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A Decision-Making Method for Autonomous Collision Avoidance for the Stand-On Vessel Based on Motion Process and COLREGs

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Abstract: A great number of collision accidents can be attributed to incongruous collision-avoidance actions between the give-way vessel and the stand-on vessel in a crossing or overtaking situation. If the give-way vessel does not take appropriate collision-avoidance action according to international regulations for preventing collisions at sea, the last barrier to pass safely is the appropriate and effective collision-avoidance action taken by the stand-on vessel. To find the proper autonomous collision-avoidance action of the stand-on vessel, a method is proposed that combines quantitative analysis rules of collision-avoidance with the deduction of nonlinear maneuvering motion process based on the mathematical model group, which conformity can reach 90%. This research presents a method to calculate the timing and most effective collision-avoidance actions for the stand-on vessel based on the four-stage theory of encountering vessels and the characteristics of vessel motion. The accuracy of the latest-action timing and the action amplitude for the stand-on vessel can be increased to the level of second and degree, respectively. A novel model of collision risk index is constructed by the latest time of the feasible collision-avoidance action on the precise of different course-altering amplitude. Methods to find the stand-on vessel's proper collision-avoidance actions in the open sea are presented. The simulation indicates the proposed method for the stand-on vessel can make correct collision-avoidance decisions autonomously.

Keywords: stand-on vessel; collision-avoidance action; encounter stage; quantitative analysis; CRI

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1. Introduction

As one of the most important modes of transportation in the world trade, the shipping industry has attracted great attention, focusing on safety. Any accidents at sea cause huge economic and life losses, as well as environmental damage. Many regulations and measures formulated by IMO, vessel's flag state, port state and vessel owners were taken to ensure the safety of vessels, but maritime accidents still frequently happen. Study shows that more than 80 percent of accidents at sea are caused by human factors [1]. More than 56% of vessel collisions, which resulted in serious maritime accidents, were caused by a vessel navigator's failure to correctly understand and execute the International Regulations for preventing collisions at sea, 1972 (COLREGs, 1972) [2]. The intellectualization of vessels has gradually become a major trend in developing the global shipping industry. Maritime autonomous surface ships (MASS) will adopt advanced automatic sensing and intelligent decision-making technology, replacing the crew for decision-making and reducing mistakes caused by human factors. Moreover, then maritime accidents are expected to be reduced [3]. International Maritime Organization (IMO) has defined the following four degrees of autonomy related to MASS [4]. At the highest degree of autonomy, a fully autonomous vessel is defined as a MASS whose operating system can make decisions autonomously and complete autonomous collision-avoidance (ACA) actions by itself. The operating system should first intelligently identify the encountering situation conforming to COLREG rules and then determine the ACA actions that can be carried out by the own vessel (OS). However, COLREG rules are composed of vague sentences and vocabularies whose core meanings are closely concerned with sea practice. How to quantitatively analyze COLREG rules is a vitally important bottleneck problem. Moreover, any feasible decision plan made by the ACA decision system should be able to be carried out by the OS. Therefore, to ensure the plan to be operational, the maneuvering process of the OS in the ACA scheme should be deducted and checked before decision-making.

Vessel ACA decision-making technologies have been studied for more than half a century, and fruitful research results have been developed. The geometric analysis method, including the geometric model solving the distance to the closest point of approaching (DCPA) and the time to the closest point of approaching (TCPA), has instructed vessel captain or officer on watch to take appropriate collision-avoidance actions in sea practice for several decades [5]. Vehicle obstacle avoidance theory based on judging the angle relation between the relative speed and relative position of two vessels gives the feasible path range of collision-avoidance action [6]. The expert system is also applied in the field of the ACA. It builds a knowledge base from COLREGs, good seamanship and captains' practical experience in collision avoidance. Lee [7] presented a fuzzy logic algorithm for the optimal collision-avoidance scheme based on the requirement COLREG rules and vessel motion data. Maneuvering experiences of captains in different situations were considered simultaneously. With developing information theory, cybernetics and system theory, studying vessel collision-avoidance upgraded to a new stage. In studying vessel collision avoidance using neural networks, collision-avoidance decisions are mainly triggered by collision risk index (CRI) [2]. At the same time, deep learning-based collision-avoidance decisions represented by genetic algorithms also provide new models for the ACA research [8]. The genetic algorithm converts the vessel's path into a series of way-points and looks for an optimal path for the OS based on safety and economy. With the continuous progress of research, researchers have gradually shifted their study to decision-making for collision avoidance among multiple ships. A method that combines offline optimal path planning and restricted A* algorithm uses the artificial potential field to expand online adaptive weighting based on the USV maneuvering response time was proposed by Singh, etc. [9,10]. This method can be used for multi-ship path decision-making.

Many previous studies have focused on the vessel except the stand-on vessel at risk of collision, which should take collision-avoidance actions as early as possible [11]. He (2015) quantified the action of the give-way vessel in the crossing situation [12]. Zheng and Wu (1999) gave the principle and timing of action for the vessel in head-on situations [13]. Woerner quantified each rule of COLREGs based on navigation practice and admiralty case law [14].

The above-mentioned studies on the timing and scheme of the ACA actions taken by the give-way vessel have promoted developing MASS. Nevertheless, the positive and appropriate collision-avoidance action taken by the give-way vessel is an important factor in ensuring the two vessels pass safely.

The collision-avoidance action of the stand-on vessel in the crossing and overtaking situation should be conforming to the COLREG rules distributed from rules 2 to 17. These rules only stipulate the principles of collision-avoidance actions, which can/should be taken by the stand-on vessels. The COLREGs only vaguely indicate that the stand-on vessel at risk of collision should first maintain her course and speed, and no appropriate action can be taken until it is obvious that the give-way vessel has not taken effective action as COLREGs required to avoid a collision. The stand-on vessel should take the most effective collision-avoidance action once the collision cannot be avoided by the give-way vessel's action alone.

In some maritime collisions, the stand-on vessel failed to fulfill the obligation of keeping course and speed required by the rules in the initial stage of the collision or obstinately insisted on the right to "keep her course and speed" granted by the rules in the immediate danger (ID) stage, resulting in serious collision accidents. The collision between CF CRYSTAL and SANCHI occurred in 2018 and eventually caused SANCHI to burn, explode, and sink, leaving three crew died and 29 crew missing [15]. In the early stages of the risk of collision formation, CF CRYSTA, which should have been kept her course and speed as the stand-on vessel, made a small heading course changed so that she could return to the planned route. When the two vessels were finally in the immediate danger situation, the main cause of the calamity that eventually occurred was that none of the vessels took the most effective collision-avoidance action.

Therefore, it is necessary to carry out a quantitative study on the timing of action for the stand-on vessel. Some experts have also adopted various methods to quantitatively analyze the timing of action by the stand-on vessel. Ni [16] established a decision-making algorithm, which combined ship maneuverability and used geometric analysis to determine the timing of the action. Szlapczynski [17] relied on the concept of the ship domain to reflect the action moment of the stand-on vessel through the distance of the action. Tsai [18] presented one model based on the dynamic game of complete information, which can calculate the critical action time for preventing a close-quarters situation. Shen used deep reinforcement learning methods, which combined the COLREGs, ship maneuverability and seaman experience, to propose one model to quantify the action timing of multiple ships in restricted waters [19].

The ACA scheme will be carried out by the program. Namely, the timing for the stand-on vessel can/should take collision-avoidance action must be calculated autonomously. It is indispensable in the ACA field to carry out quantitative analysis research, which determines the timing of the ACA action for the stand-on vessel. To ensure that the ACA scheme by the system can be fulfilled by the stand-on vessel, the vessel's scale and motion characteristics should be integrated.

The four-stage theory divides the entire two-vessel encountering process and risk of a collision into four parts [20]. Following this theory, Wang put forward a reference explanation and a quantitative estimate for the timing of action in a close-quarter situation (CS) [21]. The meanings of close-quarter situation, risk of collision (CR), immediate danger (ID), maintain course and speed are analyzed quantitatively under the frame of the four-stage theory in the two-vessel encountering process [22].

The division of the four stages by the time points plays an important role in generating the vessel collision-avoidance action scheme. The minimum distance to collision (MDT) model adapts a vessel's motion to a plane model and modifies its course to reflect the shortest distance a vessel can take to avoid collision [23]. The collision alert system based on the ship domain is also used to judge the stage of the vessel encountering, but it did not judge the stages separately from the perspective of the give-way vessel or the stand-on vessel according to the COLREGs [24]. A developed method quantitatively divides the situation into nine classes from the point of view on the stand-on vessel and combines the COLREGs and the intention of the vessel's action, and finally transforms it into four stages according to the vessel motion situation [25]. The mathematical model group (MMG) and ship domain model is combined to study the automatic collision-avoidance schemes of the stand-on vessel and the give-way vessel in different encounter situations and stages [26].

Our research clarifies the meaning of each stage in the entire encounter situation and how collision-avoidance actions should be taken by the stand-on vessel accordingly. The overall principles of the collision-avoidance actions scheme were clarified. From the beginning to the collision, the stand-on vessel experiences four stages: action unrestricted, maintain course and speed, action permitted, and action required.

Moreover, the following problems should be solved for the ACA decision-making system:

1. How can we divide the entire encounter situation (crossing or overtaking situation) into different stages and determine the ACA actions accordingly as COLREGs and good seamanship?
2. How can we include the nonlinear maneuvering motion characteristics of vessels into the methods and ensure the methods are consistent with sea practice?

It is more effective by turning the heading than changing speed to avoid collision due to the inertia force of a vessel when a vessel sails in the open sea. Moreover, the protection system of the main engine restricts the drastic change in revolution per minute (RPM). At harbor speed and below, modern merchant ships can reduce their RPM rapidly, but several minutes is need for reducing one RPM when she runs on sea speed. Namely, course alteration is the only choice to avoid collision when ships run at sea speed on the open sea. Autopilot systems have been widely used on ships since the 1960s. This kind of system can provide a ship with the ability to steer the rudder according to proportion integral derivative (PID) control rules if the target course is set. Stand conducted experiments with unmanned submersibles avoiding obstacles in unknown ocean currents by maintaining the minimum safe distance [27]. Simplified autonomous control is the most effective method for underwater vehicles to execute ACA.

The author proposes an autonomous collision-avoidance decision-making method that conforms to navigation practice and vessel motion characteristics. This method can divide stages, calculate the collision risk index, and determine the scheme of automatic collision-avoidance action for the stand-on vessel. COLREG rules and good seamanship are the basic principles. MMG model, the fuzzy adaptive PID course control system, is employed to predict a vessel's nonlinear turning motion process. Ship domain is used to decide if the target ship (TS) can pass safely.

The contributions of this article include the methods of finding the timing of the ACA for the stand-on vessel, as well as the last steering time for the OS, which in different stages based on the maximum course changing amplitude. A new CRI model that can be used for the stand-on vessel to take ACA action in restricted water areas is also proposed.

This article is structured into 6 sections, including the introduction. The encounter stage discrimination and the principle of collision-avoidance action are addressed in Section 2; some necessary basic methodologies are presented in Section 3; Section 4 discuss the solution of the last steering point and a mode of collision risk index; The actions of the stand-on vessel in two different encounter situations are simulated in Section 5; the discussion and conclusion are presented in Section 6.

2. Encounter Stage and Collision-Avoidance Action Principle

The entire encounter process of two vessels that will eventually collide can be divided into four stages, beginning when the vessels are far apart. This is the so-called "four-stage theory of a vessel encountering process" directed by COLREGs and good seamanship [28]. The four stages experienced orderly by both vessels are (1) no risk of collision (CR), (2) risk of collision, (3) close-quarter situation (CS) and (4) immediate danger (ID). Particularly for the stand-on vessel and give-way vessel in the crossing situation, rules 13, 15 and 17 provided the timing and principles of collision-avoidance actions. These connotations of these rules can be summarized as the process shown in Figure 1.

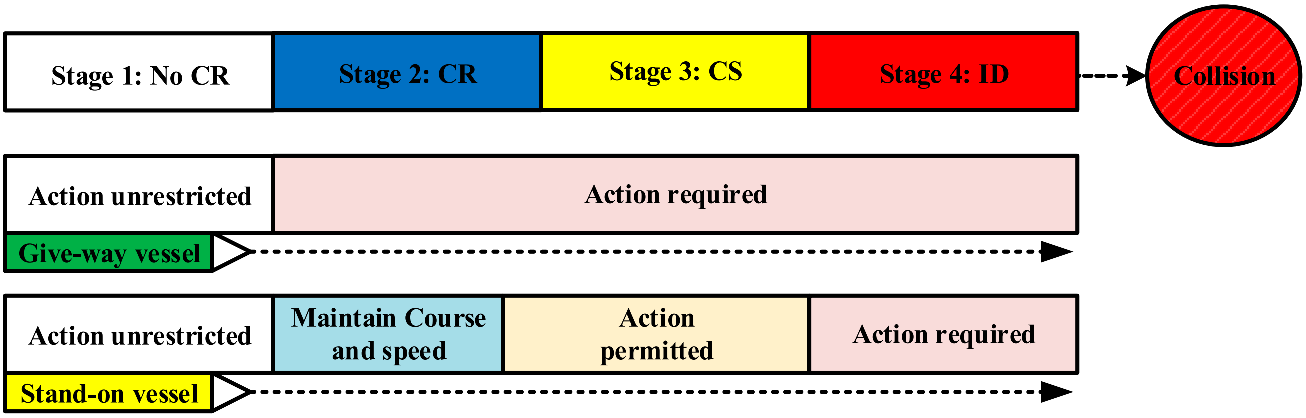


Figure 1. Stages and collision-avoidance actions that should be taken by two vessels. The four stages are divided into (1) no risk of collision, (2) risk of collision, (3) close-quarter situation and (4) immediate danger stage, and are displayed in white, blue, yellow and red colors, respectively.

The collision-avoidance action taken by the stand-on vessel in different stages is different and varies as the encountering situation develops. These actions may include course alteration and speed adjustment. Speed adjustment is nearly impossible when a vessel runs at sea speed in the open water. The reason is already described in Chapter 1. Therefore, the collision-avoidance action scheme of the stand-on vessel includes the course-altering amplitude and timing to take evasive action.

Stage 1: Far distance when the risk of collision stage is not formed.

The collision-avoidance action for the stand-on vessel is unrestricted before the risk of collision stage is formed. The amplitude of the course change should not be too small in the premise of passing safety by rule 8 and good seamanship in sea practice. It ensures TS understands the true intention of the OS and reduces the risk of misunderstandings, which have caused many accidents. The specific value can be set by the captain and is then adopted by the system.

Stage 2: The risk of collision stage is formed, but the stage of close-quarter situation is not formed.

The stand-on vessel should keep her speed and course in the initial stage after reaching the risk of collision stage. Moreover, she shall maintain the most effective way to continuously observe whether the give-way vessel has taken collision-avoidance action as required.

The stand-on vessel is permitted to take actions to avoid collision by her maneuver alone once the give-way vessel does not take appropriate action according to the rules, but not to alter course to port for a vessel on her port side in the crossing situation if the circumstance permitted.

A key problem is when the stand-on vessel is permitted to take collision-avoidance action alone. According to rule 8, any avoidance action taken by a vessel should be substantial. Therefore, it is persuasive that the timing does not appear if small-amplitude manipulation ensures the give-way vessel to pass safely. On the contrary, if the amplitude of manipulation that will ensure the give-way vessel can pass safely becomes so large that the captain of the stand-on vessel cannot tolerate it because he feels it to be dangerous, the collision-avoidance action is still not be taken. This viewpoint can be interrelated to determine the timing of a solo collision-avoidance action by the stand-on vessel. When the distance of two approaching vessels is so close that the stand-on vessel must take a large angle course alteration by the course control system, the give-way vessel is not thought to take the collision-avoidance action as COLREGs.

Namely, the timing of the stand-on vessel being permitted to take collision-avoidance action alone is coming when she finds that a sufficiently large amplitude manipulation must be taken to pass safely. Like the sea practice, the “big amplitude manipulation” by the stand-on vessel alone in the ACA decision-making system at the open sea can be preset as a sufficiently large course-angle alteration in the course control system circumstance because RPM changing is nearly impossible and useless. This angle of the course alteration in this condition may vary according to many factors, such as the scale of ships, traffic environment, etc. The value preset in the system can be input by the captain of a vessel because he has the final words. The autonomous collision-avoidance system will control the course control system to perform the collision-avoidance operation autonomously. In sea practice, it is generally believed that the meaning of "substantial deviation" mentioned in COLREGs is at least 30° or half of the speed reduction. Usually, course alteration is considered the most common method in the open sea. Therefore, the substantial deviation mentioned above collision-avoidance action be set as 30° or greater.

Stage 3: The close-quarter situation stage is formed, but the immediate danger stage is not formed.

In this stage, whatever collision-avoidance actions by the OS are taken, the TS will enter the OS's ship domain. However, collision will not happen if effective collision-avoidance actions are taken by each vessel. The stand-on vessel is permitted to take collision-avoidance action alone in this stage.

Stage 4: The stage of immediate danger is formed, but a collision has not yet happened.

According to rule 17, the OS must take the most effective action to avoid a collision in this stage, as the collision cannot be avoided by the action of a vessel alone. A substantial turn (90° or more in the course control system circumstance) must be taken in the most effective direction until the distance between the center of two vessels begins to increase.

Fuji (1971) proposed the term "ship domain", and that a vessel encounter is considered safe if neither ship's domain is invaded by other vessels [29]. Most researchers use the term ship domain to indicate the risk of vessel collisions. In the following decades, research in the field of ship domain has further developed [30]. Goodwin proposed a definition of ship domain as the effective area within a certain range around a vessel that the captain intends to prevent other vessels and stationary objects from entering. With the widespread use of electronic chart displays and information systems (ECDIS) and automatic identification systems (AIS), captains prefer to refer to the actual size and movement characteristics of other vessels to set the appropriate ship domain.

Based on the meaning of ship domain and the stage of the close-quarter situation, the period of the close-quarter situation stage is defined as the period between when the TS will not pass outside the OS's ship domain to when the OS will collide with the TS, even if the most effective collision-avoidance action is taken by one vessel [31]. This definition has been widely accepted by the maritime industry. It actually describes the physical meaning of the first moment of the close-quarter situation (FTCS) and the first moment of immediate danger (FTID). The close-quarter situation stage exists between the FTCS and FTID.

In general sea practice, steering full-rudder to avoid collision is the most effective action in the open sea. This method, which is close to human thinking and normal practice at present, is used to calculate the FTCS and FTID in previous studies [26]. However, the rudder steering angle of an autonomous vessel is decided by the system when she is equipped with a course control system or trajectory control system. The main function of the trajectory control system is to control the navigation track, track planning and navigation alarm, etc. The core part of the trajectory control system is also the course control system.

Therefore, the most effective collision-avoidance action in this situation needs to be defined separately. FTCS/FTID is redefined based on the characteristics of the course control system. FTCS means the timing after which the TS will no longer pass outside the OS's ship domain even if the most effective avoidance action is taken by the OS course control system. Namely, the TS will pass the outside of ship domain if the same action is taken before this timing. FTID means the timing after which the TS will collide with the OS even if the most effective avoidance action is taken by the OS course control system. Similarly, the TS will not collide with the OS if the same action is taken before this timing.

3. Methodology

3.1. Ship Domain and Collision Domain Model

Two coordinate systems are used in Figure 2. The fixed coordinate system XOY is built with the positive direction of X and Y axis pointing to true north and east. However, the vessel coordinate system xoy is built with the positive direction of x and y axis points to bow and starboard. The relation of the TS positions in two coordinate systems is shown as Equation (1).

$$[X,Y] = [x,y] \times A + [X_0, Y_0] \tag{1}$$

where

$$A = \begin{bmatrix} \cos(\psi) & -\sin(\psi) \\ \sin(\psi) & \cos(\psi) \end{bmatrix} \tag{2}$$

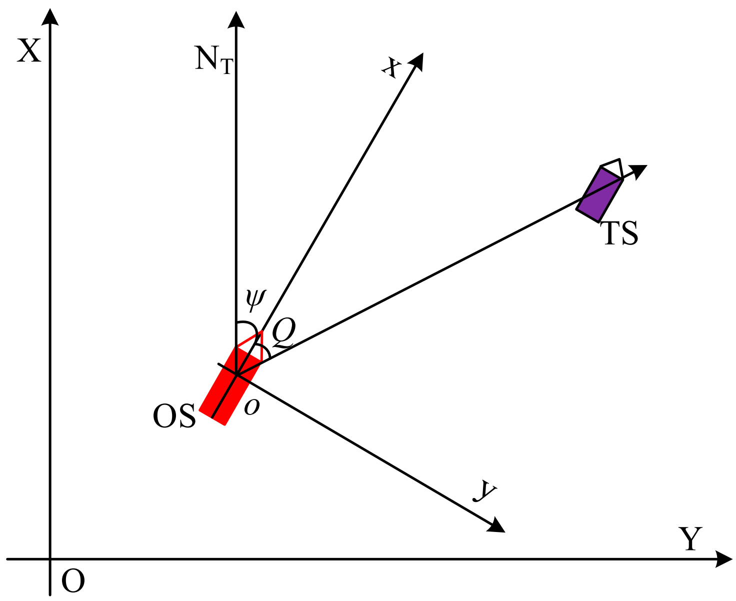


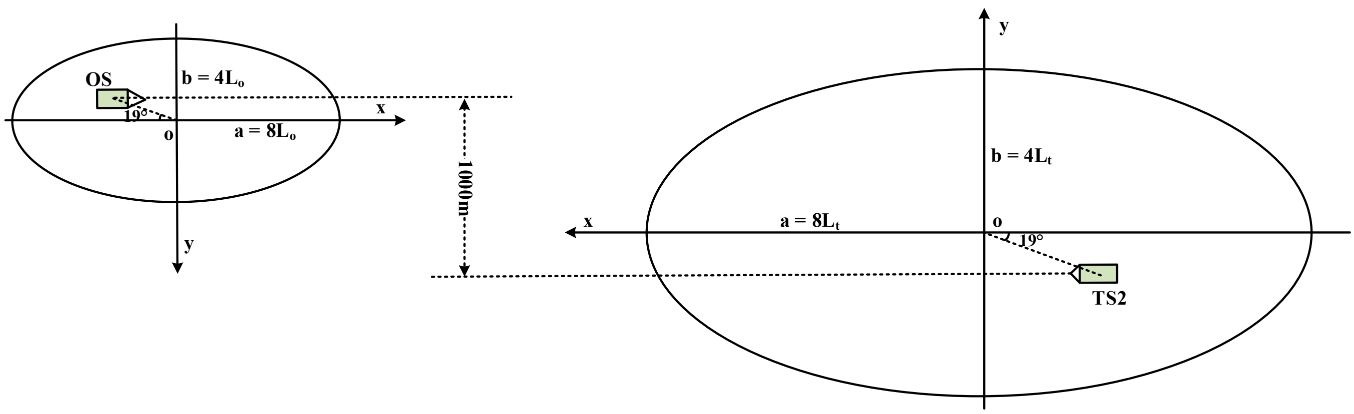
Figure 2. Two-coordinate systems. XOY is the fixed coordinate system and xoy is the ship coordinate system. ψ and Q represent the true course of the OS and relative bearing from the TS.

In the above equations, $[X_0, Y_0]$ is the position of the vessel's center in the fixed coordinate system and $[x,y]$ is the position of the TS in the vessel coordinate system. The angle ψ between two coordinate systems is the heading course of the OS. The relative bearing Q represents the angle between the fore and aft line of the OS and the bearing line of the TS.

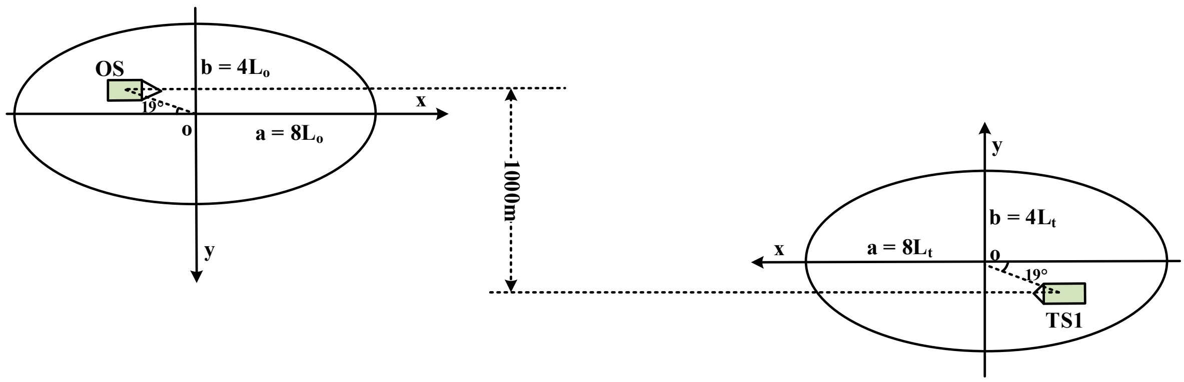
The ship domain is thought to be not violated in the traditional ship domain model. The authors, captains with many years of sea experience, selected a ship domain model in which the center of the OS is located at the rear of the circle or ellipse. To simplify data processing, a virtual ship can be set up in the center of the ship's domain. This choice is based on the rules and good seamanship because more safety distance should be kept from the front of the vessel and the starboard side according to the physical size of the OS [32].

When taking collision-avoidance actions, the captain of the OS often set a safety encounter distance closer to navigation practice based on the physical size and the speed of both vessels. The safety encounter distance is equivalent to the ship domain [33].

Appropriate ship domain range thought by ship captain/OOW is of great importance in collision-avoidance actions. On the contrary, inappropriate ship domain range setting causes the vessel to misjudge the risk of collision. It may prompt one vessel to judge a collision risk between the two vessels, while the other vessel believes that collision risk does not exist. Especially in head-on situations, some collisions have occurred because of this kind of similar uncoordinated actions. Figure 3 shows that the OS is in a head-on situation with two vessels with different overall lengths. The real ship position of the OS in head-on and crossing situations are moved from the center of the elliptical ship domain to the rear left by 199°, which can provide safer space for the OS [32]. If both vessels keep their speed and course, the distance to the closest point of approach (DCPA) in the above encounters is 1000 vm. Supposed OS and TSs using 4 times of LOA as the horizontal range of their ship domain. The OS will not take any action because she believes that TS1 has not violated her ship domain. Instead, TS1 will turn to the starboard side because its domain is greater than the DCPA. In another situation, both vessels maintain their courses because their ship domains would not violate each other. If only the physical size of the OS is considered when setting the ship domain, the risk of ship collision increases. With the ECDIS and AIS are mandatorily equipped onboard, seafarers can accurately obtain the physical size and speed of the TS. Therefore, they can use the above data to determine a reasonable safe passing distance, the same as the ship domain.



(**a**)



(**b**)

Figure 3. Two different encounters in a head-on situation. The lengths of L_o, L_{t1} and L_{t2} are 160, 336 and 160 m, respectively. (**a**,**b**) are variables that can be set accordingly based on the captain's experience and the ship's speed. The radius a and b of the elliptical ship domain in this experiment are set to 8 times and 4 times of its own LOA, respectively.

The selection of the shape of the ship domain in this article is mainly based on the maritime practice and rules of COLREGs. The new ship domain is defined as the model shown in Figure 4. R is the circle's radius in the crossing situation. a and b represent the length of the long and short semi-axis of the ellipse ship domain, respectively, in the overtaking situation. L_o is the length of the OS, and L_t is the length of the TS. The center of the virtual vessel is taken as the origin of the vessel coordinate system. The lengths of R, a, and b are also affected by the size and speed of the ship, and their values increase with increasing ship speed.

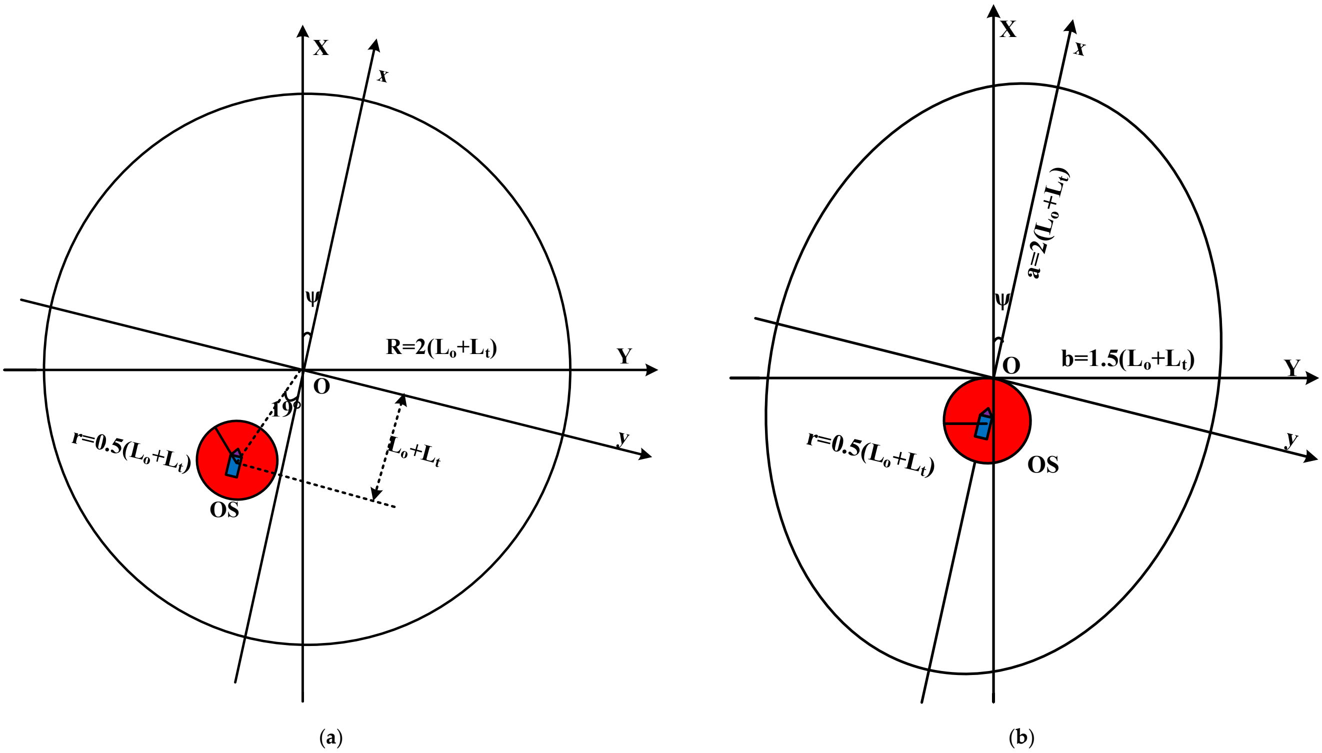


Figure 4. Range of ship domain and collision domain in the crossing/overtaking situation. (**a**) represents the domain in a crossing situation, and (**b**) represents the domain in an overtaking situation. The red circular area represents the collision domain with half the total lengths of two vessels. The ship domain in the crossing and overtaking situation. ψ represents the true course of the OS. The ship domain is represented by a circle and an ellipse in the crossing and overtaking situations.

The boundary equation of the circular ship domain in the crossing situation as follows:

$$x^2 + y^2 = R^2 \tag{3}$$

where

$$R = 2(L_o + L_t) \tag{4}$$

The boundary equation of elliptic ship domain in an overtaking situation:

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1 \tag{5}$$

where

$$\begin{cases} a = 2(L_o + L_t) \\ b = 1.5(L_o + L_t) \end{cases} \tag{6}$$

According to the four-stage theory in the previous section, a region named collision domain (CD) needs to be specified to represent the meaning of "OS collides with the TS". This means the collision is thought to occur when the TS enters the collision domain of the OS. As captains, the authors defined the collision domain as the area of a circle where the OS situates in the center. The radius is half of the sum of the two vessel lengths. Figure 4 shows the ship domain and collision domain model in the crossing/overtaking situation.

3.2. The Three-Degrees-of-Freedom MMG Model

This study focuses on the stand-on vessel in the open sea where the density of vessels is not large in good weather. Therefore, the three-degrees-of-freedom MMG model [34] can be used to simulate OS when only sway, surge, and yaw are considered in the calm sea.

$$\begin{cases} (m+m_x)\cdot\dot{u}-(m+m_y)\cdot v\cdot r = X_H+X_P+X_R \\ (m+m_y)\cdot\dot{v}+(m+m_x)\cdot u\cdot r = Y_H+Y_P+Y_R \\ (I_{ZZ}+J_{ZZ})\cdot\dot{r} = N_H+N_P+N_R \end{cases} \tag{7}$$

where m denotes the total mass of the vessel, m_x and m_y respectively indicate the additional mass in the vertical and horizontal axis directions. u, v, and their derivatives denote the velocity and acceleration in a different direction, r and $\dot{r}$ are the angular velocity and angular acceleration. I_{ZZ} and J_{ZZ} are the moment of inertia and additional moment of inertia, respectively. X and Y are hydrodynamic forces in the vertical and horizontal axis directions, N represents the turning moment. H, P and R represent the force or moment of the hull, propeller, and rudder, respectively.

With the progress and development of navigation technology, advanced equipment, such as Baidoo navigation satellite (BDS)/differential global positioning system (DGPS), and AIS, ECDIS have been successively applied in ocean navigation, which has greatly upgraded the navigation safety level of ocean-going vessels [35]. The trajectory tracking control system, which represents a new direction in developing marine science and technology, has begun to be applied to a vessel. In combination with ECDIS and BDS/DGPS, the trajectory tracking control system can repeatedly adjust the vessel's course and ensure OS sails along the preset route.

PID control is the earliest and most classic control strategy. It has the advantages of a simple algorithm, high robustness, and strong reliability. It is very suitable for control systems with precise mathematical models and is most commonly used in modern control engineering. However, the control effect of the classic PID autopilot is strongly dependent on the accuracy of the ship maneuvering motion model. Fuzzy control has lower requirements for the accuracy of ship maneuvering motion models and has more outstanding robustness and adaptability for uncertain systems and nonlinear systems.

Therefore, autonomous navigation vessels' trajectory tracking control system can adopt the fuzzy adaptive PID control method [36]. It mainly includes a fuzzy controller, servo system of steering gear and steering angle feedback device. The system inputs the fuzzy controller according to the preset course, course deviation, course deviation changes rate and other parameters to control the rudder angle. The steering gear servo system controls the rudder angle according to the rudder angle command. The actual course would be fed back to the fuzzy controller through the course feedback device after the vessel executed the steering order. The fuzzy control device calculates the course deviation and performs loop feedback until the vessel returns to the predetermined course The principle of fuzzy adaptive PID control can be shown in Figure 5.

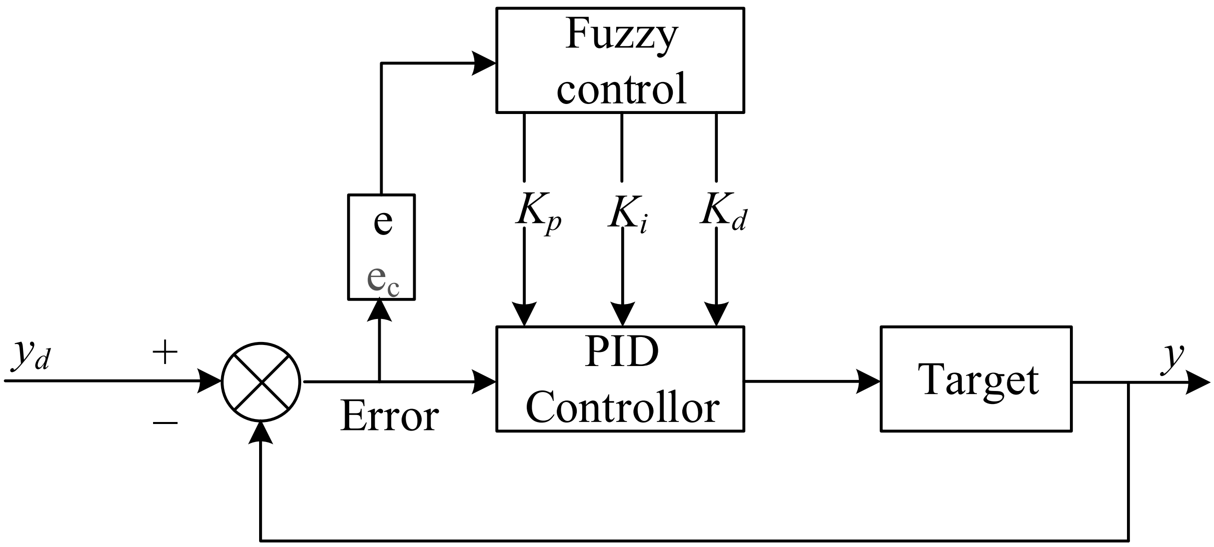


Figure 5. Principle of fuzzy adaptive PID control.

4. The Situation Factor Model Based on Course Control System

4.1. The First Time-in-Point of Collision Risk (FTCR)

The first step in making a collision-avoidance decision is to identify the type of situation and determine the stage at the exact moment when TSs are approaching. He [26] introduced the methods to identify the situation. One key issue is to divide the entire encountering process into COLREGs and use good seamanship for the stand-on vessel in the crossing and overtaking situation, provided that a course control system is already installed onboard.

As introduced in Section 2 (Figure 1), the first time-in-point of collision risk (FTCR), FTCS and FTID divide the encountering process into four stages. It is a pity that no accurate definition of situation factors (CR, CS and ID) has been not given, although the term of them are mentioned in COLREGs [23]. Despite the interpretation for situation factors having been discussed for a very long time, the definition of situation factors based on physical process at sea shown in the above studies has been accepted by most researchers. In the traditional simulation calculation for vessels to divide the encounter stage, the course alteration is realized by steering the rudder to hard a port or hard a starboard [37]. This steering method is more in line with human operation thinking. However, considering the vessel's steering decision system is required to determine the above-mentioned situation factors for the ACA actions in the ships equipped with TCS or course control system.

The meaning of FTCR can be illustrated combined with the potential collision risk. The potential collision risk means that the TS will eventually not pass outside the OS's ship domain if the TS and OS maintain their current course and speed. Two vessels begin to be at the risk of collision when the potential collision risk exists, and a certain criterion of TCPA is satisfied at the first time in point. Namely, this moment is defined as FTCR. The determination method of PCR existence was presented in the article [26]. The captain of the vessel or the MASS designer may set the appropriate data to solve FTCR automatically according to the maneuver performance of a vessel and the navigation environment. This means that this stage starts if the limited conditions of FTCR are satisfied. The captain/officers of a vessel often use the visible range of the navigation lights to judge the encounter situation for two vessels. The COLREGs rule 22 requires that the minimum visibility distance of masthead light and stern light for the power-driven vessel not less than 6 nm and 3 nm. Therefore, the quantitative standards of FTCR can be shown in Table 1.

Table 1. Quantitative standards of FTCR for the crossing and overtaking situations.

Situation	Limitations
Crossing	The potential collision risk exists, 20 min $\geq$ TCPA > 0, D $\leq$ 6 nm
Overtaking	The potential collision risk exists, 30 min $\geq$ TCPA > 0, D $\leq$ 3 nm

The TCPA shown in Table 1 should be decided and preset by the ship captain.

4.2. The First Time-in-Point of Close-Quarter Situation (FTCS)

For the model of the FTCS, much advice can be found. Wu and Zheng proposed the term of the last steering point according to the understanding of the close-quarter situation stage: OS and TS are in a close situation when the OS cannot ensure her ship domain will not be invaded by the TS even when collision-avoidance actions measure 90°, or higher angles of course alteration are taken [38]. The above-mentioned last steering point is similar to the meaning of the FTCS: The OS can prevent the TS from entering the OS's ship domain by altering the course at any time before this specific time-in-point. On the contrary, after this specific time-in-point, no matter the course alteration made by the OS, her ship domain will be invaded by the TS unavoidably. Obviously, this specific time-in-point is thought to be the FTCS.

A key challenge is finding the FTCS and the minimum course-alteration angle (θ_m) in different situations, which will ensure TS to pass outside of the ship domain, under different timings of the entire encounter situation for the stand-on vessel. The process of the stand-on vessel acting alone in the crossing/overtaking situation is shown in Figure 6.

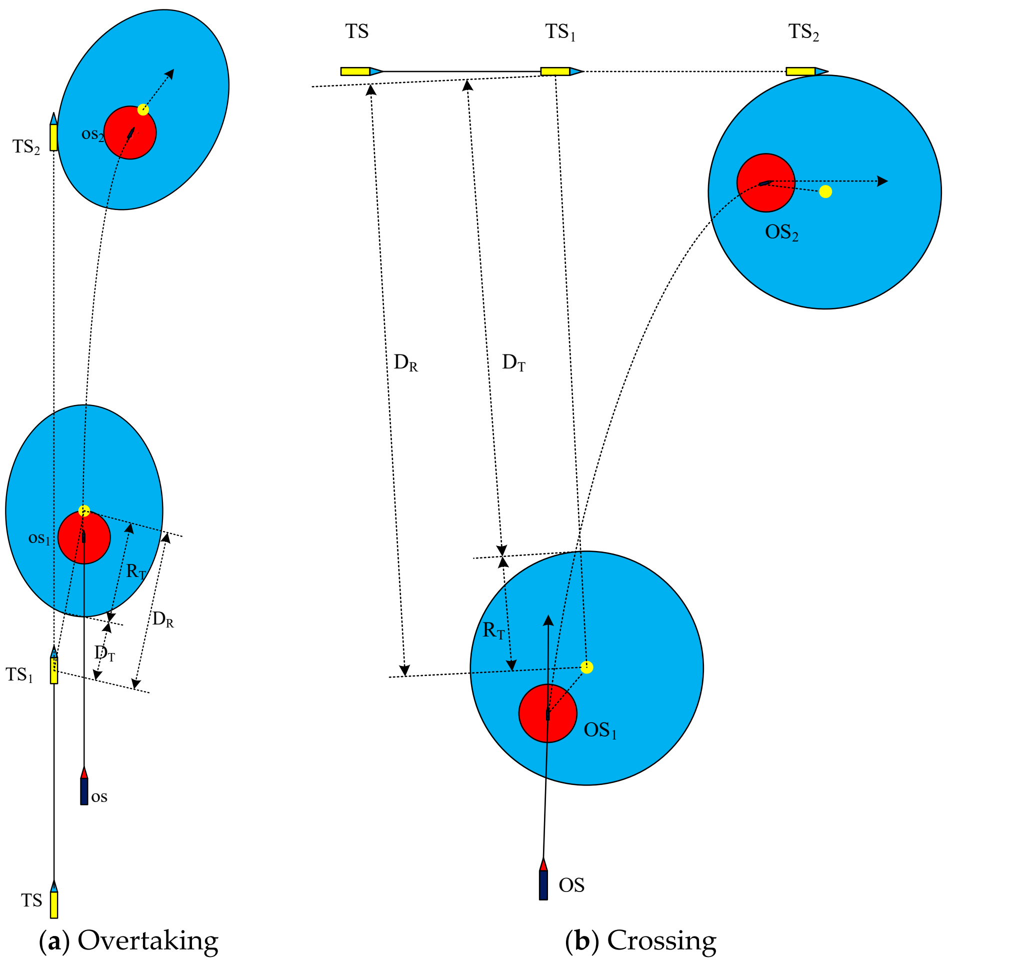


Figure 6. Collision-avoidance action by the stand-on vessel in an overtaking/crossing situation.

In Figure 6, the ship domain and collision domain are marked in blue and red, D_R is the distance between the TS and the virtual vessel, which situates in the center of the ship domain of the stand-on vessel, and D_T is the distance from the TS along the virtual center to the boundary of the ship domain. As the radius of the ship domain in the crossing situation, R_T is a fixed value but is variably in the overtaking situation.

Figure 6 shows the OS maneuvering process during which TS does not just enter the OS's ship domain once the TS does not take correct and effective collision-avoidance actions timely as required.

$$D_T{}^{(t)} = D_R{}^{(t)} - R_T{}^{(t)} \tag{8}$$

The superscript t represents the time point when the value of the variable is calculated:

$$\begin{cases} D_T{}^{(t)} = \sqrt{\left(X_v{}^{(t)} - X_t{}^{(t)}\right)^2 + \left(Y_v{}^{(t)} - Y_t{}^{(t)}\right)^2} - R_T{}^{(t)} \\ R_T{}^{(t)} = ab/\sqrt{\left(a \cdot \sin Q^{(t)}\right)^2 + \left(b \cdot \cos Q^{(t)}\right)^2} \\ \left(X_v{}^{(t)}, Y_v{}^{(t)}\right) = \left(X_o{}^{(t)}, Y_o{}^{(t)}\right) + [\sin C_o{}^{(t)}, \cos C_o{}^{(t)}] \cdot \frac{a}{4} \\ \left(X_t{}^{(t)}, Y_t{}^{(t)}\right) = \left(X_t{}^{(t-1)}, Y_t{}^{(t-1)}\right) + [\sin(C_t), \cos(C_t)] \cdot v_t \cdot \Delta t \\ a = 2(Lo + Lp) \\ b = 1.5(Lo + Lp) \end{cases} \tag{9}$$

$$\begin{cases} D_T{}^{(t)} = \sqrt{\left(X_v{}^{(t)} - X\,_t{}^{(t)}\right)^2 + \left(Y_v{}^{(t)} - Y_t{}^{(t)}\right)^2} - R_T^{(t)} \\ (X_v{}^{(t)}, Y_v{}^{(t)}) = (X_o{}^{(t)}, Y_o{}^{(t)}) + [\sin\left(C_o{}^{(t)} + 19^\circ\right), \cos\left(C_o{}^{(t)} + 19^\circ\right)] \cdot (Lo + Lt) \\ (X_t{}^{(t)}, Y_t{}^{(t)}) = \left(X_t{}^{(t-1)}, Y_t{}^{(t-1)}\right) + [\sin(C_t), \cos(C_t)] \cdot v_t \cdot \Delta t \\ R_T^{(t)} = 2(Lo + Lt) \end{cases} \tag{10}$$

where (X_o, Y_o) denotes the real position of the OS in the fixed coordinates system and (X_v, Y_v) is the virtual position of the OS. v_o, C_o and L_o denote the speed, course and LOA of the OS. (X_t, Y_t), v_t, C_t and L_t denote the position, speed, course and LOA of the TS in the fixed coordinates system.

If OS is the stand-on vessel in an overtaking situation, the equation can be set:

$$g(t_m, \theta_m) = \min\left(D_T{}^{(t)}\right) = \min(f(t, t_m, \theta_m)) \tag{11}$$

The $\min(f(t, t_m, \theta_m))$ represents the minimum value of $D_T{}^{(t)}$ in the entire encounter stage since now if OS alters course to $C_p(C_p = C_o + \theta_m)$ in the time point t_m. This means that the OS takes a collision-avoidance action by turning at the time point t_m.

The TS will enter the OS's ship domain if $\min(D_T{}^{(t)}) < 0$. On the contrary, The TS will pass outside the OS's ship domain if $\min(D_T{}^{(t)}) > 0$. When $(D_T{}^{(t)}) = 0$ it is satisfied, the TS will be tangent to the OS's ship domain. We can easily conclude that $\min(D_T{}^{(t)})$ it depends on the independent variables t_m and C_p if the same initial conditions exist between the two vessels.

In the above discussion, once there is a group of t_m and θ_m which means course alteration from C_o to C_p taken by the OS since time t_m, will result in that the TS just does not enter the OS's ship domain. Moreover, a larger course-alteration angle of the collision-avoidance action being taken or taking the same collision-avoidance action before t_m, the TS will pass outside the OS's ship domain. On the contrary, the TS will enter the OS's ship domain if a lower course-alteration angle of collision-avoidance action is taken or taken after the same collision-avoidance action t_m. The above angle ($\theta_m = C_p - C_o$) is the minimum course-alteration angle of the OS at time t_m.

Many groups of t_m and θ_m, which satisfy $\min(D_T{}^{(t)}) = 0$ and ensure the TS to be tangential to the OS's ship domain, exist in the early stages of an encounter. The OS can adopt different course-alteration angles, which are larger than or equal to θ_m, at different times to prevent the TS from entering the OS's ship domain.

When the distance between the two vessels becomes smaller, the minimum course-alteration angle gradually increases and the number of groups of t_m and C_p becomes smaller. Until a certain moment, the number of groups equals 1, the OS must take collision-avoidance action, and the course-altering amplitude is no less than θ_m at once to ensure the TS pass outside the OS's ship domain. This moment is the FTCS: the TS will enter the OS's ship domain no matter how much the OS changes its course after this moment.

Whatever if OS changes her course, the position of the OS can be calculated as:

$$\left(X_t{}^{(t)}, Y_t{}^{(t)}\right) = \left(X_t{}^{(t-1)}, Y_t{}^{(t-1)}\right) + [\sin(C_t), \cos(C_t)] \cdot v_t \cdot \Delta t \quad (12)$$

The position of the OS $(X_o{}^{(t)}, Y_o{}^{(t)})$ before the time t_m can be obtained by the uniform linear motion equation. When the course control system of the OS receives the command to alter its course, it gives the corresponding rudder command through the fuzzy adaptive PID control method. Afterward, the maneuvering movement process of the OS can be calculated by the vessel's MMG equations and the Runge–Kutta method when the initial conditions and the rudder angle of a different time are known.

Therefore, the minimum course-alteration angle (θ_m) under different times for the OS in an overtaking situation and crossing situation can be calculated as follows:

Combining the course to be steered $C_p = C_o + \theta_m$, the fuzzy adaptive PID control, the MMG equations, and initial values of the speeds, courses and positions of the OS during turning can be calculated.

The FTCS of the OS in a crossing situation can be obtained according to the flow of Figure 7.

Figure 7 shows the numerical method of the minimum course-alteration angle of the OS at different moments in the crossing situation. The OS's decision-making system can output the minimum redirection angles (θ_m) at different moments. The OS can select a series of corresponding θ_m and t_m, combined with a certain algorithm, to ensure that the TS does not enter the OS's ship domain by altering θ_m or more degrees at t_m. Namely, the OS only needs to alter a small angle when the ACA is taken by turning in the initial stage of forming a collision risk. With the increase of t_m, the required minimum course-alteration angle that can keep TS pass out of the OS's ship domain gradually increases until a certain moment when the corresponding θ_m and t_m of the OS's ship domain are invaded by the TS, no matter how much the OS takes ACA by changing her course after the above moment. The exact moment is the FTCS.

Analogically, the latest action time of the OS under a certain permissible changing course can be obtained according to the flow of Figure 8.

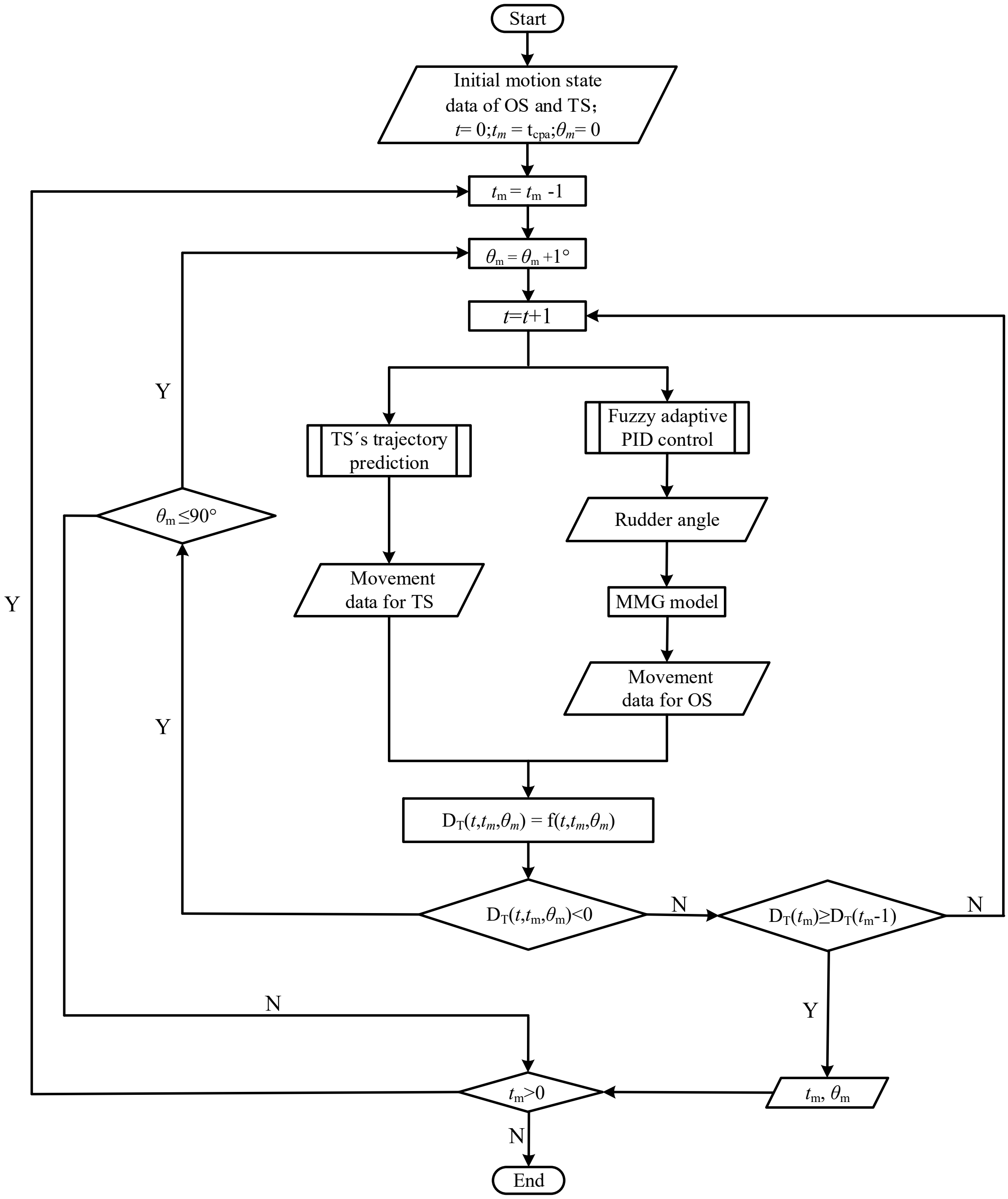


Figure 7. Numerical method of the minimum course-alteration angle based on time.

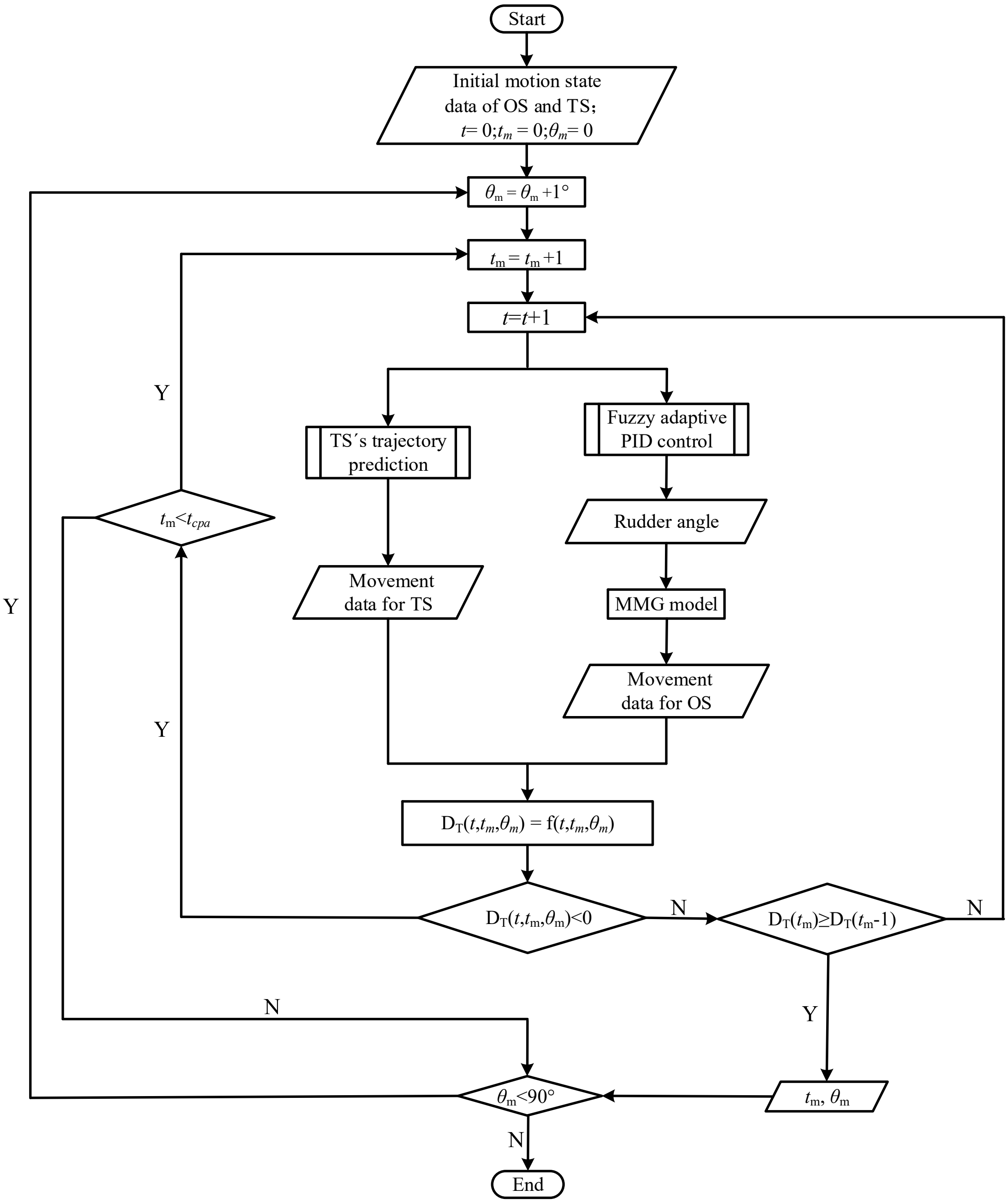


Figure 8. Numerical method of the latest steering time based on the course-alteration angle.

4.3. The First Time-in-Point of Immediate Danger (FTID)

The FTID can be defined as a time-in-point when the OS takes the most effective collision-avoidance action, and the TS is tangent to the collision domain of the OS. The numerical solving method of the FTID can be calculated like the FTCS. The collision domain area shown in Figure 4 is used to substitute the ship domain used in Section 4.2.

4.4. The Most Effective Collision Avoiding Direction

When the OS takes collision-avoidance by turning, the correct turning direction, turning time and course-alteration angle are the cornerstones of action to ensure the safety of navigation. The stand-on vessel is entitled to take any collision-avoidance action before

CR and after the timing when a sufficiently large amplitude manipulation must be taken that the TS can pass safely.

Rule 17 of the COLREGs stipulates the direction of action of the stand-on vessel in a crossing situation. The stand-on vessel should not alter to port in a crossing situation if the situation allows. However, other stand-on vessels should take the most effective collision-avoidance actions as per COLREGs. For vessels running on the open sea, course alteration is the only way, as described in Section 1. They can only decide the timing, amplitude and direction of the course alteration. It is essential to find a method that solves the more effective collision-avoiding direction between port and starboard in the course control system circumstance.

The minimum course-alteration angle at different times or the latest timing under the certain course-alteration angle that will ensure the TS can pass outside the ship's domain or the collision domain can be calculated by the methods presented above. Based on the results of these calculations, two methods can be used to determine the most effective direction when two vessels are approaching.

Method 1: Given the minimum course-alteration angle of the OS to ensure safe passing to port and starboard are α_1 and α_2 respectively, the direction of the most effective collision-avoidance action can be determined by comparing the values of α_1 and α_2. Turning to starboard will be the most effective direction of action when $\alpha_1 > \alpha_2$ exists.

Method 2: Given the course-altering amplitude to ensure safe passing is fixed, the latest steering time t_1 and t_2 for the OS to turn port and starboard can be calculated, respectively. Similarly, if t_1 is less than t_2, it turning starboard is the more effective direction for the OS because there is more time for the OS to avoid a collision.

4.5. The Decision-Making Model Based on Collision Risk Index (CRI)

Collision is one of the main factors threatening the safety of intelligent vessels. It is vitally important to take the collision-avoidance action as required. However, combined with the four-stage theory in Chapter 2, the rules only vaguely point out that the stand-on vessel can take the collision-avoidance action when it is obvious that the give-way vessel does not take any actions following the COLREGs. Therefore, it is necessary to build a CRI model for the stand-on vessel to quantify the timing when the stand-on vessel can be permitted to take the collision-avoidance action.

CRI describes the risk level of the encounter situation and the urgency of taking the collision-avoidance action. The effect factors of CRI include the TCPA, DCPA, relative position, movement characteristics, physical dimensions of the hull, speed, ship domains, surrounding environment, etc. Based on using the minimum course-alteration angle to quantify ship maneuvering difficulties at different times, a CRI model for the stand-on vessel is presented as follows:

$$CRI = \frac{\int_{t_{(FTCR)}}^{t} \theta_m^{(t)}\, dt}{\int_{t_{(FTCR)}}^{t_{(FTID)}} \theta_m^{(t)}\, dt}, t_{(FTCR)} \le t \le t_{(FTID)} \tag{13}$$

where t is the time step; $t_{(FTCR)}$ is FTCR; $t_{(FTID)}$ is FTID; ${\theta_m}^{(t)}$ is the minimum angle of all the course-alteration angles to avoid a collision at the time t.

This CRI model combines the factors of the minimum course-alteration angle in different timing during the entire risk of collision stage and close-quarter situation stage period. It can reflect the mental burden of seafarers about the ship collision risk. A larger CRI indicates a greater risk of ship collision and a greater urgency of ship collision-avoidance maneuvering; a smaller CRI shows that the OS has more time and a larger feasible course alteration range to take the collision-avoidance action. The value of CRI ranges from 0 to 1 and increases with the time going and minimum course-alteration angle rising. While "0" means there is no collision risk, even if the TS is very close to the OS, "1" means that collision cannot be avoided by the action of the OS alone.

The CRI model is consistent with the seafarers' judgment of ship collision risk and can be applied to quantify the collision risk from FTCR to the FTID. Based on the CRI model, the decision-making method of the ACA for the stand-on vessel can be shown in Figure 9.

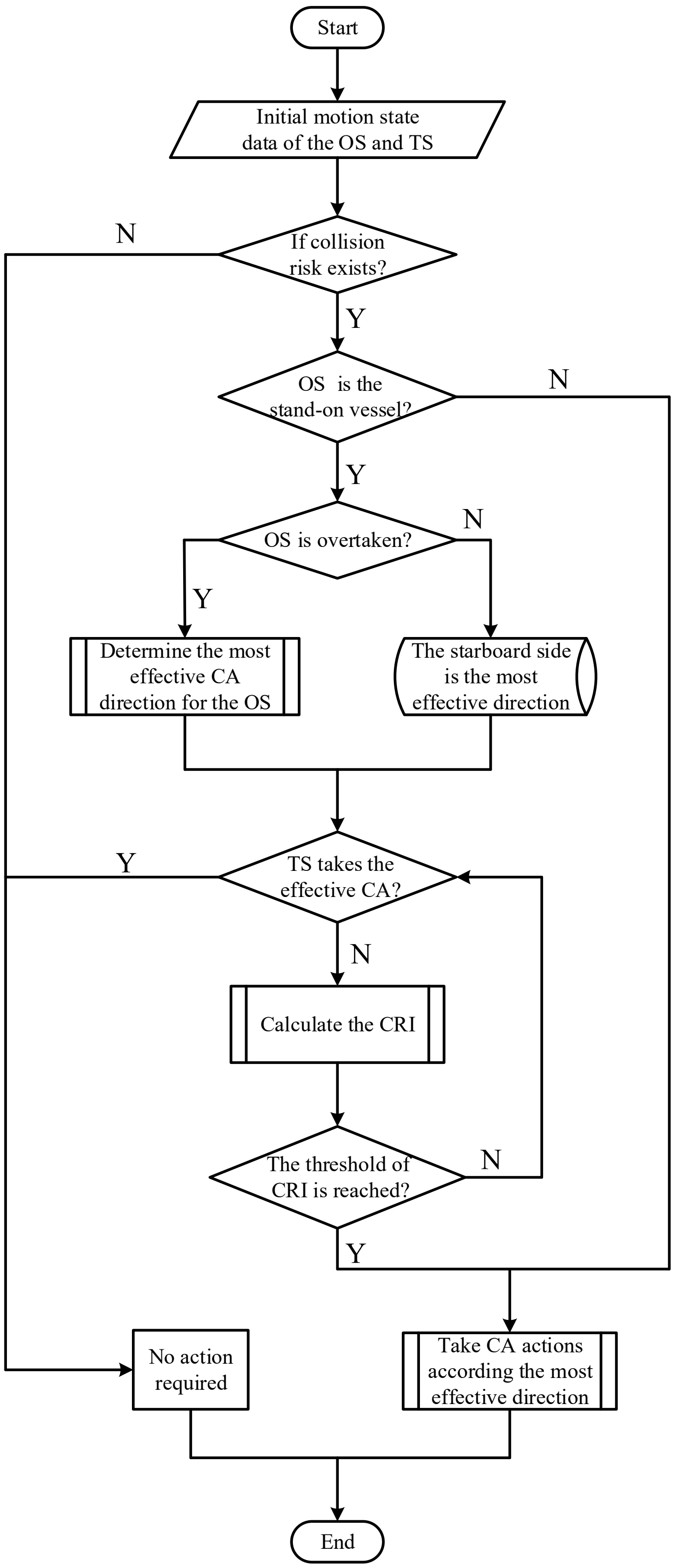


Figure 9. Flowchart of the ACA decision-making method for the stand-on vessel.

Based on the data of the initial motion state of the OS and TS, it can be judged whether the OS is a stand-on vessel or a give-way vessel when the collision risk exists in the encounter according to the COLREGs. If the OS is the give-way vessel, it should take collision-avoidance actions as required; if the OS is the stand-on vessel and the TS has taken effective actions to avoid a collision, the OS should keep its present course and speed. If the OS is the stand-on vessel and the TS does not take effective actions, the OS should determine the most effective collision-avoidance action direction, then take collision-avoidance actions when the threshold of the CRI is reached. Based on the CRI model, determine the timing and scheme of the ACA to enable the two vessels to pass safely.

5. Simulation

A bulk carrier is selected to carry out simulation experiments. Moreover, the MATLAB software is used to simulate the crossing and overtaking situations for the autonomous collision-avoidance decision-making of the stand-on vessel at the open sea. The initial state of the TS and OS are shown in Table 2. The corresponding experimental data of the simulated ship is shown in the Appendix A.

Table 2. Initial inputs in two typical encounter situations.

Situation	Vessel	LOA (m)	Pos X (m)	Pos Y (m)	Speed (m/s)	Course (°)
Crossing	OS	294	13,990	12,338	6.5	270
	TS	300	100	300	7.5	0
Overtaking	OS	294	12,800	1852	5.5	0
	TS	336	6800	1730	8.5	0

5.1. The Simulation in the Crossing Situation

The minimum course-alteration angle under different times for the stand-on vessel in the crossing encounter situation can be calculated as shown in Figure 7. Supposing the threshold of FTCR is set as 20 min, the value of TCPA is 1852 s, and 652 s can be defined as the time of FTCR, which can be obtained from the initial motion data from Table 2. It is assumed that there is enough water to ensure the stand-on vessel takes the collision-avoidance action following the COLREGs.

Setting 90° as the maximum course-alteration angle for the stand-on vessel, the simulation results show that the FTCS is 1408 s and FTID is 1644 s. The minimum course-alteration angle (θ_m) for the stand-on vessel at different times are shown in Figure 10.

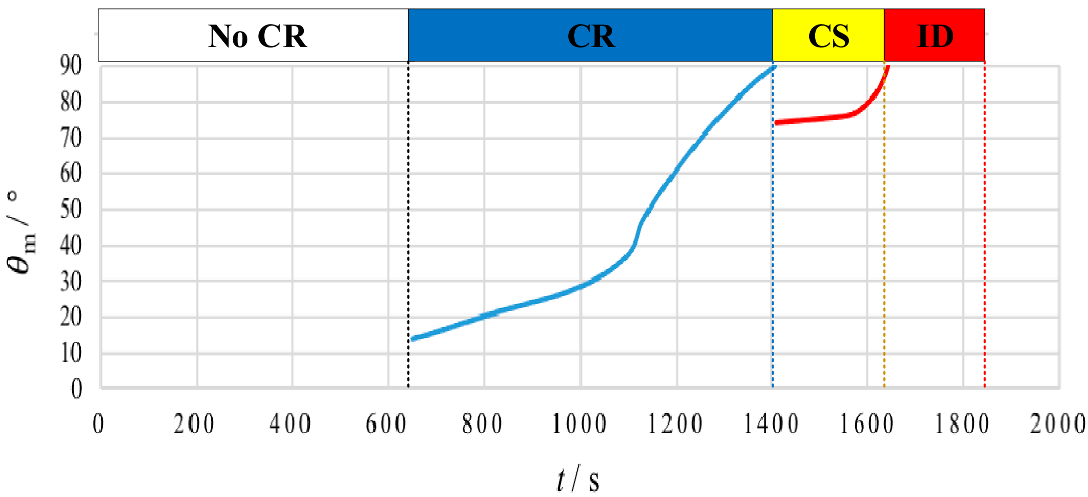


Figure 10. Minimum course-alteration angle for the stand-on vessel in a crossing situation. The blue and red curves represent the minimum course-altering amplitude required to ensure that ship domain and collision domain are not invaded at different moments by the stand-on vessel in the risk of collision and close-quarter situation stages.

In Figure 10, if the give-way vessel does not take any collision-avoidance action, the stand-on vessel can take appropriate actions before 1408 s to pass at a safe distance. For example, as the stand-on vessel, the OS can turn 42° to starboard at 1119 s to ensure her ship domain is not invaded by the TS. When the time reaches 1587 s, the stand-on vessel can only ensure that the two vessels do not collide by turning at least 78° to starboard. No matter how large the course-alteration angle is, it cannot prevent the ship domain from being invaded by the TS.

If the maximum course-alteration angle for the stand-on vessel is limited, the latest course-altering time to avoid the ship domain/collision domain being invaded can be determined according to Figure 10. If it is set as 30°, the latest course-altering time for the stand-on vessel is 1023 s.

According to the simulation results, the values of FTCR, FTCS and FTID are 652 s, 1408 s and 1644 s in this experiment, respectively. The CRI for the stand-on vessel could be calculated by integrating the minimum course-alteration angles ($\theta_{(t)}$) at different times in the close-quarter situation and immediate danger stages, and the results are shown in Figure 11.

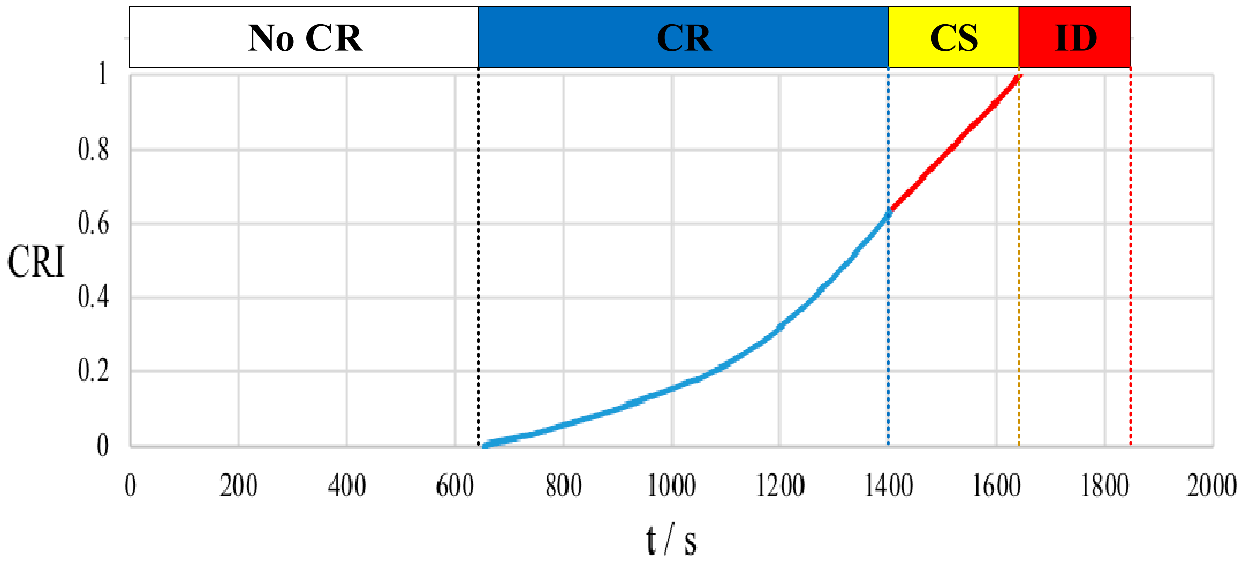


Figure 11. CRI for the stand-on vessel in a crossing situation.

If the stand-on vessel stubbornly keeps the course and speed in the crossing situation until the FTID, this does not conform to the requirements of good seamanship and the COLREGs and may cause a collision. The CRI model can provide a threshold value of when the stand-on vessel should take the ACA action. If the threshold of the CRI allowing the stand-on vessel to take the collision-avoidance action is preset as 0.5, the OS should take the ACA action by turning 80° to starboard at 1322 s in this experiment.

5.2. The Simulation in the Overtaking Situation

The rules do not specify the course-altering direction for the stand-on vessel in the overtaking situation. Hence, the stand-on vessel should first judge the most effective course-altering direction before taking the collision-avoidance action according to the method in Section 4.4.

Based on the initial motion data in Table 2, the DCPA and the TCPA can be calculated as 122 m and 2000 s, respectively, in the overtaking situation. The minimum course-alteration angles (θ_m) to port/starboard taken by the stand-on vessel at different times to avoid the TS from entering the OS's ship domain/collision domain are shown in Figures 12 and 13.

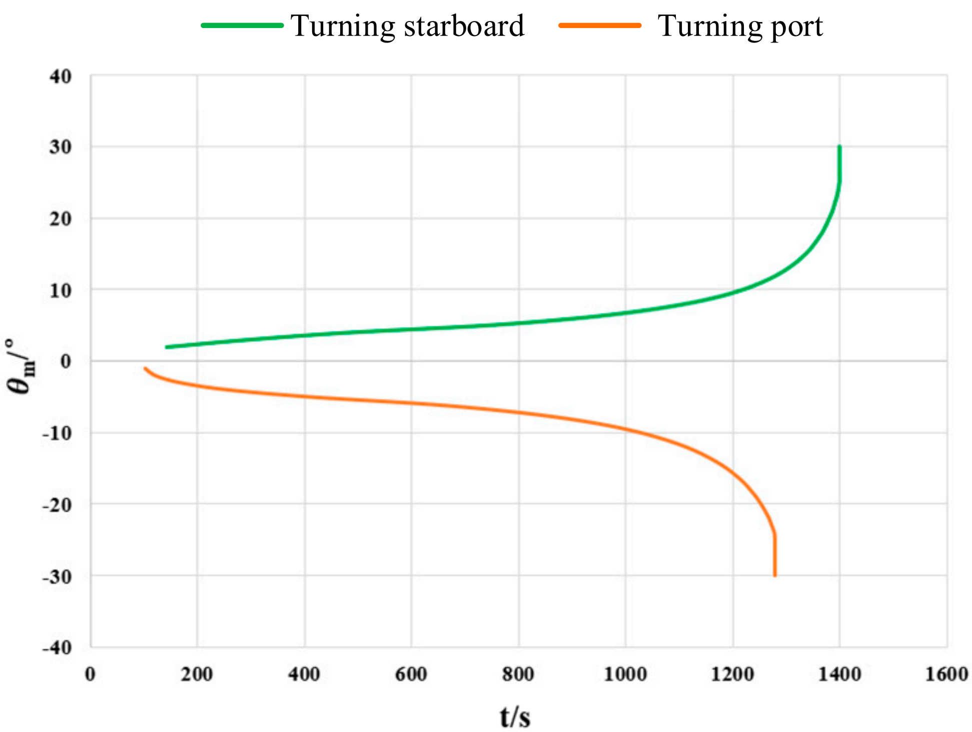


Figure 12. Minimum course alteration angles at different times when the ship domain is not violated.

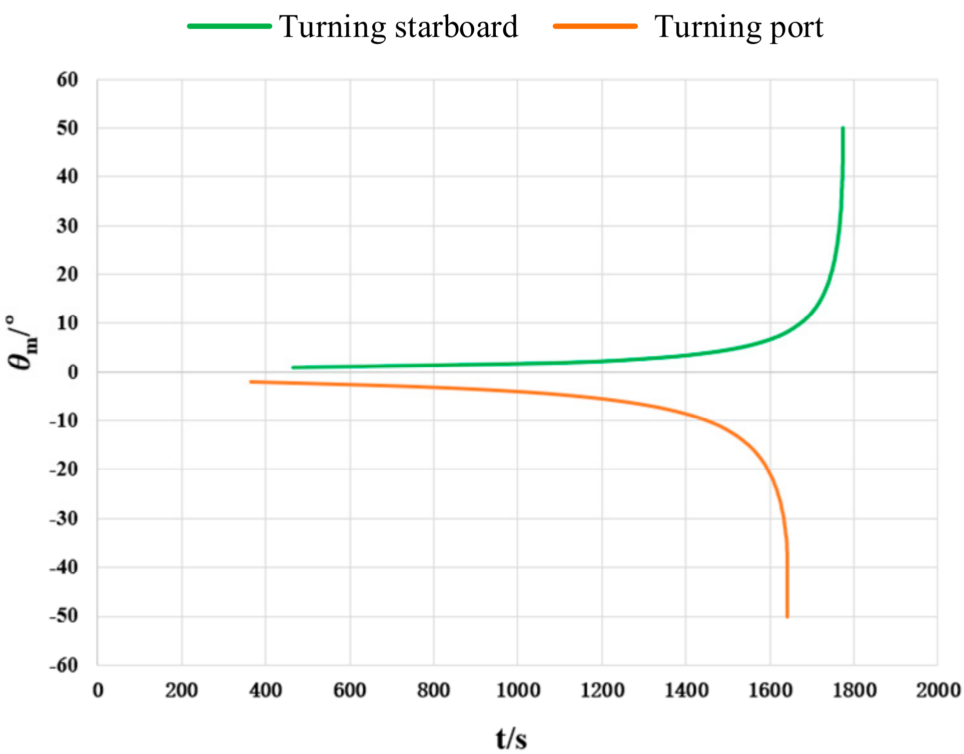


Figure 13. Minimum course alteration angle under different times when the collision domain is not violated.

As shown in Figures 12 and 13, turning to starboard is the most effective collision-avoidance action to ensure the stand-on vessel's ship domain/collision domain is not invaded by the TS. Turning 25° and 4° to starboard ensures the TS will not enter the ship domain and collision domain at 1398 s, respectively. The collision cannot be avoided by any turning alone after 1771 s. Similarly, the values of FTCR, FTCS and FTID are 142 s, 1398 s, and 1771 s, respectively. The minimum course-alteration angles for the stand-on vessel at different times are shown in Figure 14.

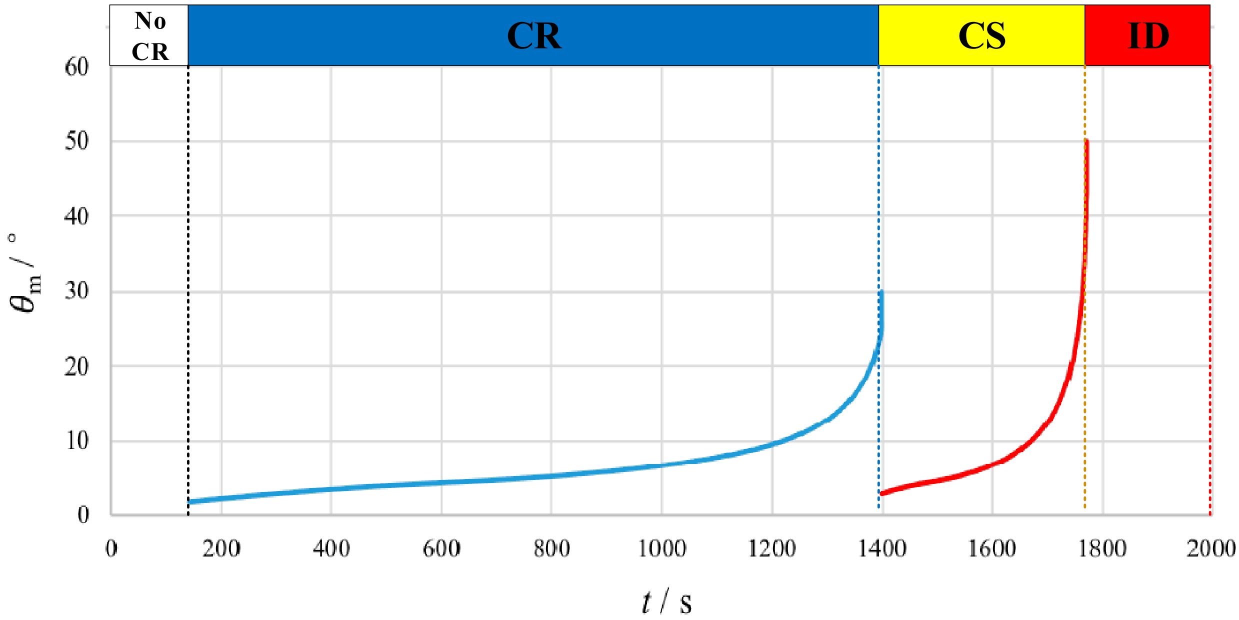


Figure 14. Minimum course-alteration angle for the stand-on vessel in an overtaking situation. The blue and red curves represent the minimum course-altering amplitude required to ensure that ship domain and collision domain are not invaded at different moments by the stand-on vessel in the risk of collision and close-quarter situation stages.

According to Figure 14, the CRI is shown in Figure 15.

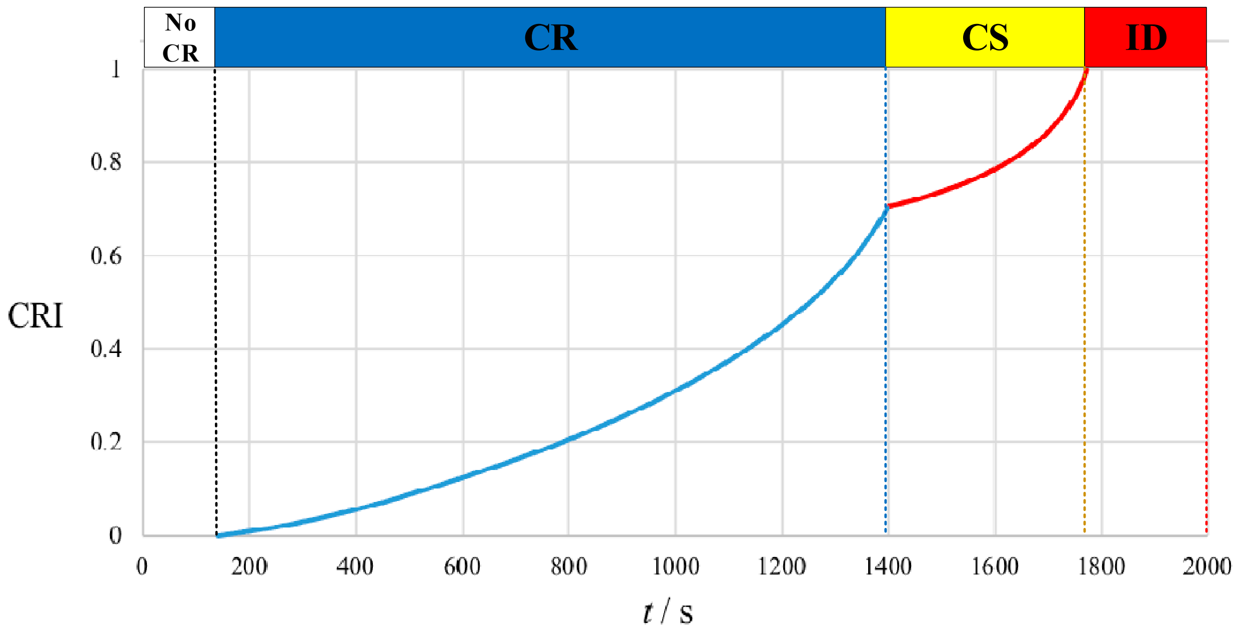


Figure 15. CRI for the stand-on vessel in an overtaking situation.

Similarly, if the maximum course-alteration angle for the OS is 20°, the stand-on vessel should alter the course before 1379 s to avoid forming the close-quarter stage situation with the TS. The stand-on vessel can also take the effective collision-avoidance action before 1744 s to ensure two vessels do not collide.

As mentioned in Section 5.1, provided that the give-way vessel does not take any collision-avoidance action, and the threshold of CRI is set as 0.5, the stand-on vessel should turn 10° or more to starboard at 1205 s to ensure the OS's ship domain is not invaded.

6. Conclusions

Based on the principle of COLREGs, this paper summarizes the views of the shipping industry on the timing and scheme of collision-avoidance actions for the stand-on vessel. The MMG model and fuzzy self-adaptive PID control method are integrated into the vessel course control system to simulate the vessel motion. Then, we present the quantitative theoretical model and algorithm of ships' encounters. Simultaneously, the CRI model, which can be used to conduct the quantitative analysis of the timing for the stand-on vessel to take collision-avoidance action, is presented. As mentioned above, the timing of taking collision-avoidance action for the stand-on vessel can be quantified from the following aspects:

1. At open sea, the latest action time and scheme for the stand-on vessel can be determined by the FTCS and FTID;
2. When the course-alteration angle for the stand-on vessel is limited by circumstance or other factors, this method can also be used to determine the latest-action timing in different stages during ships' encounter based on the ship motion characteristics;
3. For the stand-on vessel at the open sea, the captain or the MASS designer can set the CRI threshold value, the timing allowed to take collision-avoidance actions, and the scheme can be quantified simultaneously.

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Appendix A. Prototype Vessel and Simulation

The prototype vessel is the M/V Cape Splendor, a capsize bulk carrier. The parameters for the prototype vessel are shown in Table A1.

A comparison of the turning circle in sea trail and MMG model at maximum rudder angle is shown in Figures A1 and A2. The advanced distance of the ship in the digital simulation model and sea trail model when turning starboard was 2.86 times and 3.07 times of LOA, and the tactical diameter of the ship in the digital simulation model and sea trail model when turning starboard was 2.74 times and 2.51 times of LOA, respectively. The above results proved that the coincidence degree of the digital model could reach 91%.

Table A1. Simulated parameters for the bulk carrier.

Vessel Name		Cape Splendor	
Length overall	297 m	Breadth	50 m
Draft	16 m	Displacement	236,847 m^3
Molded depth	24.9 m	Block coefficient	0.8369
Rudder area	93.98 m^2	Prismatic coefficient	0.8399
Rudder height	12.7 m	Number of blades	4
Rudder width Up	6.7 m	Propeller pitch	6.0525 m
Rudder width Down	8.1 m	Propeller diameter	8.4 m
Maximum RPM	91 r/min	Maximum designed speed	15.3 kts

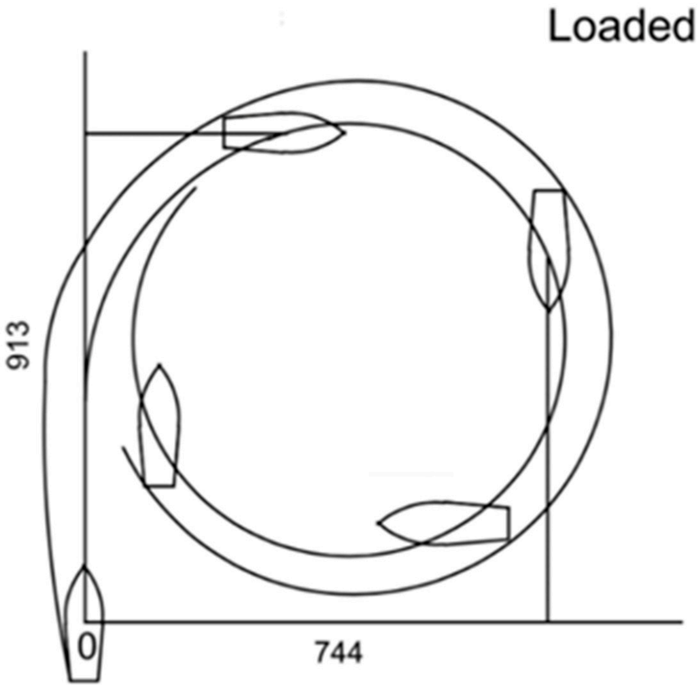

Figure A1. Turning circle at maximum rudder angle (sea trail).

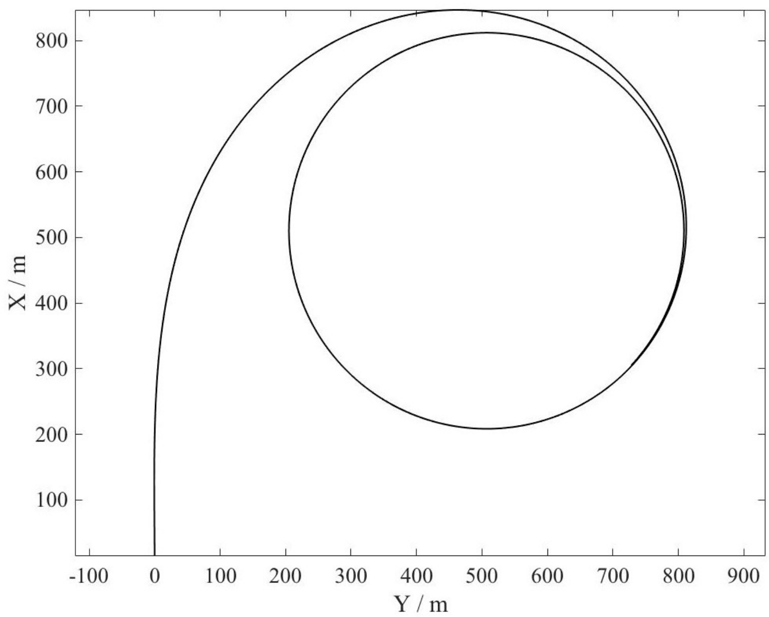

Figure A2. Turning circle at maximum rudder angle (digital MMG model).

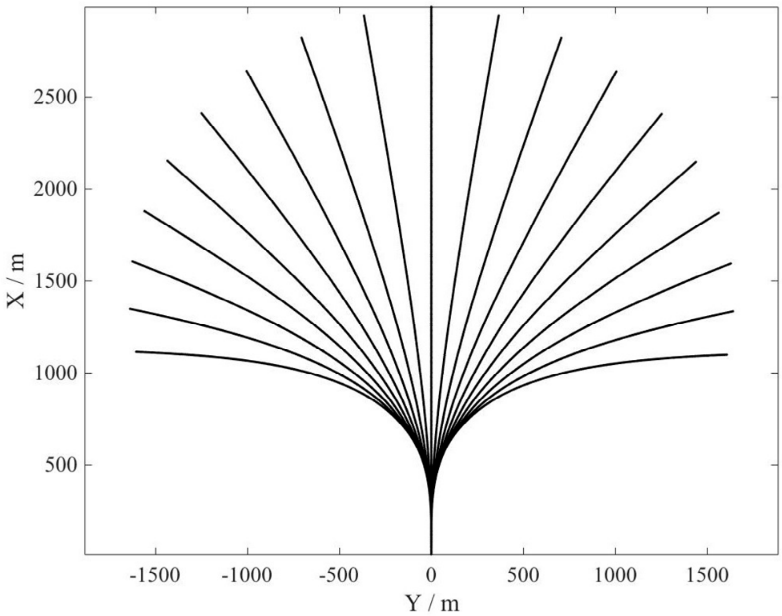

Figure A3. Simulation of the course control system.

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