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BOW CROSSING RANGE CORRELATION OF SMALL VESSELS – AIS DATA ANALYSIS WITH PROSPECTIVE APPLICATION TO AUTONOMOUS SHIPS

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Abstract: The development of technology has reduced the crews of ships. This trend leads to at least partial elimination of human crews in favour of autonomous ships. As more and more of them will be introduced, a safety problem arises when manoeuvring the ships in relation to each other. Therefore, there is a need to identify the factors that have an impact on determining how to maintain safe distances between ships in order to find relationships that will be useful for the development of autonomous ships. This can currently only be analysed on samples of manned vessels. Therefore, this paper aims to analyse the correlation of the Bow Crossing Range (BCR) with other ship-related data provided by AIS on ships up to 100 m long. The results of this study may be found interesting by academia, maritime industry, and autonomous ship developers.

Keywords: Bow Crossing Range (BCR); AIS data; ship collision avoidance; maritime risk and safety; maritime traffic analysis; Maritime Autonomous Surface Ships (MASS).

1. INTRODUCTION

The development of technology is bringing new innovative solutions to the maritime sector. One of them is the idea of autonomous ships, which in the future may, to some extent, replace traditional manned ships. Autonomous ships (also referred to as Maritime Autonomous Surface Ships, MASS) are expected to be implemented on a large scale not sooner than in 2035, but there are some prototypes already operational [Kooij and Hekkenberg 2021]. The general concept of the technology consists in making the prospective vessels independent, to a certain degree, of human involvement. Regardless of the degree to which this can actually be achieved, independence from human cognitive processes would require a substitute. To this end, autonomous decisions will need to be based on measurable criteria for a vast quantity of processes within the autonomous maritime system [Wróbel et al. 2021], including collision avoidance.

The process of implementing so-related solutions shows the limitations and risks that the developers of MASS have to face in order to achieve the intended goal.

One such problem is developing techniques to allow ships to safely interact with each other. Starting from the safe domain concept [Hansen et al. 2013], through Closest Point of Approach (CPA) and Time to Closest Point of Approach (TCPA) as safety indicators [Sang et al. 2016; Li et al. 2021] and ending with analyses of the navigation parameters selected by the Officer on Watch (OOW) [Zhang 2015], the feasibility of these aspects is considered for the safety of navigation. Attempts are being made to establish relatively rigid thresholds to enable safe navigation in both fully-manned and autonomy-intensive maritime traffic.

Among these indicators, (T)CPA is likely the most widely used one. However, knowing the (T)CPA only provides information about the distance at which ships will pass and the time it will take. This information is valuable but somewhat incomplete from the point of view of navigation safety and situation awareness [Gil et al. 2022]. The picture can be complemented by the Bow Crossing Range (BCR) as its value also says whether the target vessel will pass forward or aft of the ship. To this end, the BCR is understood as the distance at which one ship crosses ahead of another's bow (or astern, if negative). Knowing the value of (T)CPA will enable autonomous ships to comply with COLREG Rule 8d) (safe passing distance), while the value of (T)BCR will allow them to comply with Rule 15 (crossing situations) [IMO 2003]. As the anti-collision algorithms will work based on a neural network or other learning algorithm [Statheros, Howells and Maier 2008], the conclusion to be drawn is that the values of both (T)CPA and (T)BCR must be used during the training of this algorithm. Should the control systems of autonomous ships be based on artificial neural networks, it is of utmost importance that the proper variables and their values are used as an input – in conjunction with other, potentially relevant factors.

Therefore, the goal of this paper is to investigate the importance of the ship's dimensions, speed, and type, and the daytime in relation to the BCR value. The study was carried out within the scope of ships not more than 100 metres long. The value of 100 metres in length describes small ships, and these will probably be the first autonomous ships to come into regular service. As a matter of fact, the ships that are most likely to be the first full-scale autonomous maritime transport technology demonstrators will be operated by the companies Yara and Asko. These are to be 80 and 66 metres long, respectively [Kongsberg Gruppen 2017].

Merchant, fishing, sailing, and passenger ships operating in the Baltic Sea, in particular the Danish straits, as well as part of the North Sea were taken into account in the study. The data was obtained from the Danish Maritime Authority. The sample includes AIS reports from 01 January 2016 to 31 December 2020. On their basis, the ships with an overall length of not more than 100 metres were isolated. The distance (line of sight) qualifying two ships to the BCR calculation was set to 3 NM. On one hand, this was due to the fact that there is no widely-accepted industrial standard of what minimum BCR should be maintained under what circumstances, and this is also not addressed in the scholarly literature. On the other, the sidelights of ships larger than 50 metres have a range not less than 3 NM (as per COLREG Rule 22 a). Therefore, it is easy to judge on this basis whether the ship passed the other's bow (at least at night). Thus, it was assumed that the BCR occurs at this distance at a maximum.

All individual instances of the BCR situation are shown in Fig. 1 in the form of purple points presented on a scatter plot. The research area covers the Danish straits, the western part of the Baltic Sea and the North Sea.

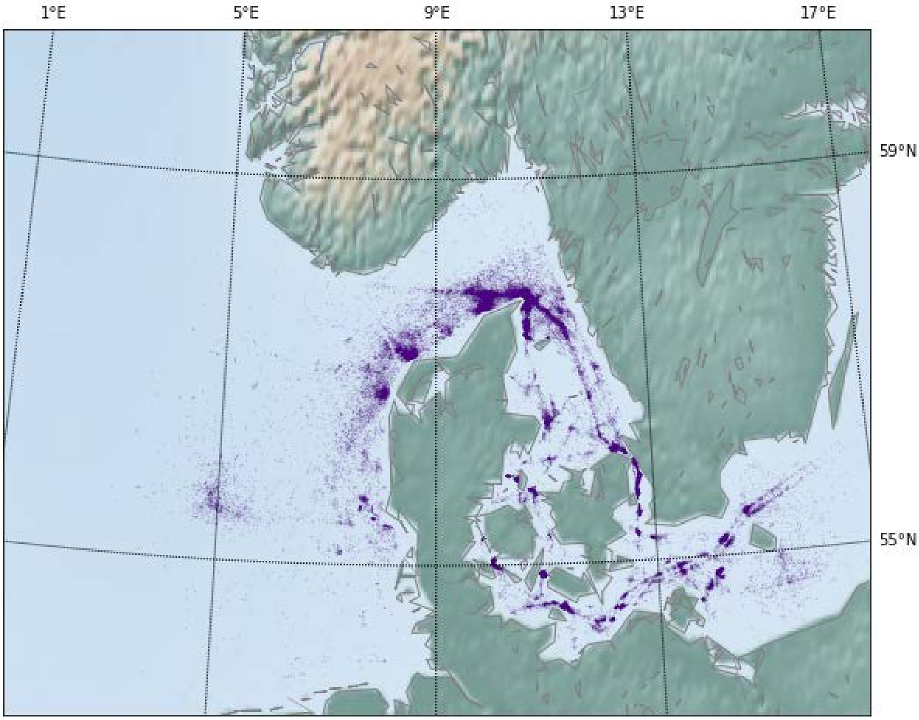

Fig. 1. Map of BCR occurrences

The BCR situations predominantly occur in coastal shipping, in narrow passages and in areas of heavy traffic [Ożoga and Montewka 2018]. Ships operating in these areas are particularly prone to collisions [Gil, Wróbel and Montewka 2019]. Much fewer ship-to-ship encounters are recorded in regions further away from the land, because ships have a larger manoeuvring area and thus encounter fewer near misses [Zhang 2015]. It can be concluded that in the open sea, the trend towards the amount of BCR generally decreases, while in restricted areas and in areas with dense traffic, the BCR situation increases in quantity.

2. MATERIALS AND METHODS

The data was obtained from the publicly available database maintained by the Danish Maritime Authority [Danish Maritime Authority, n.d.]. The sample includes AIS reports from 01 January 2016 to 31 December 2020 (5 years). On their basis, ships meeting the criterion $L \leq 100$ m were isolated.

The Danish Maritime Authority collects AIS reports from ships navigating mainly in their coverage area. The AIS is a system by which ships transmit and receive data in the form of an identification report, among other information. It is an omni-directional communication network involving ships and shore stations.

The AIS report contains:

- static data, entered into memory during device installation and updated only when changes are made by authorised persons;
- dynamic data which is information from external ship's facilities linked to AIS [Wawruch and Stupak 2010], such as: gyrocompass, log, Global Navigation Satellite System (GNSS).

The types as well as the individual percentage of ships are shown in Fig. 2. Cargo, fishing, and tanker vessels predominate, while sailing, HSC (High Speed Craft) and passenger vessels are in the minority.

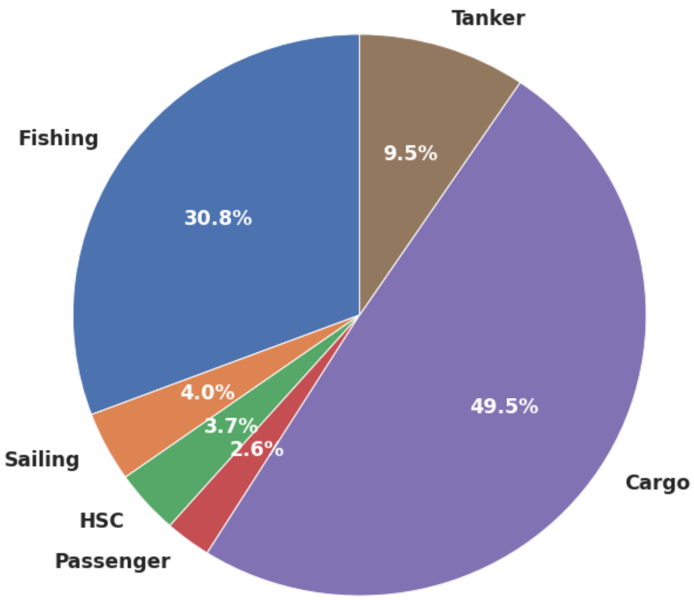

Fig. 2. Ships included in the study: breakdown by type

Next, thanks to the geographic coordinates provided in the AIS reports, the position of each examined vessel was determined. However, it should be noted that AIS data can be incorrect or unreliable [Zhao, Shi and Yang 2018; Yang, Wu and Wang 2021], so it was necessary to eliminate reports that failed to maintain data integrity. Based on the data on the position, course, and speed of the ships, it was possible to determine the distance at which the vessels passed in front of each other – the BCR itself.

In order to analyse vessel traffic in terms of the BCR situation, a ship encounter analysis was performed. Such an operation was possible by processing the data provided by the AIS reports in a proprietary tool for projecting ships' routes. For the purpose of further analysis, the ships were divided as the follows: the target ship (TS) is the ship that passes in front of the own ship (OS). Fig. 3 depicts the division.

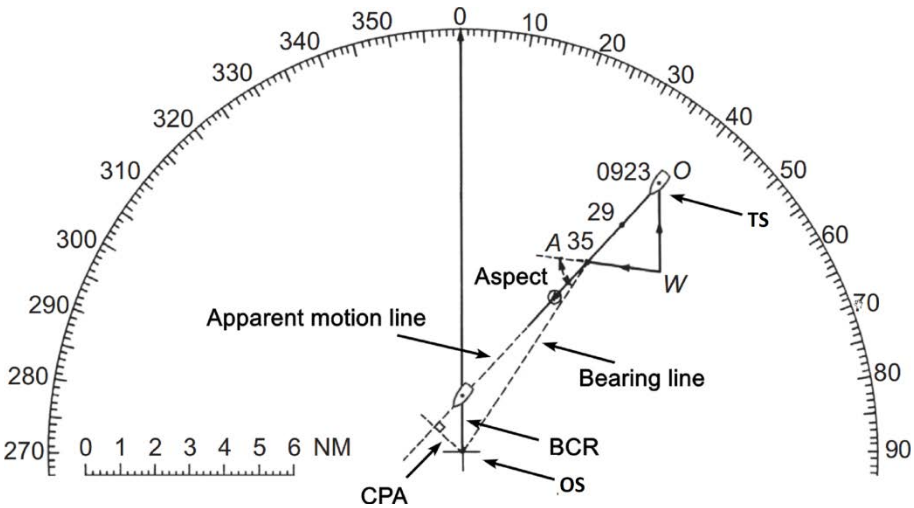

Fig. 3. Graphical representation of CPA and BCR on a radar relative-motion plot

Based on the timestamp included in the AIS report, it was possible to determine whether the encounter occurred during the day or night. It was assumed that the night begins when the sun is at least 12° below the horizon. The day begins when the sun rises above 12° below the horizon. The location of the ships was taken into account. In order to determine the time of day, a proprietary tool was created using mathematical methods and astronomical assumptions. The input data was the timestamp values included in the AIS report and the result was the time of day expressed as DAY/NIGHT.

The example model of the BCR situation along with all analysed data is presented in Fig. 4.

Example ship meeting data

OS SOG	OS LOA	OS beam	TS SOG	TS LOA	TS beam	REL speed	Day time
4.6	40.0	8.0	7.3	42.0	8.0	10.8	DAY

Fig. 4. Example row of BCR situation data

Further analysis was carried out around the specified BCR values, and the presented graphs visualising the results were obtained using statistical calculation tools.

3. RESULTS

The first part of the results of the analysis is shown in Fig. 5. Static parameters of ships as well as their Speed Over Ground (SOG) do not affect the BCR value.

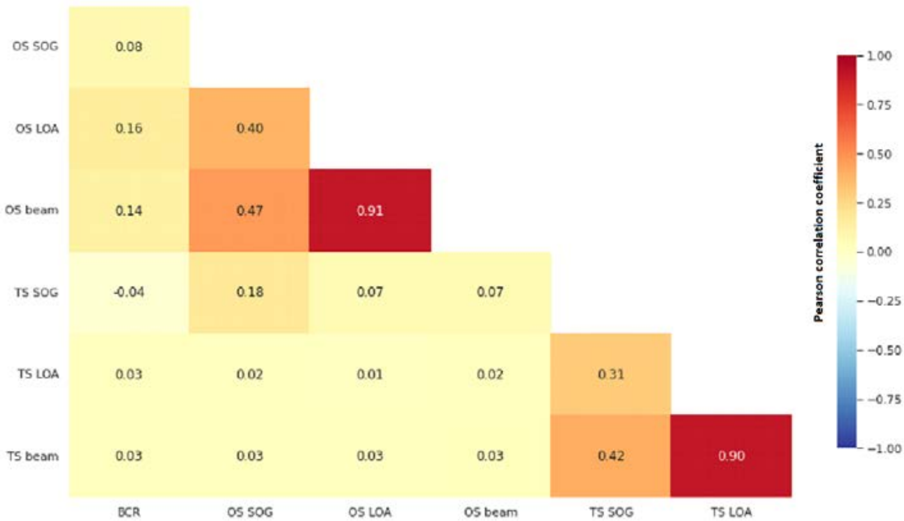

Fig. 5. Correlation map

The results indicate that none of the above-mentioned variables used in the analysis significantly influenced the value of the BCR. However, the relative differences between the variables show the degree of involvement of particular variables in relation to other – less important ones.

The comparison of the BCR situations with respect to the daytime from the OS and TS views are presented in Figs. 6–7 (obtained from the analysis of the timestamp), respectively.

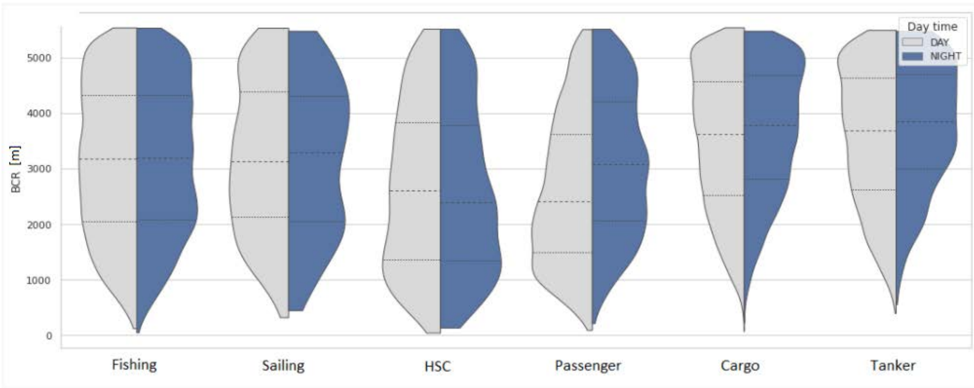

Fig. 6. Correlation plot – OS vessels with respect to daytime

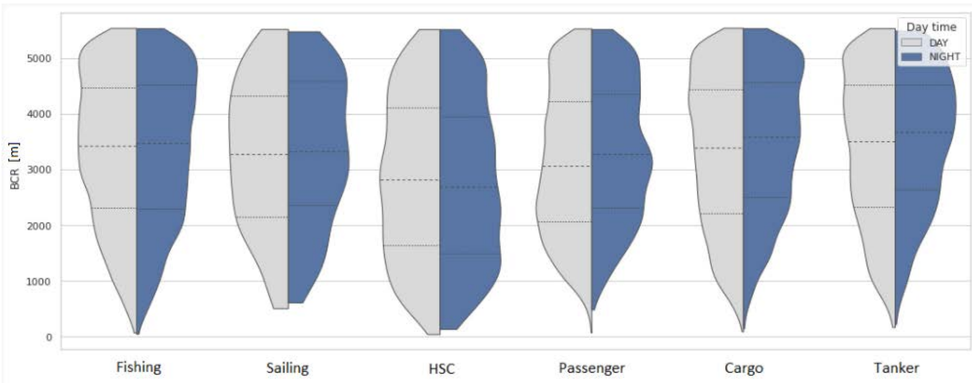

Fig. 7. Correlation plot – TS vessels with respect to daytime

For the fishing vessels, the BCR values do not differ noticeably due to the time of the day. All quartiles (dashed lines) in the day and night charts are very close to each other, which indicates an equilibrium between the values in the sample. The curves representing the distribution density do not have any distinct bulges, which indicates a tendency to dynamically adopt various BCR values, but mainly in the range of 2000–5000 m.

The BCRs calculated for sailing vessels are similar regardless of the daytime, below the first quartile and above the third quartile. This means that 25% of the BCR occurrences for sailing vessels are less than approximately 2000 m (1st quartile) and 75% of BCR values are less than approximately 4300 m (3rd quartile). The median (the middle dashed line) indicates a slight variation between the values during the day and night – the BCR values at night are slightly higher than during the day. The KDE curve (Kernel Density Estimation) shows that during the day, sailing ships tend to reach BCR values in the range of 2000–4000 m, and within 5000 m, while at night these values are around 2000 m and 3500–5000 m.

HSC vessels tend to maintain the lowest BCR values of all types analysed. The density of occurrences does not differ significantly depending on the time of day. Around 25% of observations of BCR values are less than 1200 m. The median was at the level of 2000–2500 m, while 75% of all observations do not exceed the value of 4000 m.

Passenger ships show the greatest variation in terms of BCR values during the daytime, with a median of around 2500 m. Less than 25% of the BCR values were less than 1400 m, and 75% of the observations did not exceed 3700 m. At night, there was a noticeable increase in the BCR values and a decrease in the tendency to maintain the BCR at the level of 1000–2000 m (as in the case of the daytime) in favour of possibly higher values. The median was at the value of around 3000 m, 25% of all observations were less than 2000 m and 75% of all recorded BCR occurrences did not exceed the value of 4200 m.

Cargo ships show no significant differentiation in BCR values depending on the time of day. The Kernel Density Estimation (KDE) curve indicates that this type of vessel showed a significant difference in BCR values, with a tendency to reach values in the 4000–5000 m range. The medians were maintained around BCR values of 3500–4000 m, less than 25% of all BCR values did not exceed the value of 2500–3000 m, and 75% of all BCR values did not exceed 4600 m.

The distributions of BCR values for tankers and cargo vessels are similar. A clear difference here is the density of BCR occurrences, which reaches more frequent occurrences for a wider range of 3000–5000 m in the case of tankers.

From the perspective of the TS, the fishing vessels tend to have an even distribution of BCR values regardless of the time of day. However, the density of BCR occurrences is slightly higher during the day for values in the range of 3000–5000 m.

Sailing ships being TS show more regular BCR values in the range of 2000–5000 m than when they were OS. The quartile values do not differ significantly in comparison to OS.

OS HSCs show less contrast in BCR values. The research shows that in this case, HSC vessels had values that were equally differentiated and the distribution of quartiles did not change significantly in relation to the OS.

The passenger vessel chart is smoother from the OS perspective. The daily chart changed significantly in relation to the TS vessels – the values of all quartiles increased and are around 2000 m for the first quartile, 3000 m for the median and slightly above 4000 m for the third quartile.

Regardless of the role of cargo ships and tankers in the encounter, their BCRs were similar. There is a noticeable increase in the density of higher BCR values for the night time.

The study showed that during both day and night, HSCs more often reach BCR values of less than 3 NM as the TS, the passenger vessels tend to cross in front of the bow at shorter distances during the daytime, and cargo and tanker vessels both during the day and at night tend to cross in front of the bow at greater distances.

4. DISCUSSION

The results presented above show that there is no strict relation between bow crossing range and any of the studied variables concerning ship movement and dimensions. Such a conclusion is valuable for future developers of anti-collision systems used on autonomous ships. With the assumption that these systems will operate on the basis of artificial neural networks [Statheros, Howells and Maier 2008], it is postulated that the results eliminate unnecessary features, and consequently minimise overfitting [Chen and Jeong 2007]. Therein, the results indicate that the features considered have little, if any, effect on the BCR. Thus, prospective autonomous ships will need to run the BCR calculations independently and regardless of the type of encounter. Should there be any strong correlation with any of the considered features, it might mean that BCR calculation and indication should be prioritised over other features of a given encounter, advocating for the risk of collision.

There is a possibility that the value of the BCR may depend on other factors that were not explored in this study, such as the weather or intended routes of ships not involved in the encounter. However, there is also the possibility that the BCR may correlate with factors that are not part of an AIS report, such as: experience of the OOWs, their cognitive abilities and situational awareness, master standing/night orders. The possible existence of a link between the BCR and variables that are not accessible via AIS may pose a challenge in designing autonomous ships. There may be a need to put a new system in place that can take those variables into account to assess the ship's true navigational situation.

Furthermore, if a strong correlation between ships' intended routes and BCRs is found, such a system should provide autonomous ships with access to that information. However, this, in turn, may constitute a potential threat to ships' security and safety.

Regarding the results breakdown with respect to daytime, the differences may result from the different level of visibility and human perception. During the day, navigators likely feel more confident with better visibility. The situation is the opposite during the night [Bandara et al. 2020]: much more limited visibility imposes more attention on the navigator, who wants to positively affect the level of safety and so increases the distance from the other ship, which has a direct impact on reducing the risk of a collision [Zhang 2015].

Affected vessels tend to maintain distances greater than or equal to 3 NM both day and night, with the exception of passenger vessels, which clearly behave in the opposite way during daylight. This may result from various factors, with the most important being that it is a passenger ship – it is likely due to the specificity of this type of ship and the fact that these ships move along strictly defined routes. By treating these results as a reliable illustration of navigators' habits, they may provide a comparative reference for the BCR values achievable by autonomous ships. Following this lead, it will be possible to determine the value of deviation of the behaviour of autonomous ships from manned ones.

A limitation of the study is the possibility of incorrect results due to inaccurate AIS data. Even after the rejection of clearly unreliable reports, it is impossible to completely eliminate the risk that an individual AIS report is inconsistent with the facts [Zaidan 2017; Zhao, Shi and Yang 2018; Yang, Wu and Wang 2021].

5. CONCLUSIONS

The purpose of this paper was to examine the relationships between certain characteristics of ships as contained in the Automatic Identification System (AIS) report, and the Bow Crossing Range (BCR) value during their encounters. With a longer time horizon, the study was to determine the impact of AIS data on the navigation safety of small autonomous ships and their control algorithms. The study was performed with proprietary software that made it possible to analyse a 5-year sample of AIS reports, in BCR situations, in terms of mutual correlations between the BCR value and the data contained in the AIS report.

The study showed that the vessel Speed Over Ground (SOG) and dimensions had no effect on the BCR value. In contrast, the time of day and vessel type are the aspects that showed an affect on the BCR value. The results of the study show that the time of day and ship type should be considered as factors that indirectly determine the safety of future autonomous vessels, assuming the impact of the BCR on the safety of navigation.

As there is no apparent link between the studied variables and the value of the BCR, the results of the study imply that other factors potentially lie behind the variability of the BCR values.

It can thus be concluded that the studied variables do not significantly influence the BCR of ships of Length Overall (LOA) under 100 metres. It can be assumed that there is potentially a correlation of the BCR with other variables that were not included in the study (e.g. weather, human element, location). If the BCR proves important for the design of autonomous ships, further research is needed to establish whether a correlation between the BCR and other factors exists.

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