Ship Collision Risk Assessment Based on D-S Evidence Theory

Liujiang Zheng, Longhui Gang*, Dongqin Liu, Xusheng Wang

Dalian Maritime University, Liaoning, Dalian, 116000, China

*Corresponding author's e-mail: `ganglh@dlmu.edu.cn`

Abstract. Accurately and effectively assessing the collision risk between ships is of great significance for the formulation of ship collision avoidance decisions. However, in different encounter situations, different evaluation indicators may play different roles, making it difficult to accurately and effectively calculate the risk of such ship collisions. Therefore, this article proposes a ship collision risk assessment model based on the D-S evidence theory. The model selects five factors: nearest encounter distance, nearest encounter time, relative distance between ships, relative orientation, and ship speed ratio to establish an evaluation index membership function. On this basis, the joint basic probability allocation method is used to evaluate the risk of ship collision. Three different ship collision scenarios were set up to validate the collision risk model of the ship, and the experimental results verified the effectiveness of the model.

Keywords: Ship collision risk; Risk evaluation indicators; Membership function; D-S Evidence Theory

1 Introduction

With the development of the economy and the acceleration of trade globalization, the global shipping industry has achieved great development. The number of ships is increasing day by day, and the process of large-scale and rapid ships is accelerating. The maritime transportation industry is becoming increasingly prosperous, and the traffic density is gradually increasing, leading to an increasing incidence of maritime traffic accidents, with collision accidents being the majority. With the advancement of technology and the optimization of algorithms, research on ship collision avoidance decision-making is increasingly achieving automation and intelligence. As an important research direction for ship collision risk assessment, it is of great significance to conduct in-depth research on ship collision risk in achieving autonomous collision avoidance and improving navigation safety. In recent years, various experts and scholars have achieved good research results in the study of ship collision risk. However, in the research process, the changes in the impact of different evaluation indicators on ship collision risk under different encounter situations were not fully considered. This article mainly focuses on the above issues for research.

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Yan Qingxin [1] established a collision hazard model based on the geometric principles of ship collision using a comprehensive evaluation method, but the model only considered geometric parameters and ignored other factors, resulting in poor applicability. Chen Jianhua et al. [2] and Yuan Yongqi et al. [3] combined neural networks and fuzzy reasoning in calculating collision risk, but there is still a lack of integration with maritime collision avoidance rules. Xu Wen [4] combined the principles of collision geometry and modified the membership function based on factors such as sea visibility and ship maneuverability, proposing a method for calculating the composite collision risk of ships. Li Yishan [5] constructed a ship collision risk prediction model using a classification regression tree method based on the complex nonlinear relationship between the degree of ship collision risk and its influencing factors. Yuan Yongqi [6] improved the BP neural network to evaluate the risk of ship collision, and the accuracy of the improved BP neural network was greatly improved. Liu [7] proposed a multi ship collision risk assessment model based on cooperative game theory, which can effectively reflect the risk of multi ship collisions. Help monitoring operators better understand the global collision risk. LiuZhao [8] proposed a ship collision risk calculation method that considers spatiotemporal urgency using mutation theory. Shaobo Wang et al. [9] analyzed domain based collision hazard models based on parameters such as the degree and time of invasion in the ship domain, divided navigation scenarios, and provided a collision hazard parameter calculation model for multi ship encounters. Zhen [10] proposed a new arena based regional ship collision risk assessment method to address the difficulty in accurately quantifying collision risks in complex water environments where multiple ships meet. Szlapczynski [11] elaborated on the establishment criteria and influencing factors in the field of ships, and provided a specific calculation scheme for domain parameters. Through comparison with DCPA/TCPA parameters, it was shown that this domain parameter has more superiority in ship collision avoidance. Misganaw et al. [12] combined machine learning with Dempster Shafer theory to propose a new CRI estimation model that improves computational efficiency while ensuring CRI prediction accuracy.

In summary, this article uses five basic evaluation indicators: DCPA, TCPA, distance of target ship, relative orientation, and ship speed ratio. Considering that different evaluation indicators have different effects on ship collision risk in different encounter situations, combined with D-S evidence theory, a new ship collision risk assessment model is established.

2 Ship Collision Risk Assessment Model Based on D-S Theory

2.1 D-S Evidence Theory

As is well known, D-S evidence theory is a flexible mathematical tool used to handle uncertain and incomplete information, and to solve prior probability problems by tracking display probability metrics that may lack information. Considering that DCPA, TCPA, target ship distance, relative orientation, and ship speed ratio have different impacts on ship collision risk in different encounter situations, D-S evidence theory is used to combine basic probability allocation as evidence to obtain a convincing assessment of ship collision risk.

BPA can apply membership functions as independent variables to support a given hypothesis, i.e. data comes from membership function values. For example, if there are two ships that meet and each ship has a membership function, the normalized BPA is shown as equation (1): Formatting author affiliations

$$m_j(S_i) = \frac{u_j(S_i)}{\sum_{i=1}^{S} u_j(S_i) + k(1-\gamma_j)(1-\alpha_j\beta_j)} \tag{1}$$

Among them is the maximum membership function α_j, which can be expressed as $\alpha_j = \max\{u_j(S_i)\}$. Where β_j is the maximum relative membership function extracted by each factor from the normalized weighting factor w_j, as shown in equation (2):

$$\beta_j = \frac{w_j\alpha_j}{\sum_{i=1}^{N} u_j(S_i)} \tag{2}$$

Where γ_j is the confidence coefficient, as shown in equation (3):

$$\gamma_j = \frac{\alpha_j\beta_j}{\sum_{j=1}^{k} \alpha_j\beta_j} \tag{3}$$

Among them, α_j represents the horizontal comparison between the ship with the highest risk under the same membership function and other ships, and the vertical comparison between different membership functions.

If the sum of all established BPA is 1, then the uncertainty of BPA is shown in equation (4):

$$m_j(\Theta) = 1 - \sum_{i}^{N} m_j(S_i) \tag{4}$$

In the D-S evidence theory, the joint probability allocation (JBPA) of two membership functions is shown in equation (5):

$$\begin{aligned} m_{1\cap 2}(S_i) &= m_1(S_i) \oplus m_2(S_i) = \\ &\frac{m_1(S_i)m_2(S_i) + m_1(S_i)m_2(\Theta) + m_1(\Theta)m_2(S_i)}{1 - \sum_{i=1}^{N} m_1(S_i) \sum_{i=1}^{N} m_2(S_i)} \end{aligned} \tag{5}$$

The uncertainty of JBPA is shown in equation (6)

$$m_{1\cap 2}(\Theta) = 1 - \sum_{i}^{N} m_{1\cap 2}(Si) \tag{6}$$

The JBPA of the three membership functions is shown in equation (7):

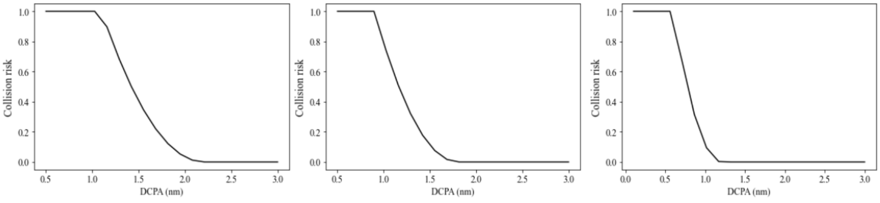
$$\begin{aligned} m_{1\cap 2\cap 3}(S_i) &= m_1(S_i) \oplus m_2(S_i) \oplus m_3(S_i) \\ &= m_{1\cap 2} m_1(S_i) \oplus m_3(S_i) \\ &= \frac{m_{1\cap 2}(S_i)m_3(S_i) + m_{1\cap 2}(S_i)m_3(\Theta) + m_{1\cap 2}(\Theta)m_3(S_i)}{1-\sum_{i=1}^{N} m_{1\cap 2}(Si)\sum_{i=1}^{N} m_3(S_i)} \end{aligned} \tag{7}$$

Through the above steps, JBPA can be applied to five membership functions, which can represent the degree of ship collision risk. The larger the JBPA, the greater the degree of ship collision risk. Therefore, when this ship encounters multiple target ships, the collision risk level of the multiple target ships is ranked, and the ship with the highest collision risk is given priority to take collision avoidance actions.

2.2 Membership Function of Evaluation Indicators

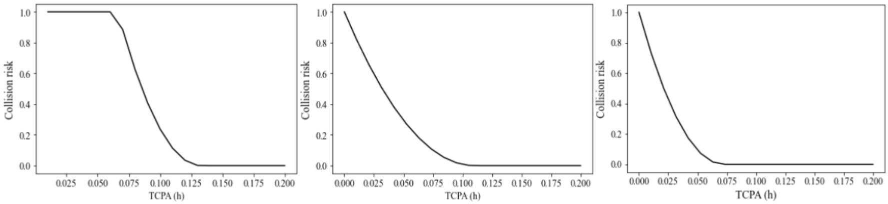
Table 1. Formula for membership function of evaluation indicators

Evaluating indicator	Membership functions
Minimum Encounter Distance DCPA	$U_{dcpa} = \begin{cases} 1, & \lvert DCPA\rvert < d_1 \\ (\frac{d_2 - \lvert DCPA\rvert}{d_2 - d_1})^2, & d_1 \le \lvert DCPA\rvert \le d_2 \\ 0, & \lvert DCPA\rvert > d_2 \end{cases}$
Minimum Meeting Time TCPA	$U_{tcpa} = \begin{cases} 1, & 0 \le \lvert TCPA\rvert < t_1 \\ (\frac{t_2 - \lvert TCPA\rvert}{t_2 - t_1})^2, & t_1 \le \lvert TCPA\rvert \le t_2 \\ 0, & \lvert TCPA\rvert > t_2 \end{cases}$ $t_1 = \begin{cases} \frac{\sqrt{d_1^2 - DCPA^2}}{\mathrm{v_r}}, \lvert DCPA\rvert \le d_1 \\ \frac{d_1 - \lvert DCPA\rvert}{v_r}, \lvert DCPA\rvert > d_1 \end{cases}$ $t_2 = \frac{\sqrt{d_2^2 - DCPA^2}}{v_r}$
Relative distance R	$U_R = \begin{cases} 1, & 0 \le R < D_1 \\ (\frac{D_2 - R}{D_2 - D_1})^2, & D_1 \le R \le D_2, \quad D_2 = 1.7\cos(\theta_T - 19^\circ) + \sqrt{4.4 + 2.89\cos^2(\theta_T - 19^\circ)} \\ 0, & R > D_2 \end{cases}$
Relative orientation θ_T	$U_{\theta_T} = \frac{1}{2}\left[\cos(\theta_T - 19^\circ) + \sqrt{\frac{440}{289} + \cos^2(\theta_T - 19^\circ)}\right] - \frac{5}{17}$
Ship speed ratio k	$U_k = \frac{1}{1 + \frac{2}{k\sqrt{k^2 + 1 + 2k\sin C}}}$



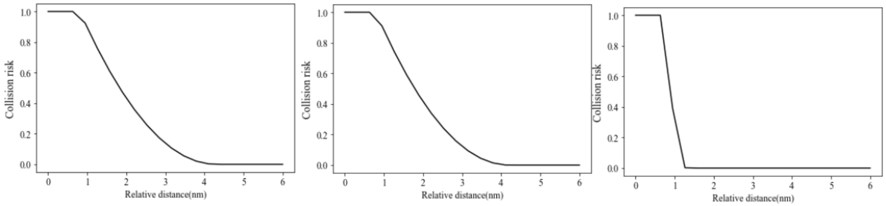
(a)Encounter (b)crossing situation (c)overtaking

Fig. 1. Membership function diagram under different encounter situations



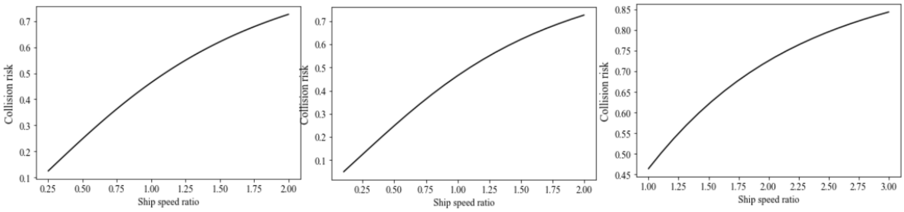
(d)Encounter (e)crossing situation (f)overtaking

Fig. 2. Membership function diagram under different encounter situations



(g)Encounter (h)crossing situation (i)overtaking

Fig. 3. Membership function diagram under different encounter situations



(j)Encounter (k)crossing situation (l)overtaking

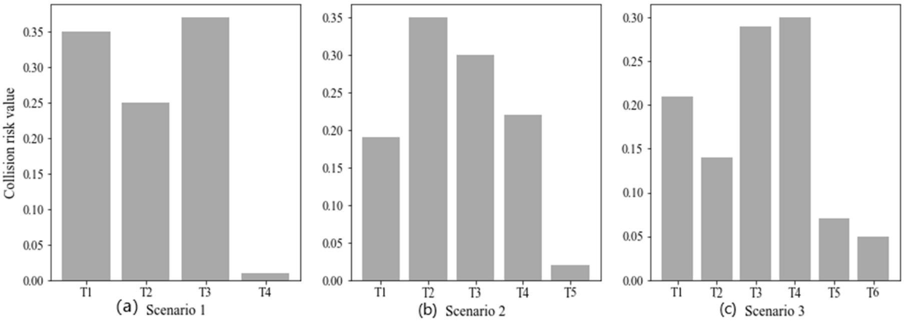
Fig. 4. Membership function diagram under different encounter situations

Through the AIS data of Lao tieshan, the degree of belonging function of the ship under different encounters is shown in Figs. 1, 2, 3 and 4. The membership function diagram for different encounter situations is shown in Figure 1. The membership function diagrams of different evaluation indicators under different encounter situations are shown in the figure, revealing that different evaluation indicators have different impacts on the collision risk of ships under different encounter situations. The membership degree increases with the decrease of DCPA and. If the membership degree is zero, the two ships will not collide. The degree of influence of the membership functions of various evaluation indicators on collision risk varies with the encounter of different ships, making collision risk more reasonable and quantitative. Generally speaking, U_{dcpa} U_R exposed the risk of ship collision The U_{tcpa} complexity of space reveals the temporal complexity of collision risk, and $U_{\theta T}$ U_k is also related to the difficulty of ship collision avoidance. To verify the effectiveness of the collision risk assessment model proposed in this article.As shown in Table 1.

Table 2. Part ship experimental data

No.	Relative distance nmile	Relative azimuth °	Target ship speed kn	The speed of the ship kn	Target ship course°	The course of the ship°
1	1.52	252	15	9	261	82
2	1.44	106	13	9	60	82
3	1.67	65	14	9	202	82
4	1.77	57	13	9	179	82
5	1.85	124	18	9	289	82
6	1.37	135	15	9	5	82

3 Validation of Model



(a) Scenario 1 (b) Scenario 2 (c) Scenario 3

Fig. 5. Collision risk assessment ranking

This article sets up three different encounter scenarios, and the experimental data is shown in Tab. 2. In scenario one, the ship forms an encounter with target ship 1 during navigation, target ship 2 intersects and meets target ship 3, and target ship 4 forms an overtaking situation, forming different encounter scenarios. As shown in the Figure 5, the JBPA of the four ships is calculated to be 0.35, 0.25, 0.37, 0.01, with target ship 3 having the highest collision risk, followed by target ship 2, The collision risk of target ship 4 is relatively low. Similarly, in experimental scenario two and three, the ships are in different encounter situations. The D-S evidence theory is used to rank the collision risk levels of the ships. Target ship two has the highest collision risk, followed by target ship three. The collision risk of the other three target ships is relatively small. In scenario three, as shown in the figure, the risk of ship collision is target ship 4>target ship 3>target ship 1>target ship 2>target ship 4>target ship 5. This model can accurately and effectively calculate the collision risk of ships in different encounter situations.

4 Conclusion

Based on the D-S evidence theory, a ship collision risk assessment model is established by introducing JBPA and membership functions. Considering the impact of different evaluation indicators on ship collision risk in different encounter situations, the method proposed in this paper can evaluate the collision risk of ships in different encounter situations through analysis and research of different experimental scenarios, effectively overcoming the shortcomings of existing solutions, Being able to effectively evaluate the risk of ship collisions not only has certain theoretical significance, but also has far-reaching implications. However, this method has a limitation as it takes a long computation time. Therefore, in future research, efforts should be made to minimize computational complexity as much as possible.

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