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Factors Influencing the Action Point of the Collision Avoidance Manoeuvre

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Abstract: Perhaps the most problematic issue regarding navigation safety management is the unknown, or unknowable, is the navigator's decision made in the face of a dangerous situation. This applies particularly to collision-avoidance. The aim of the article is to identify factors that influence the moment of decision during a collision-avoidance manoeuvre and to define theoretical distributions that can be used during modelling of a navigator's behaviour. The applicable research was divided into two stages. In the first, the distance between ships and the time to closest point of approach (TCPA) were analysed. In the second, the influence of the size of the target ships and relative speed were investigated. The advantage of the paper is its use of actual observations collected in real situations. The proposed approach allows for a better understanding of the navigator's actual decision-making, which will be instructive in measures taken to improve navigational safety.

Keywords: collision avoidance; closest point of approach; safety of navigation; AIS; ARPA

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1. Introduction

Human error remains one of the most common causes of maritime accidents [1–3], responsible for between 40% and as much as 90% or even more of accidents [4–6]. This applies in particular to collisions, largely because in most cases of such potential danger, both parties must make the correct decision for ships to pass safely.

According to the Convention on the International Regulations for Preventing Collisions at Sea (COLREG) [7] an encounter situation can be divided into four stages: when the distance between ships is great enough to assume that there is no risk of collision, and ships are free to take any action; when the distance has decreased to the degree that there is a risk of collision and the give-way ship is required to take action, and the stand-on ship must keep her course and speed; when it is clear that the give-way ship is not taking action thus that stand-on ships are permitted to take action to avoid collision; and when it is not possible to avoid the collision by the give-way ship manoeuvre and the stand-on ship must take action to avoid the collision.

Quite naturally, too many variables are present at any given time for COLREGs to offer defined times or distances when the given stages begin and when the actions should be taken. Rule 8 states that "Any action to avoid collision shall be taken in accordance with the Rules of this Part and shall, if the circumstances of the case admit, be positive, made in ample time and with due regard to the observance of good seamanship". Rule 16 adds that "Every vessel which is directed to keep out of the way of another vessel shall, thus far as possible, take early and substantial action to keep well clear." This is where science is mocked by common sense, essentially, some of the best experts in navigation have been reduced by the difficulty of the task to the maritime equivalent of driving instructors: Try not to hit anything. Based on such ambiguous yet obvious information, it is difficult to build a collision-avoidance decision model that would reflect the navigator's behaviour in collision situations. Nonetheless, the development of such models is necessary to enhance maritime safety by improving navigation intelligence and autonomy in a technical way while avoiding decisions based on subjective experience, thereby eliminating human error to the greatest degree possible [8,9].

The crucial questions required to model the decision-making process are when to begin collision-avoidance manoeuvres and what factors should be taken into account. According to Cockcroft [10], the distance between ships at the moment the give way ship starts the manoeuvre should be between 5 to 8 NM on the open sea. However, this distance can vary depending on the prevailing conditions, mainly influenced by traffic intensity, size of the available area, type of encounter, speed and relative speed of the ships, size and manoeuvrability of the vessel, visibility, etc. In other words, just about every variable one can conjure [11,12].

Most of the research on decision-making is based on indirect data, methods such as expert studies or analysis of AIS records [13–15]. The other approach is to analyse the actions taken by navigators in simulated conditions [13,16–18].

Zhou et al. [19] determine the action point of collision-avoidance to minimise fuel consumption while ensuring the operational safety of the ship. Fang et al. [20] calculated collision-avoidance in heavy traffic areas with a very short distance. On the other hand, Hu et al. [21] estimated the safe distance to start collision-avoidance manoeuvre was 8 NM, Ni [22] performed trajectory planning for collision-avoidance, using action point at 6 NM for crossing and head-on situation, and 3 NM for overtaking situations. Some authors did not specify an action point distance but focused on solving the problem by ensuring a safe passing distance [23–28].

The present work aims to identify the most important factors influencing the action point in collision situations. The results are based on actual observations collected in real situations during watches carried out by navigators. The data were then subjected to statistical analysis enabling the identification of factors influencing the moment of making a decision to avoid a collision or close-quarters situation.

2. Materials and Methods

The required data were gathered during a 6-month of observation (March-September) carried out on board by a designated person (other than the officer of the watch (OOW)) on a container ship with a capacity of approx. 12500TEU. The observations were gathered during the watches carried out by all officers. Detailed data of the vessel are presented in Table 1. During the research, the vessel navigated between ports of South America and eastern Asia. The records cover high-depth open water, coastal waters and restricted water areas such as fairways, straits, rivers and traffic separation schemes.

Table 1. Main parameters of the container carrier.

LOA	366 [m]
Breadth	48 [m]
Gross tonnage	140,000
Max. draft	16 [m]
Speed	19.2 [kt]

Records were made in real-time in a specially prepared table on the basis of the data presented by AIS, radar/ARPA and own observations. It takes into account the distance between the ships, relative bearing, size of the target ship, CPA (closest point of approach—estimated point in which the distance between the own ship and another object target will reach the minimum value), TCPA (time to CPA), COG (course over ground), SOG (speed over ground), area type. Assumed parameters were recorded for all encounter situations for which the initial distance (before the manoeuvre) at CPA was lower than 1NM, irrespective of which ship was the give way vessel. The records were made at 3 specific moments:

- When an encounter situation was noticed by the OOW
- When the manoeuvre was started
- When the CPA was reached

The records concerning the starting point of the manoeuvre were analysed for nearly 200 encounter situations (67% in the open and 33% in the restricted sea area). It was assumed that the most important factors defining the moment of starting the manoeuvre were the distance between the ships and the TCPA. The analysis of the collected data was divided into 2 stages. The first included the initial analysis of parameters, consisting of a calculation of basic statistics such as mean value, standard deviation, minimum and maximum value, range. In the next step, the histogram of the examined variable was determined, the last step fitting the theoretical distribution. Despite the limitations associated with taking negative values, it was assumed that the most universal distribution allowing a description of a selected random variable was the normal distribution. The hypothesis of normal distribution was verified on the basis of the Shapiro–Wilk test. A standard value of the significance level ($p = 0.05$) was adopted.

As the hypothesis of normal distribution was not confirmed for all cases, a more detailed analysis was required. On the basis of the statistical tests (Kolmogorov–Smirnov, Chi-squared) the goodness of fit of the selected theoretical distributions was compared. On the basis of initial selection, the following theoretical distributions were taken into account in the analysis:

- Normal,
- Weibull,
- Rayleigh,
- Log-normal

The second stage involved determining the influence of selected factors on the moment of starting the anti-collision manoeuvre. Based on the collected data, the influence of the following factors was examined:

- Relative speed
- The size of the target ship

The calculations were made with the use of Microsoft Excel and Statistica software.

3. Results

3.1. Stage I

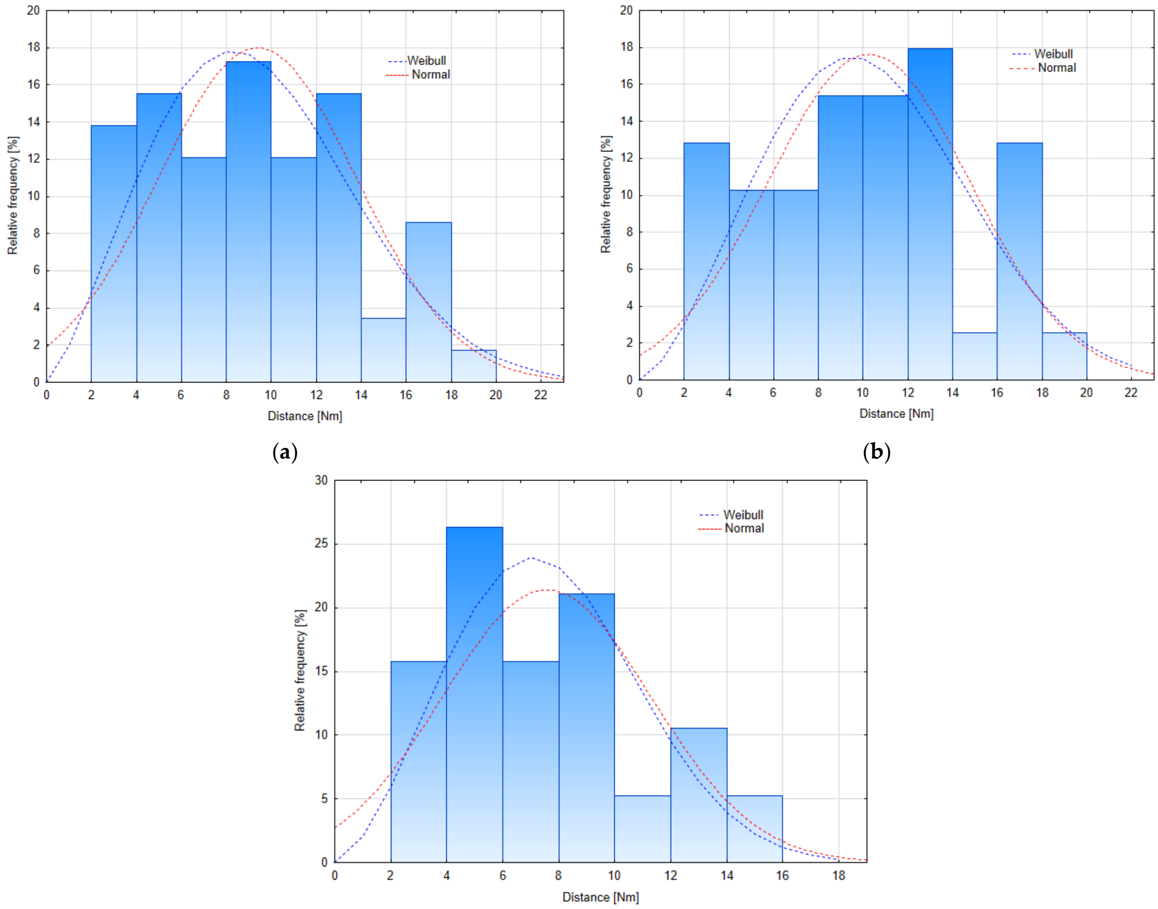
3.1.1. Distance between Ships at the Start of the Manoeuvre

The first parameter examined was the distance between the ships at the time of making the decision to start the manoeuvre. Calculations were initially carried out for all situations and then separately for open and restricted sea areas. The results are presented in Table 2.

Table 2. Basic statistics for the distance between ships at the start of the manoeuvre.

Value	All Situations	Open Sea	Restricted Sea
Mean	9.4 NM	10.3 NM	7.6 NM
Standard deviation	4.4. NM	4.5 NM	3.7 NM
Min	2.7 NM	3.5 NM	2.7 NM
Max	19.8 NM	19.8 NM	14.8 NM
Range	17.1 NM	16.3 NM	12.1 NM
S-W p-value	0.0295	0.16	0.14

The distributions of the distance between the ships at the start of the manoeuvre are shown in the histograms (Figure 1).



(**a**) (**b**) (**c**)

Figure 1. Histograms of the distance between ships at the start of the anti-collision manoeuvre and the best fitted theoretical distributions for all situations (**a**) in the open sea area (**b**) and in the restricted sea area (**c**).

3.1.2. Time to CPA (TCPA) at the Start of the Manoeuvre

On the basis of the gathered data, basic statistics on the TCPA at the start of the manoeuvre were calculated. As for the distance between ships, all situations were initially analysed, regardless of the type of area, then for the open and restricted sea areas separately. The obtained results are presented in the Table 4.

Table 3. *p*-values and distributions parameters calculated for the distance between ships at the start of the anti-collision manoeuvre.

Distribution	**All Situations**			**Open Sea Area**			**Restricted Sea Are**		
	K-S *p*-Value	**Chi-Squared *p*-Value**	**Distribution Parameters**	**K-S *p*-Value**	**Chi-Squared *p*-Value**	**Distribution Parameters**	**K-S *p*-Value**	**Chi-Squared *p*-Value**	**Distribution Parameters**
Weibull	0.445	0.301	10.62; 2.30	0.797	0.223	11.59; 2.51	0.698	N/A	8.59; 2.56
Normal	0.406	0.002	9.38; 4.44	0.849	0.472	10.26; 4.53	0.502	N/A	7.57; 3.73
Rayleigh	0.384	0.166	7.32	0.368	0.728	7.91	0.672	0.335	5.93
Log-normal	0.132	0.025	2.11; 0.53	0.293	0.112	2.22; 0.51	0.497	N/A	1.90; 0.52

The Shapiro–Wilk test did not confirm the normality of the distribution (p-value < 0.05) for all situations analysed together, while for the situations divided according to the type of area, it confirmed the normality of the distributions. This is mainly due to the differences in the manoeuvring methods in different water areas.

The results of fitting selected theoretical distributions are presented in Table 3. The best fitted distributions are presented in Figure 1. The results show that for all situations analysed together and for the situations in restricted sea areas, the Weibull distribution is the best fitted to the obtained measurements. For the situations in the open sea areas, the results indicate that according to the K-S test, the best fitted theoretical distributions are normal and Weibull, while the chi-squared test indicates the Rayleigh distribution.

Table 4. Basic statistics for the TCPA at the start of the manoeuvre.

Value	All Situations	Open Sea	Restricted Sea
Mean	26.7 min	30.1 min	19.7 min
Standard deviation	14.0 min	14.9 min	8.3 min
Min	5.5 min	13.2 min	5.5 min
Max	82 min	82 min	39 min
Range	76.5 min	68.8 min	33.5 min
S-W p-value	0.00002	0.0002	0.481

The distributions of the TCPA at the start of the manoeuvre are shown in the histograms (Figure 2).

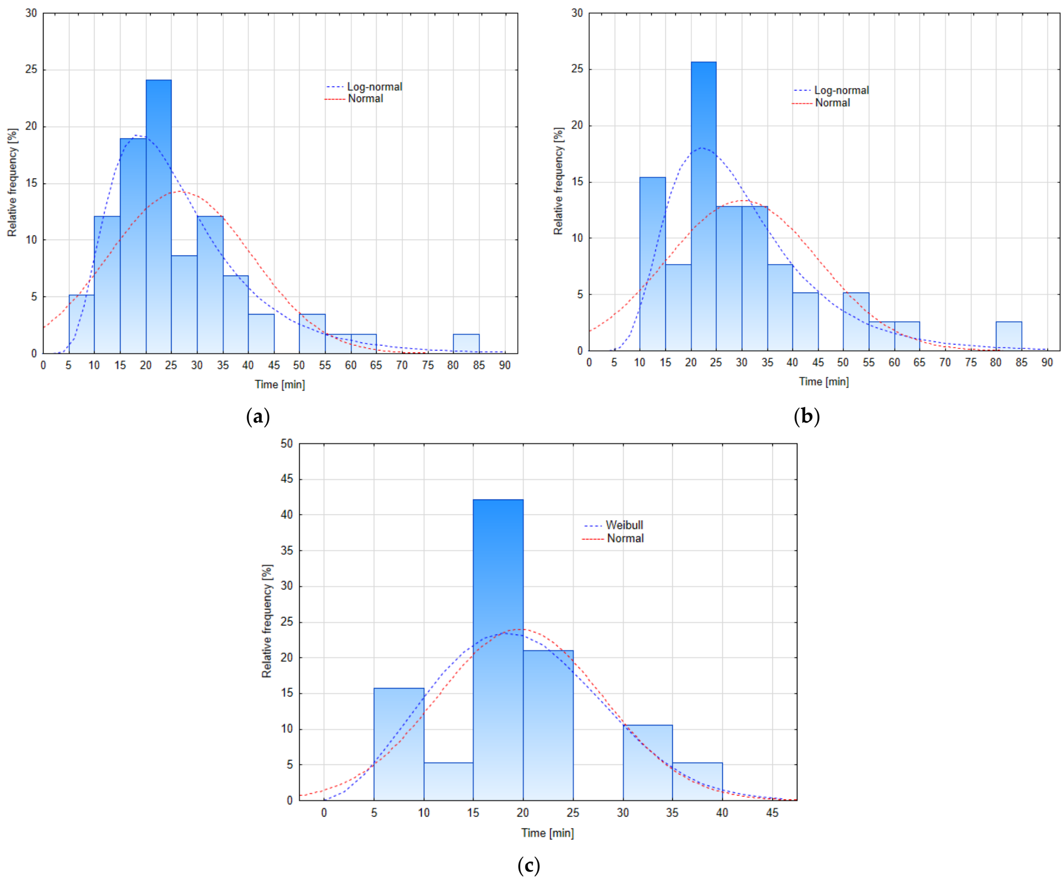


Figure 2. Histograms of the TCPA at the start of the anti-collision manoeuvre and the best fitted theoretical distributions for all situations (**a**) in the open sea area (**b**) and in the restricted sea area (**c**).

Despite the fact that the Shapiro-Wilk test confirmed the normality of the distribution for the restricted sea area, the shape of the histogram and the results for all situations and for open sea areas suggest consideration of other theoretical distributions (e.g., log-normal). The results of fitting selected theoretical distributions are presented in Table 5.

Table 5. *p*-values and distributions parameters calculated for the TCPA at the start of the anti-collision manoeuvre.

Distribution	All Situations			Open Sea Area			Restricted Sea Are		
	K-S *p*-Value	Chi-Squared *p*-Value	Distribution Parameters	K-S *p*-Value	Chi-Squared *p*-Value	Distribution Parameters	K-S *p*-Value	Chi-Squared *p*-Value	Distribution Parameters
Log-normal	0.932	0.718	3.17; 0.49	0.832	0.389	3.30; 0.45	0.406	N/A	2.88; 0.47
Rayleigh	0.356	0.560	21.27	0.363	0.024	23.71	0.266	0.071	15.04
Weibull	0.297	0.168	30.25; 2.05	0.408	0.252	34.15; 2.17	0.782	N/A	22.16; 2.60
Normal	0.079	0.009	26.7; 14.0	0.172	0.105	30.1; 14.9	0.631	N/A	19.67; 8.31

The results show that for all situations analysed together and for the open sea area, the log-normal distribution is the theoretical distribution best fitted to the obtained measurements. For the restricted area the best fitted distribution is Weibull.

3.2. Stage II

3.2.1. Influence of Relative Speed on the Distance between Ships and TCPA at the Start of the Manoeuvre

In order to assess the influence of the relative speed on the distance between ships and the TCPA value at the start of the manoeuvre, the speed was divided into intervals, and then the average distance was determined for each of them. For such prepared data, trend lines were determined, and the value of the R2 coefficient was calculated. The results are shown in Figure 3. The values of R2 equals 0.81 for distance and 0.72 for TCPA.

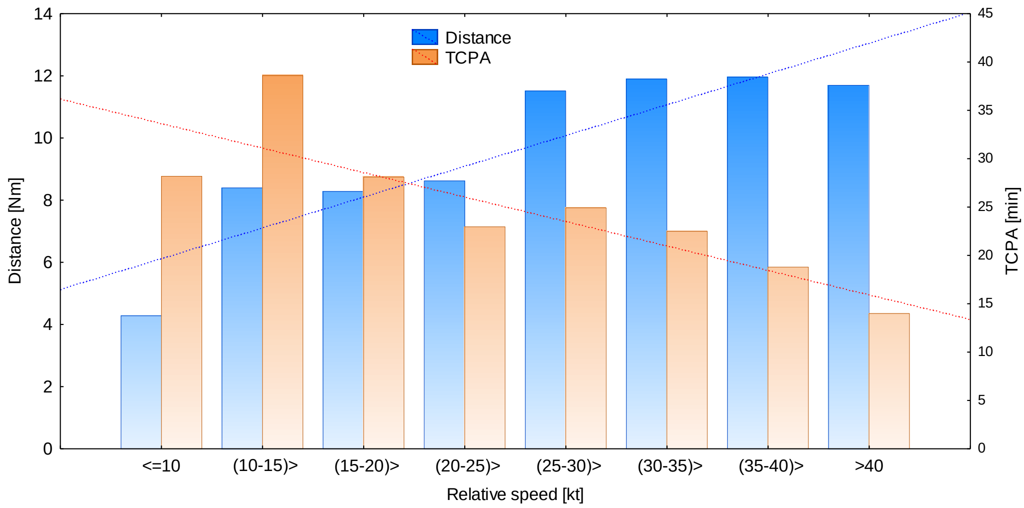


Figure 3. Relation between relative speed, TCPA and the distance between ships at the start of the manoeuvre.

3.2.2. Influence of the Size of the Target Ship on the Distance between the Ships and the TCPA at the Start of the Manoeuvre

The second examined factor influencing the starting point of the manoeuvre was the size of the target ship. The calculations were performed in the same way as for the evaluation of the influence of the relative speed. The obtained results are presented in the Figure 4, the values of R2 equals 0.61 for distance and 0 for TCPA.

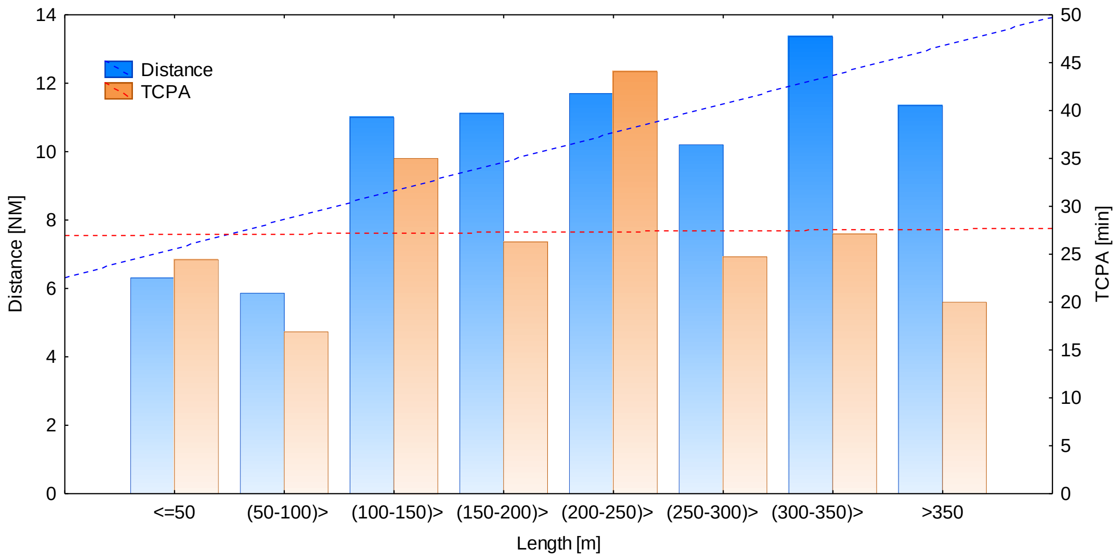


Figure 4. Relation between length of the target ship, TCPA and the distance between ships at the start of the manoeuvre.

4. Discussion and Conclusions

On the basis of the results of the statistical analysis, it can be stated that the navigator's decision-making process in encounter situations is influenced by such factors as:

- Type of sea area
- Relative speed of the ships
- Size of the target ship

As the presented results were obtained on the basis of data collected for one ship, in order to build a more comprehensive model of the navigator's behaviour in the encounter situations, it is recommended to repeat the research for other types and sizes of ships.

One of the most interesting observations is that majority of the anti-collision manoeuvres start at a distance greater than the assumed in the literature [10,21,22] as the distance at which the give-way vessel should start the manoeuvre. This is mainly due to the development of navigational equipment such as radars and AIS that allows navigators to obtain information about the situation from long distances. The average distance between ships when the manoeuvres started was 9.4 NM (respectively, 10.3 NM and 7.6 NM for open and restricted sea areas). It was observed that over 70% of the manoeuvres started before the distance between the ships decreased to the assumed 6 NM limit (77% for the open sea areas and 58% for the restricted areas). The behaviour of the navigators in the pre-COLREG situations should be subjected to more detailed analysis in the future. The S-W test confirmed that if the situations are analysed separately for the open and restricted sea areas, it is possible to use the normal distribution to model the distances between ships at the start of the anti-collision manoeuvre. Further tests showed that the Weibull is the best fitted theoretical distribution.

The results achieved for the analysis of the TCPA value for all situation at the start of the manoeuvre showed that most of them start between 15 and 25 min before CPA is reached. The average TCPA for all analysed situations is 26.7 min. The manoeuvres in open sea areas started earlier, the average TCPA was 30.1 min and for the restricted sea areas the average TCPA was 19.7 min. On the basis of statistical tests, it is not possible to definitely indicate the best fitted theoretical distribution. In further analysis, log-normal distribution should be considered.

The second stage of analysis was focused on the assessment of the influence of relative speed and the size of the target ship on the decision-making of the navigator. The results show that the influence of relative speed is significant both for the distance and TCPA at the start of the manoeuvre. For the relative speed not higher than 10 knots, the average manoeuvre started at a distance of 4 NM and when the TCPA was ca. 28 min. For the relative speed between 10 and 25 knots, the average distance at the start of the manoeuvre was about 8 NM, and for the relative speed higher than 25 knots the average distance was about 12NM. It can be stated that the higher the relative speed the lower the TCPA at the start of a manoeuvre. On the basis of the results, it can be assumed that for navigators the distance is a factor that has a greater influence on the decision of manoeuvre start than the TCPA.

The results achieved for the size of the target ship shows the correlation between the length of the target ships and the distance between ships at the start of the manoeuvre. It is especially visible for ships smaller than 100 m, for which the manoeuvres start at a distance almost twice as little than for the bigger ships.

A correlation between the size of the target ship and the TCPA at the start of the manoeuvre was not observed. It confirms the observation that decisions about the manoeuvre's start is made on the basis of the distance between the ships rather than the TCPA.

For the open sea areas, where there is more space and the traffic intensity is lower, the manoeuvres were started earlier. It was also noticed that most of the manoeuvres start at long distances, especially for the open sea areas. Such manoeuvres do not always comply with the COLREG regulations and can be subjected to more detailed analysis in the future. The best theoretical distributions, which can be used to model the distance and TCPA at the start of the manoeuvre are Weibull and log-normal distribution, respectively.

The analysis of the influence of the relative speed and the size of the target ship on the distance and the TCPA at the start of the manoeuvre shows that these factors are taken into consideration by the OOW, but the decision about the start of this is made on the basis of the distance between the ships rather than the TCPA.

However, as much of this redounds to what common sense would dictate, a qualitative study of actual encounter situations would likely yield a great deal more information. This study might be perceived as a necessary first step toward a full understanding of the behaviour of navigators in collision-avoidance scenarios. Confirming the obvious is quite necessary in science, yet even the obvious must be twice confirmed where possible. Therefore, let this paper end with the strong suggestion that as comprehensive as possible, a qualitative study be embarked upon that leaves no doubt as to the factors that truly affect the behaviour of navigators in collision-avoidance scenarios.

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