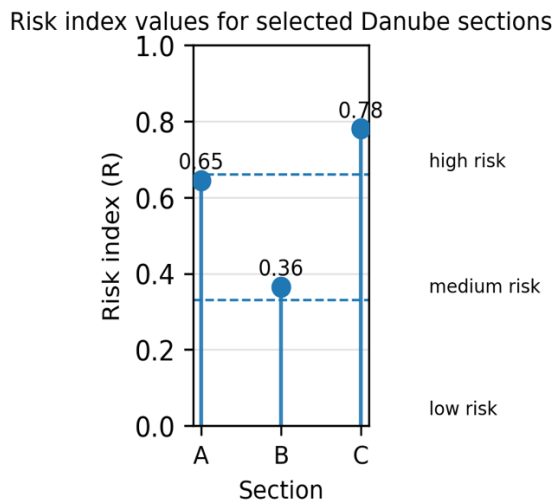
**Table 3.** Classification of Risk Categories Based on the Risk Index Range

| Indicator | Description           | Weight ( $\omega$ ) |
|-----------|-----------------------|---------------------|
| H         | Traffic density       | 0,30                |
| V         | Speed variability     | 0,25                |
| M         | Manoeuvring frequency | 0,20                |

Source: Author's own processing

The results presented in Table 2 indicate that Section C exhibits the highest risk value (0,78), confirming that

narrow section requiring frequent manoeuvring represent an increased level of risk. In contrast, Section B demonstrates a low risk level (0,365), which is characteristic of open and less congested sections where navigation is relatively smooth. Section A reaches a medium risk level (0,645), which is typical for port areas with increased traffic intensity.



**Fig. 1.** Graphical representation of the interpretation of risk index results on the international Danube waterway  
Source: Authors.

## Conclusion

The main objective of the conceptual approach to navigational safety risk assessment on inland using AIS data was to demonstrate how these data can be transformed into an analytical tool capable of identifying hazardous waterway section through the calculation of a risk index. This approach enables the quantification of navigational risk levels based on real-world vessel behaviour and supports the management and optimisation of inland waterway operations.

The paper proposed a methodology that combines five fundamental indicators derived from AIS data-traffic density, speed, variability, manoeuvring frequency, relative vessel proximity, and navigation channel curvature. These indicators represent essential aspects of vessel behaviour that influence the occurrence of hazardous situations within navigation channels. Their weighting was determined based on a review of relevant literature and expert judgement, with traffic density assigned the highest importance, followed by speed variability and manoeuvring frequency. By applying these weights, a synthetic risk was developed that aggregates multiple operational characteristics into a single numerical indicator. This index enables the comparison of different waterway sections in terms of risk and allows their classification into low-, medium-, or high-risk categories. An illustrative calculation performed on three model section of the Danube River demonstrated that sections characterised by higher traffic density and more frequent

manoeuvring achieve significantly higher risk values than open sections with smoother traffic flow. These results indicate that the proposed calculation is capable of realistically reflecting the complexity of navigational conditions and vessel behaviour that contribute to increased collision and accident risk. A key added value of proposed approach lies in its transparency and adaptability. The methodology allows for the modification of indicator weights, the expansion of the indicator set, and the incorporation of additional variables derived from AIS data, such as course changes, distances to navigation marks, crew reaction time, and other relevant parameters. This creates opportunities for the development of a comprehensive system capable of dynamically monitoring the evolution of risk situation in near real time and integrating with River Information Services (RIS).

Another significant contribution is the potential application of the results in inland waterway planning and operational processes. The risk index may serve as a supporting tool in decision related to navigation channel adjustments, buoy placement, the definition of speed limits, or the deployment of control and monitoring stations. It can also be applied as a supplementary instrument for public authorities, waterway administrators, and RIS providers in contexts where regular monitoring and preventive measures are required. The conceptual nature of the approach further allows for scientific validation through simulations and empirical data. Future research should primarily focus on the calibration of indicator weights based on statistical analyses of historical AIS dataset and on the integration of external factors influencing navigational safety, such as hydrological conditions (water level, flow velocity, channel width), visibility, and meteorological effects. A particularly promising direction is the application of artificial intelligence and machine learning methods for the automatic identification of vessel behaviour patterns that precede hazardous situation. Although the results presented in this paper are illustrative in nature, they clearly demonstrate the practical applicability of AIS data for inland navigation safety assessment. Their implementation could significantly contribute to enhancing safety and operational efficiency on inland waterways. The integration of the proposed methodology into information and monitoring systems would facilitate a transition from static risk assessment towards a dynamic, data-driven safety management framework capable of progressive implementation.

AIS represents a valuable data source for modern navigational safety management which, when combined with analytical tools and conceptual models, can provide a robust framework for accident prevention, operational optimisation, and more effective governance of inland waterway transport.

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