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Shih-Tzung Chen
Department of Merchant Marine, National Taiwan Ocean University, Taiwan, ROC

Ming-Feng Yang
Department of Transportation Science, National Taiwan Ocean University, Taiwan, ROC,
yang60429@email.ntou.edu.tw

Sheng-Long Kao
Department of Transportation Science, National Taiwan Ocean University, Taiwan, ROC

Mengru Tu
Department of Transportation Science, National Taiwan Ocean University, Taiwan, ROC

Jun-Yuan Kuo
Department of International Business, Kainan University, Taiwan, ROC

See next page for additional authors

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RESEARCH ARTICLE

Research on the Collision Risk of Ships off Keelung Based on AIS Data

Shih-Tzung Chen [a], Ming-Feng Yang [b,c,d,*], Sheng-Long Kao [b,c], Mengru Tu [b], Jun-Yuan Kuo [e], Yen-Ting Chao [f], Huang-Kai Hsu [b]

[a] Department of Merchant Marine, National Taiwan Ocean University, Taiwan, ROC
[b] Department of Transportation Science, National Taiwan Ocean University, Taiwan, ROC
[c] Intelligent Maritime Research Center, National Taiwan Ocean University, Taiwan, ROC
[d] Department of International Business, Providence University, Taiwan, ROC
[e] Department of International Business, Kainan University, Taiwan, ROC
[f] Department of Business Administration, Taipei City University of Science and Technology, Taiwan, ROC

Abstract

In previous literature, several computational methods have been proposed to analyze collision risks for vessels navigating at sea, most of which rely on the calculation of DCPA and TCPA between two vessels. However, this study adopts an enhanced version of the Vessel Conflict Ranking Operator (VCRO) to assess vessel collision risks. This approach not only considers the relative distance and relative velocity between two vessels but also takes their relative aspect into account. This methodology was applied to real-world vessels' dynamic data collected through AIS. From a near-collision perspective, it identifies high-risk areas near Keelung water where commercial vessels and fishing boats are more likely to collide. The hope is that in the near future, this method can be integrated into maritime collision warning systems (CWSs) of VTS (Vessel Traffic Service) and/or offshore wind power to enhance safety and navigation in maritime environments.

Keywords: Collision warning systems (CWSs), Vessel conflict ranking operator (VCRO), Automatic identification system (AIS), Maritime safety

1. Introduction

In today's international trade, maritime transport is the main mode of transport for trade logistics. Since the volume of cargo that a ship can carry during transportation is several times higher than that of air cargo, in most cases, the transportation costs using sea transport are comparatively lower than using air transport. However, it is estimated that 90 % of the goods in international trade are transported by sea [1]. Although the number of dangerous incidents in marine transportation is relatively low every year, due to the huge capacity of ships, once an accident occurs, not only the loss of cargo but also the impact of marine environment damage is quite significant. According to the statistical data, the most frequent maritime accidents are groundings, ships collision and fire [2]. In order to reduce the risk of marine accidents, there are also many research, analysis and development.

Using risk modeling and risk analysis it is possible to translate the data into a map of marine incident risk areas and determine which areas are at high risk of ship collisions. It will also include a mechanism for evaluating the effectiveness of risk control projects. In these documents, many applications of maritime risk analysis have been proposed [3—5].

Statistics and analysis are performed using maritime incidents. This process allows to better determine the correlation between parameters and

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* Corresponding author at: Department of Transportation Science, National Taiwan Ocean University, Taiwan, ROC.
E-mail address: yang60429@email.ntou.edu.tw (M.-F. Yang).

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increase the information about maritime accidents. By employing the method described above, we can gain a better understanding of the distribution of different types of maritime accidents, the occurrence rates of various ship incidents involving conditions, and the factors contributing to maritime accidents [6,7].

In recent years, offshore wind power in Taiwan is in the development stage. Since the construction of offshore wind power generators is different from that of traditional wind power generators, the construction process will affect the ships in the nearby waters, and the increase of ship density may increase the chance of ship collision. Accidents during maritime operations can increase project costs and timelines, and even pose risks to personnel. This not only adds to expenses but also reduces operational efficiency.

As maritime vessel density increases, having a mechanism in place to reduce the risk of vessel collisions can enhance the safety of maritime operations, improve operational efficiency, and reduce unnecessary personnel casualties and cost burdens. Therefore, this paper uses the AIS data to calculate the Vessel Conflict Ranking Operator (VCRO) between two vessels, and uses the value to determine the risk of collision between two vessels to improve the safety of vessel operation. Offshore wind power sites are highly dense with ships during the construction process, and more care needs to be taken regarding the risk of ship collisions so that ships can operate in a safer environment.

2. Literature review

In this chapter, the previous research on the application of AIS data in marine traffic, the research methods of near-miss collision environment in traffic, and the model reference of the application of GIS in this research for the overall research framework are described.

2.1. AIS data in maritime transportation research

AIS data is increasingly used in the research of marine transportation safety and marine traffic engineering. AIS data is also a crucial source of information for maritime traffic management, providing an effective means to access both dynamic and static information about vessels. AIS data is a platform for information exchange between ships and land, and its data contains a lot of real-time navigation data, including the ship's latitude and longitude, the ship's speed and the ship's heading, etc. With these data, we can clearly know the various states of the ship when it is navigation at marine.

In the early stages of AIS application, there were indeed concerns and criticisms regarding inaccurate AIS vessel information due to human data entry errors or navigational instrument inaccuracies [8]. However, in recent years, the data quality has improved dramatically year after year [9,10]. A better outcome may be achieved by the proper placement of antennas [11]. Several research on ships have used AIS data to date, including collision avoidance studies [12], vessel channel analysis [13], strategies for analyzing the risk of marine vessel collisions [5,14−16].

2.2. Collisions avoidance

Although analogous studies in the field of land-based road traffic research, such as traffic conflict technique (TCT), have been conducted, ship collision near-miss detection is a relatively new field [17]. We can use near-collision data from two vessels to explore scenarios where ships come very close to colliding, but do not actually collide, and identify high-risk locations for potential collisions, rather than just focusing on the locations where accidents occur. After all, prevention is better than cure. To help users comprehend the system's degree of safety, the TCT concept takes into account all conflict scenarios, including both actual accidents and accidents that users may experience while using the transportation system. The main principle is that different levels of encounter likelihood have varied fault tolerances, and as a result, accidents are more likely to occur. Because data on ship collisions is just like the tip of the iceberg in terms of maritime traffic risk, adopting the TCT concept has the significant advantage of allowing us to gather more reference data for the analysis of navigation safety.

Due to their distinct adaptability, many conflict resolution techniques used in road traffic studies are inappropriate for ship transportation at marine [18]. A more accurate ship pairwise conflict strategy needs to be developed.

In the context of ship collision avoidance, the common practice involves using ARPA (Automatic Radar Plotting Aid) navigation equipment to scan and track targets on the nearby water surface. It utilizes the values of DCPA (Distance to Closest Point of Approach) and TCPA (Time to Closest Point of Approach) between two vessels to assess the risk of collision. However, from the perspective of VTS (Vessel Traffic Service), this method can lead to cognitive overload for VTS operators, resulting in human errors [19]. Therefore, Yim and Lee [20] proposed a framework for evaluating the collision risk between a vessel and a bridge. This framework assesses probabilistic collision risks by defining the positional relationship between vessels and bridge piers.

Additionally, Liu et al. [21], introduced a technology that integrates real-time information from both ARPA and AIS (Automatic Identification System). This integration aims to enhance Collision Warning Systems (CWSs) built solely on ARPA, addressing their limitations in ignoring vessel types, sizes, and tonnages. This approach obtains vessel information from AIS static messages and supplements or amends vessel's dynamic information using ARPA data.

This article employs the Vessel Conflict Ranking Operator (VCRO) [22] to assess the risk differentiation of vessels in near-collision situations, in which the VCRO model is expanded for more realistic scenarios. Through these collision evaluation, we can identify which sailing vessels in the area are in a high-risk state and take measures to warn them.

2.3. Geographic information system

A geographic information system (GIS) is a data management system containing specific spatial information. A computer system that, by definition, centralizes, stores, processes, and presents georeferenced data. In order to help in solving real-world geographic information challenges, GIS may merge spatial information with decision support systems. The growth of geographic information science, geographic knowledge information, geographic information digitization, and geographic information technology all require relevant science and study, which is covered by GIS information.

In this research, layers, geographic coordinates, and projections are employed as some of the fundamental GIS concepts. Geographic information records are presented as numbers, and in order to convert these numbers into usable data, appropriate software must be used to represent them. After the data is represented in this way, it can then be visualized using software analysis to combine the research data with actual maps.

In this research, a GIS system was utilized to statistically record and mark locations where near-collisions frequently occurred. The data used for this analysis was collected from AIS signals in the vicinity of Keelung in April 2022. The results were compiled after applying the VCRO.

2.4. Conceptual framework for research

The conceptual basis for the strategy in this study is depicted in Fig. 1. To differentiate all ships in non-

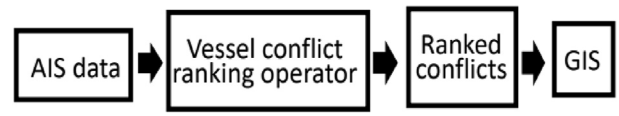

Fig. 1. Conceptual framework for research.

collision occurrences, AIS data of all ships within the target range are first gathered and analyzed over a period of time. In these events, VCRO values are computed on a one-to-one basis using the latitude, longitude, sailing speed, and vessel heading of the vessels in the AIS data, and are presented in the form of a line chart. According to the level of risk, it is categorized as either high-risk value, medium-risk value, or low-risk value. Different risk levels are identified by different colors in the GIS buffer analysis, ultimately resulting in a map that provides information on the various levels of risk.

3. Defining the vessel conflict ranking operator

VCRO is an evaluation of the collision risk between two boats in the absence of a collision, and it ranks the evaluated values. An event with a higher risk level has a greater danger of collision for both boats, whereas an event with a lower risk ranking carries a higher likelihood that both vessels will be operating safely. The VCRO is developed based on the assessment criteria established by maritime experts, and the mathematical model and AIS data required for the assessment are designed according to their expert definitions [22].

3.1. Model content

The distance to closest point of approach (DCPA) and time to closest point of approach (TCPA) have been employed in several prior studies to evaluate the risk of ship collision. However, DCPA and TCPA may not consistently and accurately depict the gravity or likelihood of a ship collision.

For instance, during a ship encounter, the DCPA tends to decrease as multiple ship crossings occur, but in situations where two ships run parallel, the DCPA may not provide a sufficient explanation when it reaches its minimum value. This is because the DCPA measurement does not account for the sailing direction of the ships, potentially leading to incorrect assessments in certain unique cases.

To overcome these limitations, the VCRO utilizes a mathematical model that can be more broadly applied to various ship encounter scenarios, thereby addressing the aforementioned issues associated with DCPA and TCPA measurements. The model takes into account the following factors [22]:

1. The distance of the two ships
2. The relative speed of the two ships
3. The aspect difference between the two ships.

The three factors discussed above can indicate the level of complexity involved when two ships come into contact, and the value is determined by analyzing how the factors are interrelated in terms of the risk involved in navigating without a collision. The model is presented in a way that focuses on the risk of collision, rather than on the specific actions and timing involved in avoiding a collision between ships.

3.2. Model structure

When constructing the mathematical model for the VCRO, the likelihood of a ship collision is taken into account. The model factors in distance, relative speed, and aspect.

The likelihood of a collision between two ships cannot be entirely determined by their distance from one another; additional elements must be taken into consideration. The likelihood of colliding will rise as the distance shrinks.

According to the above relationship between distance and VCRO, it can be explained by the following equation [22].

$$VCRO \sim f\left(x^{-1}\right) \tag{1}$$

In Fig. 2, the relative speed is calculated from the actual heading and actual speed of the two ships. As a ship's speed increases, its reaction time becomes shorter, and as the relative speed between two ships increases, the risk of collision for each ship also increases. The following mathematical equation shows the effect of relative speed on VCRO.

$$VCRO \sim f(y) \tag{2}$$

when one ship is overtaking another, the risk of collision cannot be fully determined by considering only the distance and relative speed between the two ships. It is necessary to also take into account the aspect of the two ships in order to accurately assess the risk.

In Fig. 3, the term "aspect" refers to the relative position of two ships, and it is defined as the difference in heading angle between the two ships. The range of "aspect" is [−180, 180]. If the angle is negative, it means the two vessels have passed DCPA and are currently moving apart (refer Fig. 3). Assume an odd periodic function g(z) with a period of 2π, as follows.

$$VCRO \sim f(g(z)) \tag{3}$$

The following describes the relationship of where x: distance, y: relative speed and z: aspect to the VCRO mathematical model:

$$VCRO \sim f\left(x^{-1}, y, g(z)\right) \tag{4}$$

The periodic function $\gamma(t)$ with period T can be expanded using a Fourier series as follows:

$$\gamma(t) = \sum_{k=-\infty}^{+\infty} a_k \cdot e^{jk\left(\frac{2\pi}{T}\right)t} \tag{5}$$

$$a_k = \frac{1}{T}\int_T^{\infty} \varphi(t)\cdot e^{-jk\left(\frac{2\pi}{T}\right)t} \tag{6}$$

$$e^{j\theta} = \cos\theta + j\cdot\sin\theta \tag{7}$$

As $g(z)$ is an odd function as follows:

$$g_0(x) = \sum_{-\infty}^{+\infty} b_k \cdot \sin(kx) \tag{8}$$

Where $b_k = a_k \cdot j, x$ as angle.

Using the first two items of the Fourier series to reduce the computational complexity, citing previous research to get the following mathematical formulas [22]:

$$g_0(x) = m\cdot\sin x + n\cdot\sin(2x) \tag{9}$$

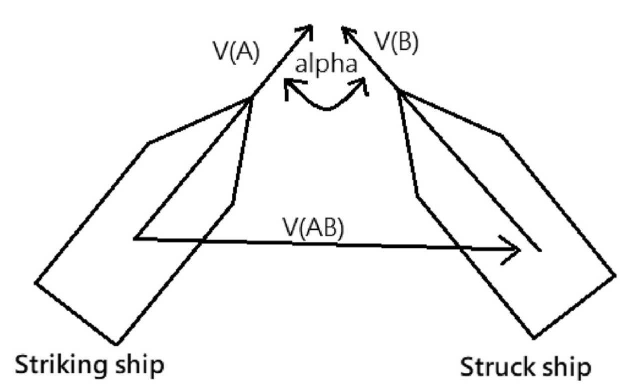

Fig. 2. Relative speed y.

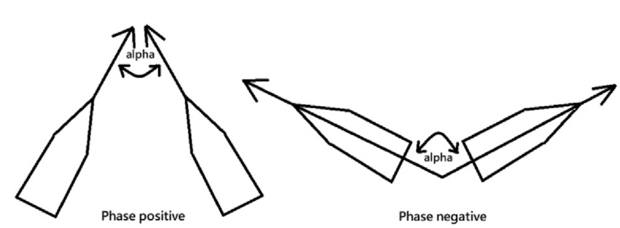

Fig. 3. The phase z.

Combining function (4) and (9), the VCRO can be expressed as follows:

$$VCRO_{(x,y,z)} = \left(\left(kx^{-1}y\right)\left(m\cdot kx^{-1}y\right)\left(m\cdot\sin(z)+n\cdot\sin(2z)\right)\right) \quad (10)$$

The multiplication method is used to combine the distance between two ships and their relative speed because these are the shared factors that influence the likelihood of a potential collision between the two ships. If the distance between two ships is sufficiently large and their relative speed is low, then the likelihood of a potential collision between the two ships will be low as well.

In the special case where the aspect is between [175, −175] and [5, −5]. It is difficult to have a chance that the actual aspect of the two ships is 0 or 180 in a practical situation. Building on this theory, this paper establishes an interval for situations where two ships come into contact. When the heading angle difference between two ships falls within the range of plus or minus 5°, the aspect factor is not taken into consideration. In such cases, the relative distance and relative speed between the two ships are the most critical factors influencing the likelihood of a potential collision [23]. The following is the formulation of the VCRO in this case.

$$VCRO_{(x,y)} = \left(kx^{-1}y\right),\quad z \in \{[175,5],[-175,-5]\} \quad (11)$$

In [22], It is evident that the values of k, m, and n are calculated using the least squares method. To apply this method, all AIS data from ships within the study area must be used for the calculation. The following is the operational model of the least squares method.

$$f_0 = \min\left(\sum \Delta VCRO_i\right) = \min\left(\sum_i^n kx_i^{-1}y_i(m\sin z_i + n\sin 2z_i)^2\right) \quad (12)$$

Let

$$\begin{cases} \dfrac{\partial f_0}{\partial k} = 0 \\ \dfrac{\partial f_0}{\partial m} = 0 \\ \dfrac{\partial f_0}{\partial n} = 0 \end{cases} \quad (13)$$

Then

$$km^2\sum_i^n x_i^{-2}y_i^2\left(\sin^2 z_i + \sin^2 2z_i\right) + 2kmn\sum_i^n x_i^{-2}y_i^2 \sin z_i \sin 2z_i = m\sum_i^n VCRO_i x_i^{-1}y_i \sin z_i + n\sum_i^n VCRO_i x_i^{-1} y_i \sin 2z_i \quad (14)$$

$$km\sum_i^n x_i^{-2}y_i^2 \sin^2 z_i + kn\sum_i^n x_i^{-2}y_i^2 \sin z_i \sin 2z_i = \sum_i^n VCRO_i x_i^{-1} y_i \sin z_i \quad (15)$$

$$kn\sum_i^n x_i^{-2}y_i^2 \sin^2 2z_i + km\sum_i^n x_i^{-2}y_i^2 \sin z_i \sin 2z_i = \sum_i^n VCRO_i x_i^{-1} y_i \sin 2z_i \quad (16)$$

This study cites the k, m, and n of VCRO from the [22] research to analyze the AIS data collected this time. The ranking interval of ship collision likelihood may vary depending on the scope of the research being conducted. We will re distinguish the calculated VCRO.

The following is the VCRO mathematical model after the parameters are cited in this paper:

$$VCRO_{(x,y,z)} = \left(\left(3.87x^{-1}y\right)\left(\sin z + 0.386\ \sin(2z)\right)\right) \quad (17)$$

Where $k = 3.67, m = 1, n = 0.386$

4. Application

We utilize simulated data for computations in order to check the validity of the assumptions because the scenario configuration used in this study differs from that used in other studies. For the simulation setup, we will consider various encounter scenarios between two vessels, including crossing, head-on, and overtaking. To create a more realistic maritime encounter scenario, different avoidance routes will be simulated for each of the various encounter scenarios.

This chapter will utilize a simulation data format similar to that of real AIS data. Parameters such as the longitude and latitude of the two ships, the respective speed of the two ships, and the respective heading of the two ships will be employed, and the resulting calculations will be presented through a continuous graph. The output will display the course of the two ships at a specific time, the variation of the distance between them, the alteration of the relative speed of the two ships, and the moment when the two ships reach the distance of closest point of approach (DCPA).

4.1. Model calculations: visual graphics

The following six figures presented below depict the encounters between two ships in crossing, overtaking, and head-on situations, as well as different avoidance methods employed. Among them, Vessel_A is the object of observation, which is utilized to monitor the dynamic changes of the two ships in various encounter scenarios. The top picture shows the route map of two ships during an

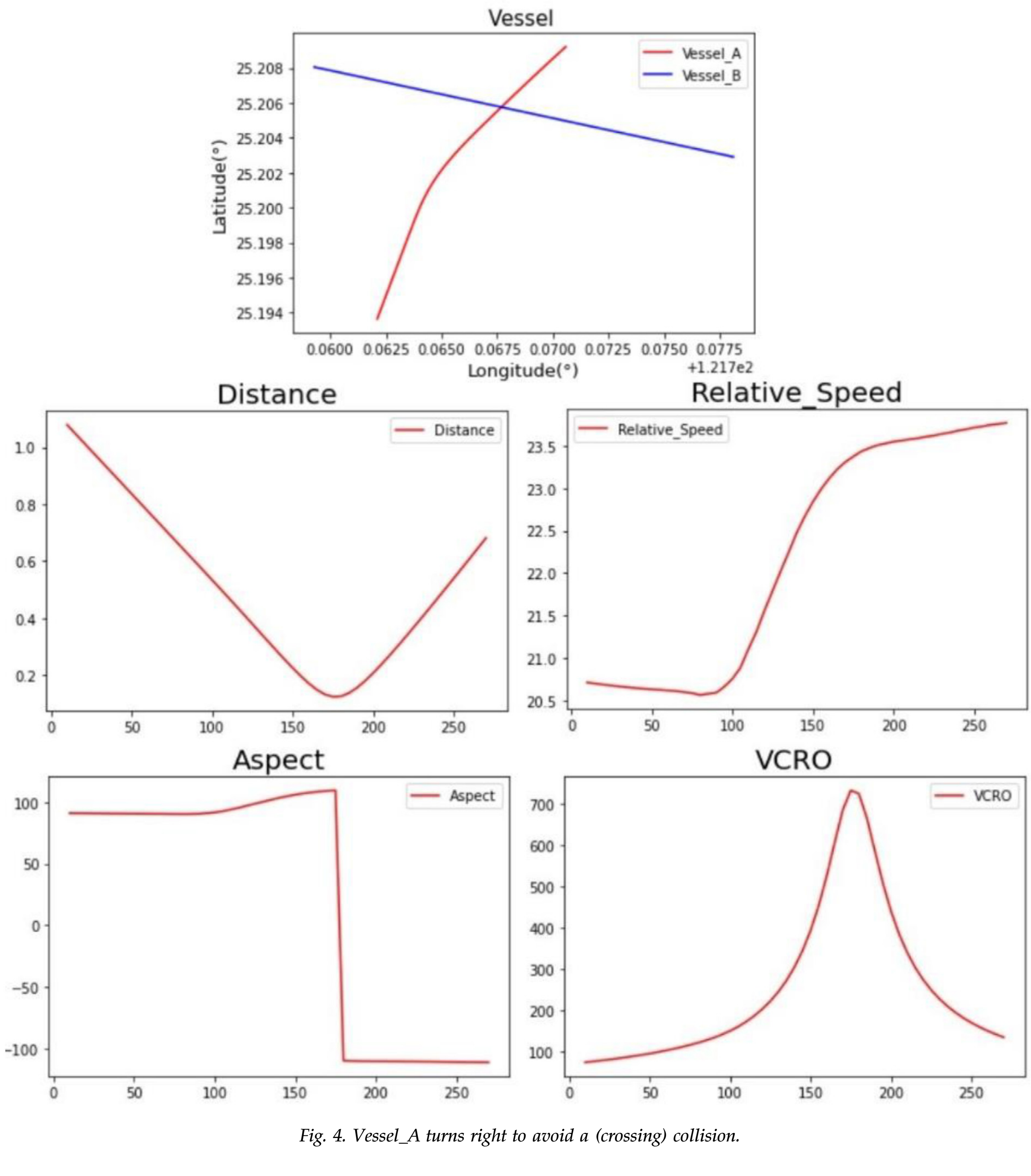

Fig. 4. Vessel_A turns right to avoid a (crossing) collision.

encounter, and the four figures below it shows the changes in relative distance, relative speed, relative orientation, and VCRO value calculated by the model. The timeline in the graph is set to show changes every five seconds, and the Aspect graph displays the point in time when the two ships reach their closest point of approach and start to move away from each other.

In Fig. 4, The original route of the two ships would result in collision, so the observing ship made a right turn to avoid it. In the aspect diagram, it can be seen that the value changes from positive to negative at the 175th second, indicating that the two ships passed their closest point of approach (DCPA) at this time. This can also be confirmed in the distance figure. The VCRO diagram indicates that the

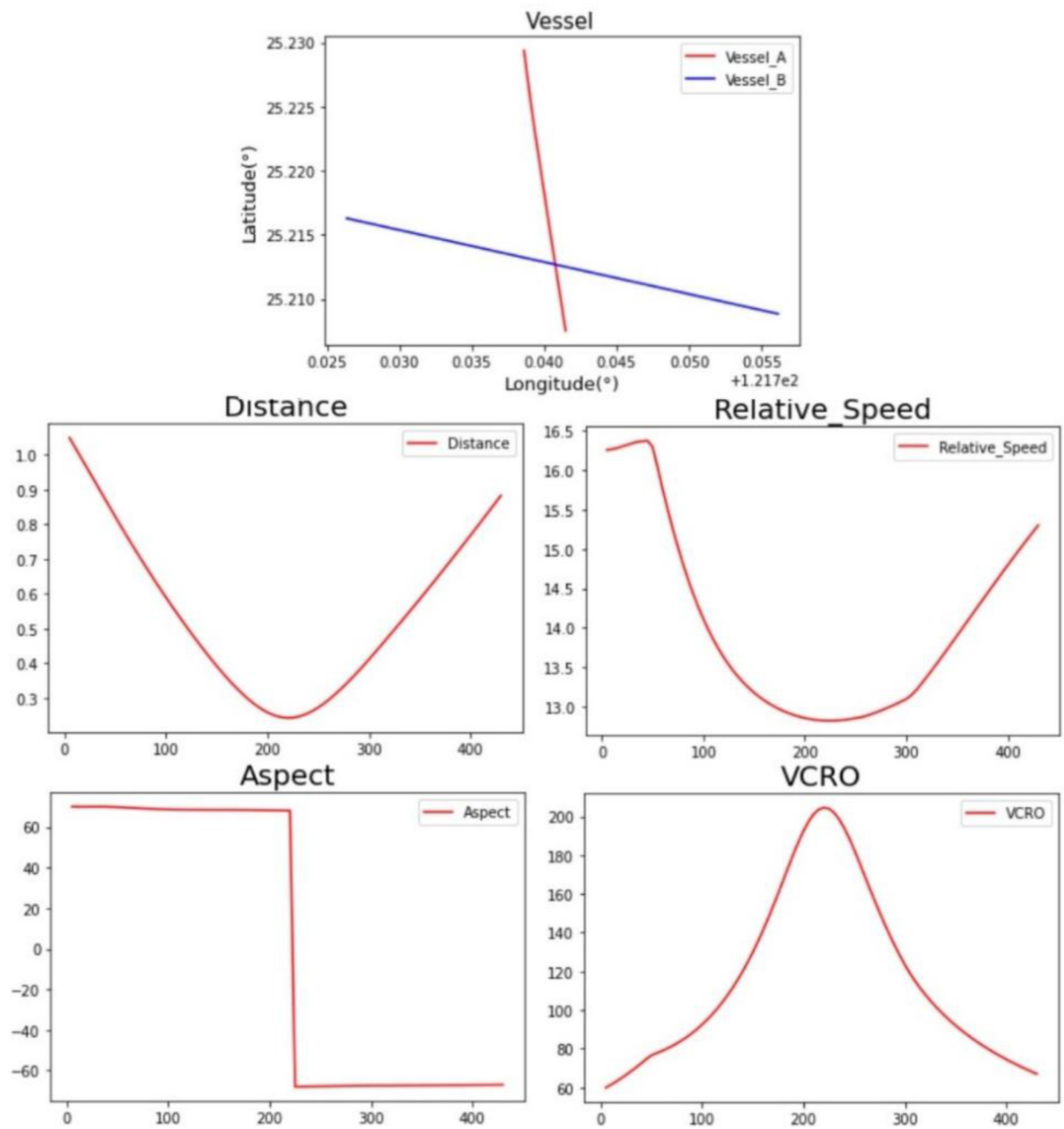

Fig. 5. Vessel_A decelerates to avoid a (crossing) collision.

highest value occurs at the same time point as the DCPA, and once the danger has passed, the value rapidly decreases.

In Fig. 5, Shows a cross encounter between two ships, and in this case, the observation ship did not alter its course, instead it slowed down its speed to avoid a collision. When comparing the graph in Fig. 4, we can observe that the relative speed has the greatest influence on the value of VCRO when the encounter environment is the same, as shown by Eq (14). Figs. 4, and Fig. 5, depict cross encounter scenarios, with the distinction being the avoidance maneuver executed by the observing vessel. A substantial variation in the VCRO value at its peak can be achieved solely by altering the speed difference.

In Fig. 6, In the head-on contact scenario, the observation ship started to turn right at the 130th second to avoid, and continued to do so until the two ships crossed DCPA at the 185th second. The

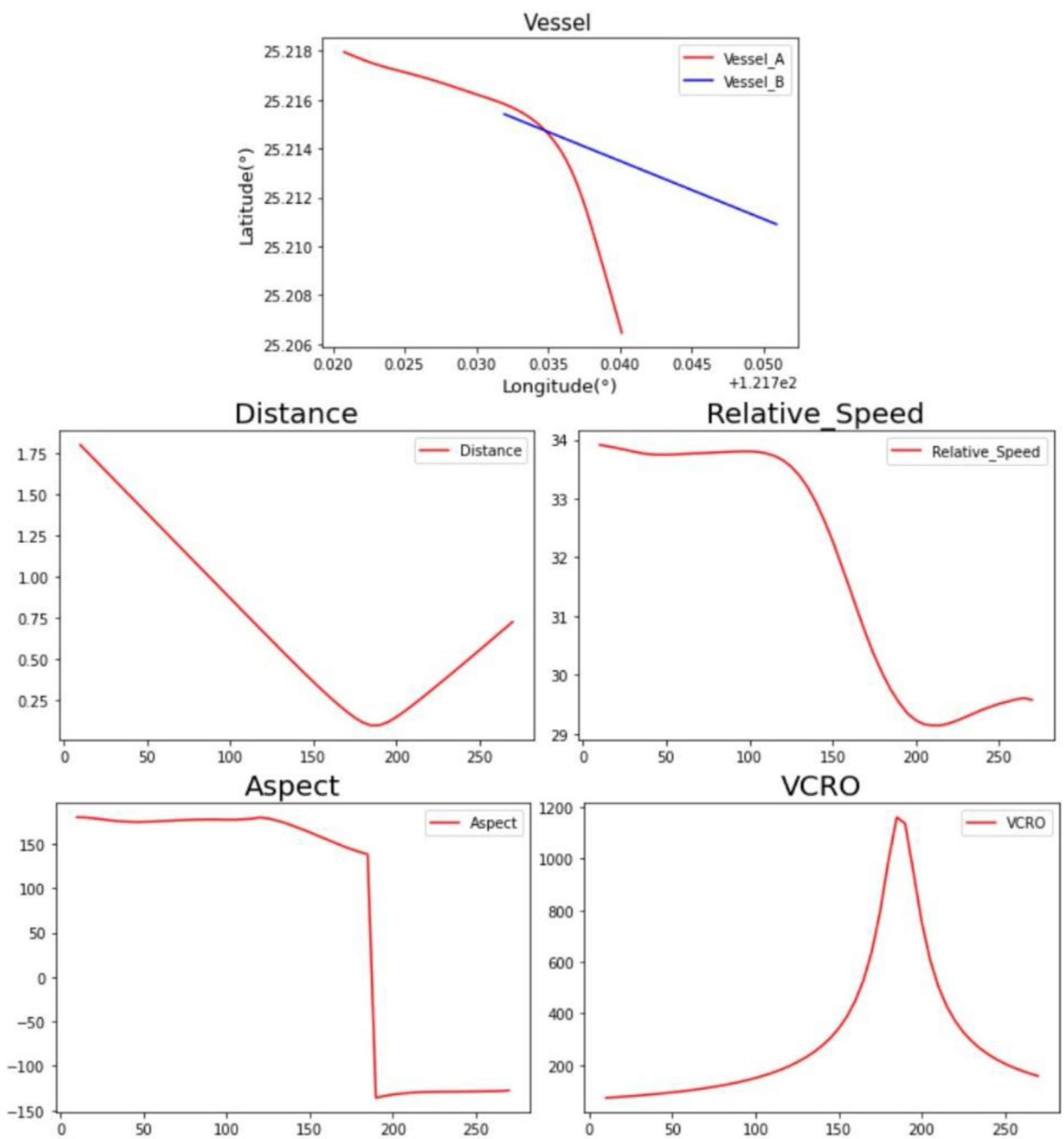

Fig. 6. Vessel_A turns right to avoid a (head-on) collision.

observation ship's speed dropped throughout this time, while the observed ship kept moving ahead at its initial speed and angle. Nevertheless, because the angle interval we inserted in the model is set to 5°, the value will fluctuate about 0 on the VCRO diagram.

In Fig. 7, Shows that the observation ship started to maneuver left to avoid it at 245 s and continued doing so until the two ships crossed the DCPA at 315 s. By comparing Figs. 6 and 7, we can observe that the discrepancy between the two values in the VCRO graph is significant. This is because, in a head-on encounter scenario, the aspect and range between the two vessels are more critical, and even a slight difference in the angle may lead to a substantial increase in the VCRO numerical leap.

In Fig. 8, The two vessels were in an overtaking scenario, and at the 15th second, the observing ship initiated a right turn and prepared to overtake. The observing vessel accelerated from the 85th second until the 235th second when it successfully completed overtaking the other vessel. As depicted

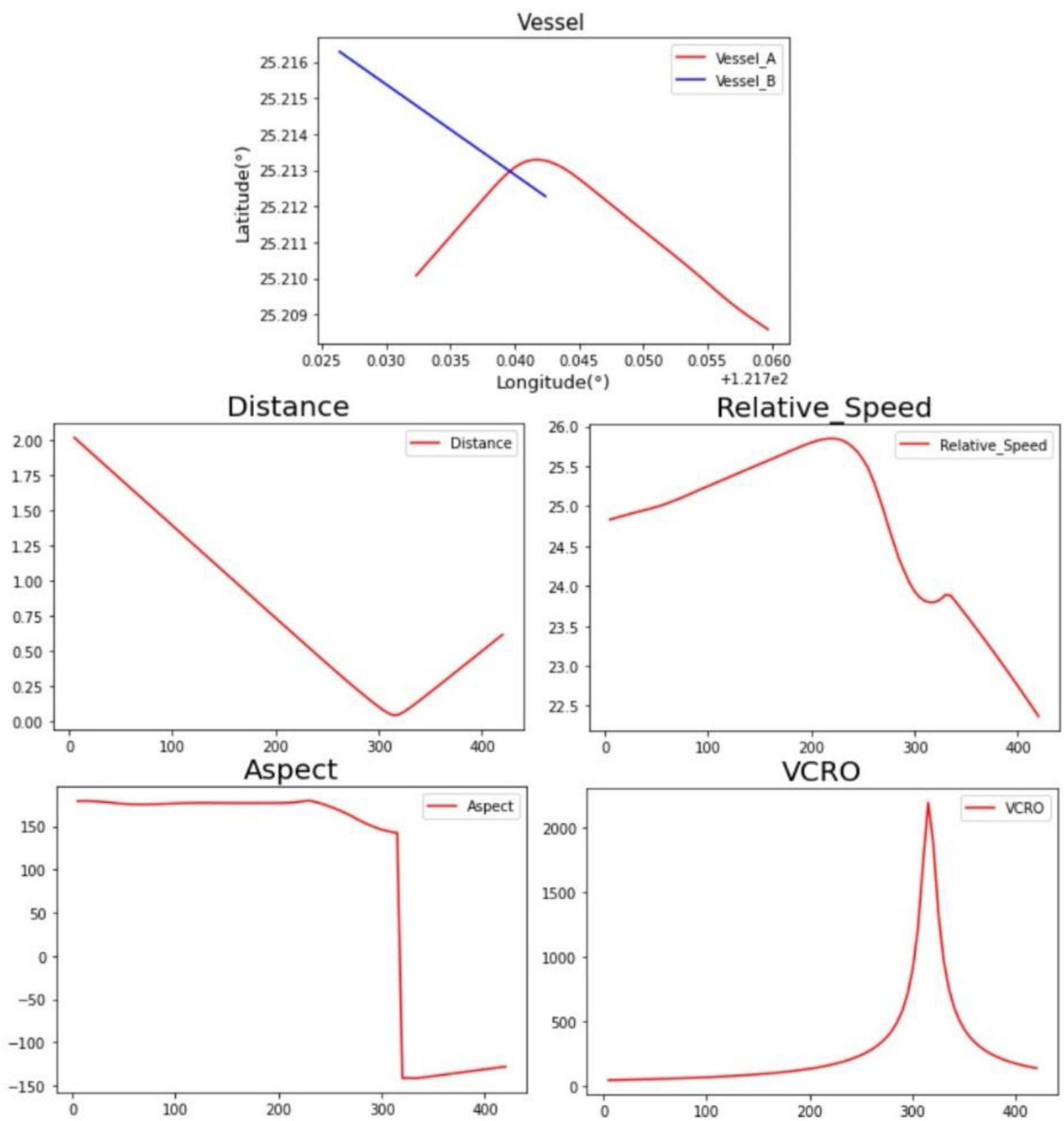

Fig. 7. Vessel_A turns left to avoid a (head-on) collision.

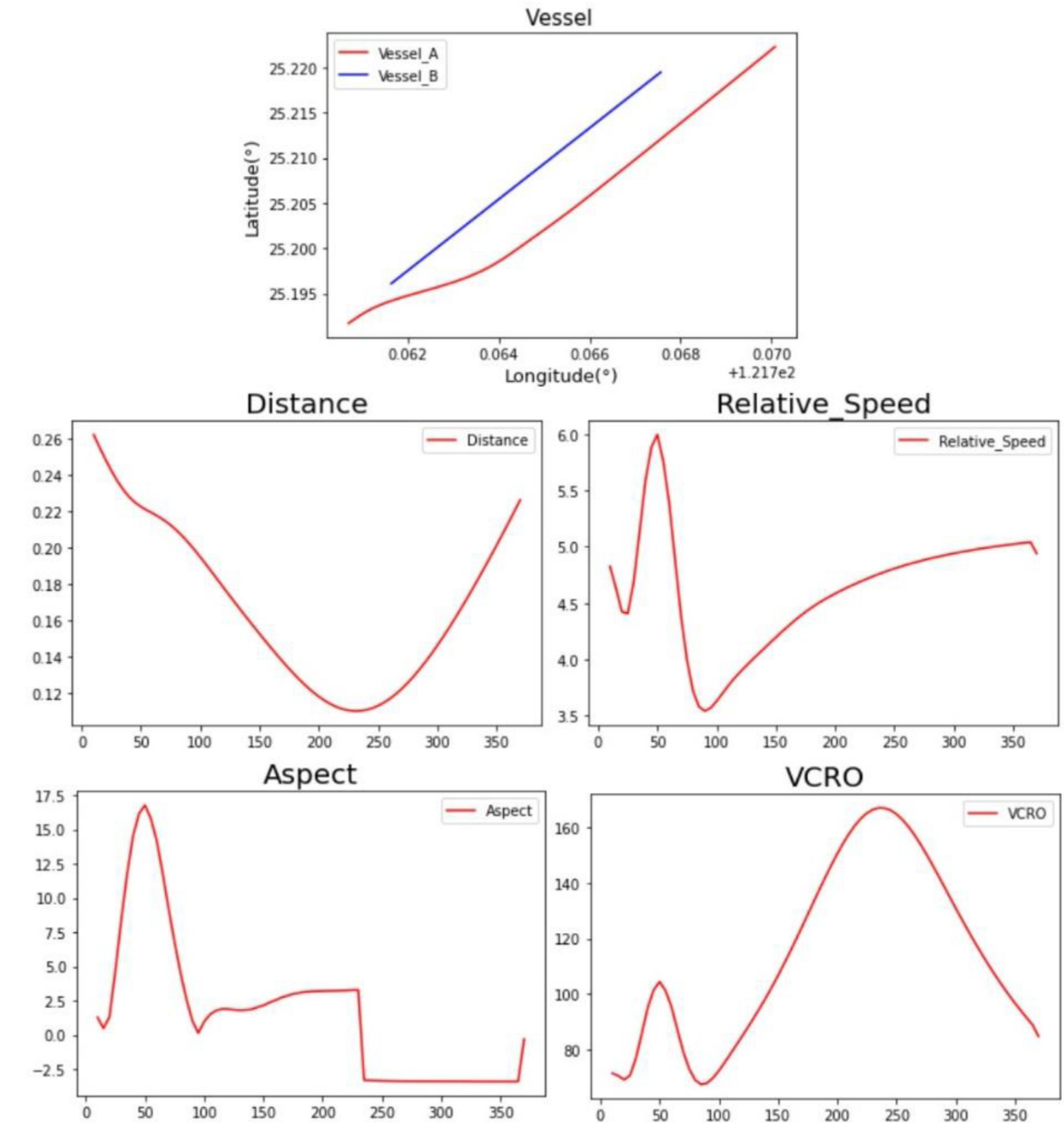

Fig. 8. Vessel_A turns right to avoid an (overtaking) collision.

in the aspect diagram below, the value underwent a transition from a positive to a negative value. Among these scenarios, the VCRO attains its highest value when the observing vessel executes a right turn, even though the peak does not coincide with the DCPA. Therefore, it can be inferred that the parameter weights in the overtaking scenario are substantially distinct from the other scenarios.

In Fig. 9, As the rear ship makes a left turn and passes the front ship, the value of the closest point of approach VCRO value immediately increases. When the two ships are traveling in the same direction and reach the closest point, the VCRO reaches its peak. This occurs when the course difference between the two ships is almost negligible, and their relative speed is high, increasing the risk of collision in an instant.

By comparing Figs. 8 and 9, it can be observed that the VCRO numerical variation follows a similar pattern to that of the aspect diagram. And the

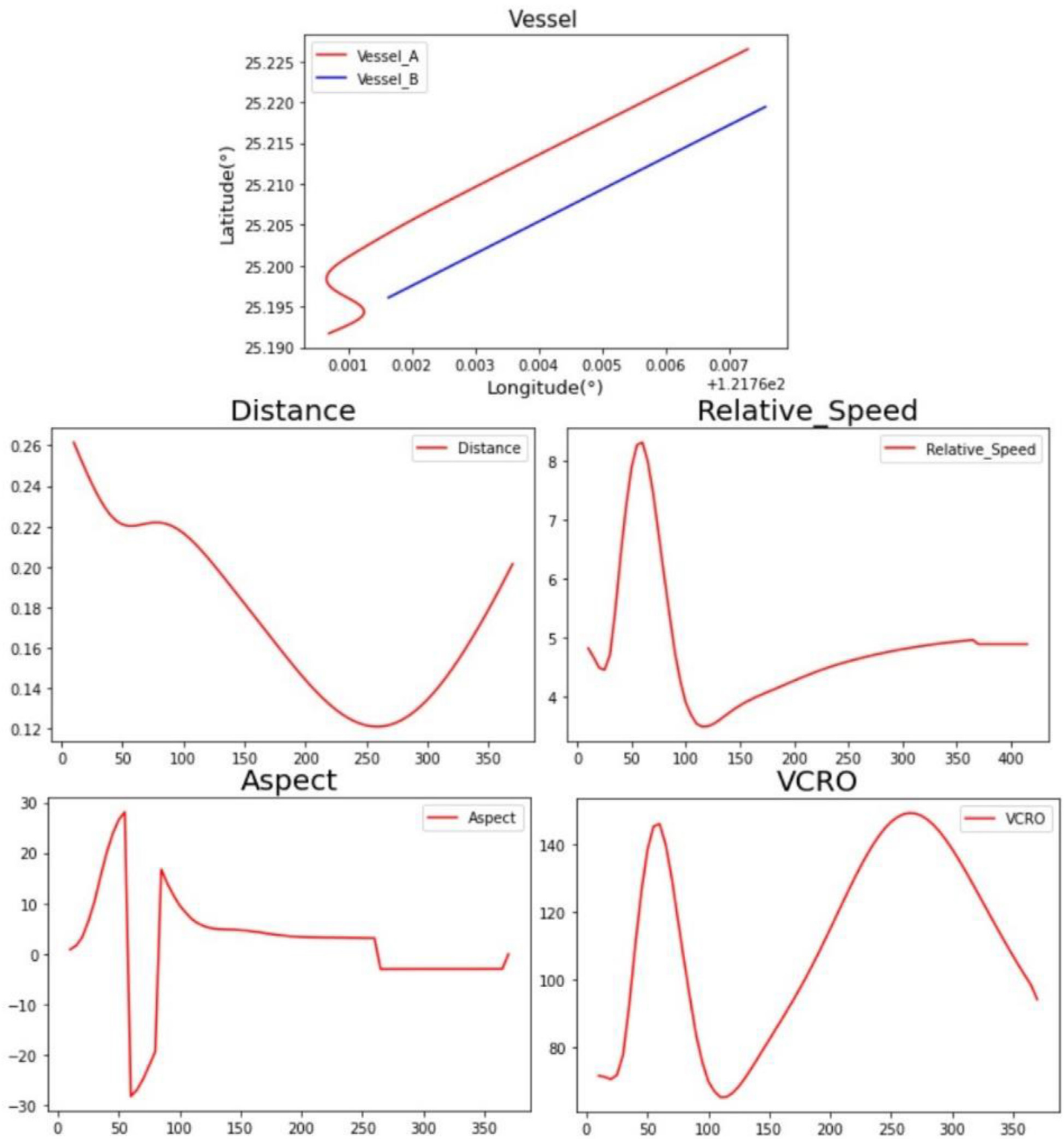

Fig. 9. Vessel-A turns left to avoid an (overtaking) collision.

highest point of VCRO does not appear in DCPA. The rationale for this is that despite the proximity of the two vessels, the risk of collision is relatively low when the vessels are moving in parallel forward directions. Nevertheless, in Figs. 8 and 9, it can also be observed that during an overtaking encounter scenario, the value variation of VCRO is most sensitive to the relative aspect of the two vessels.

Table 1 displays the sample data employed in this simulation. We conducted simulations involving three types of ships rendezvousing at sea and extracted the data corresponding to each parameter when the VCRO value was maximal. From equation (17), it can be observed that the calculation of VCRO takes into account not only the distance (x) and relative speed (y) between two vessels but also their aspect (z). When two vessels are in a head-on or overtaking situation, a slight change in direction for either vessel can usually prevent a collision. However, in a crossing situation, the collision risk is

Table 1. Sampled scenes and variable values.

Figure	Model	Distance (nm)	Relative speed (knot)	Aspect	MAX VCRO
4&5	Cross	0.12	23.37	109.41	514.8
		0.12	17.53	69.8	690.25
6&7	Head on	0.1	29.75	138.14	329.26
		0.04	23.8	142.33	521.3
8&9	Overtaking	0.1	10.12	20.95	237.67
		0.15	10.42	24.78	195.41

relatively higher because the collision cross-sectional area is larger compared to the previous two scenarios.

Based on the preceding analysis, it can be confirmed that in the three encounter scenarios, the VCRO value in the overtaking environment varies considerably with the relative aspect of the two vessels, and the maximum VCRO value in the overtaking encounter scenario is not attained at the point of closest approach. As discussed in Section 3.1, in certain specific encounter scenarios, the DCPA model alone may not be adequate for accurately evaluating the risk of collision between two ships, and the relative aspect of the two vessels must be taken into account to calculate the risk value more effectively.

4.2. Result

The experiment results suggest that the VCRO values obtained in this experiment may have been overestimated because the simulation was conducted under the assumption of a high collision risk environment, which may not always be the case in real-world scenarios.

To gain a better understanding of whether the locations in this area indeed have a higher collision risk, the latitude and longitude of encounters were plotted on a GIS map. In Fig. 10, the red dots represent high-risk zones for ship collisions as analyzed in this experimental evaluation. These areas, particularly in the vicinity of the entrance and exit lanes of Traffic Separation Scheme of Keelung Harbor, close to Keelung Island and Yehliu peninsula, constitute greater dangers that ships may face in this specific maritime region. When two vessels cross paths within these areas, the risks of collision are heightened, necessitating increased vigilance from the crew to prevent such incidents. This study applied the aforementioned VCRO analysis model to evaluate the hotspots for near-collisions when there is a significant presence of fishing vessels (approximately over a hundred at the time) operating at sea near Keelung. This includes both vessels entering and leaving Keelung Harbor and those navigating through the nearby waters.

Fig. 10. The high-risk spots of the region.

5. Conclusion

The VCRO model employed in this paper utilizes AIS data to evaluate the collision risk of two paired vessels. As the likelihood of encountering vessels moving parallel to each other is extremely low in actual maritime operations, the existing model defines a distinct range for situations where an oncoming vessel and an overtaking vessel intersect. The previous model's practical flaws can be fixed by using this interval, which will also bring the model's depiction of offshore vessel activity closer to reality. Also, by applying this model to the sea region used for offshore wind power, the ship navigation will be safer, and the time and cost of repairs following ship accidents shall be significantly decreased.

This study highlights that when there is a high concentration of fishing vessels operating near the waters around Keelung, particularly in the vicinity of the entrance and exit lanes of Traffic Separation Scheme of Keelung Harbor, close to Keelung Island and Yehliu peninsula, the likelihood of vessel encounters significantly increases. Through the assessment using VCRO, it becomes effective in identifying hotspots for near-collisions in these areas.

Furthermore, the assessment model of VCRO can also be applied to offshore wind power as part of ship collision avoidance warning systems. It is hoped that by using the methods proposed in this study, operational vessels can safely complete their tasks, leading to a significant reduction in post-accident maintenance time and costs.

In the future, there will also be attempts to utilize GIS data from offshore wind power and real AIS data from vessels navigating in the nearby waters for analysis. This analysis will use the calculated VCRO data to assess hotspots for near-collisions in the vicinity of wind farms. This information can then be used to determine risk value ranges, which will be crucial for evaluating the risks of vessel operations in those high-risk maritime areas.

Conflict of interest

The authors declare no conflict of interest.

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