A framework for ship-ship collision risk assessment based on ALARP principle

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Abstract: The paper offers a framework for an operational method for assessing the risk of ship-ship collisions based on the well-known As Low As Reasonably Practicable (ALARP) principle. The suggested method defines three zones based on subjective and objective criteria, similar to the ALARP basis. Furthermore, we introduced fourth zone, defined by the Event Horizon boundary beyond which an accident become inevitable. The framework proposes a representation of human performance to attempt to offer information on the temporal, human-centered progression of the collision risk and its evaluation during a ship-ship encounter. This approach results in a complex yet feasible and operationally intuitive way to assess and mitigate the risk of collisions. This can be applicable to both manned and unmanned ships.

Keywords: Risk of collision, ALARP-principle, Maritime risk and safety, Human performance

1. INTRODUCTION

Human performance is one of the most important factors in both sustaining safe operation of imperfect maritime systems and as a contributor to accidents at sea. Maritime accidents can have catastrophic effects on the marine environment, people involved, or society. Mitigating and preventing the associated risks is highly important.

In the context of accident prevention various methods and metrics are used, among the indices used in the context of ship operation, the prevailing role of the Closest Point of Approach (CPA) index is recognized [1] [2]. Also human performance and its organizational context has been investigated by researchers, since the maintenance of safety margin and the accident avoidance process are not exclusively a kinematics problem [3] [4].

To integrate risk in the decision-making process, risk acceptance principles need to be adopted. One of those, well known in risk science, is called ALARP: "*as low as reasonably practicable*". It aims to categorize the risk values [5] [6] based on adopted acceptance criteria. However, in the context of ship-ship collision, where decisions are made by a human (officer on the bridge), this principle is implicitly followed but not formulated explicitly. Often an arbitrary division is made of the analyzed space to define the relevant boundaries, rarely adopting statistical methods or quantitative modeling [7].
In order to account for the tempo-spatial aspects of the analyzed process, the metric of complexity has been introduced recently [6] [8] [1].

However, these methods are not human-centered and may not fully consider situational perceptions and other factors, which vary depending on the progression of the ship-to-ship encounter, neither the existing methods are based on a solid methodology. Therefore, it is essential to develop a methodology allowing thorough and comprehensible analysis of the ship-to-ship encounter at all phases.

To close this knowledge gap, this research presents a novel, well-founded, and intuitive framework for operational risk assessment of ship-ship collisions. As a result, it incorporates both objective and subjective criteria. The ALARP principles applied to combine different concepts and receive a holistic approach. The framework offers details on the collision risk's grading and temporal advancement during a ship-to-ship encounter combined with a representation of human performance.

The paper is structured as follows: in section 2, an overall modelling framework is introduced, while the underlying scientific foundations and adopted methods are given in section 3. Subsequently section 4 presents the results and discusses their application. Finally, section 5 concludes the paper.

2. FRAMEWORK

The process of collision avoidance can be divided into three phases: **detection**, **assessment**, and **action**. The framework aims to facilitate phases two and three of collision avoidance maneuvers. For this purpose, three risk zones are established in accordance with the ALARP principle (Fig. 1.):

1. The zone of **acceptable risk** determined by eliciting experts' knowledge.
2. The **tolerable risk** zone reflecting a risk gradient and is estimated by analyzing human performance factors and empirical data.
3. **Unacceptable risk** area is possible to mitigate only by a special available means, for instance larger rudder deflections. The dimensions of this zone are determined by in-house collision simulator applying ship motion model.

Within the unacceptable risk zone there sits the Event Horizon (EH), which defines the critical boundary around our own ship demarcating an area that corresponds an inevitable occurrence of collision. Once the EH boundary is crossed it is impossible to avoid an event regardless of the actions taken, so the risk in that point equals 1.

To establish the zones and risk gradient for the *tolerable risk* zone in a manner that is both sound and justifiable, several approaches can be taken. These are briefly described in the following sections.

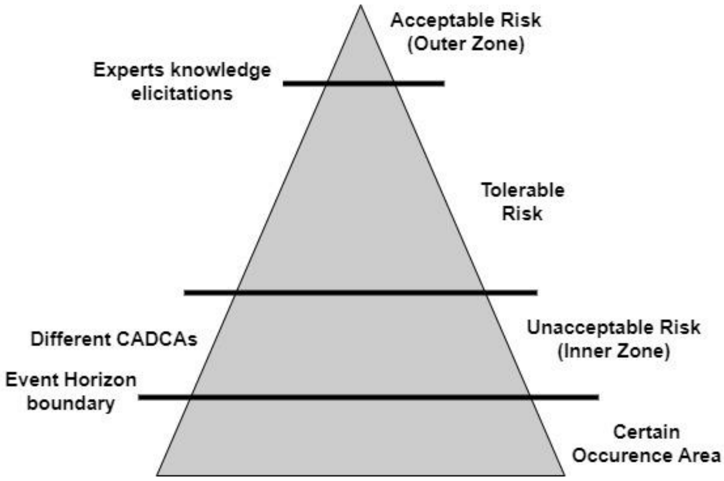

Figure 1. ALARP principle overlay on event horizon boundary and gradient concept to assess risk of ship-ship encounter.

3. METHODS

3.1. A method to define the acceptable risk zone

To enhance comprehension of the practical approach to risk assessment and its gradation in ship-to-ship encounters, it is important to identify the optimal moment for executing maneuvers as perceived by seagoing practitioners. In terms of collision risk assessment, it is important to note that this boundary serves as the starting point for the navigator to evaluate the severity of the approach and determine the advisability of an evasive maneuver. To establish this limit, which in our case is the boundary between negligible and tolerable risk, experts' knowledge elicitations were conducted.

To get reliable results, navigators were asked about their preferences for distances when performing evasive maneuvers under favorable conditions for each of the 12 relative bearings (every 30°) at which a potential target vessel was located. This results in a polygon shape area around the own ship, referred to as arena. Since it is based on preferences and declarations rather than observation we call it a declarative arena. To combine the results from all the respondents and obtain generic declarative arena a weighted geometric mean was used, since the weights reflected the level of maritime experience of respondents. The weights were given higher values as the experience level increased. Finally, a dodecagonal ship arena was identified as a representation of the boundary when risk might be classified as non-negligible based on the experience of respondents. Once a ship enters the arena, it steps into the tolerable risk zone where the risk gradient is determined using methods based on human factors analysis, as outlined below.

3.2. Methods to define the risk gradient within the tolerable risk zone

3.2.1 Human reliability analysis

Given that human error is often cited as a primary contributing factor in maritime accidents, the use of Human Reliability Analysis (HRA) techniques can be an effective means of representing human performance. HRA tools offer several advantages but are demanding in terms of information required to perform the analysis reliably. Sufficient information is required to perform a task decomposition, task classification by type, identification of foreseeable Performance Shaping Factors (PSFs), and assessment of their strength of effect to generate a Human Error Probability (HEP). However, in principle, this could allow for a general representation of increasing task difficulty and time pressure as a vessel approaches the EH where this outcome has been recognised by crew.

3.2.2 Event risk classification method

The Event Risk Classification Method (ERC-M) is based on the methodology developed for aviation. Unlike HRA, ERC-M is not limited to looking at one particular class of causal and contributory factor (i.e. human performance) as any type of barrier may be included in the analysis. The method considers a ship-to-ship interaction as the event, and a collision is the foreseeable worst-case outcome. The consideration of risk controls in the ERC-M replace a numerical or ordinal (e.g. low, medium, high) measure of probability. The lack or ineffectiveness of barriers (i.e., risk controls) identified between the event and the unwanted outcome is used as a proxy for increasing probability towards the EH.

3.2.3 Methods based on systems theories

Depending on the application of the EH model, it may be necessary to explore the factors and their interplay within socio-technical systems and their environment before the EH boundary. Two potential alternatives that provide greater penetration into complexity are Leveson's Systems Theoretic Accident Modelling and Processes (STAMP) model and associated Systems Theoretic Process Analysis (STPA) [9] and Hollnagel's Functional Resonance Accident Model (FRAM) [10].

In contrast to conventional failure-focused approaches, STPA is a qualitative method that considers the system as a whole, defines the system structure, identifies the functions that control the system and the ways the functions fail leading to the loss of control. In our case a target ship breaching the EH boundary during the encounter can be clearly defined as a loss of control scenario in STPA. Nonetheless, it is possible to identify additional, more complex loss of control scenarios that correspond with a transition between negligible, tolerable, and intolerable risk zone limits under ALARP. As the distance from the EH boundary decreases, risks related to loss of control functions connected to ALARP boundary transitions may be viewed as becoming increasingly serious.

According to FRAM, accidents are an "outcome of unexpected combinations of normal performance variability" [10]. The transition through ALARP zones to eventually approach and cross the EH boundary would be regarded as an abnormal state in terms of FRAM, due to growing large variability in the system functions' performance. The change in variability explains how the system moves from a condition that allows for regular operation while maintaining a space between ships to one that is dangerously close to each other and ultimately fails (i.e., collides). FRAM is intended to facilitate understanding of how this could occur.

3.2.4 Traffic analysis based on AIS data

Ultimately, the decision on the distance to perform an evasive maneuver in the event of a risk of a collision is at the judgement of the human operator. It may be postulated that different distances when collision avoidance maneuvers are carried out correspond to different levels of risk as perceived by navigators. Therefore, reverse engineering and the spatial-temporal analysis of distances could be employed to determine how risk is perceived and to determine its gradient. To achieve this, it might be helpful to consider utilising large Automatic Identification System (AIS) data sets that record dynamic properties of a vessel such as course speed or position. Based on these data, it is possible to identify encounter situations and then, through traffic analysis, to determine triggering evasive action distances. By drawing up a histogram of maneuver execution distance frequencies over a given distance, it is possible to derive a relationship to estimate the perceived risk for validation with operators.

Upon reaching a specific proximity threshold, the frequency of evasive maneuvers performed by navigators tends to diminish. The manoeuvre itself becomes dangerous, and avoiding a collision can only be accomplished through the implementation of exceptional measures that are not employed during everyday navigation. These can thus be classified as an unacceptable risk area. Different levels of risk in this area can be defined by different measures to be taken to avoid a collision, such as abnormally large rudder deflections. The following section describes a method for defining the risk gradient in this area.

3.3. A method to define the unacceptable risk zone

To define a region of unacceptable risk a concept of CADCA (Collision Avoidance Dynamic Critical Area) is adopted. CADCA represents a type of critical area around a ship, which, by simulating the ship's maneuvers, makes it possible to determine the envelope of the area determining the distance of execution of the so-called last-chance maneuver.

During simulation studies, an exhaustive set of geometrical arrangements of the own ship and an obstacle (stationary like an oil rig or being in motion like another ship) is considered. This makes it possible to consider all operationally reasonable combinations of mutual angular positions of the two objects, as well as their dimensions and exact shapes. During the simulation process, a distance called MDTC (Minimum Distance to Collision) is determined along with the relative bearing to the object. MDTC indicates the first distance between the objects at which the implementation of a specific evasive maneuver will allow avoiding a collision [11] [12]. This is achieved by repeatedly superimposing a predefined ship trajectory determined for various operating parameters (rudder deflections, initial ship speeds, etc.). The set of determined MDTC values is then maximized to consider the worst-case navigational scenario, and an area envelope for each of the ship's maneuvers is consequently composed. For a closer look at the conceptual and computational foundations, the CADCA determination method, and an in-depth analysis of its results please see [13] [14]. In addition, past applications of the CADCA concept can be found in [3] [15] [16].

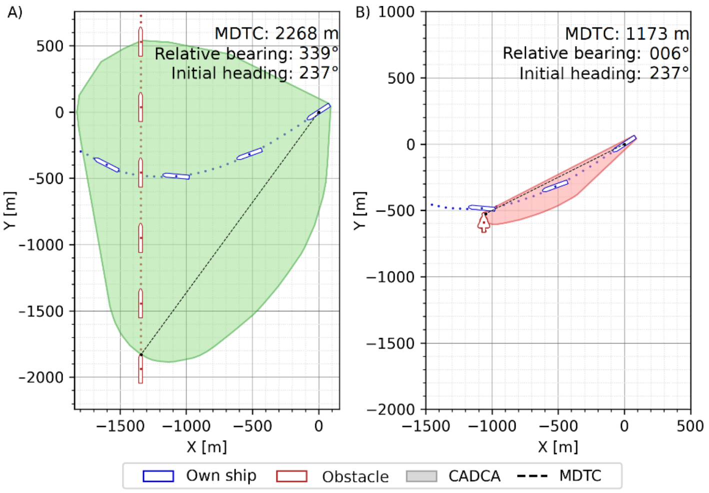

Figure 2. Sample CADCA concepts determined for exemplary simulation scenarios during encounters of Ro-Pax ship with another moving vessel (Part A) and stationary oil rig (Part B)

Since CADCA, by its definition models last-chance maneuvers for selected ship parameters (see Fig. 2. - part A for a ship in motion, part B for a stationary oil rig), it can therefore be considered that this type of evasive action should be considered unacceptable in terms of operational risk level. Nevertheless, a last-chance maneuver for a slight rudder deflection is still not a definitive indication that a collision is inevitable; after all, more decisive measures can be used, such as increasing the rudder angle. However, using the maximum parameters of the vessel resulting from her maneuverability, i.e., the largest possible rudder deflection at the vessel's current speed, ultimately indicates that a collision cannot be avoided if the limit of such CADCA is reached by an obstacle (in relative motion). Thus, intermediate CADCA envelopes can be used to model the risk level in the frameworks' region where, in principle, it has reached an unacceptable level. In turn, the EH can be defined at the boundary of the last CADCA. Breaching this boundary would inevitably lead to a collision.

4. RESULTS AND DISCUSSION

This section presents the results of the boundaries delineating the tolerable risk zone from both sides. Subsequently, the application of selected methods for determining the risk gradient within this zone will be discussed.

4.1. Declarative arena

To find out when navigators become aware of an encounter situation, we have considered practical knowledge and seafaring experience. We assume that the distance measured in the survey at which an average navigator signals his willingness or expectation that the evasive manoeuvre should be carried out corresponds to the boundary between the acceptable risk zone and the tolerable zone. The generalized declarative arena for open waters is shown in Fig. 3. The blue-color envelope delineates the distances at which the navigator's perception of risk ceases to be negligible, depending on the bearing at which the target ship is located, and steps into the area of the tolerable risk zone. It makes the relationship between perceived collision risk and bearings interpretable graphically. It is important to note that there is significantly more caution and risk at an earlier stage of the encounter (i.e., over approximately 4 NM) when the target is placed on the starboard bow sector. Targets positioned astern seem to draw less attention, and 2.5 NM is the distance at which the risk is no longer negligible. Much higher amounts of caution are given to bearings ahead of the bow as one's own ship moves forward.

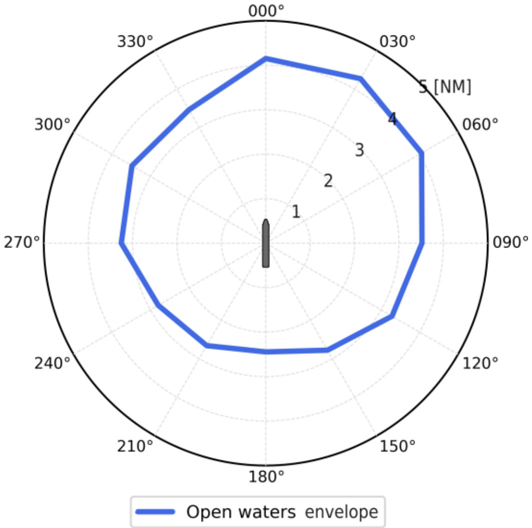

Figure 3. Declarative ship arena under favorable conditions

4.2. CADCA and event horizon

During a dangerous ship encounter it is usually possible to find several potential solutions to a given close-quarters situation e.g., by considering different parameters of own ship’s maneuver. As the CADCA changes its boundaries depending on the maneuvering capabilities of a ship, it is thus possible to determine various critical areas for a particular evasive maneuver characterized by a unique set of ship operational parameters, such as rudder deflection, forward speed, course alteration, etc., see, for instance, Fig. 4. where the CADCAs are provided for various rudder deflections and initial own ship heading (025° ± 10°). Part A depicts the sample critical areas determined for moving Ro-Pax target vessel, while part B presents the areas determined during the encounter with oil rig

Given the above, it would be possible to model an increase in risk level within an unacceptable risk region when the target crosses successive critical areas (CADCAs). In such a situation, as the last-chance type of maneuvers is considered, the risk exceeds the practically acceptable level. It is however still possible to avoid a collision by own hard-to-side maneuvers. For consideration of only own, single evasive maneuver, a collision becomes inevitable as far as the target reaches the ultimate CADCA, which delimits the EH due to constraints arising from ship maneuverability.

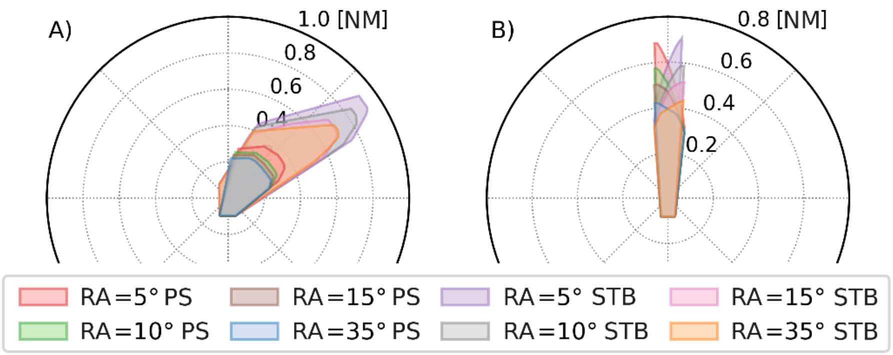

Figure 4. Exemplary CADCA results for various rudder angles (RA) and one selected initial ship heading (025° ± 10°)

The EH concept allows us to clearly delineate an accident from a non-accident sequence by defining the necessary and sufficient immediate antecedents that make an accident inevitable. This has utility as it enables us to capture the difference between the factors and their state that result in an unwanted outcome (i.e., a collision) and associated harm, and state of those same factors when they do not propagate to a harmful outcome.

When looking at real incidents, the concept of a “near miss” or “close call” is often used to express a scenario where it is plausible that accident could occur but did not. This difference is significant. Understanding what is different in a sequence of events to lead one to become a near miss, and other to become and accident helps focus practical and proportional safety management. Therefore, it is also useful to integrate this understanding into safety models so that they can reflect the mechanisms underlying different outcomes.

Using the EH and CADCA perspectives in accident modelling enables analysts to look back from an accident to determine a system's proximity to harm from the sequence of precursor events to define the necessary and sufficient antecedents to a collision. It is also useful to define exactly what factors constitute hazards that are causally linked to the harm through valid mechanisms [17]. Prospectively, these perspectives allow consideration of different encounter scenarios to understand how hazardous they are and to better understand how close a given scenario is to a loss of separation leading to an actual event.

4.3. Representation of maneuvering spaces in the tolerable risk zone

Finding an appropriate way to represent maneuvering spaces through the gradient between the inner and outer zone before the EH in relation to ALARP presents a challenge in principle. Choosing techniques and representations that can be populated with reliable data from the available sources and that allow for efficient and balanced risk communication to various possible users according to their role and task context create additional practical problems. The boundary of the EH is in essence probabilistic, representing the transition over the boundary of collision risk from <1 to 1. This emphasizes the use of quantitative methods. However, qualitative representations may be more meaningful for the purposes of practical safety management. The summary of the potential methods with their pros and cons is given in Table 1.

HRA tools are used to calculate a HEP for defined tasks performed by people. Particularly in the maritime industry, HRA tools may find it difficult to capture the variability and interactions between the ship, the crew, and the existing environmental conditions, as well as other factors that define the operational domain as it was designed for the nuclear industry. Furthermore, in any case where raw probabilistic representations of risk are approaching real time, HRA and probabilistic representations in general face unique challenges for the representation and communication of risk. The Generic Task Types (GTTs) and presence of PSFs considered within HRA are valid in terms of their known effects on human performance, providing they are calibrated to the task environment in question – in this case, maritime. However, such detailed analysis based on a task decomposition and human error perspective may not provide any greater insight into the proximity of an encounter is to the EH and accident than that provided by the temporal and physical dynamics of the encounter at ship level. This may be more constructively expressed in terms of retention of margin between ships involved in an encounter than narrowly focusing on specific human failures. In fact, the temporal-physical dynamics of the encounter are likely governed by many factors - human, technical, organizational - all interacting with their embedded environment.

Although not probabilistic, ERC-M can provide a meaningful representation of the proximity of the EH boundary based on the remaining barriers and their effectiveness, as well as whether the boundary is getting closer or further away. Similarly to HRA, it is not designed as a tool for real-time use, which may pose difficulties in quantifying the risks of a fluctuating traffic environment. In utilizing the ERC-M, it is imperative to exercise caution in identifying barriers that can be logically substantiated as causal or contributory factors to, or the preservation of margin from, the identified outcome. These barriers will also vary on a case-by-case basis.

In terms of compatibility with the probabilistic frame of the EH boundary, previous works has shown that both STPA and FRAM may be represented in Bayesian Networks (BNs). The use of BNs allows qualitative risk to be converted into quantitative risk. Autonomous ships [18] and remote pilotage operations [19] are two recent examples in the maritime domain. In addition, there are examples of FRAM models in the maritime industry [20] that are depicted using BNs. Nevertheless, this approach is still in its inchoate stages and merely attempts to convert qualitative risks into quantitative ones.

The need to restrict the application of these methodologies to the case study of a specific ship which is closed system severely limits their utilization. Very detailed models could be produced, but this requires the availability of precise, relevant input data. Accurate gradient determination in the context of ship collision risk should be a flexible system that works in a variety of situations and is applicable to the range of cases. This is an impediment to the application of these methods.

The analysis of maneuvering spaces by means of empirical data would undoubtedly allow the risks to be defined quantitatively with reasonable precision, which would be justified in relation to the probabilistic EH boundary. However, the analysis of a large AIS data set requires preprocessing and assumptions as it does not provide information on external and internal factors influencing the encounters. Therefore, it does not lay out a complete picture but only analyses the effect of these actions. Thus, it can be challenging to correctly distinguish between evasive maneuvers and those that result from normal navigation conditions, such as course alterations. To this end, it may be necessary to assume that the intention of the action in question is indeed present when the relative bearing changes by an arbitrarily fixed value. Furthermore, the granularity of AIS messages sent by ships can also present a challenge. To obtain accurate movement trajectory data, interpolation may be necessary, which is only an approximation of the actual traffic distribution.

Table 1. Summary of methods to represent maneuvering spaces

Method	**HRA**	**ERC-M**	**STPA/FRAM**	**AIS Data**
Output	Qualitative	Qualitative	Qualitative/ Transformable to quantitative	Quantitative
Suitability for purpose	Focuses on human performance which is reported as a dominant in maritime accidents Represent human performance compatible with the probabilistic frame of the EH	Incorporates safety barriers preventing from accident Although not probabilistic, it can provide a representation of how close the EH boundary is based on the remaining barriers and their effectiveness	Treats the system as a whole Enables the identification of unwanted outcomes because of complex system interactions and not only failures Enables to facilitate and understand the transition from a state of normal ship-to-ship separation distance to a precariously tightly coupled state, which can ultimately result in a collision	Implementation of a substantial data set allows for the achievement of high precision results Ease of generalisation Ability to precisely quantify risks
Limitations	Developed for nuclear industry Capturing mutual interactions between ship, crew, and other conditions limited to one contributory factor Not designed as a tool for real- time use	Developed for aviation Necessity to properly identify preventing barriers Requires detailed analysis based on a task decomposition and error	Converting qualitative risk into quantitative risk is hindered Application restricted to the one specific case - lack of generalisation Necessity of accurate and pertinent input data	The necessity of preprocessing and assumptions Lack of data on external factors influencing encounter No information on the causality of the maneuvers

5. CONCLUSION

The incorporation of the declarative arena and the CADCA into the ALARP enables to define the two boundaries representing the tolerable risk zone from both sides. These are, respectively, the limit within the risk ceases to be negligible and the EH boundary preceded by an unacceptable risk zone. The principal challenge is to ascertain the risk gradient within the tolerable risk zone.

The latter can be achieved in several ways, both qualitative and quantitative. While qualitative, HRA takes a very narrow perspective on accident causation and is not designed for maritime risk. ERC-M has been developed for the maritime domain but is deliberately moved away from quantitative approaches. In the case of STPA or FRAM, the translation of risk from qualitative to quantitative is hindered. Moreover, the approaches are typically developed for a specific case so whether they may be used in a generalizable way needs exploration. An accurate quantitative risk gradient, which can be obtained through an AIS data set, does not consider external factors and human influence.

However, utilizing a comprehensive AIS dataset may be coupled with other methods discussed above to identify an optimal balance between accuracy and a holistic approach. What approaches may support usable presentation of real-time risk determination based on a more sophisticated understanding of conditions based on approaches discussed here also needs further investigation.

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