

A Novel Ship Domain-oriented Parameter of Ship Collision Risk Considering the Ship Maneuverability and Encounter Situation

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Abstract

The identification of ship collision risks is an important element in maritime safety and management. The concept of the ship domain has also been studied and developed since it was proposed. Considering the existing trend that the ship domain is increasingly widely used in collision risk-related research, a new domain-oriented collision risk factor, i.e., the current state of domain (CSD), is introduced in this paper, which can effectively reflect the current state and show a certain predictability of collision risk from the perspective of the ship domain. To further prove the rationality of the CSD, a series of different simulations consisting of three typical encounter scenarios were conducted, verifying the superiority of the proposed parameter.

Keywords Ship collision risk; Close quarters; Ship maneuverability; Ship domain; Maritime safety; Current state of domain (CSD)

1 Introduction

How to effectively and accurately evaluate the risks of ship–ship collision is an important problem, especially regarding the increasing maritime traffic volume (UNCTAD, 2020). Supported by advanced equipment, such as the Electronic Chart Display and Information System, automatic radar plotting aids (ARPAs), and automatic identification system, people can obtain real-time information about the movement of a particular ship and the traffic situation around it (Zhang et al., 2021a; Zhang et al., 2021b). This information, especially the dynamic information with the time series, undoubtedly lays a firm foundation for the analysis

of collision risk and ship manipulative decisions. As a kind of passive warning system, the widely used ARPA system uses two classic parameters, i.e., the distance at the closest point of approach (DCPA) and time at the closest point of approach (TCPA), which is a textbook example (Chin and Debnath, et al., 2009). As relative indicators to measure the collision risk of a single ship pair, the DCPA and TCPA are of great value and significance. For operators under actual sea traffic conditions, it is far from enough to make an accurate judgment by only relying on the state of ownership. Hence, we need some relative parameters, just like the DCPA and TCPA, but there are still some flaws. Szlapczynski thought that the major flaw of the DCPA/TCPA is their ignorance of the target's bearing and aspects, and it is not its only limitation (Szlapczynski et al., 2016). Zhang W strongly argues against the possibility of misclassification in using the DCPA/TCPA for the assessment of collision risk, and they proposed a diverse indicator, i.e., vessel conflict ranking operator, which utilizes the relative speed, heading difference, and ship distance to rank the severity of ship encounters (Zhang et al., 2015). The effectiveness of the systematic method and multiple indicators in the collision risk evaluation has been proven by many research works (Liu et al., 2019; Cucinotta et al., 2017; Montewka et al., 2010; Chai et al., 2017).

One of the representative approaches among these quantitative methods is the collision risk index (CRI) (Szlapc-

Article Highlights

- A comprehensive analysis of current studies centered on the collision risk index is conducted in this work;
- A new parameter to measure the collision risk between ships from the perspective of the ship domain called CSD is proposed to evaluate the problem in dynamic situations;
- A series of simulations consisting of three typical encounter scenarios on 15 specific situations were conducted.

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zynski et al., 2021). The CRI is widely used in maritime research. However, some shortcomings seriously limit its application in different conditions, such as the weight difference of some parameters (e.g., heading and speed) in different encounter situations (Szlaczynski et al., 2018), lack of standardization on parameters, problems in the aggregation method of variables, and lack of consideration of ship maneuverability, which has been strongly proven to be an important factor in many maritime-related works (e.g., ship arenas) (Davis et al., 1980; Colley et al., 1983). Gil introduced and developed the concept of the Collision Avoidance Dynamic Critical Area, a critical area that delimits the closest distance that can be used to ensure the safety of ship encounters (Gil et al., 2020; Gil et al., 2021). This kind of research that combines ship maneuverability with the ship domain is of great reference significance for the CRI.

To assess the risk of ship collision scientifically and make the current CRI method effective, this study systematically analyzes recent research works and developments concentrated on the CRI from the view of comparison. Then, a new domain-oriented collision risk factor called the current state of domain (CSD) is proposed. It aims to mine the current trend of introducing ship domain concepts into the CRI research and the analysis of the changing regularity of ship domain-related parameters under three encounter scenarios of two ship byways of simulations, i.e., head-on situation, overtaking situation, and crossing situation. The possible collision avoidance behavior taken by ships are guided by the International Regulations for Preventing Collisions at Sea (COLREGs): paragraph (a) of Rule 14, paragraph (b) of Rule 13, and paragraph (a) of Rule 15. The ship maneuverability is considered during the simulation process. Its purpose is to be closer to the specific situation, especially in close-quarter situations (IMO, 1981), and it is implemented by the Nomoto motion equation and proportional–integral–derivative (PID) con-

trol. The simulation results show the existing problems in the current CRI study and the superiority of our newly proposed parameters in the aspect of collision risk detection and reflection.

The rest of the paper is organized as follows: Section 2 provides a detailed review of the current CRI research from multiple perspectives. Section 3 provides an explanation of the calculation method and specific ship domain, where the CSD is also defined. Section 4 describes the situation of various ship encounters and demonstrates the deficiencies of common CRI parameters, such as the DCPA. Section 5 describes the mathematical model used in subsequent simulations and presents and analyzes the simulation results using three encounter scenarios of two ships. Section 6 provides the paper's conclusions.

2 Related works on the CRI

In the maritime field, especially maritime traffic, collision avoidance begins with assessing the risk of collision and the category of methods that quantify the results of this risk analysis into a numerical value, i.e., CRI. When this index violates a preset threshold, a collision alarm is launched by a triggering system. The concept of the CRI was first proposed by Kearon, and the approach used in his research to obtain the specific value of the CRI was to combine the DCPA and TCPA into one parameter using a polynomial equation (Kearon et al., 1979). This became one of the methods that have been often used in subsequent research.

In recent studies, it has become a trend to integrate more parameters into the CRI to obtain more scientific and reliable results, although this may cause disunity of dimensions or other problems.

Table 1 shows an overview of the factors considered in the CRI methods presented in the literature. Different meth-

Table 1 Summary of the research on the CRI

	M1	M2	M3	M4	M5	M6	M7	M8	M9
DCPA and TCPA	+	+	+	+	+	–	–	+	+
Ship type	–	–	–	–	–	–	–	–	–
Ship length	–	+	–	–	–	+	–	–	+
Ship position	–	–	–	+	+	–	+	+	+
Ship speed	–	+	–	–	+	+	+	+	+
Ship heading	–	–	–	+	+	–	+	–	–
Maneuverability	–	–	–	–	–	–	–	–	–
Encounter situation	–	–	+	–	–	–	–	–	+
Ship domain	–	–	–	–	–	+	–	–	+
Traffic complexity	–	–	–	–	–	–	–	–	–
Expert opinion	+	–	+	–	–	–	–	–	+
Simulation	–	+	–	+	+	–	–	+	+
Real data	–	–	+	–	–	+	+	–	–

Notes: M1: Chin et al., 2009; M2: Lee et al., 2001; M3: Mou et al., 2010; M4: Nguyen et al., 2018; M5: Zhao et al., 2016; M6: Zhang et al., 2019; M7: Zhang et al., 2015; M8: Gang et al., 2016; M9: Goerlandt et al., 2015.

ods apply different parameters, such as the DCPA/TCPA, ship position, and ship speed. Although there are many parameters or methods available for CRI research, they still show great differences in the application frequency. The DCPA and TCPA are the most frequently used parameters in research based on actual data or simulation experiments. Some physical variables, such as ship length, ship position, and ship speed, are also widely used in determining collision risk. Undoubtedly, the addition of these variables makes the determination process of ship collision risk more scientific and reasonable than ever. It also includes some studies that introduce the ship domain or ship maneuverability into the collision risk assessment.

However, there are still some flaws in the current CRI research. For instance, most of the aforementioned studies ignore the impact of ship maneuverability in the process of avoiding collisions. In addition, few cases consider the encounter situation and ship domain simultaneously in the study of ship collision risk. To fill this gap, we will perform a further analysis of the parameters used in current CRI studies and endeavor to propose a new parameter of the CRI that comprehensively considers ship maneuverability, encounter situation, and ship domain.

2.1 Factors in the CRI

The DCPA and TCPA are two variables of different dimensions. At the quantitative analysis level, the aforementioned dimensional problem arises. The most intuitive way to deal with this problem is weighting, where the DCPA and TCPA are integrated by assigning weights to them. Chin's approach is shown in Equation (1):

$$\hat{\tau}_m = \hat{\beta}_1 \times \text{DCPA} + \hat{\beta}_2 \times \text{TCPA} \quad (1)$$

$$\text{TCPA} = \text{TCPA} \frac{V}{L}$$

where the weight parameters are known parameters from the regression estimate process (Chin et al., 2009). This is consistent with the generalized form of CRI measurement, as shown in Equation (2).

$$\text{CRI}_1 = w_1 f(\text{DCPA}) + w_2 f(\text{TCPA}) \quad (2)$$

This form is widely adopted because of its intuitiveness, but in general, it is a relatively rough processing approach, and the exact method to process the DCPA/TCPA is not fixed. To solve this problem, many attempts have been made.

Lee conducted nondimensionalized processing for the DCPA and TCPA and then further reasoned using the fuzzy reasoning method (Lee H J, Rhee K, 2001). The specific mathematical methods used by him are presented as Equations (3) and (4):

$$\text{TCPA} = \text{TCPA} \frac{V}{L}, \quad (3)$$

$$\text{DCPA} = \text{DCPA} \frac{1}{L}, \quad (4)$$

where L is the length of the ship and V is the speed of the ship. The ship length and speed are also considered to some extent. An exponential relationship was established between the DCPA and TCPA values and risk in Mou's research (Mou et al., 2010). The equations are as follows:

$$R_{\text{colli}} = R_{\text{basic}} F_{\text{tcpa}} F_{\text{cpa}} F_{\text{angle}}, \quad (5)$$

$$F_{\text{tcpa}} = \exp^{-\text{tcpa}/10}, \quad (6)$$

$$F_{\text{cpa}} = \exp^{-|\text{cpa}|}, \quad (7)$$

where R_{colli} and R_{basic} stand for the dynamic and basic risks of collision, respectively; F_{angle} accounts for the different degrees of danger as a function of the type of encounter, and F_{tcpa} and F_{cpa} are the relative multipliers of the TCPA and CPA, respectively. tcpa is the value of the TCPA (min), and cpa is the value of the CPA (nm).

Different from the additive superposition in the generalized form, multiplicative stacking was selected when the final collision risk parameters were synthesized. This is more reasonable because, first, time and distance are relative concepts. If two ships encounter each other at a very close distance, the time left for the giving way ship to avoid collision will be shortened. Second, in some special cases, although the distance between the two ships is already very close, it does not pose a potential high collision risk. In this case, the weighted addition of the DCPA and TCPA may lead to misjudgment.

In addition, the exponential form is more sensitive to the changes in independent variables and can better simulate the rapid increase or attenuation of risks in the actual situation.

In Nguyen M. C.'s research, he also used the weighted stacking method to quantify the CRI (Nguyen et al., 2018). However, he set the weight of the TCPA at five times that of the DCPA. He believes that the TCPA has a much stronger impact on the ship collision risk than the DCPA. In his research, the value of the CRI is calculated as follows:

$$\text{CRI} = \alpha_{\text{DCPA}} U_{\text{DCPA}} + \alpha_{\text{TCPA}} U_{\text{TCPA}} + \alpha_R U_R + \alpha_{\Delta B} U_{\Delta B}, \quad (8)$$

where U_{DCPA} , U_{TCPA} , U_R , and $U_{\Delta B}$ are the membership functions that represent the DCPA, the time to the closest point of approach, and the distance and the azimuth of the ship and target ship, respectively. Each factor has different effects on the collision risk. The numbers α_{DCPA} , α_{TCPA} , α_R , and $\alpha_{\Delta B}$ are weights ranging from 0 to 1, and they have a total value of 1. This result indicates the effects of the collision capability of each membership function on the colli-

sion risk.

This insight is very different from that of Zhao Y's research, which used the analytic hierarchy process calculation to determine the weight values of the DCPA and TCPA as 0.453 5 and 0.360 4, respectively (Zhao et al., 2016). Their outcome claims that the proportions of the DCPA and TCPA are similar and that the DCPA is slightly larger than the TCPA. However, there is still a similar point. In the studies of Nguyen M.C and Zhao Y, the DCPA and TCPA play a major role in the overall CRI evaluation, accounting for more than 50% of the total, and the proportion reached more than 81% in Zhao Y's research.

In conclusion, as the earliest parameters used in ship collision risk analysis, the DCPA and TCPA still play an irreplaceable role in the current CRI research and even the entire maritime research system. Moreover, many efforts have been made to integrate the new parameters into the CRI. For example, the degree of domain violation (DDV) and time of domain violation (TDV) introduced by Szlapczynski et al. have gained considerable attention (Szlapczynski et al., 2021).

2.2 Ship domain in the CRI

The ship domain or navigation safety domain was first introduced by Fuji in 1971 (Fuji Y, Tanaka K, 1971): "a two-dimensional area surrounding a ship which other ships must avoid – it may be considered as the area of evasion." The ship domain here is a relatively crude concept, but it is pioneering. Subsequently, on the basis of Fuji's work, several related research works focused on the development of the ship domain were made (Goodwin, 1975; Van der Tak and Spaans 1977; Davis et al., 1980; Hansen et al., 2013; Du et al., 2021; Zhang and Meng, 2019; Pietrzykowski, 2008; Zhu et al., 2001; Wang, 2010). The concept of the ship domain was also applied to other aspects of maritime, especially those related to safety.

Fundamentally, the CRI is a value reflecting the risk of collision, and the ship domain is also for navigation safety and collision avoidance in most cases. Therefore, some researchers believe that the two concepts constitute a competitive relationship and represent two very different approaches to risk analysis (Szlapczynski et al., 2017).

However, some studies have added certain values or change rules that can reflect the characteristics of the ship domain into the CRI analysis system (Goerlandt et al., 2014; Zhang et al., 2016).

The general rationale of a domain modeling approach in collision risk assessment takes the form of Equation (9):

$$f = N_p N_c, \quad (9)$$

where N_c is the number of encounters and N_c is the causation probability that an encounter becomes a collision (Goerlandt et al., 2014). Thus, the determination of a ship col-

lision risk in a certain area can be divided into two processes:

A. Determine the number of ship encounters in this area within a given period

B. Determine the probability of a normal encounter changing into a collision

This kind of classification is also consistent with the navigation experience that all ship collisions are the result of ship encounters, and not all ship encounters will lead to a collision between ships. The ship domain is also used in both processes.

However, regarding the role of a plethora of domain shapes, few studies have tested the link between the ship domain and potential ship collisions or collision risks (Zhang et al., 2016). This is also related to a problem with the concept of the ship domain itself, namely, its lack of universality; since Fuji came up with this concept, most of the research work relevant to the applications of the ship domain has focused on small areas or confined waters (Fuji Y, Tanaka K, 1971). Even today, about 50 years later, it is still a tough task to come up with a single-ship domain that could be applied to all circumstances. Therefore, many scholars have made explorations aimed at improving the adaptability of the ship domains; the fuzzy method and probabilistic ship domain are the typical representatives (Pietrzykowski, 2008; Zhao et al., 1993; Zhang and Meng, 2019).

Generally, the boundary of the ship domain is dealt with by the fuzzy method or a similar fuzzy method. In the face of a potential collision risk, the first step for the ownership is to make a judgment of the current situation. The subsequent actions of the collision avoidance behavior are based on this kind of subjective judgment. In other words, navigators' knowledge referring to the assessment of navigational situations makes a basis for determining the ship's fuzzy domain (Pietrzykowski, 2008).

Zhao thought that the boundary of a ship domain should be fuzzy and first proposed the concept of the fuzzy boundary for the domain (Zhao et al., 1993). The domain shapes and sizes are influenced by various factors, i.e., human factor, type of the area, movement parameters, encounter type, and size of the other ships. However, some further questions about these influencing factors are not fully answered in the article, including the specific determination of a variety of human factors (e.g., knowledge, skills, and mental and physical qualities). Considering the numerous parameters above, the complexity of ship domains and related computations in practical applications have been considered by some researchers (Szlapczynski et al., 2016). Faced with these problems, a kind of ship domain named the probabilistic ship domain is also a promising approach.

Zhang and Meng proposed a novel probabilistic ship domain named α -domain, which could be intrinsically suit-

able for ship collision risk evaluation (Zhang et al., 2019). Specifically, the risk level determined by the probabilistic ship domain is a continuous value. Compared to the traditional ship domain models, it is more suitable for quantitative collision risk.

Essentially, the probabilistic domain is data-driven, whereas the fuzzy domain always depends on expert knowledge.

2.3 Numerical continuity and risk grading of the CRI

Compared to the traditional ship collision risk analysis, the biggest characteristic of the CRI is its quantitative expression of risks that makes risk analysis more scientific and accurate. Moreover, some approaches that could only provide the results of two risk statuses, i.e., risk or safe status. This is the scientific and interpretable advantage of the CRI.

Meanwhile, the exact numerical representation of a risk may not be very helpful or convenient to the navigator or the monitor's judgment, especially methods that use complex mathematical processes in the final synthesis of CRI results. Therefore, the grading of the CRI is also a fixed way during processing.

A common classification method is to classify the risk of ship collisions into three levels. According to Nguyen M.C.'s research, when $CRI \geq 0.6667$, there is a high probability of collision, so the vessel needs to take immediate action to avoid the collision. When $0.3333 \leq CRI < 0.6667$, it is likely to collide, so the vessel needs to be noted. When $CRI < 0.3333$, there is a low probability of collision, so the vessel needs to be tracked (Nguyen et al., 2018). A similar division can be seen in Zhou and Wu's research, where the vessel collision risk is divided into three levels according to the CRI: "low risk" ($0 \leq CRI < 0.4$), "moderate risk" ($0.4 \leq CRI < 0.7$), and "high risk" ($0.7 \leq CRI < 1$) (Zhou et al., 2004). This is not the only classification of the CRI. For example, Gang L believes that the rating threshold determined by Zhou and Wu can be appropriately adjusted according to the actual situation (Gang et al., 2016).

Furthermore, most of the assessment grades of the CRI were divided in an equal way. The difference only exists in the number of categories of the CRI that the researchers classified as corresponding to the risk. Different from the methods used in the two studies mentioned above (Nguyen et al., 2016; Zhou et al., 2004), Zhao et al. (2016) graded the risk into five levels: "extremely high risk" (EH), "high risk" (HR), "moderate risk" (MR), "slight risk" (SR), and "safe" (S), and the risk interval related to each level is $[1-0.8]$ $[0.8-0.6]$ $[0.6-0.4]$ $[0.4-0.2]$ $[0.2-0]$. This is a more nuanced classification. However, unlike Zhou and Wu's research, there are no recommendations about the specific actions that should be taken by the navigators.

3 Analysis of the proposed domain-based parameters

Combined with the above analysis related to the ship collision risk, we consider it promising to introduce the ship domain and its derived parameters into the quantitative analysis of the CRI. In this section, a new domain-oriented collision risk factors the CSD is introduced, which is a domain-based parameter that could be used in the CRI system. The related analysis and calculation methods of the CSD are also described.

3.1 Definition of the CSD

The CSD is a domain-based value used to quantify the DDV and reflect the dynamic trend of its change in the current ship encounter situation. It is not a static parameter that simply represents the current situation but more of a dynamic state tracking and monitoring method that could take into consideration the changing rate of the ship domain state.

The CSD is calculated based on two parameters: the overlapped area of the ship domain and the rate of change of the overlapped area. To be specific, under a given circumstance, the mathematical function of the CSD can be defined as Equation (10):

$$CSD = S_{poa}/S_{domain} + k \times R_s, \quad (10)$$

where S_{poa} is the area of the overlapped domain, S_{domain} is the area of the ship domain, R_s is the changing rate of the proportion of the overlapped domain, and k is a coefficient that is determined by Equation (12).

$$R_s = (S_{poa}/S_{domain})_t - (S_{poa}/S_{domain})_{t-1} \quad (11)$$

$$\begin{cases} k = 0 & \text{head-on} \\ \text{if } R_s > 0 & k = -10 \\ \text{if } R_s < 0 & k = 10 & \text{crossing} \\ \text{if } R_s > 0 & k = -5 \\ \text{if } R_s < 0 & k = 5 & \text{overtaking} \end{cases} \quad (12)$$

To facilitate subsequent description, S_{poa}/S_{domain} is abbreviated as POA (proportion of the overlapped area), so this formula can also be expressed as follows:

$$CSD = POA + k \times R_s \quad (13)$$

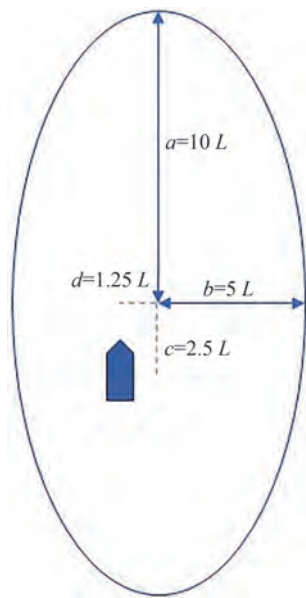
We assigned different values to the parameter k according to different situations, which is first related to the value of R_s . If R_s is positive, the value of parameter k is negative; otherwise, the value of parameter k is positive. The purpose of this design is to achieve the correction effect of the R_s parameter on the POA parameter, i.e., the change rate of the overlapping area in the ship domain on the cur-

rent overlapping area in the sense of collision risk determination. It also makes the proposed CSD parameter dynamic. In addition, the specific value of the parameter k was determined according to the different situations of the meeting.

When two ships of different sizes encounter each other, according to our method that relies on the vessel size as a part of the domain definition, there will inevitably be conflicting judgments about the danger of collision between the two ships. Therefore, we stipulate that the CSD value is equated between two vessels using the maximum value calculated from the viewpoint of each individual vessel. Similar approaches can be seen in other studies of the ship collision risk (Bukhari, A. C et al., 2013; Goerlandt, F., et al, 2015).

3.2 Eccentric elliptical ship domain

In this study, we selected an elliptic ship domain that will be used in the following research, and its specific shape is shown in Figure 1.



a —semi-major axis, b —semi-minor axis, c —deviation of the ship's center on the long axis, d —deviation of the ship's center on the minor axis

Figure 1 Eccentric elliptical ship domain

The major reasons for choosing this kind of ship domain are as follows:

- 1) A standard shape of the ship domain is convenient for subsequent mathematical expression and approximate processing.
- 2) Eccentric is a prominent character of the classic domain; the hull is not at the center of the elliptic ship realm, that is, the starboard part is larger than the port part and the fore part is larger than the back part. This feature is widely inherited and accepted that it remains in this article.
- 3) Some recent views about ship domains have been re-

viewed. In particular, some statements about navigators may incline to larger domains in many cases (Hansen et al., 2013). Therefore, a domain with a larger size is selected in this study to better focus the analysis on the overlapped domain area.

4) The length of the semi-major axis and semi-minor axis, which are the two most important variables in determining the elliptical ship domain, is considered. Unlike some classic research that does not allow the overlapping of ship domains (Fujii Y, Tanaka K, 1971), the idea of our study is to allow a certain extent of ship domain overlap and analyze the rate of change of the overlap on this basis. Therefore, a bigger ship domain size is needed to maintain the continuity of parameters related to the ship domain throughout the ship collision avoidance process. In other words, although a larger domain will lead to many more domain violations, it also means that they are more sensitive to small changes in the change rate. Eventually, we chose the eccentric elliptical ship domain with $a = 10 L$ and $b = 5 L$, which has also been applied in other studies on ship domains (Szlapczynski et al., 2016).

3.3 Explanation of the CSD

It is not an uncommon practice to introduce the overlapping phenomena of the ship domain as an indicator of ship collision alarm or analysis. Some researchers have considered that the risk of collision exists as long as two ship domains are overlapping and that the ship should take evasive actions immediately (Kijima et al., 2003). Hence, they believed that the ship domain should occupy a decisive role. This view may be rational and acceptable when only taking the small ship domain into account. However, in the case of this circumstance, we could only draw a rough binary conclusion, safety or danger, and the specific collision risk cannot be effectively quantified. Hence, it is more reasonable to make a direct quantitative analysis of the overlapping phenomenon of the ship domain.

In addition, it is not sufficient to evaluate a situation by only considering a certain moment of parameters, especially for a continuous process of movements, such as ship encounters. Taking the ship domain overlap as an example, in some cases, although the current overlapped area is large, the rate of change is also large, so the overlapped area between the two ships is rapidly decreasing, and they are rapidly moving away from each other. Thus, it is not reasonable to infer that there is a high risk of collision between the two vessels. However, if we only consider the current performance of the overlapped area, it is easy to make a false judgment. For example, Szlapczynski's DDV parameter quantifies the risk degree between the target ship and the own ship by enlarging or shrinking the target ship's domain at a specific moment (Szlapczynski et al., 2016). Such a treatment is similar to the idea of calculating the POA in the CSD calculation formula proposed in this pa-

per. That is, the DDV can only represent the risks determined by the location of the target ship and own ship and their respective ship domain at the current time. Such parameters can be misleading when dealing with some special cases, as shown in Figure 2. The same is true for small overlapped areas but rapidly increasing situations. A schematic diagram of the above two cases is shown in Figure 2

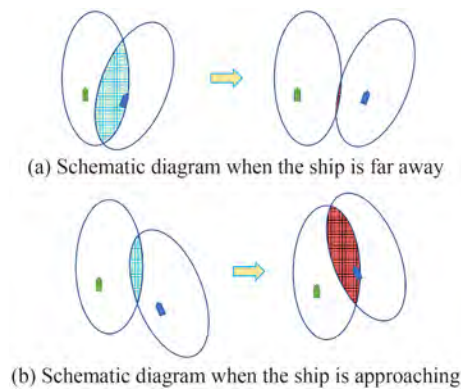


Figure 2 Schematic diagram of a moving ship

Taking the abovementioned samples into consideration, we decided to combine the overlapped area of the ship domain and the rate of change at which the two ships encounter to produce a parameter that can better describe the changing situation in the domain violation.

In addition, considering the dimension and numerical problems, the phenomenon of “a large number submerges the small number” occurs when the overlapping areas of the two vessels are directly superimposed with their changes. In other words, due to the small value of the change in the overlapped area, it will be diluted by the larger value of the change of the overlapped area to a large extent. Hence, the final result cannot effectively reflect the dynamic trend change of the ship domain.

Therefore, at the mathematical level, we chose to divide the area of the overlapping part of the ship domain by the area of the whole ship domain. The obtained overlapped area is then superimposed with the change rate. The factor that can reflect the situation of the ship domain in the ship encounter, namely CSD, can be obtained through this processing method.

4 Examples of the deficiency of the DCPA

In this section, we will first discuss the DCPA, which is the most commonly used parameter in the current CRI analysis. By comparing the parameters of the DCPA and domain-based parameter, the necessity of introducing the ship domain, especially the overlapped area of the ship domain, into the collision risk study is further illustrated.

To make the comparison results representative, we se-

lected 15 scenarios under three main encounter situations: head-on, overtaking, and crossing. For the 15 encounters, the specific situations are in line with or close to the near-miss concept.

This setting aims to control the variables to a certain extent. A near-miss itself is also a concept closely combined with collision risk in maritime research, and it is reasonable to use it as the uniform setting standard for specific situations. Generally, a near-miss is a situation in which encountering ships have almost collided (but without any physical contact) (Szlapczynski et al., 2021). In our research, we adopted Yoo SI's definition of a near-miss because of its conciseness. He defined a near-miss as thresholds of DCPA < 0.1 NM, TCPA < 3 min, and ship distance < 0.3 NM (Yoo et al., 2018). The schematic diagram of various scenarios is shown in Figure 3.

The relevant data in Figure 3 are gathered in Table 2.

A total of 15 specific situations of the three types of encounters can be observed. Compared with the figure above, for the own ship placed in (0, 0), the simulation results shown in the picture have covered the most common encounters, which include the target ships coming in different directions and at different speeds. In these cases, the own ship is not always a stand-on ship according to COLREGS. This setting is convenient for analyzing the collision risk after adopting collision avoidance behavior.

According to the data in the table, the DCPA parameter for all the encounter situations, which include S1 to S14, is 0.1 NM. However, the proportion of the overlapped area (POA) of each corresponding encounter is quite different. In terms of numerical analysis, the distribution ranges from a minimum of 1.78% to a maximum of 86.30%. Moreover, both extremes occur under the head-on encounter, i.e., S2 and S3. This is a great example of the limitations of the DCPA. For S2 and S3, except for the same DCPA value of 0.1 Nm, other parameters, such as the relative speed and the relative position of ships, are greatly different, and S2 fully conforms to Soo SI's definition of a near-miss. Based on the abovementioned data and navigation knowledge, the encounter type of S2 is much more dangerous than that of S3. In addition, the POA can significantly indicate the difference in collision risk between them, but only relying on the DCPA in this case may result in misleading.

Another phenomenon is worthy of attention, unlike the aforementioned head-on encounter scenario, which has a significant difference in the distribution of POA values. When two ships form a crossing encounter, the POA, i.e., the value of the proportion of overlapped domain areas, is relatively stable, and the value is concentrated between 30% and 60%. Based on the simulation results, crossing encounters are always accompanied by a medium level of domain violation. In other words, just from the perspective of the ship domain, there is a certain risk of collision. The simulation results are also consistent with the results of

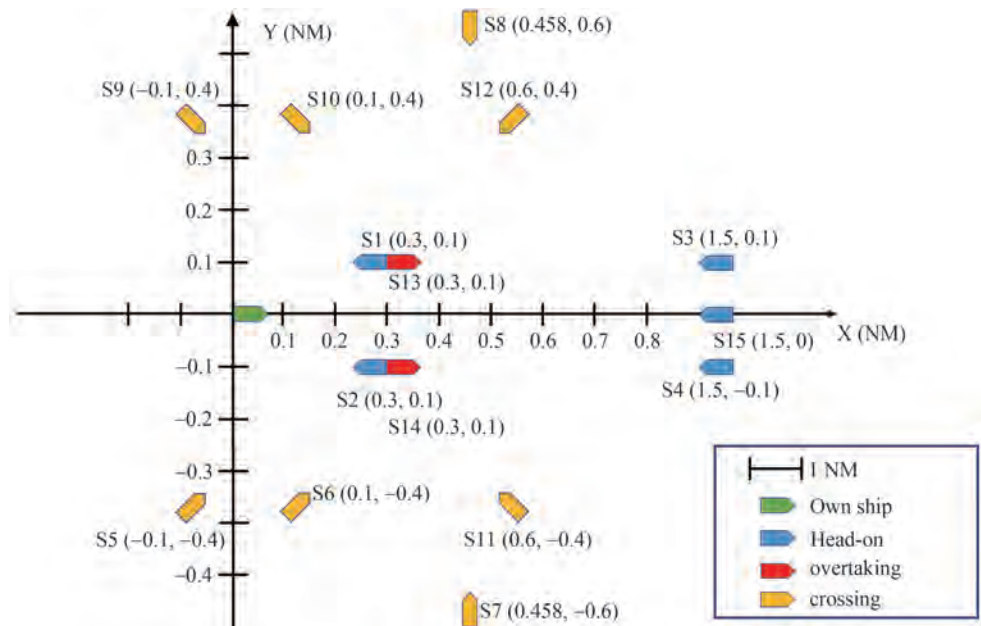


Figure 3 Description of various scenarios

Table 2 Detailed data of various scenarios

Situation	Target X	Target Y	DCPA	TCPA (s)	Ship distance	Ship domain violation (%)	Own ship speed (°)	Target ship speed (°)	Relative VX	Relative VY
S1. head-on	0.3	0.1	0.1	76	0.312 5	50.70	7-90	7-270	-14	0
S2. head-on	0.3	-0.1	0.1	76	0.312 5	86.30	7-90	7-270	-14	0
S3. head-on	1.5	0.1	0.1	179	1.495	1.78	13-90	17-270	-30	0
S4. head-on	1.5	-0.1	0.1	179	1.495	6.30	13-90	17-270	-30	0
S5. crossing	-0.1	-0.4	0.1	143	0.409 6	43.14	10-90	10.2-45	0	10
S6. crossing	0.1	-0.4	0.1	143	0.409 6	41.05	10-90	10.2-45	0	10
S7. crossing	0.458	-0.6	0.1	180.3	0.74	39.90	10.5-90	10.5-0	-10.5	10.5
S8. crossing	0.458	0.6	0.1	180.3	0.74	31.14	10.5-90	10.5-180	-10.5	-10.5
S9. crossing	-0.1	0.4	0.1	143	0.409 6	49.51	10-90	10.2-135	0	-10
S10. crossing	0.1	0.4	0.1	143	0.409 6	51.35	10-90	10.2-135	0	-10
S11. crossing	0.58	-0.4	0.1	186.2	0.700 9	58.70	6-90	6.2-315	-12	6
S12. crossing	0.58	0.4	0.1	186.2	0.700 9	36.40	6-90	6.2-225	-12	-6
S13. overtaking	0.3	0.1	0.1	179	0.314 6	66.68	10-90	4-90	6	0
S14. overtaking	0.3	-0.1	0.1	179	0.314 6	66.65	10-90	4-90	6	0
S15. head-on	1.5	0	0	179	1.5	4.39	13-90	17-270	-30	0

some studies that focused on the intersection angle of ship encounters (Szlupczynski et al., 2018).

In summary, this chapter conducts a simulation analysis of the situation of ship encounters in a near-miss or close-to-near-miss state. In particular, there is a great difference in the actual risk degree under the specific encounter situation when the DCPA index is 0.1 nm. In addition, the comparison between the POA and DCPA in the same situation explains to some extent the rationality of introducing the ship domain, especially the overlapped area of the ship do-

main, into the risk analysis. This is the basis for the evaluation performance under the consideration of collision avoidance behavior in the next section.

5 Dynamic performance of the CSD

In the previous chapter, we considered the near-miss situation as a centralized background for risk analysis and conducted a simulation analysis on 15 specific ship en-

counter scenarios. Through a comparative analysis of data, the effectiveness and sensitivity of the POA in reflecting ship collision risk are explained to a certain extent. However, all of the above situations are static. That is, although in each case, dynamic information, such as the ship's speed and heading, are set separately, we only analyzed the situation of ship encounters under a specific time node, which is not enough for a complete evaluation of the performance of the CSD factor during the entire procession of ship encounters.

For the above consideration and also for the continuity of the study, in this section, we will further analyze the dynamic ability of the CSD parameter to describe risk changes in the collision avoidance process considering ship maneuverability and COLREGS.

5.1 Mathematical model of the ship maneuvering motion

The mathematical relationship between the rudder angle δ and the ship's heading angle ϕ is expressed as Equation (14) (Yang et al., 2003):

$$\ddot{\phi} + \frac{K}{T} \dot{\phi} = \frac{K}{T} \delta, \quad (14)$$

where K is the steering quality index, and T is the steering quality time constant. These parameters are a function of the ship's constant forward velocity and its length. This formula will serve as the basis for simulating the ship heading adjustment in this research.

The mathematical model of the velocity of ship maneuvering can be expressed as Equation (14) (Yoshimura et al., 1978):

$$\dot{V} + a_{vv}V^2 + a_{rr}\dot{\phi}^2 + a_{\delta\delta}V^2\delta^2 = a_{nn}n^2 + a_{nv}nV, \quad (15)$$

where V is the velocity of the ship, n is the propeller revolution, a_{nn} and a_{nv} are thrust coefficients, and a_{vv} , a_{rr} , and $a_{\delta\delta}$ are damping coefficients.

5.2 Simulation experiment

To reduce unnecessary variables and make the simulation intuitive, in the whole simulation experiment, the own ship and target ship have the same principal particulars and maneuverability characteristics. This part of the research is based on Wang Xin's work (Wang X, et al., 2017). Based on his research, the PID control is used as the specific ship motion control mode, and the PID control mechanism parameters are $K_n = 0.1$, $K_p = 10$, $K_d = 150$, and $K_i = 0.001$. Other specific parameters are shown in Table 3.

5.2.1 Scenario 1: Head-on situation

In this part, the S1 scenario of the above encounter is an-

Table 3 Principal particulars and maneuverability characteristics of the sample ship

Length (m)	126.0	K	0.48	a_{vv}	1.4×10^{-4}
Breadth (m)	20.8	T	216.5	a_{rr}	101.5
Draft (m)	8.0	K_E	1	$a_{\delta\delta}$	1.6×10^{-3}
Block coefficient	0.681	T_E	2.5	a_{nn}	1.4×10^{-2}
Displacement (t)	14.278	N (r/min)	120	a_{nv}	5.9×10^{-4}

alyzed in detail, and the initial coordinates of the own ship and target ship are (0, 0) and (0.3, 0.1), respectively. The initial heading angles of the own ship and target ship are 90° and 270° , respectively. The initial velocities of the own ship and target ship are the same, i.e., 7 kn. Clearly, the current encounter situation of the own ship and target ship reached a close-quarter situation. According to paragraph (a) of Rule 14 of COLREGs, when two vessels meet in opposite or nearly opposite directions, and there is a collision danger, each vessel shall alter its course to the starboard so that each shall pass on the port side of the other. To compare and illustrate the effectiveness of the dynamic performance of the CSD under different collision avoidance behaviors, it is assumed that there are two patterns of action to avoid a collision:

A. Under this pattern, it is supposed that the action to avoid collision is taken by the own ship or target ship alone.

B. Under this pattern, it is supposed that the action to avoid collision is taken by both encounter ships.

In Pattern A, only one of the two ships in the situation takes avoid action. As described in Section 5.2, as the own ship and target ship have the same principal particulars and maneuverability characteristics, we supposed that the action to avoid collision is taken by the target ship alone. To be more specific, the target ship will alter its course to the starboard in three kinds of extensions (30° , 45° , and 60°) during the simulation procession. The simulation results are presented in Figures 4~10. The trajectories of two ships at time $t = 100$ s, 200 s, and 300 s are shown in Figure 4.

Figure 5 shows the curve of the dynamic DCPA and TCPA when the target ship alters its course to 315° , with an avoidance angle of 45° .

Through the abovementioned diagrams, especially the trajectory diagram of the target ship, we can obviously notice the influence of ship maneuverability characteristics, such as large inertia, time delay, and nonlinearity, on the ship collision avoidance movement. This result also confirms the necessity of considering ship maneuverability in the simulation process. As shown in Figure 5, the DCPA begins to change rapidly at $t = 0$. That is, after the target ship begins to take collision avoidance behavior, the TCPA rapidly increases, indicating a reduction in the ship collision risk. That is, from the perspective of the DCPA and TCPA, the collision risk between the two ships continues

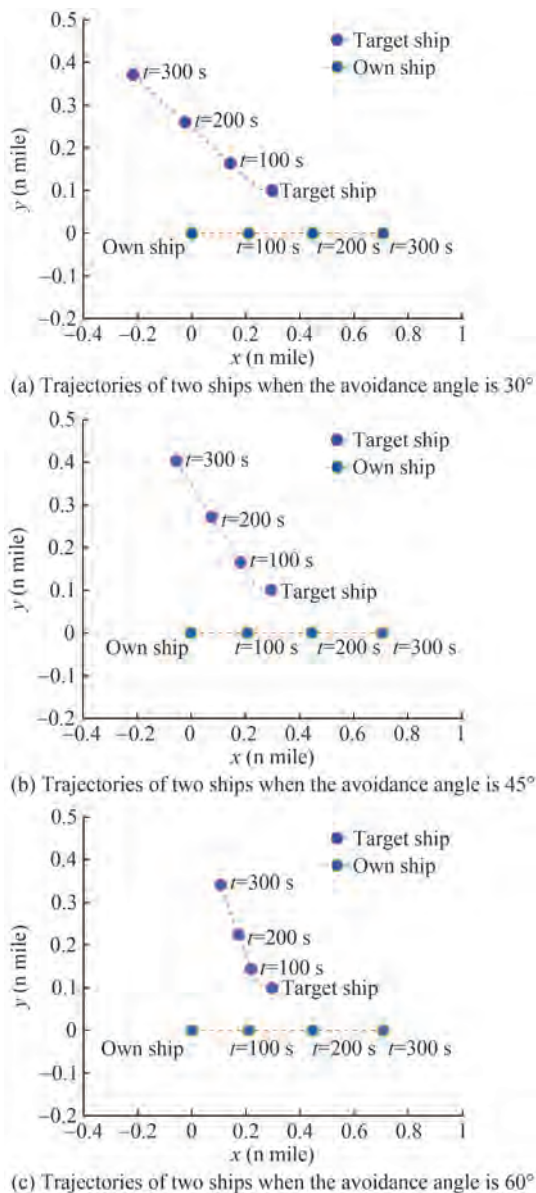


Figure 4 Trajectories of two ships in S1. Pattern A

to decrease during the entire course of the ship encounter, starting from $t = 0$.

However, as shown in Figure 6, during the process of avoiding a collision, the relative distance between the own ship and the target ship experiences a decreasing to increasing trend. The relative distance between the two ships reached a minimum value of around 70 s. From the perspective of navigation, as the relative distance between ships decreases, the collision risk increases. This feature cannot be effectively reflected in the changing trend of the DCPA/TCPA.

In Pattern B, the action to avoid collision is taken by both encounter ships. Compared to Pattern A, it is also a typical collision avoidance behavior under a head-on situation. Analogously, for the sake of comparison, the adjust-

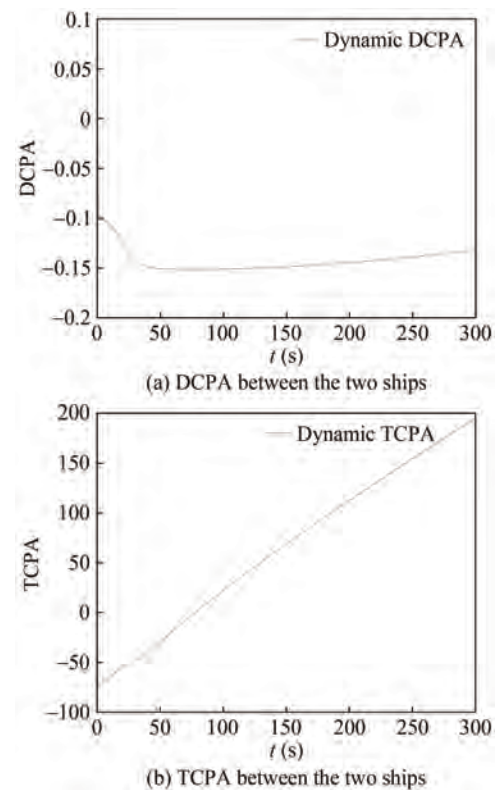


Figure 5 DCPA and TCPA between the two ships in S1. Pattern A

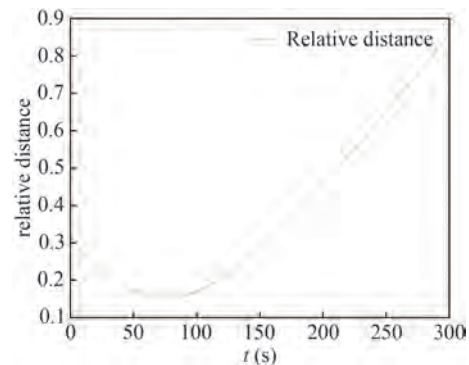


Figure 6 Relative distance between the two ships

ment angles for the ship maneuvering of the two ships were set as 30° , 45° , and 60° . The trajectories of the two ships at time $t = 100$ s, 200 s, and 300 s are shown in Figure 7.

For the sake of comparison, Figure 8 shows the DCPA/TCPA curve between the own ship and the target ship when the two ships both changed their course to the starboard at 45° .

Although the situation of the single-ship avoidance in pattern A has changed to that of the two-ship avoidance in pattern B, there is no significant difference in the two indicators of the DCPA and TCPA. In particular, the curve trend shows a strong similarity, and there are only differences at some extreme values, such as the lowest DCPA value.

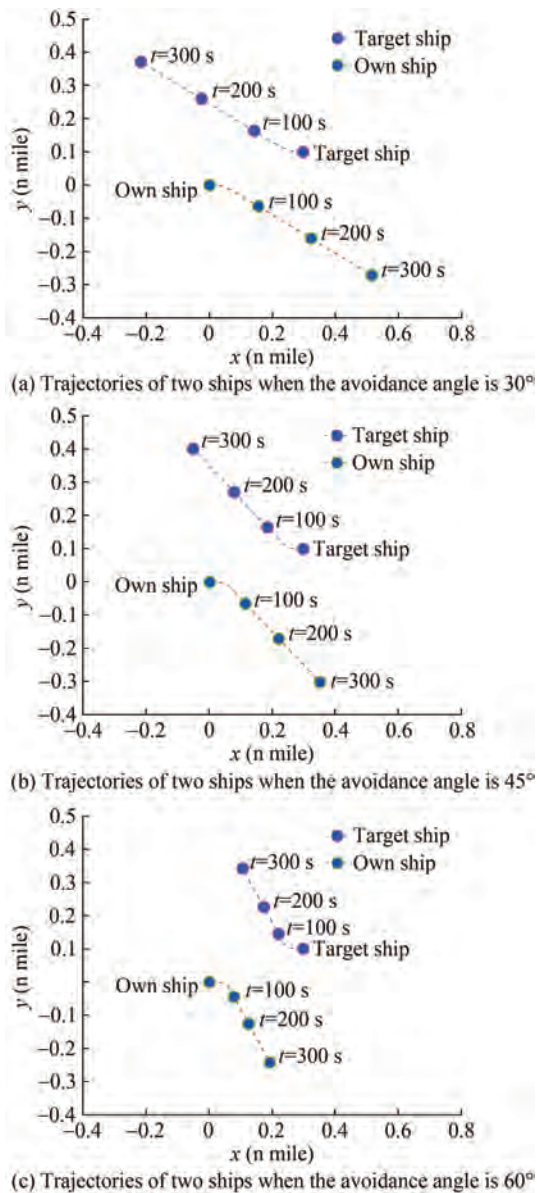


Figure 7 Trajectories of two ships in S1. Pattern B

Figure 9(a) presents the curves of the DCPA and TCPA between the own ship and the target ship. In Figure 9(a), although there is an obvious difference in the predetermined angle of the heading adjustment, the difference ultimately reflected in the change in the DCPA value is even small. In particular, the two curves of the ship's heading adjustment of 45° and 60° show the red and yellow curves in the figure, which are very close to each other. Moreover, the three curves are highly similar or even completely overlapped in the initial stage of about $t = 0$ s to $t = 35$ s. This feature is also reflected in the corresponding part of Figure 9(b).

The analysis of the traditional DCPA/TCPA indexes in the dynamic process of different collision avoidance behaviors in the head-on situation is presented above. Generally, it has the following characteristics:

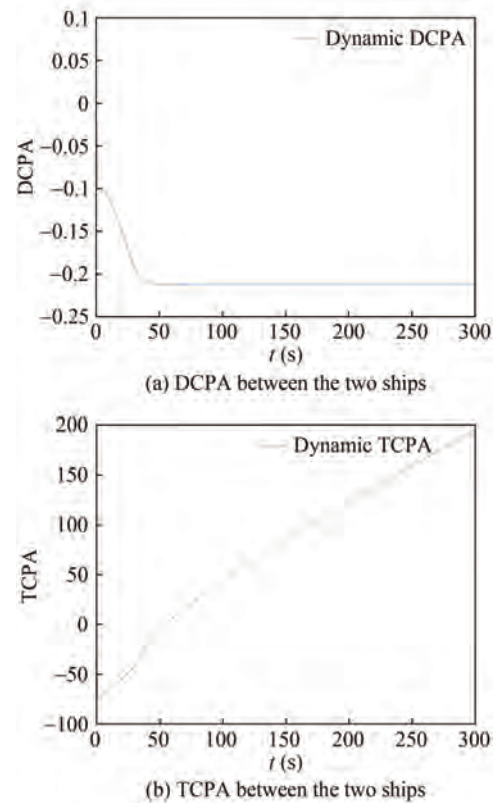


Figure 8 DCPA and TCPA between the two ships in S1. Pattern B

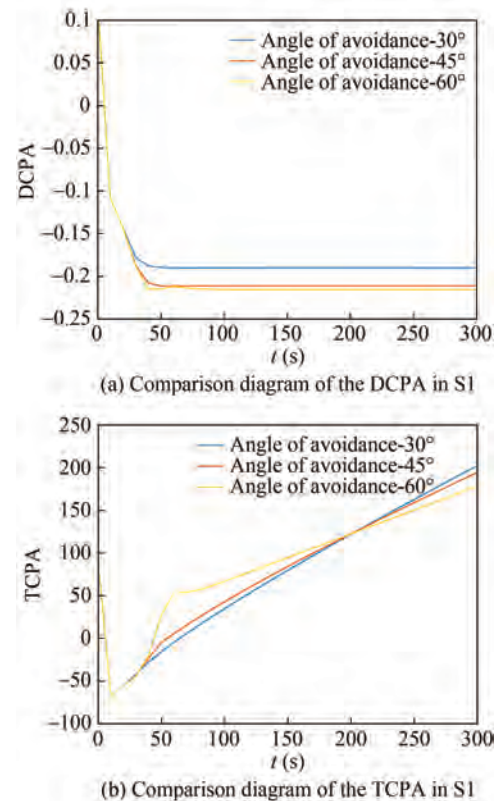


Figure 9 Comparison diagram of the DCPA and TCPA

1) In the initial stage, that is, at the beginning of the collision avoidance behavior, the DCPA/TCPA index variation trends are approximately completely consistent under different collision avoidance angles or show a high degree of similarity. This phenomenon should be affected by the ship's own maneuverability performance.

2) The value changes of the indicators are highly limited in reflecting the difference in collision risk changes caused by different collision avoidance amplitudes, especially reflected in the TCPA.

Similarly, to make the comparative test scientific, we also conducted a simulation test on the performance of the proposed CSD parameters according to the two possible collision avoidance choices of Pattern A and pattern B. All relevant parameters involved in the simulation experiment remain unchanged, and the specific values are shown in Section 5.2.

Figure 10(a) shows the curves of the CSD under a specific situation of Pattern A. The three curves in different colors in the figure represent the changes in the CSD parameters under avoidance amplitudes of 30° , 45° , and 60° . Similarly, Figure 10(b) depicts the simulation result of the CSD under Pattern B.

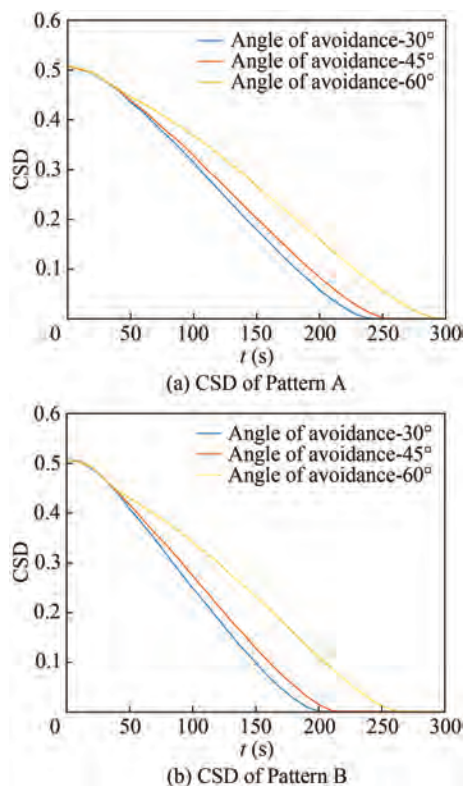


Figure 10 CSD of S1

Obviously, regardless of having Pattern A with a single ship's avoidance or Pattern B with both ships' avoidance, the CSD can describe the whole dynamic process of a ship avoiding collision and reflect it effectively through regular

numerical changes. As time goes by, the value of the CSD parameter also continues to decline, and among the three preset avoidance ranges, the value of the CSD with the preset avoidance range of 30° declines the fastest. Of course, it is the first one to get to 0 at about 240 s in Pattern A and at about 200 s in Pattern B.

Moreover, the CSD parameters decrease at a significantly faster rate in Figure 10(b) (Pattern B, i.e., the situation in which both ships involved in the encounter take starboard avoidance) compared with that in Figure 10(a). From the perspective of navigation knowledge, Pattern B shows a faster decline rate of collision risk than Pattern A. In other words, the proposed CSD parameter can effectively reflect this characteristic. Compared with the aforementioned DCPA/TCPA parameter curves, which are highly similar, it further reflects the rationality and advantages of CSD parameters.

5.2.2 Scenario 2: Crossing situation

In this part, the S7 scenario of the above encounter is analyzed in detail, and the initial coordinates of the own ship and target ship are (0, 0) and (0.458, -0.6), respectively. The initial heading angles of the own ship and target ship are 90° and 0° , respectively. The initial relative distance is 0.41 n mile. The initial velocities of the own ship and target ship are the same, i.e., 10.5 kn. Obviously, the current encounter between the own ship and the target ship constitutes a crossing situation, and the specific intersection angle is 90° , which was considered by some studies to be the most dangerous ship intersection angle (Szlapczynski et al., 2018). In consideration of this, S7 was used as a typical crossing scenario for the simulation analysis in this study.

According to paragraph (a) of Rule 15, the own ship and target ship in S7 reach the crossing situation to involve the risk of collision. Acting according to COLREGS, the own ship shall keep out of the way of the target ship and avoid crossing ahead of the target ship. Because the collision avoidance rules do not make specific provisions on the ship avoidance angle and consider the complexity and diversity of the actual maritime traffic environment, we supposed that the action to avoid collision taken by the own ship will contain three different avoidance ranges (30° , 45° , and 60°). The simulation results are presented in Figures 11~14.

The trajectories of the two ships at time $t = 100$ s, 200 s, and 300 s are shown in Figure 11(a), (b), and (c), respectively.

In the three simulated tracks shown in the figure, the own ship can cross its own track from the stern of the target ship after taking corresponding avoidance maneuvers and meet the requirements of COLREGS for a crossing situation that the give-way vessel needs to avoid crossing ahead of the stand-on vessel. That is, the three avoidance options of different amplitudes are in line with the rules and hence are feasible. Accordingly, the ability of each pa-

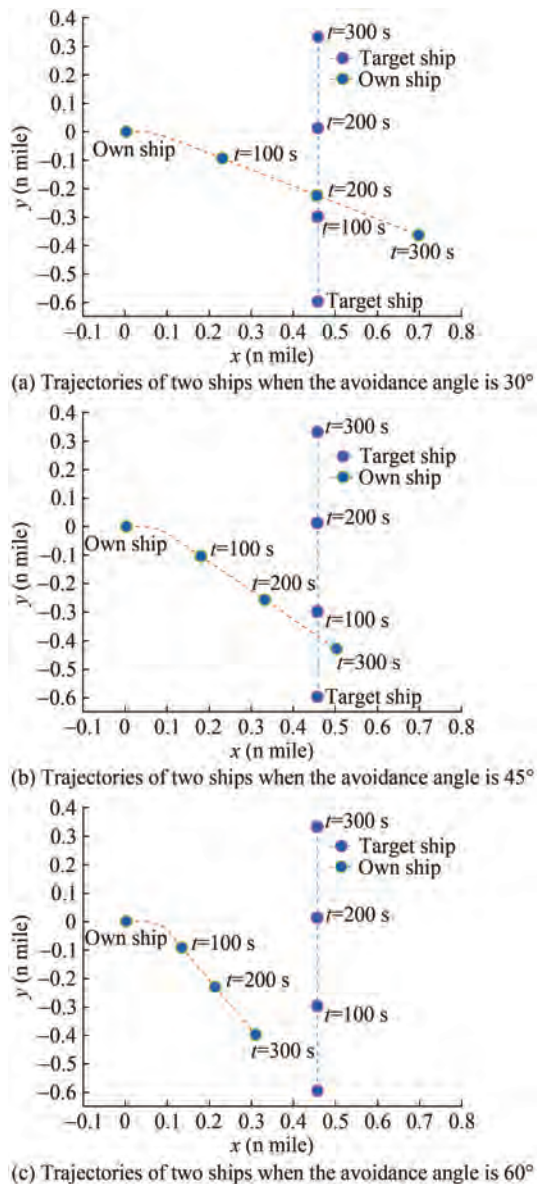


Figure 11 Trajectories of two ships in S7

parameter to depict risks in the collision avoidance process will be further analyzed below.

Figures 12(a) and Figure 12(b) present the curves of the DCPA and TCPA between the own ship and target ship under crossing situations, respectively. This is similar to Figure 9(a) and Figure 9(b), i.e., head-on situation, where the curves of the DCPA and TCPA show a strong similarity, especially in the TCPA, and the three curves remain almost perfectly overlapping during the whole encounter process.

Figure 13(a) shows the curves of the CSD under the specific situation of S7. The three curves in different colors in the figure represent the changes in the CSD parameters under avoidance amplitude angles of 30° , 45° , and 60° . For the sake of comparison, we also depict the numerical variation of the ship domain-overlapped area under S7 in

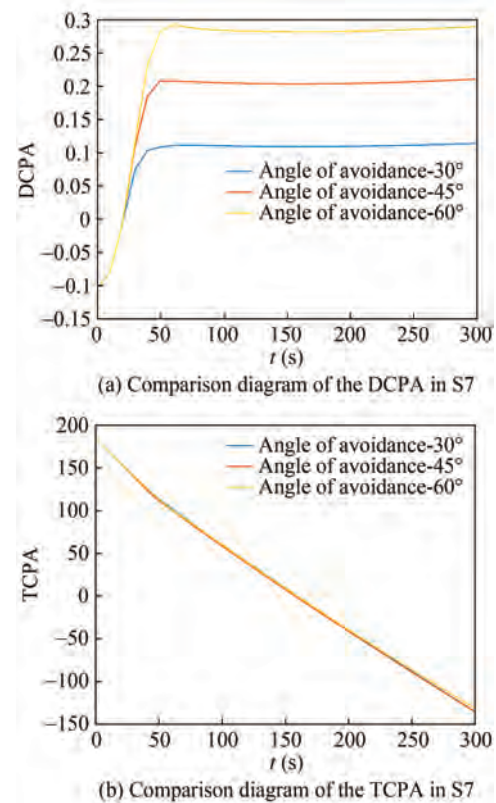


Figure 12 DCPA and TCPA between the two ships in S7

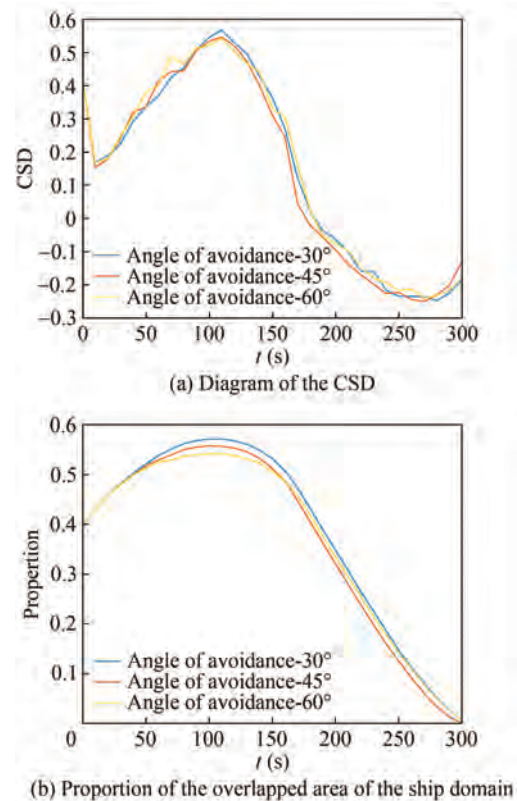


Figure 13 CSD and variation in the ship domain overlapped area under S7

Figure 13(b) to further illustrate the advantages of using CSD parameters.

For the crossing encounter situation, e.g., S7, after taking the starboard steering action of the give-way vessel, that is, the own ship in S7, the change in the CSD index is the sudden attenuation of the CSD value around 0–10 s, as shown in Figure 13(a). In other words, the new parameter proposed in this paper, namely CSD, is reflected in the rapid decline of collision risk between ships. It is reasonable to consider nautical knowledge and COLREGS. If the give-way vessel takes the behavior in accordance with the COLREGS in the encounter, it will certainly be reflected as a sudden decline in the aspect of collision danger at that moment. However, we cannot see the effective reflection and description of this feature in Figure 13(b), which is the change in the overlapped area of the ship domain.

Another point worth noting is the change phenomenon of the CSD index increasing first and then decreasing rapidly in the time range of 10–175 s. We analyzed the rapid increase in the CSD value at the beginning from the perspective of the ship movement and the formation of collision risk between ships at sea based on the trajectory diagram in Figures 11(a), (b), and (c). Although the ship has taken the starboard avoidance behavior, from the perspective of common CRI indicators, such as the ship's relative position and relative course, the two ships under the encounter state are still getting close to each other, and there are increasing potential collision risks. Figures 14(a), (b), and (c) show the relative distance curve of different avoidance amplitudes in S7.

As shown in the figures above, because S7 simulates a crossing-encounter scenario, the relative distance between the two ships minimizes at the moment when the give-way vessel passes the stern of the stand-on vessel. After this moment, the risk of collision between ships can decrease rapidly and even be nonexistent. As shown in Figure 13(a), the CSD value starts to decrease rapidly around $t = 150$ s and decreases to 0 around $t = 180$ s, which is specifically consistent with the relative distance of the ships shown in Figure 14(a), (b), and (c).

5.2.3 Scenario 3: Overtaking situation

In this part, the S13 scenario of the above encounter is analyzed in detail, and the initial coordinates of the own ship and target ship are (0, 0) and (0.3, 0.1), respectively. The initial heading angles of the own ship and target ship are the same, i.e., 90° . The initial relative distance is 0.3146 n mile. The initial velocity of the own ship and target ship is 10 and 4 kn, respectively.

According to paragraph (b) of Rule 13, the own ship and target ship in S13 reach the overtaking situation to avoid the risk of collision. When acting according to COLREGS, the own ship that is overtaking the target ship shall keep out of the way of the target ship that is being overtaken. We supposed that the action to avoid collision taken by the own ship will

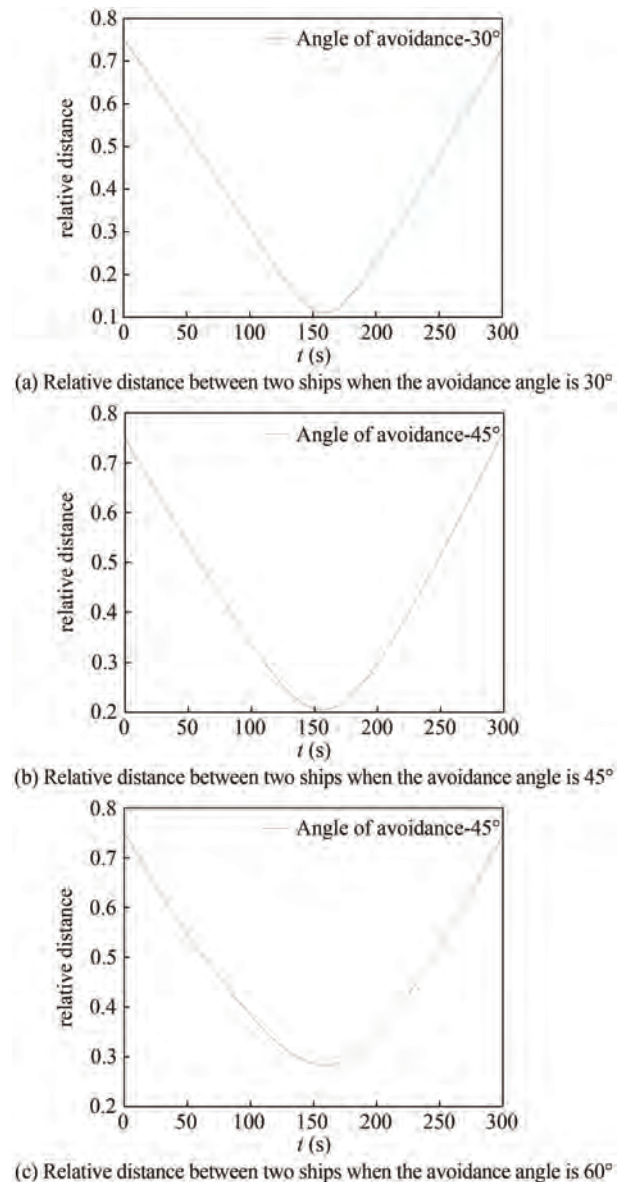


Figure 14 Relative distance between two ships in S7

contain three different avoidance ranges (30° , 45° , and 60°). The simulation results are presented in Figures 15–17.

The trajectories of two ships at time $t = 100$ s, 200 s, and 300 s are shown in Figure 15(a), (b), and (c), respectively.

Although the own ship has adopted different ranges of collision avoidance behaviors, it can achieve the purpose of safety and meet the requirements of COLREGS for overtaking situations. That is, the three avoidance options of different amplitudes are in line with the rules and hence are feasible. Based on this, the ability of each parameter to depict risks in the process of collision avoidance will be further analyzed below.

Figures 16(a) and Figure 16(b) give the curves of the DCPA and TCPA between the own ship and target ship under overtaking situations, respectively. By comparing the

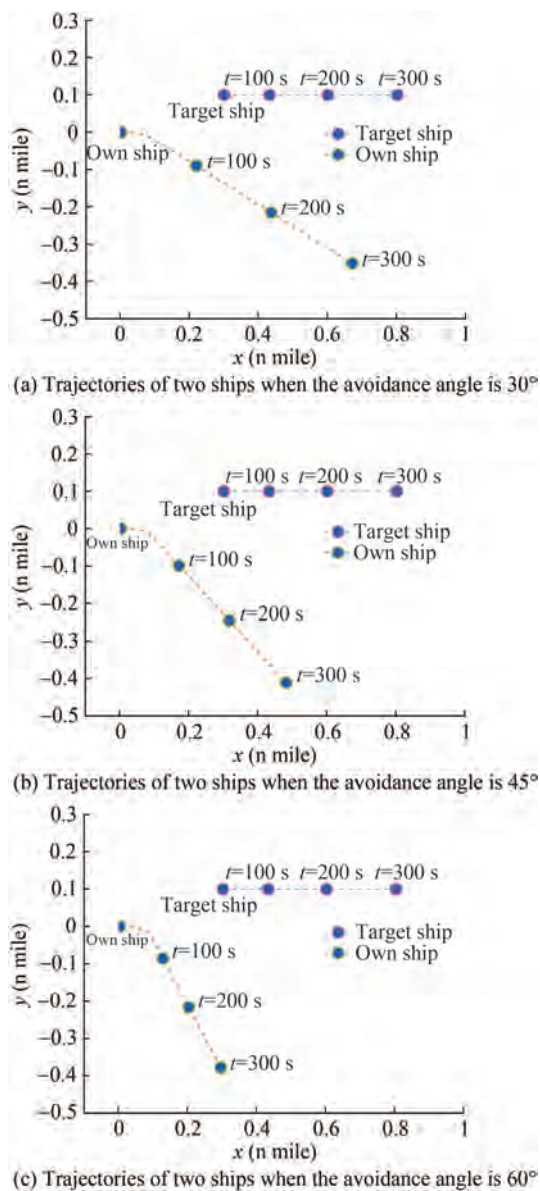


Figure 15 Trajectories of two ships in S13

head-on situation (Figure 9(a) and Figure 9(b)) and overtaking situation (Figure 12(a) and Figure 12(b)), one of the biggest features is that the curves of the DCPA and TCPA exhibit a high degree of resolution, and we can clearly distinguish the curve under different avoidance amplitudes. Similarly, the initial phase of the curve, that is, the almost complete overlapped part, is a reflection of the specific collision avoidance maneuvering taken by the ship and the maneuverability ability of the ship.

Figure 17(a) shows the curves of the CSD under the specific situation of S13. The three curves in different colors in the figure represent the changes in the CSD parameters under avoidance amplitude angles of 30° , 45° , and 60° . For the sake of comparison, we also depict the numerical variation of the ship domain overlapping area under S13 in

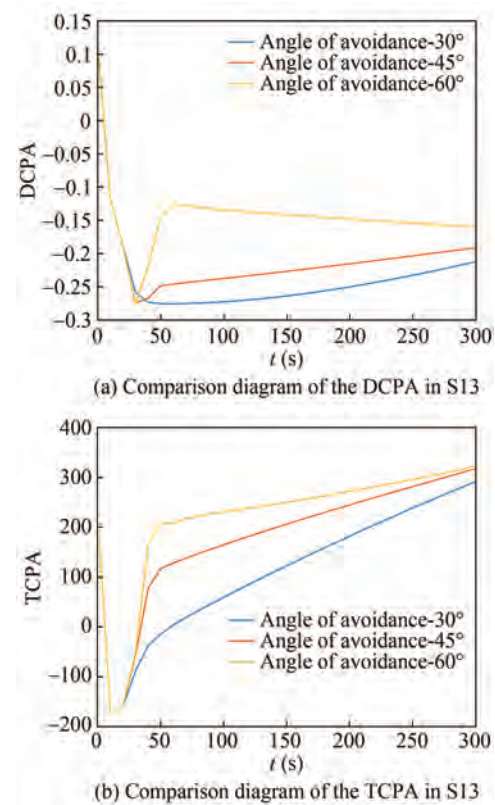


Figure 16 DCPA and TCPA between the two ships in S13

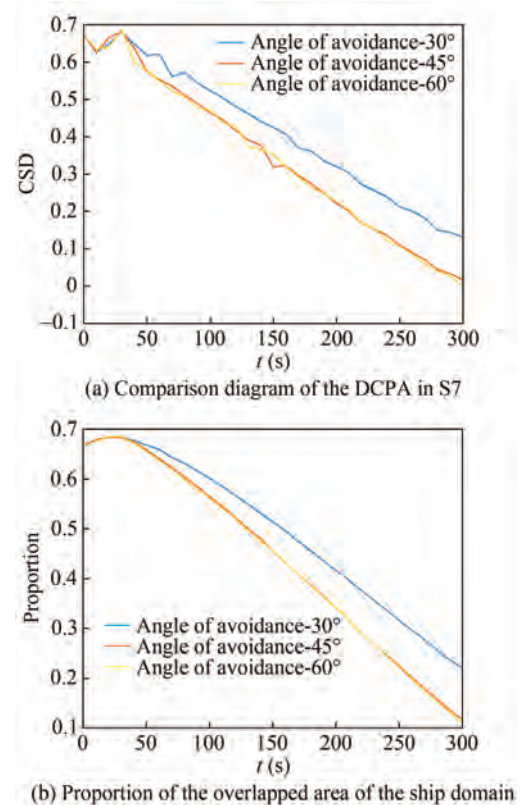


Figure 17 CSD and variation of ship domain overlapped area under S13

Figure 17(b) to further illustrate the advantages of using CSD parameters. The comparison between the two figures shows that the proposed CSD parameter shows better distribution characteristics at the numerical level than the original ship domain overlapped area ratio parameter. That is, the proposed CSD parameters can respond quickly after collision avoidance maneuvering and can reflect the variation characteristics of collision risk in the case of overtaking.

By contrast, the original ship domain overlapped area ratio parameter exposes two obvious defects. First, at the stage when the ship adopts the collision avoidance behavior, i.e., at the time period of 0–25 s, as shown in the figure, its response to collision risk is slow, and there is no significant change in the numerical value. Second, at the final time point $t = 300$ s, the value of the ship domain overlapped area ratio parameter is still greater than 0.1, which is unreasonable from the perspective of reflecting collision risk. If it is directly used as one of the parameters of collision risk, it does not accord with the relevant navigation cognition in the case of overtaking.

5.3 Discussions and analysis

The main purpose is to further design a method to test the dynamic performance of the CSD based on the basis of the static simulation experiment in Section 4. In the selection of experimental methods, the particularity of ship data in the real navigation process is considered due to internal factors, including its own ship size, ship maneuverability characteristics, and the influence of external factors, such as water conditions and surrounding traffic situation. If we choose to use the data of only one region, waterway, or port as the data source, the applicability of the proposed parameter, namely CSD, will be reduced. In addition, due to the accuracy of various ship state recording equipment or information errors and information loss caused by improper human operations, these phenomena also affect the reliability of actual ship data to a certain extent (Harati-Mokhtari et al., 2007; Mccauley et al., 2016; Yang et al., 2022).

To avoid the unnecessary problems mentioned above, we decided to use a ship model simulation to perform this part of the research. At the same time, using the simulation research method, we carried out the experimental analysis of different collision avoidance measures and various collision avoidance ranges that ships may take under a certain situation of encounter, which also makes the research and analysis have better flexibility. We introduced a framework that includes a mathematical model of ship motion and a ship collision avoidance model and conducted a series of simulation experiments based on this framework.

First, to make the simulation of the dynamic process of ship collision avoidance scientifically and reasonably, we applied the Nomoto model to describe and simulate the change law of ship motion characteristics, including the course and speed. This model is a relatively mature ship

model and has been widely used in the simulation calculation of ship maneuvering motion and the design and analysis of ship maneuvering motion control systems. Then, we decided to use PID control to simulate the ship handling process. The main reason for adopting the PID control algorithm is that the PID control algorithm is adopted in the automatic control system of the vast majority of ships in the world. Therefore, to accurately describe the current actual situation, the PID control algorithm is adopted here.

In Section 5.2, we simulated three kinds of ship encounters, namely, head-on situation, crossing situation, and overtaking situation, considering the ship maneuverability and COLREGS. A variety of feasible collision avoidance options with different amplitudes were designed for each situation, and we also made a further simulation of the feasible measures. Compared with the traditional and commonly used ship collision risk description parameters, including the DCPA and TCPA, the CSD parameter proposed in this paper shows a better and more detailed ability to describe real-time ship collision risk. In particular, in crossing situations, the sensitivity of the CSD parameter is concentrated and contrasted with that of the TCPA parameter. The CSD parameter is also a more reasonable description of ship collision risk in the overtaking situation.

Although ship maneuverability has always been an important factor that cannot be ignored in ship collision risk assessment and even the whole maritime traffic research, its effect on risk assessment has not been fully researched in this study. When designing the simulation experiment, the own ship and target ship were set to have the same main characteristics and maneuverability characteristics. Such a setting reduces the computation cost and makes the experimental process clearer. However, there is still a lot of room for further improvement. In future research, important factors, including the ship type, maneuverability, and other ship characteristics, still need to be used for a more detailed and comprehensive analysis and to further improve the performance of the proposed parameters in a variety of complex situations.

6 Conclusion and future works

In this paper, a new domain-oriented collision risk factor called the CSD has been introduced. According to the CSD, the collision risk of an encounter is described by three computing methods corresponding to three different encounter situations, i.e., head-on situation, crossing situation, and overtaking situation. First, a comprehensive analysis of the current studies centered on the CRI was made. In particular, the role of the ship domain in the CRI research and some current research results are discussed. Second, as the main research content of this paper, we defined a new parameter to measure the risk of collision between

ships from the perspective of the ship domain. This parameter was computed using two variables: the proportion of the overlapped domain and the changing rate of the proportion of the overlapped domain. Ships keep moving in a continual state, so it is not sufficient to judge the risk by only considering the current state of factors. Thus, we adopted a calculation model that combines the current overlapped situation of the ship domain and its change rate to track and monitor the trend of collision risk effectively. To validate the proposed parameters, a series of simulation experiments were conducted to evaluate its dynamic performance. The results show that the CSD parameters can reflect the state and change of the ship domain in real time in the case of a two-ship encounter.

To the best of our limited knowledge, the major limitation of the current work lies in the aspect of the ship type: After all, the ship type is classified as one of the main factors in a ship collision risk assessment. Different ship types also mean that the ships have varying physical characteristics, such as length, width, stroke, and turn, which would seriously affect the safety of navigation. For some special types of ships, such as cargo ships and oil tankers, the relationship between the ship type and transportation safety is even closer, so there has been a lot of specific research on them (Zhou Q et al., 2016; Ahola M et al., 2014).

However, the effect of the ship type was not sufficiently considered in the present study. In future studies, this area can serve as a focus for further improvement. For example, we can fine-tune the details of the ship domain we used depending on the ship type to achieve better performance.

In addition, our work makes no mention of multi-ship encounters, which have been proven to be very important in the research on ship collision risk by many other studies (Szlapczynski et al., 2021; Du, L et al., 2020). In particular, the comparison and comprehensive applications with other similar methods in complex situations can become an important part of the future development of our method.

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