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A COLREG-compliant ship collision alert system for stand-on vessels

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ABSTRACT

Bridge alarms are a plausible way to reduce the ship collision probability by timely alerting the officer on watch of a conflict. However, there currently are no dedicated methods for alerting a stand-on ship to compensate the unawareness of or inactive response of a give-way ship to dangerous encounter situations. Therefore, this article proposes a collision alert system from the stand-on ship perspective to trigger the stand-on ship's involvement in the conflict elimination. The developed method quantifies the terms of the COLREGs regarding the stand-on ship's responsibility for conflict elimination. The conflict severity is divided into 9 classes based on the ship intention estimation, conflict evolution analysis and COLREGs scrutiny. These are linked with the 4 stages of the encounter process to helps stand-on ship clarify her action responsibilities as per the rules and classify the alert into four levels. The available maneuvering margin of the stand-on ship is considered to improve the accuracy of severity ranking. The results of several case studies in open water with good visibility indicate that the proposed method can support the stand-on ship to correctly understand the rules and to fulfil her duties.

1. Introduction

The International Regulations for Preventing Collisions at Sea (COLREGs, 1972) consists of various rules for instructing the navigators on how to act under different encounter scenarios. 56% of major maritime collision includes violation of COLREGS (Statheros et al., 2008). Correctly understanding and following the rules in COLREGs is important for passing safely. However, the COLREGs rules do not provide specific guidance in actual operation (Hilgert and Baldauf, 1997; Du et al., 2020b), especially for the stand-on ship under the conflict threat (Du et al., 2020a). Hence, a contextual appreciation is required by the officers on watch, based on which the actions of conflict resolution are enacted.

According to COLREGs, the obligation of give-way ship is relatively explicit and constant when the collision risk exists. The give-way ship is required to act early and sufficiently. However, the responsibilities of the stand-on ship vary at different stages. Moreover, there currently are no clear guidelines to delineate each encounter stage for the stand-on ship. Dangerous encounters and even ship collisions where misinterpretations of the COLREGs rules by navigators of the stand-on ship are not rare. The accident report of China Maritime Safety Administration, 2018, and MAIB, 2015 and 2019, can attest this.

The stand-on ship's action helps prevent dangerous encounters, while the role of the stand-on ship is not often considered (Du et al., 2020a). Considerable research has been dedicated to quantifying the COLREGs for eliminating conflict (Johansen et al., 2016; Szlapczynski and Krata, 2018). Nonetheless, most of these strategies are designed from the give-way ship perspective only, or without distinguishing the stand-on ship or the give-way ship (Du et al., 2020a). It is therefore important to conduct conflict analysis on the activation of the stand-on ship's role in conflict elimination to improve safe conflict resolution of ships encountering one another.

Accurately grasping the current encounter stage and understanding its corresponding obligations are the prerequisites for the stand-on ships to take appropriate actions in compliance with COLREGs. Ship collision alert helps alert the ship of a collision hazard timely rather than directly proposing collision avoidance maneuvers in the current circumstance (Szlapczynski and Szlapczynska, 2017a). The development of collision alert systems (CAS) has attracted significant attention in the maritime domain (Baldauf et al., 2011; Menon et al., 2013; Simsir et al., 2014; Goerlandt et al., 2015; Szlapczynski and Szlapczynska, 2017a; Rizogiannis and Thomopoulos, 2019; Gil et al., 2020). However, these

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existing works do not consider the difference of the identity of the ship (such as the stand-on ship or give-way ship) as specified in the COLREGs.

Furthermore, many works aim to find the critical condition that alerts the ship to take evasive action. Beyond this critical condition, a collision cannot be avoidable, such as Last Time to Take Action (Zhuo and Tang, 2008), Minimum Distance to Collision (Montewka et al., 2010, 2014) and Last Line of Defence (Baldauf et al., 2017). Some works have considered COLREGs for encounter categorization, but few of them has distinguished the responsibilities of ships at different stages of the encounter, especially for the stand-on ship. A stand-on ship acting too early may violate Rule 17 of the COLREGs, while a stand-on ship acting too late but before this critical condition has fewer maneuver options.

Table 1
Conflict severity ranks based on the stand-on ship's action obligation.

Stages	OS's action obligation	Stage of protective layers	Conditions incorporating with Rule 17 in COLREGs		Measurements	Alert level
Stage 1	Unrestricted	FLoD: × SLoD: ×	CS1	(1) No conflict.	IC=0	Safe
Stage 2	Not allowed	FLoD: √ SLoD: × TLoD: ×	CS2	(1) Conflict exists; (2) TS is aware of the existing conflict; (3) TS takes the positive evasive action; (4) This evasive action complies with COLREGs.	(1) IC=1 (2) Int=1 (3) AQ=1 (4) Col=1	Caution
			CS3	(1) Conflict exists; (2) TS is aware of the existing conflict; (3) TS takes the negative evasive action; (4) The available maneuvering margins of OS is high. (5) This evasive action complies with COLREGs.	(1) IC=1 (2) Int=1 (3) AQ=-1 (4) AMM=H (5) Col=1	
Stage 3	Permitted	FLoD: √ SLoD: √ TLoD: ×	CS4	(1) Conflict exists; (2) TS is aware of the existing conflict; (3) TS takes the positive evasive action; (4) This action violates COLREGs.	(1) IC=1 (2) Int=1 (3) AQ=1 (4) Col=0	Warning
			CS5	(1) Conflict exists; (2) TS is aware of the existing conflict; (3) TS takes the negative evasive action; (4) The available maneuvering margins of OS is medium. (5) This evasive action complies with COLREGs.	(1) IC=1 (2) Int=1 (3) AQ=-1 (4) AMM=M (5) Col=1	
			CS6	(1) Conflict exists; (2) TS is not aware of the existing conflict; (3) TS takes the negative evasive action; (4) The available maneuvering margins of OS is high. (5) This action violates COLREGs.	(1) IC=1 (2) Int=0 (3) AQ=-1 (4) AMM=H (5) Col=0	
			CS7	(1) Conflict exists; (2) TS is not aware of the existing conflict; (3) TS takes the negative evasive action; (4) The available maneuvering margins of OS is medium. (5) This action violates COLREGs.	(1) IC=1 (2) Int=0 (3) AQ=-1 (4) AMM=M (5) Col=0	
Stage 4	Required	FLoD: √ SLoD: √ TLoD: √	CS8	(1) Conflict exists; (2) TS is aware of the existing conflict; (3) TS takes the negative evasive action; (4) The available maneuvering margins of OS is low. (5) This action violates COLREGs.	(1) IC=1 (2) Int=1 (3) AQ=-1 (4) AMM=L (5) Col=0	Alarm
			CS9	(1) Conflict exists; (2) TS is not aware of the existing conflict; (3) TS takes the negative evasive action; (4) The available maneuvering margins of OS is low. (5) This action violates COLREGs.	(1) IC=1 (2) Int=0 (3) AQ=-1 (4) AMM=L (5) Col=0	

Note: IC denotes the conflict index; Int denotes the intention estimation; Col denotes COLREGs scrutiny; AQ denotes action quality; AMM denotes available maneuvering margins; CS is the conflict severity; TS is target ship. √ means active. × means inactive.

Besides, the available maneuvering margin (AMM) of a ship is not considered in existing studies of alerting the ship of a collision hazard. The AMM represents the ship's capability to avoid ship collision. A higher AMM means that the ship has more space and time to execute a collision avoidance maneuver, and hence a higher chance to eliminate a dangerous encounter. The lack of knowledge of a vessel's AMM may lead to inaccurate detection of actual danger (Huang and van Gelder, 2019a, b). Huang et al. (2019c) considered the capability of a ship to prevent ship collision when measuring the ship collision risk in dense water area. However, the COLREGs are not considered in that work.

The stand-on ship has an important role in conflict elimination during dangerous encounters. Quantifying her action responsibilities at different encounter stages in compliance with COLREGs is a first step to develop a CAS targeted for vessels in a stand-on situation. Furthermore, the AMM of a ship is an important factor to consider for accurately estimating the risk. Given the above, the primary aim of this work is to propose a CAS from the stand-on ship's perspective. By answering what is the action obligation of a stand-on ship at different encounter stages, our work alerts the ship of a collision hazard timely rather than directly proposing collision avoidance maneuvers. This CAS furthermore quantifies the action responsibility of the stand-on ship at different encounter stages in compliance with COLREGs. The AMM is considered to improve the accuracy of ranking the collision risk. Besides, the influence of the own ship on the decision of the target ships is considered.

This work contributes to the construction of 'Stand-on Ship as Second Line of Defense' (SLoD) (Du et al., 2020a), and contains (1) a proposed method for classification of conflict severity and the clarification of stand-on ship's action responsibility at each different conflict level, (2) the design of a collision alert system to support the stand-on ship to accurately understand the current conflict state and her corresponding action responsibilities, and (3) the application of the proposed method to specific case studies concerning open sea navigation with good visibility.

The remainder of this paper is organized as follows. Section 2 focuses on the quantitative analysis of the conflict process, including quantifying encounter stages, conflict severity and alert level. Section 3 elaborates on the design of the ship collision alert system from the stand-on ship perspective. Section 4 presents the case study to demonstrate the feasibility of this proposed method. A discussion and some recommendations for future research are provided in Section 5. Section 6 concludes. The list of the notations and abbreviations are also given in Table 1 and Table 2 respectively in the Appendix.

2. Quantitative analysis of conflict process

Developing an approach for quantitatively describing the conflict process is a precondition for the construction of CAS for alerting the stand-on ship to act properly in compliance with COLREGs. This includes quantifying alert levels at different encounter stages and quantifying conflict severity, which are elaborated in Section 2.1 and Section 2.2 respectively.

2.1. Quantifying alert levels at different encounter stages

2.1.1. Relevant rules in COLREGs

Rule 11 mentioned that Rules from 12 to 18 apply to vessels in sight of one another.

Rule 15 concerns the action rule in crossing situation. The give-way ship should avoid crossing ahead of the other vessel if the circumstances of the case admit.

Rule 17 focuses on the action by the stand-on ship. It can be interpreted as follows:

(i) The stand-on ship is **not allowed** to maneuver when the risk exists unless one of the following two conditions is met.
(ii) The stand-on ship is **permitted** to maneuver if the give-way ship does not act appropriately in compliance with these rules (in particular Rule 8, 13, 14 and 15).
(iii) The stand-on ship is **required** to maneuver when the collision cannot be avoided by the action of the give-way vessel alone.

Rule 18 determines the responsibilities between different types of vessels. For instance, a power-driven vessel underway shall keep out of the way of a vessel engaged in fishing.

2.1.2. Quantifying encounter stages

The rules addressed in Section 2.1.1 design three protective layers for ships to prevent collisions. Three protective layers, which are illustrated in Fig. 1, are concluded by Du et al. (2020a) as: 'Give-way ship as First Line of Defense' (FLoD), 'Stand-on Ship as Second Line of Defense' (SLoD) and 'Both ships as Third Line of Defense' (TLoD). In Fig. 1, the green color means no conflict and none of FLoD, SLoD and TLoD is activated. Yellow, orange and red color represents the activation of FLoD, SLoD and TLoD respectively.

FLoD is activated by the occurrence of ship conflict. Specifically, when there is a conflict between a ship pair, the give-way ship is required to act. When the SLoD is activated by the Rule 17(ii), the stand-on ship is permitted to act for conflict elimination, while the obligation of the give-way ship does not vanish since the FLoD is activated. When the encounter situation goes worse that the conflict cannot be avoided by the give-way ship's action alone (see Rule 17(iii)), TLoD is activated, where both ships are required to act by COLREGs.

Based on the order of activation of three protective layers, a conflict process can be divided into four stages (Fig. 2). The conflict severity increases from Stage 1 to Stage 4.

In **Stage 1**, there is no conflict existing period. Both of ship pair has unrestricted action. Hence, the FLoD, SLoD and TLoD are inactive.

In **Stage 2**, a conflict emerges. The stand-on ship shall maintain her course and speed, and the give-way ship is required to act to eliminate the conflict. Hence, only FLoD is activated.

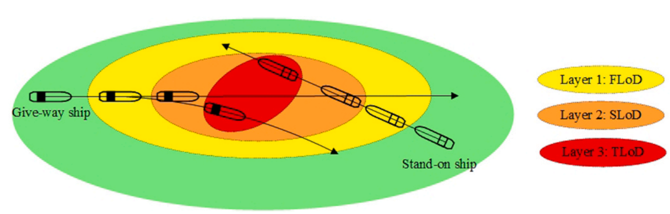


Fig. 1. Three protective layers of elimination of conflict in good visibility (shape and size of the layers for illustration purposes only) (Du et al., 2020a).

Table 2
Four crossing encounter scenarios for demonstrating the model rationale.

Encounter scenarios	OS					TS				
	$P_0 : m$	$\|V\|:m/s$	$C_0 :\ ^0$	$t_{TP} : s$	$C_{TP} :^\circ$	$P_0 : m$	$\|V\|:m/s$	$C_0 :\ ^0$	$t_{TP} : s$	$C_{TP} :^\circ$
Scenario 1	(-2000, 6000)	5	210	100	30	(0, 0)	5	90	/	/
Scenario 2									200	30
Scenario 3									200	−40
Scenario 4									550	−20

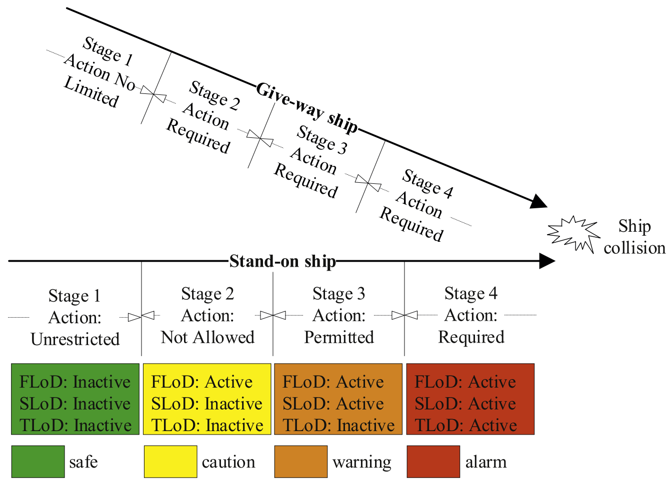


Fig. 2. The four stages of the encounter process relating to the ship's action obligation, the activation of three protective layers, and the alert level.

In **Stage 3**, a conflict develops as it is evident that the give-way ship does not act properly according to COLREGs. The obligation of the give-way ship is to act, while that of the stand-on ship is action permitted. Hence, both FLoD and SLoD are activated.

In **Stage 4**, a conflict escalates so that it cannot be eliminated by the give-way ship's action alone. Thus, both ship pair are required to act for passing safely, and therefore the FLoD, SLoD and TLoD are activated.

2.1.3. Quantifying alert levels

In line with the IMO 2007 recommendations (IMO, 2007), four levels of alert are adopted, which are then linked to these four encounter stages.

- The alert level at Stage 4 is '**alarm**' to indicate navigators on the stand-on ship that the action is required immediately for the conflict elimination (marked as red color in Fig. 2).
- The alert level at Stage 3 is '**warning**' to indicate navigators on the stand-on ship that the action is permitted for the conflict elimination, as the dangerous situation may develop if no action is taken (marked as orange color in Fig. 2).
- The alert level at Stage 2 is '**caution**' to indicate navigators on the stand-on ship that no action is allowed but attention and special consideration of the current situation are required due to the existing conflict (marked as yellow color in Fig. 2).
- The alert level at Stage 1 is '**safe**' as the ship pair can pass safely, posing no action restriction on each other (marked as green color in Fig. 2).

2.2. Quantifying conflict severity

2.2.1. Conflict: concept and measurements

The conflict is defined as a situation of near collision which has great potential to be a collision (Lei et al., 2017). A conflict can be measured when a restricted area around one ship is projected to be violated by another vessel (Wang, 2010; Weng and Xue, 2015).

The elliptical ship domain is selected to describe the restricted area around one ship as it is the most realistic one based on empirical data (Hansen et al., 2013). The major radius of elliptical ship domain is four times of the ship length and its minor radius is 1.6 times of the ship length (Fujii and Tanaka, 1971). Hence, the conflict is determined by checking whether one ship remaining her current course and speed is projected to violate the elliptical domain around the other ship.

2.2.2. Conflict severity

2.2.2.1. Concept and measurements. The conflict severity corresponds to the nearness to an accident, which relates to how close this interaction is to be an accident (Du et al., 2020b). A conflict with higher severity implies more similarity to an accident.

To support the stand-on ship to read the hazardous situation and understand her responsibility, the severity of the conflict is measured according to the interpretation of Rule 17 in COLREGs. In particular, the action responsibilities of the stand-on ship in each encounter stage are in focus. Further, to measure the conflict severity more accurately, the AMM for a ship to eliminate the conflict is also considered.

Accordingly, the conflict severity can be quantitatively subdivided by evaluating (1) whether a conflict exists, (2) whether the give-way ship is aware of the exiting conflict, (3) whether the conflict can be eliminated by the give-way ship's action alone, (4) whether the AMM of the stand-on ship is sufficient, and (5) whether the give-way ship's action violates the COLREGs. These are determined by five aspects respectively: (1) conflict detection, (2) intention estimation of the give-way ship, (3) action quality (AQ) assessment of the give-way ship, (4) AMM calculation of the stand-on ship and (5) COLREGs scrutiny of the give-way ship.

Conflict detection is elaborated in Section 3.3, where *IC* denotes the index of conflict. $IC = 1$ if a conflict exists, otherwise, *IC* is 0.

Intention estimation of the give-way ship is elaborated in Section 3.4, through an index denoted *Int*. $Int = 1$ means that the give-way ship is aware of the exiting conflict and acts. $Int = 0$ means that the give-way ship is not aware of the exiting conflict, or at least that it does not act in accordance with the COLREGs.

For the give-way ship's AQ assessment, two categories are used: positive evasive action and negative evasive action. Its index is *AQ*. $AQ = 1$ means the give-way ship takes positive evasive action and $AQ = -1$ means the give-way ship takes negative evasive action. More details are in Section 3.5.1.

Definition 1. Positive evasive action is the action from one ship that can effectively eliminate the potential conflict without additional assistance from the other ship.

Definition 2. Negative evasive action refers to an action of a ship that cannot eliminate the potential conflict, with or without additional assistance from the other ship.

AMM calculation is elaborated in Section 3.5.2 and its index is *AMM*. It is divided into three classes: high (H), medium (M) and low (L).

COLREGs scrutiny is denoted with the index Col (see Section 3.6). $Col = 1$ means the give-way ship's action obeys the COLREGs. $Col = 0$ means that the give-way ship's action violates COLREGs.

2.2.2.2. Conflict severity classification. The conflict severity (CS) is refined into 9 classes. The conditions, measurements, and alert level of each class are specified in Table 1. Own ship (OS) is the stand-on ship and target ship (TS) is the give-way ship. From CS1 to CS9, the conflict severity increases.

Stage 1 contains CS1. The condition of CS1 is no conflict. There is no action limitation for the OS as FLoD, SLoD and TLoD are inactivated. The alert level is 'safe'.

Stage 2 contains CS2 and CS3. Conflict generates and only the FLoD is activated. The OS's action obligation is 'not allowed'. The alert level is 'caution' (Rule 17a(i)). For CS2, (1) TS is aware of the existing conflict, (2) TS takes positive evasive action, and (3) TS's action complies with the COLREGs. For CS3, (1) TS is aware of this existing conflict, (2) TS's action complies with COLREGs, (3) TS takes negative evasive action, and (4) the AMM of OS is high.

Stage 3 contains 4 classes of conflict severity, including CS4, CS5, CS6 and CS7. In Stage 3, the FLoD and SLoD are activated, and OS is permitted to act. This alert level is 'warning' (Rule 17a(ii)). For CS4, (1) TS is aware of this existing conflict, (2) TS takes positive evasive action, and (3) this action violates the Rule 15 in COLREGs. CS5 is similar to CS3, except that the AMM of the OS is medium. For CS6, the TS is not aware of the existing conflict but the AMM of OS is high. CS7 is similar to CS6 but AMM of the OS is medium.

Stage 4 contains CS8 and CS9. The FLoD, SLoD and TLoD are activated and the OS is required to act. The alert level is 'alarm' (Rule 17b). CS8 is similar to CS3 and CS5, but the AMM of the OS is low. CS9 is similar to CS6 and CS7, but the AMM of the OS is low.

2.2.2.3. Multi-vessel encounter scenarios. This work is to alert the stand-on ship of a collision hazard timely. However, the determination of the collision avoidance manoeuvres in the current circumstance still needs navigator's involvement. Our method provides assistance to the navigator in multi-encounter situations. Through analyzing the encounter process between ship pairs, the navigator can clearly understand her action obligations and the corresponding risk levels at different encounter stages for different vessels. It is then up to the navigator to interpret this information and take the appropriate action.

The multi-vessel encounter is divided into several ship-pair encounters, and conflict between the own ship and other target ships are assessed separately. As the multi-vessel encounter is more complicated, the following aspects are clarified.

(1) Alert sequence

The alert level determines the alert sequence. The higher-level alert has a higher priority. The level of alert is divided into four levels: safe, caution, warning and alarm, according to the different collision risk levels (Table 1). Therefore, the alert sequence ranks from high to low is alarm, warning, caution, and safe. The nine levels of conflict severity (from CS1 to CS9) are used within the CAS to reveal the cause leading to the current encounter situation. This helps clarify the action obligation as per the rules.

For instance, a ship encounters with two ships, and OS is in the stand-on position, see Fig. 3(a). The encounter risk between OS and TS1 is CS3, while that between OS and TS2 is CS8. The alert level of CS3 is 'caution', and that of CS8 is 'alarm'. The alert level of this situation is determined as 'warning'.

If the levels of the alert for different vessels are the same, the alert sequences are the same regardless of whether the levels of the conflict severity are the same or different. If the encounter risk between OS and TS1 is CS4, and that between OS and TS2 is CS6, see Fig. 3(a). The alerts of CS4 and CS6 are warning, and they have an equal alert level.

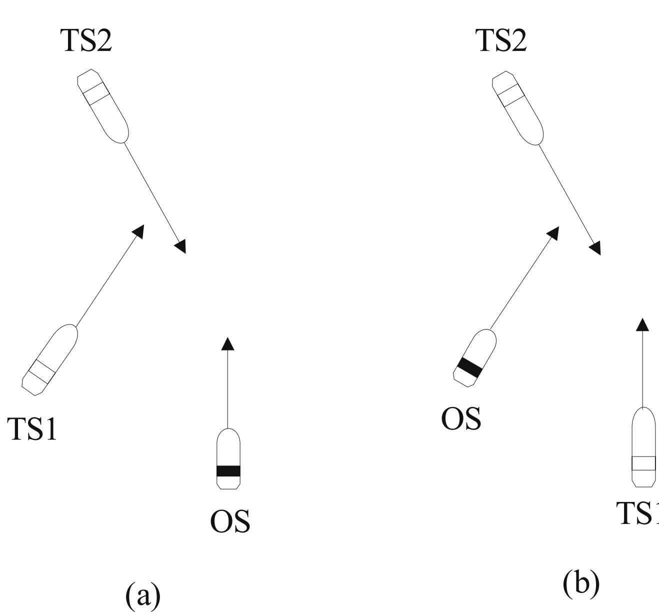


Fig. 3. Typical multi-vessel encounter scenarios.

(2) Action responsibilities

There are two possible situations where a ship has different collision avoidance responsibilities, see Fig. 3. One is that the ship has different collision avoidance responsibilities but with the same identity. As shown in Fig. 3(a), OS is the stand-on ship for both the ship pair encounters between OS and TS1, and between OS and TS2. If the OS has different collision avoidance responsibilities, the principle is 'Highest Risk First'. If the encounter risk between OS and TS1 is CS3 (action not allowed), while that between OS and TS2 is CS8 (action required), the OS is required to take evasive action.

Another is the rule conflict, where a vessel can have two identities simultaneously, e.g. stand-on and give-way vessel for different vessels, as shown in Fig. 3(b). OS is give-way ship encountering with TS1, meanwhile OS is the stand-on ship encountering with TS2. The OS is required to act when the conflict between OS and TS1 exists. If the collision risk is CS3 between OS and TS2 simultaneously, the OS is required to keep her current course and speed. Under this situation, the higher level of action obligation has a higher priority. Hence, this CAS informs that the OS is required to act, and the alert level is 'alarm'.

3. Methodology

3.1. Structure of CAS from stand-on ship perspective

Fig. 4 illustrates how the CAS supports the stand-on ship in understanding the encounter stage and her action responsibility (Du et al., 2020a). When the OS encounters a TS in which OS is in the stand-on position, the following five steps are triggered and repeated continuously during the encounter.

(1) Conflict detection: if there is no conflict, OS has no action limitation. If a conflict exists, then (2) the TS's intention estimation is performed.

- If the TS is aware of the existing conflict, (3) the TS's AQ is assessed and (4) the COLREGs is referred. Afterwards, (5) the OS's AMM calculation is performed.
- If the TS is not aware of the existing conflict, the TS's action is negative and violates the COLREGs. Hence, only (5) the OS's AMM is calculated.

Finally, the proposed CAS from the stand-on ship perspective provides her action obligation and alert level to support stand-on ship's decision-making. The Step (1)(2) have been done in previous work (Du et al., 2020a). Therefore, the remaining steps, including Step (3)(4)(5), are the focus of this work.

3.2. Algorithm design of CAS from stand-on ship perspective

The algorithm of utilizing CAS from the stand-on ship perspective to clarify the encounter stage, OS's action obligation and alert level is designed in Fig. 5. OS is the stand-on ship.

The inputs for this method are the traffic safety-related information of this ship pair involving into conflict. The identity of two ships are determined according to their relative course and relative position (Goerlandt et al., 2015). This CAS is activated only if OS is the stand-on ship. For OS, the planned trajectory $PT_{OS}(x,y,t)$, speed $V_{OS}(t)$ and course $C_{OS}(t)$ are known. Her maneuverability (turning ability index K and turning lag index T) (Nomoto et al., 1956) is also explicit. From the OS's perspective, the historical and current motion data of TS, including position $P_{TS}(x, y, t)$, speed $V_{TS}(t)$ and course $C_{TS}(t)$, can be obtained through AIS receiver.

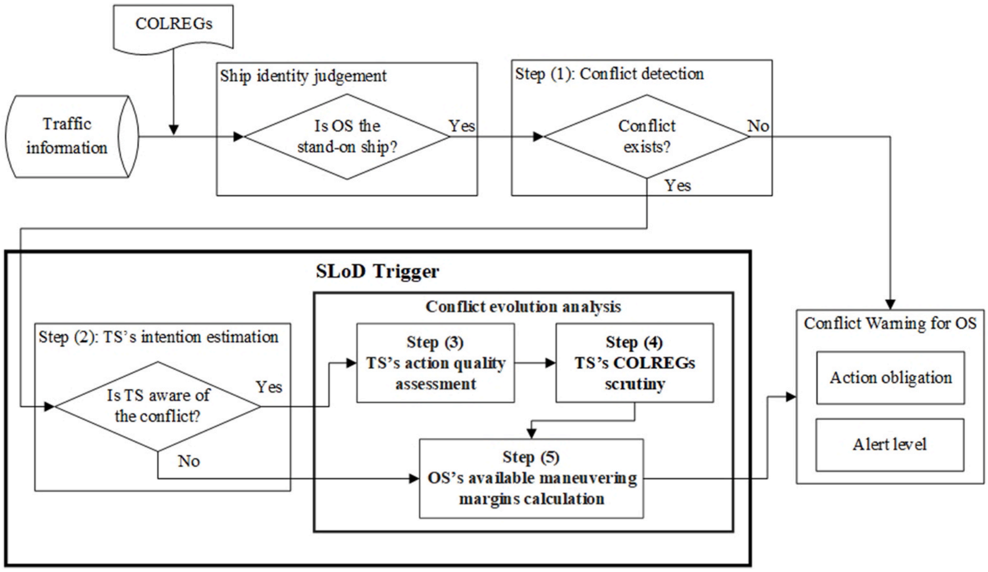


Fig. 4. Conceptual diagram of how the conflict alert system supports OS in the stand-on position to understand the situation and her corresponding action responsibility (Du et al., 2020a).

The outputs of the CAS are the action obligation of OS ('unrestricted', 'not allowed', 'permitted', 'required') and alert level ('safe', 'caution', 'warning', 'alarm'). This module links 9 classes of conflict severity with the 4 encounter stages in accordance to COLREGs, based on the logic presented in Table 1.

This designed algorithm contains three main sub-modules: conflict detection module detects the conflict between the ship pair; give-way ship's intention estimation module estimates the intention of the action that is taken by the TS; conflict evolution analysis module assesses TS's AQ and calculates OS's AMM, and refers to the rules in COLREGs. Each module is elaborated from Section 3.3 to 3.5.

3.3. Conflict detection module

The velocity obstacle (VO) projects the spatiotemporal relationship between a ship pair involved in an encounter situation into one ship's velocity domain. Based on this, the conflict can be judged by checking whether the velocity of the ship falls into this velocity obstacle zone (Huang et al., 2018; Chen et al., 2018). The non-linear velocity obstacles (NL-VO) algorithm considers the dynamic nature of ship action during the whole encounter process (Huang et al., 2018, 2019a, Du et al., 2020a, 2019). Therefore, the NL-VO algorithm is selected for the conflict assessment (Step (1) in Figs. 4 and 5).

In Fig. 6, the TS's velocity space is divided into three segments by a velocity obstacle zone, namely *S1* (the area in red), *S2* (the grid area in yellow) and *S3* (the grid area in blue). The TS's velocity in the *S1* segment will lead to conflict with OS in the future. In the figure, an example velocity V_{TS1} indicates this. However, if the TS's velocity is not in the *S1* segment, such as V_{TS2} in *S2* and V_{TS3} in *S3*, the ship pair can pass safely. The difference between TS's velocity in S2 and S3 is elaborated in Section 3.6.

Therefore, the conflict can be detected:

$$IC(t_0) = \begin{cases} 1, & if \ \ \mathrm{RV}(V_{TS}(t_0)) \cap S_{NL\_VO}(t_0) \neq \varphi \\ 0, & \mathrm{else} \end{cases}, \tag{1}$$

where $S_{NL\_VO}(t_0)$ is the velocity obstacle zone at current moment t_0 in TS's velocity space, see Fig. 6. The formula derivation process is elaborated in Huang et al. (2017). $\mathrm{RV}(V_{TS}(t_0))$ is TS's reachable ship velocity, which is determined by her current velocity $V_{TS}(t_0)$ and her turning ability, see Du et al. (2020a). If the TS's reachable ship velocity $\mathrm{RV}(V_{TS}(t_0))$ has a non-empty intersection with the NL-VO set $S_{NL\_VO}(t_0)$, a conflict exists (Fig. 5). Otherwise, there is no conflict, see CS1 in Table 1.

3.4. TS's intention estimation module

In Du et al. (2020a), ship intention is defined as the motivation of the actions that is taken by the ship, aimed at attaining certain navigational objectives, such as accident avoidance and route-following. The ship intention of TS during the encounter process is classified as normal navigation and evasive action (Du et al., 2020a). These can be distinguished by checking whether the conflict exists when the ship action changes. There is an assumption here that the course alteration is the only way used to eliminate conflict. The TS's intention can be estimated (Step (2) in Figs. 4 and 5):

$$Int(t_0) = \begin{cases} 1, & if \ \ IC(t_0) = 1 \& \Delta C_{TS}(t_0) \neq 0 \\ 0, & \mathrm{otherwise} \end{cases}, \tag{2}$$

where $Int(t_0) = 1$ means that the TS is aware of the conflict and alters her course for conflict elimination. $\Delta C_{TS}(t_0)$ is the course change of TS. The examples of the CS2 and CS3 indicate this, see Fig. 5 and Table 1. $Int(t_0) = 0$ means that TS is not aware of the exiting conflict, or at least that it does not act in accordance with the COLREGs, such as the CS6 and CS7 as indicated in Fig. 5 and Table 1.

3.5. Conflict evolution analysis

Conflict evolution analysis checks whether the exiting conflict can be eliminated by TS's adopted action, with or without additional assistance from OS. The COLREGs is scrutinized to check whether TS's action violates the COLREGs. TS's AQ assessment (Step (3) in Figs. 4 and 5), TS's COLREGs scrutiny (Step (4) in Figs. 4 and 5) and OS's AMM calculation (Step (5) in Figs. 4 and 5) are the main component of the conflict evolution analysis.

For the condition that TS is not aware of the existing conflict, only OS's AMM is calculated to specify the action obligation of OS.

For the condition that TS is aware of the existing conflict, there are two possible results of TS's AQ assessment. If TS is found to take positive evasive action, only COLREGs scrutiny is needed afterwards to distinguish whether OS's action obligation is 'not allowed' or 'permitted'. Otherwise, if the TS takes negative evasive action, the OS's AMM calculation is needed to determine OS's obligation: action permitted, or

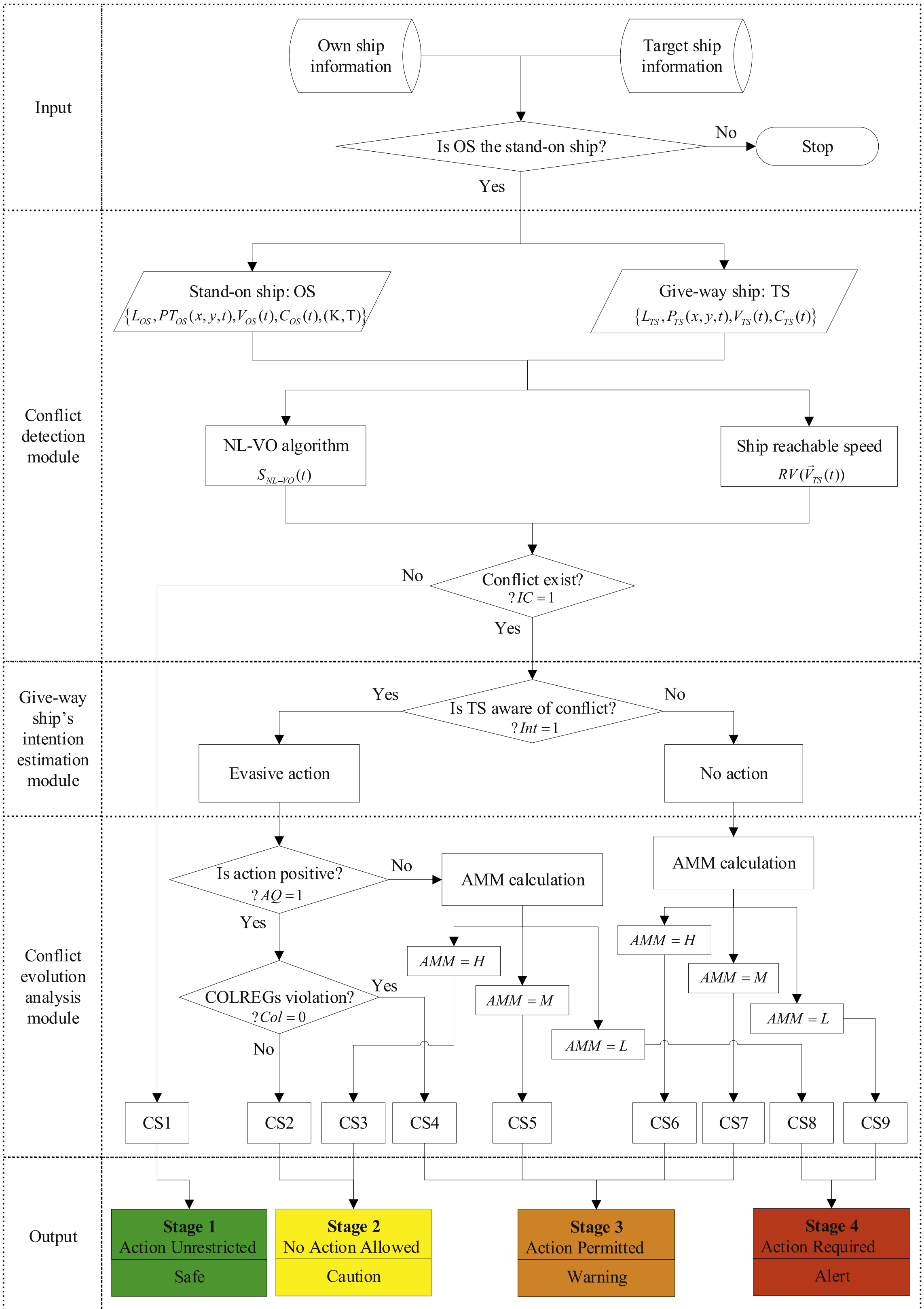


Fig. 5. The algorithm of utilizing CAS from stand-on ship perspective to clarify the alert level and OS's action obligation.

action required.

3.5.1. TS's AQ assessment

TS's AQ is assessed by checking whether the conflict can be eliminated by TS's adopted action alone. Learning from earlier work (Zhuo and Tang, 2008; Montewka et al., 2014), there is a critical state that a conflict can be eliminated by TS's evasive action alone if the TS acts before a certain critical point. Here, assumptions are that the TS

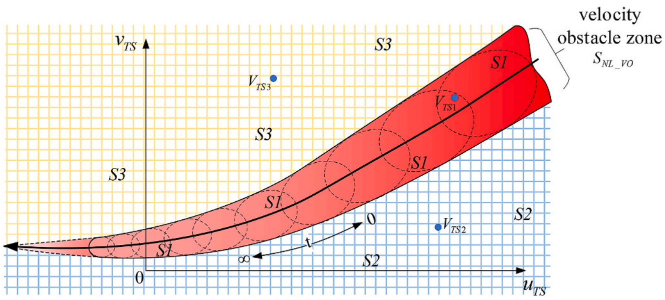


Fig. 6. Ship conflict in TS's velocity space based on NL-VO algorithm.

only alters the course for conflict elimination and the rate of turn $ROT(t)$ of the TS remains unchanged within a certain time. Therefore, this critical state for the TS can be defined from the spatial scales, as follows:

$$\begin{cases} \min DisTS = \min\{Dis(\langle P_{OS}(t), P_{TS}(t)\rangle) | \min Dis(\langle P_{OS}(t:end), \tilde{p}_{TS}(t:end)\rangle) \geq R\} \\ \tilde{p}_{TS}(t+\Delta t) = P_{TS}(t) + |V_{TS}(t)| \begin{bmatrix} \cos(C_{TS}(t) + ROT(t)\cdot\Delta t) \\ \sin(C_{TS}(t) + ROT(t)\cdot\Delta t) \end{bmatrix} \cdot \Delta t \\ ROT(t) = (C_{TS}(t) - C_{TS}(t-\Delta t))/\Delta t \end{cases}, \tag{3}$$

where $\min DisTS$ is the critical state for TS in spatial scales. $Dis(\langle P_{OS}(t), P_{TS}(t)\rangle)$ is the relative distance between a ship pair when the TS starts to maneuver at time t. $|V_{TS}(t)|$ is the magnitude of TS's speed. The $\min Dis(\langle P_{OS}(t:end), \tilde{p}_{TS}(t:end)\rangle)$ is the minimum distance between the OS's trajectory P_{OS} (black color line with arrow in Fig. 7) and the TS's predicted trajectory $\tilde{p}_{TS}$ (blue color dotted line with arrow in Fig. 7) after t. OS's trajectory P_{OS} is known. The OS predicts TS's trajectory $\tilde{p}_{TS}$ based on the TS's constant $ROT(t)$ that is observed by OS.

Therefore, TS's AQ can be classified as follows:

$$AQ(t_0) = \begin{cases} 1, & if \;\; Dis(\langle P_{OS}(t_0), P_{TS}(t_0)\rangle) \geq \min DisTS \\ -1, & \text{otherwise} \end{cases}, \tag{4}$$

where $AQ(t_0) = 1$ means TS takes positive evasive action, see Definition 1 in Section 2.2.2.1. The CS2 and CS4 are the examples indicating this, see Table 1 and Fig. 5. $AQ(t_0) = -1$ means TS takes negative evasive action, see Definition 2 in Section 2.2.2.1. The CS3 and CS5 are the situation that the TS takes negative evasive action, see Table 1 and Fig. 5.

3.5.2. COLREGs scrutiny

As specified in Rule 15 in COLREGs, the give-way ship should avoid crossing ahead of the other vessel in crossing encounter situation. This

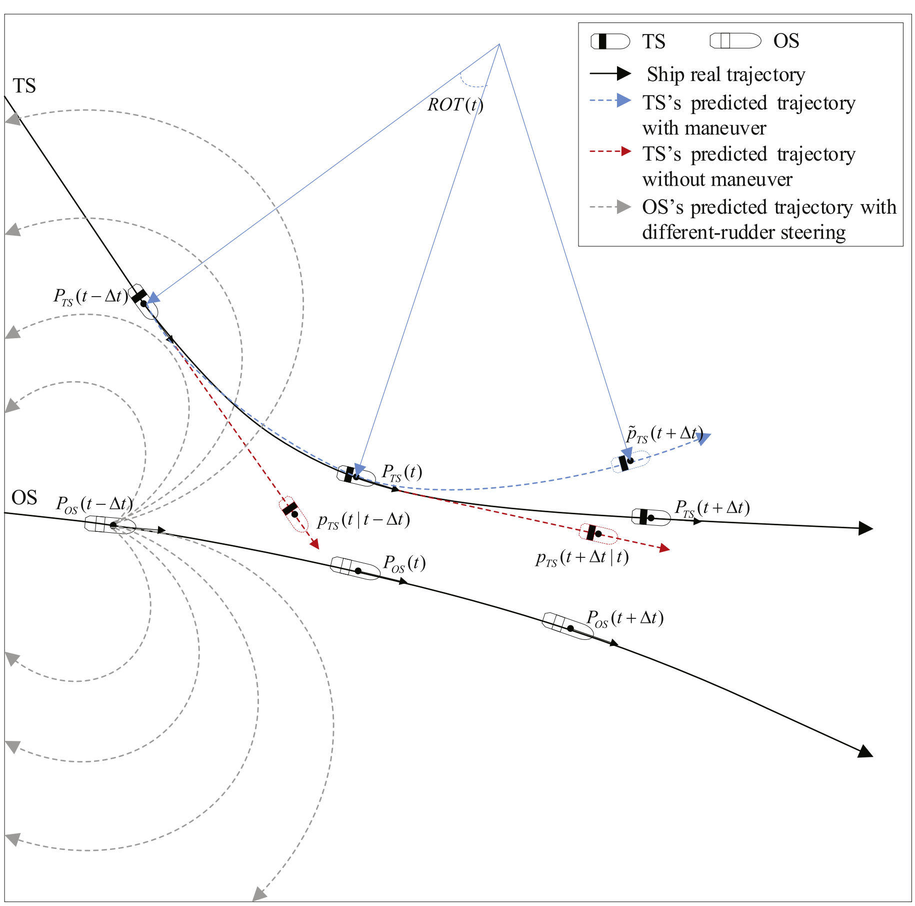


Fig. 7. The ship trajectory of a ship pair involving into conflict: the actual ship trajectory is black line with arrow; the predicted trajectory of TS with the constant velocity is red dotted line; the predicted trajectory of TS based on constant ROT is marked in blue color. Grey dotted line with arrow represents the predicted ship trajectory of OS based on her maneuverability.

can be assessed using the NL-VO algorithm.

$$Col = \begin{cases} 1, & \text{if} \quad V_{TS} \in S2 \\ 0, & \text{if} \quad V_{TS} \in S3 \end{cases}, \tag{5}$$

where $Col = 1$ means the TS's evasive action obeys the COLREGs, while $Col = 0$ means the evasive action of the give-way ship violates the COLREGs. In Fig. 6, if the TS's velocity falls in zone *S2*, there is no conflict between OS and TS. The OS will pass the closest point of approach (CPA) earlier than the TS. Hence, the TS's evasive action is in compliance with the COLREGs, see the CS2 in Table 1. If TS's velocity is in zone *S3*, the conflict can be eliminated by TS's evasive action alone, but the TS's evasive action violates Rule 15 in COLREGs as this leads the TS to pass the OS ahead of its bow, see CS4 in Table 1. Details of the proof of this are shown in Appendix A in Huang et al. (2018).

3.5.3. OS's AMM calculation

As course alteration is the most used and most effective way for ship conflict elimination (Baldauf et al., 2017), the OS is assumed to only alter her course with velocity unchanged to eliminate the conflict.

The change of ship heading after rudder steering is determined by the ship's maneuverability. The Nomoto model (Nomoto et al., 1956), a simplification of Maneuvering Modeling Group (MMG) model, is commonly used to describe ship maneuverability because it only requires limited inputted parameters, in comparison with Abkowitz model (Zhang and Zou, 2011) and MMG model (Tao et al., 2019). Therefore, the Nomoto model (Nomoto et al., 1956) is adopted to calculate the OS's available velocity after steering (Du et al., 2020a):

$$\begin{cases} RV_{OS}(\delta) = |V_{OS}(t)| \cdot \begin{bmatrix} \cos(C_{OS}(t_0) + \phi_\delta) \\ \sin(C_{OS}(t_0) + \phi_\delta) \end{bmatrix} \\ \phi_\delta = \int\limits_t r dt = \mathrm{K}\delta\left(t - \mathrm{T} + \mathrm{T} \cdot e^{-t/T}\right) \end{cases}, \tag{6}$$

where $RV_{OS}(\delta)$ is the OS's reachable velocity after steering with a demanded rudder angle δ, with $-35^\circ \le \delta \le 35^\circ$. ϕ_δ is the change of ship heading based on her turning ability with a demanded rudder angle δ. r is the corresponding yaw rate. The OS's turning ability index K and turning lag index T vary with ship length and velocity.

Under a demanded rudder angle δ, the conflict can be eliminated if the OS's velocity can be moved out from the TS's velocity obstacle zone, according to the NL-VO algorithm:

$$IC_\delta = \begin{cases} 1, & \text{if} \quad \exists V_{OS}(t) \in RV_{OS}(\delta) : V_{OS}(t) \cap S_{NL\_VO}(t) = \varphi \\ 0, & \text{otherwise} \end{cases}, \tag{7}$$

Here, $IC_\delta = 1$ means that at least one ship speed inside her available speed set $RV_{OS}(\delta)$ is outside the velocity obstacle zone $S_{NL\_VO}(t)$. Therefore, the conflict can be eliminated by the OS's maneuver with a demanded rudder angle δ. $IC_\delta = 0$ means that the conflict cannot be eliminated with this maneuver. For the calculation of TS's velocity obstacle zone $S_{NL\_VO}(t)$, the TS is assumed to keep her current motion state. Specifically, if $Int(t_0) = 0$, TS is assumed to sail in a straight line with constant speed (see the red dotted line in Fig. 7). If $Int(t_0) = 1$, the TS's trajectory is predicted based on the observed $ROT(t)$ (see the blue dotted line in Fig. 7).

The AMM is measured based on the proportion of maneuvers by which the OS can eliminate potential conflicts, to all its available maneuvers (Huang et al., 2019c):

$$AMM(t) = \begin{cases} H, & \text{if} \quad \dfrac{\sum \delta_s(t)}{\delta_a(t)} \ge \tau_1 \& IC_{\delta_s(t)} = 1 \\ M, & \text{if} \quad \tau_1 > \dfrac{\sum \delta_s(t)}{\delta_a(t)} \ge \tau_2 \& IC_{\delta_s(t)} = 1 \\ L, & \text{if} \quad \dfrac{\sum \delta_s(t)}{\delta_a(t)} < \tau_2 \& IC_{\delta_s(t)} = 1 \end{cases}, \tag{8}$$

where δ_s is the value of the adopted rudder angle that makes $IC_\delta = 1$. δ_a is all OS's available rudder angle and $-35^\circ \le \delta_a \le 35^\circ$. τ_1 and τ_2 are the thresholds to divide the AMM into three classes: high (H), medium (M) and low (L). CS3 is the example of $AMM(t) = H$. CS5 and CS8 are the examples of $AMM(t) = M$ and $AMM(t) = L$ respectively, see Table 1. τ_1 and τ_2 are set as 80% and 60% respectively.

4. Case study

Two groups of case studies are conducted to demonstrate the feasibility of the proposed method. The first group includes four simulated two-ship encounters, shown in Section 4.1. The second group consists of one multi-vessel encounter extracted from historical AIS data, shown in Section 4.2.

4.1. Two-ship encounters based on simulations

4.1.1. Encounter scenarios design

Rules 11 to 18 in the COLREGs only apply to vessels in sight of one another. Four crossing encounter scenarios in good visibility between a ship pair are designed as the analyzed context. The stand-on ship is set as the OS.

4.1.1.1. Ship attributes. For the OS, the ship length L_{OS} is 100m. The change interval of rudder angle is 5°. For the OS's turning ability index, $\mathrm{K} = 2V_{OS}/L_{OS}$ and $\mathrm{T} = 2L_{OS}/V_{OS}$ (Hong and Yu, 2000). For the TS, its length L_{TS} is 100m.

4.1.1.2. Sailing-related ship motion data. The earth-fixed coordinate system O-X-Y is adopted. OX points to east and OY points to north. Ship course is the angle at which the OX axis rotates anticlockwise to the ship velocity. The simulation time is 600s. The time interval for updating the ship motion and the calculations for the CAS are set as 10s.

The initial position P_0 of the OS is (−2000m, 6000m). The TS set initially in the origins of the axis system. The magnitude of ship speed $|V|$ is fixed as 5 m/s. The initial course C_0 of the OS is 210^0 and that of the TS is 90^0. t_{TP} is the designed turning time and C_{TP} is the course change at the turning points. $C_{TP} > 0$ means the ship turns to port.

The OS will turn to port 30^0 at 100s. For the TS, due the uncertainty of ship action, there are many possibilities for her action when there is a conflict (Chauvin and Lardjane, 2008). Therefore, four encounter scenarios are designed as shown in Table 2. The differences between each scenario is the TS's action time and magnitude of course deviation.

In Scenario 1, the TS sails a straight line.

In Scenario 2, the TS turns to port 30^0 at 200s.

In Scenario 3, the TS turns to starboard -40^0 at 200s.

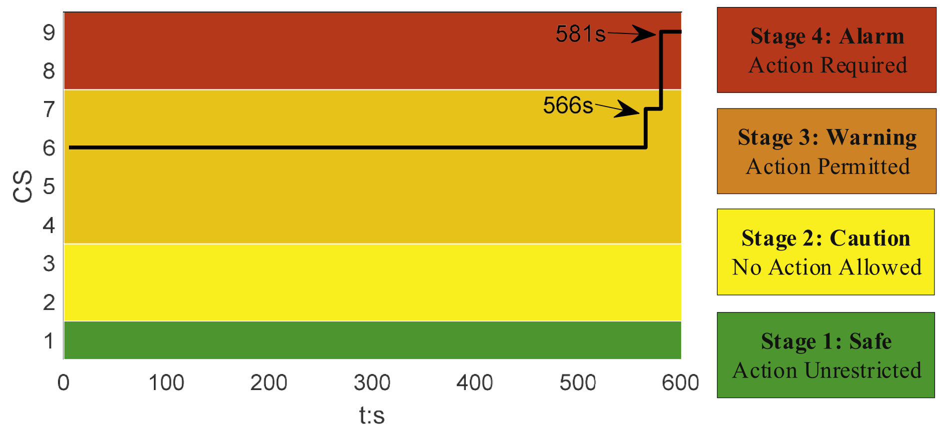
In Scenario 4, the TS turns to starboard -20^0 at 550s.

4.1.2. Results

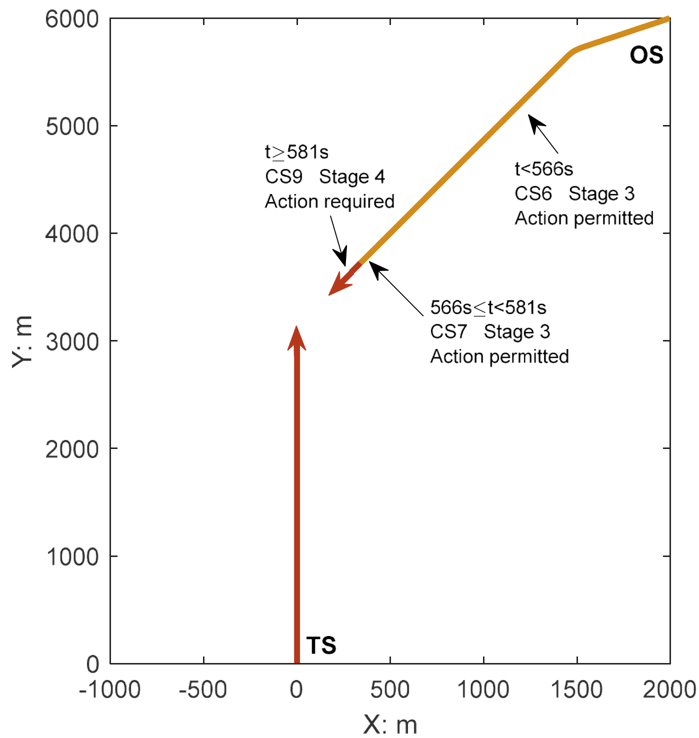
The results of these four designed encounter scenarios are elaborated from Section 4.1.2.1 to Section 4.1.2.4. The different colours indicate different levels of conflict severity and alert during different encounter stages. Green, yellow, orange and red represents safe, caution, warning and alarm respectively, consistent with the color scheme in Table 1 and Fig. 5.

4.1.2.1. Scenario 1. Fig. 8 is the visualization of ship conflict analysis in Scenario 1, as developed in Table 2. From the start of the simulation, a conflict is present. TS does not show any response when the conflict exists. Because the AMM of the OS is high before 566s in Stage 3, the conflict severity is determined as CS6 (Fig. 8(a)). This is in the Stage 3 that the FLoD and SLoD are activated. Therefore, the OS's obligation is 'action permitted' (Fig. 8(b)), and the alert level is 'warning'.

Afterwards, the AMM of OS decreases to medium from 566s to 581s, so the conflict severity increases to CS7 in Stage 3 where FLoD and SLoD



(a) The determination of the encounter stage and the level of conflict severity in temporal scales



(b) The OS's obligation at different encounter stage in spatial scales

Fig. 8. Visualization of ship conflict analysis in Scenario 1, as per Table 2.

are activated. Hence, the OS's obligation is still 'action permitted' and the alert level is 'warning'.

When the OS's AMM drops to low after 581s, the conflict severity becomes even more serious, reaching CS9 in Stage 4. The FLoD, SLoD and TLoD are activated. Hence, the OS's obligation changes to 'action required'. The alert level is 'alarm'.

4.1.2.2. Scenario 2. Fig. 9 illustrates the result of conflict analysis in Scenario 2, as developed in Table 2. Before the TS's action at 200s, the level of conflict severity is CS6 (Fig. 9(a)), which means that the TS does not act but OS's AMM is high. This is in Stage 3 where FLoD and SLoD are activated. Therefore the OS's obligation is 'action permitted' and alert level is 'warning' (Fig. 9(b)).

The TS takes evasive action at 200s. After the ship steers to turn with a demanded rudder, the *ROT* increases gradually and stables at its peak. The observed *ROT* at 206s does not reach its peak. At 206s, the conflict cannot be eliminated with TS's action alone, while the OS's AMM is still high. Therefore, the level of conflict severity falls to CS3 at 206s. This is in Stage 2, with only the FLoD activated. The OS's obligation is 'action not allowed', and the alert level is 'caution'.

At 211s, the observed *ROT* stables at its peak. The conflict is expected to be eliminated by TS's positive evasive action. However, this evasive action violates Rule 15 in COLREGs because the TS is expected to cross the OS by its bow ($V_{TS} \in S3$). Consequently, the level of conflict severity increases to CS4 at 211s (Fig. 9(a)). The FLoD and SLoD are activated in Stage 3. The OS's obligation is 'action permitted' and the alert level is 'warning' (Fig. 9(b)).

With this evasive action, the TS successfully moves her velocity outside the VO zone at 226s. Thus, the conflict is eliminated at 226s. Afterwards, the level of conflict severity falls back to CS1 (Fig. 9(a)) in Stage 1 so that the OS can move unrestricted, with the alert level being 'safe' (Fig. 9(b)).

4.1.2.3. Scenario 3. Fig. 10 shows the results of Scenario 3, as indicated in Table 2. From the onset of the simulation to 200s, a conflict exists, and the TS shows no response. The conflict severity is CS6 as OS's AMM is

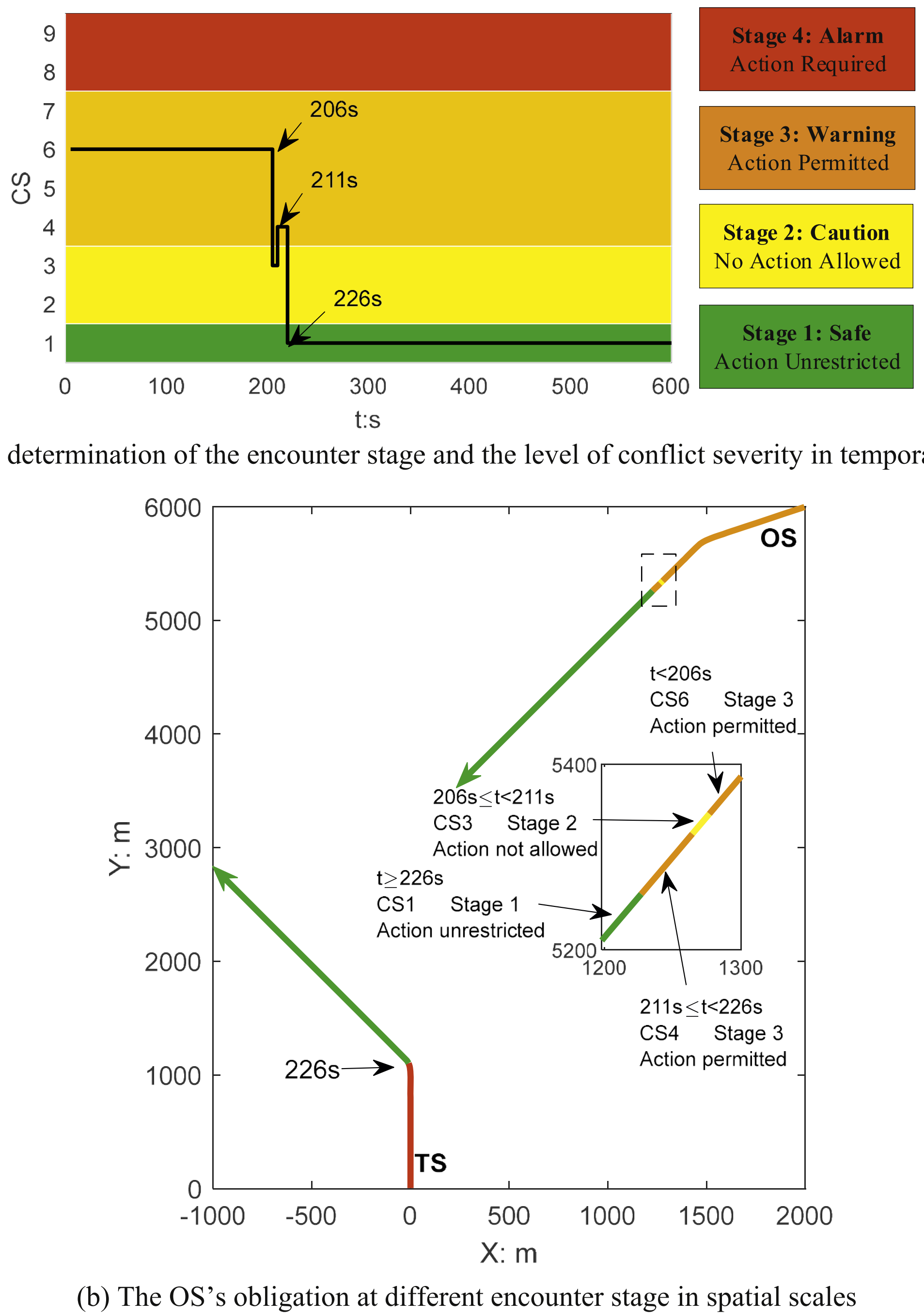


Fig. 9. Visualization of ship conflict analysis in Scenario 2, as per Table 2.

high. The FLoD and SLoD are activated in Stage 3 (Fig. 10(a)). Therefore, the OS's obligation is 'action permitted' and the alert level is 'warning' (Fig. 10(b)).

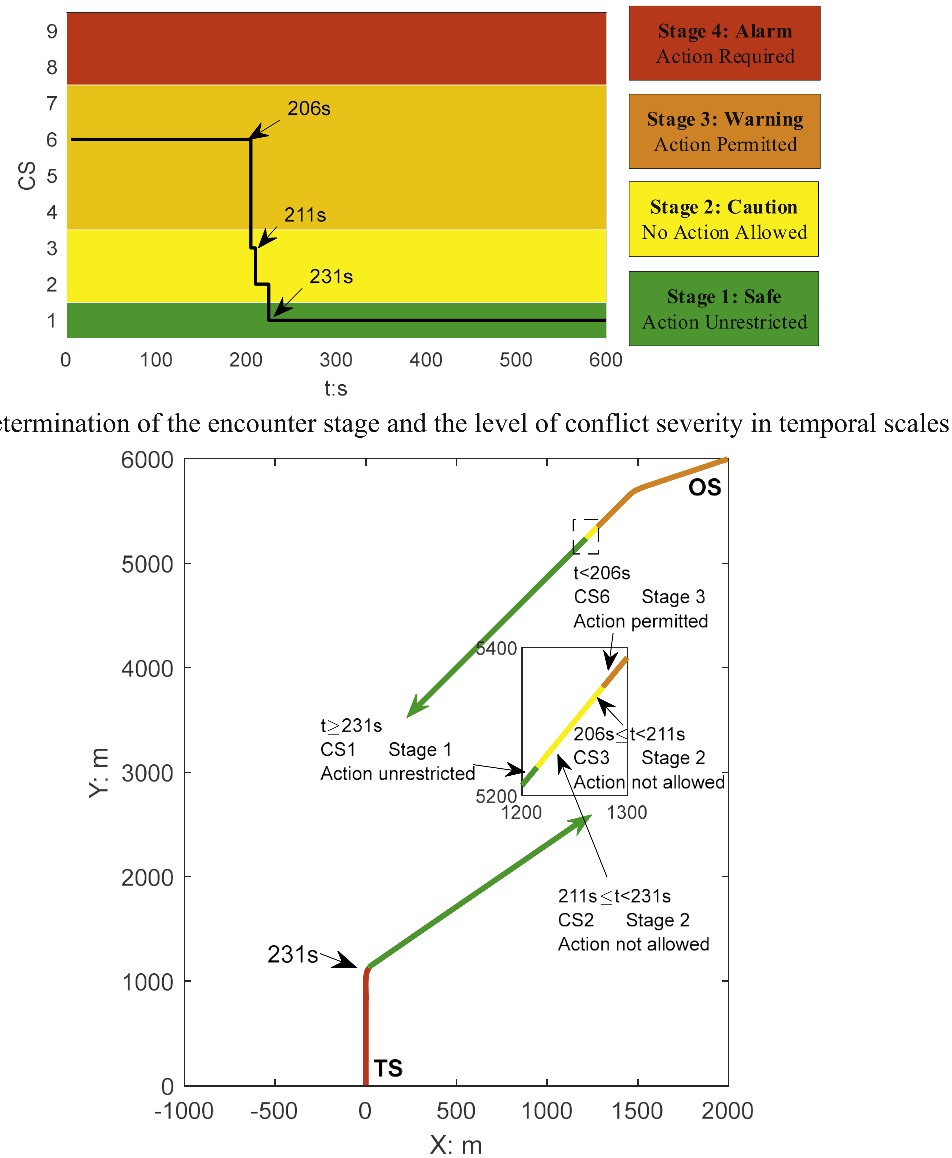
The TS turns to starboard at 200s. After the ship turns with a demanded rudder, the *ROT* increases gradually and stabilized at its peak around 211s. With the TS's maneuver, the conflict severity falls from CS6 to CR3 at 206s and to CR2 at 211s. The encounter stage changes from Stage 3 to Stage 2. The conflict is expected to be eliminated by TS's positive and legal evasive action alone. During this period, only the FLoD is activated, indicating that the OS's obligation is 'action not allowed' and the alert level is 'caution' (Fig. 10(b)).

From 231s onwards, the conflict between OS and TS3 is eliminated. Hence, the conflict severity is marked as CS1. The FLoD, SLoD and TLoD are inactivate. The OS can move unrestricted and the alert level is 'safe'. Consequently, the TS's action is positive and legal.

4.1.2.4. Results of scenario 4. Fig. 11 presents the evolution of the conflict severity between the OS and TS in Scenario 4, as indicated in Table 2 (Fig. 11(a)), and the change in the OS's obligation during the whole encounter process (Fig. 11(b)).

The conflict severity is CS6 at the beginning of the simulation time. Before the TS's right turn at 550s, it remains in CS6 in Stage 3. The FLoD and SLoD are activated. The OS's obligation is 'action permitted', with the alert level at 'warning'.

The TS starts to change her course from 550s. The conflict severity increases to CR8 from 556s as the TS's action is not efficient to eliminate the existing conflict and the AMM of the OS is low (see Table 1 and



(a) The determination of the encounter stage and the level of conflict severity in temporal scales

(b) The OS's obligation at different encounter stage in spatial scales

Fig. 10. Visualization of ship conflict analysis in Scenario 3, as per Table 2.

Fig. 5). This is in the Stage 4, where the FLoD, SLoD and TLoD are activated. Hence, the OS's obligation is 'action required' and the alert level is 'alarm' (Fig. 11(b)).

After the TS finishes the steering and stabilizes at the designed new course around 586s, the TS keeps sailing in a straight line with a constant course. As the conflict still exists and the ship pair keeps approaching, the conflict severity becomes more serious, increasing to CS9 at 586 in Stage 4. The FLoD, SLoD and TLoD are activated. The OS's obligation is 'action required' and the alert level is 'alarm'.

4.2. *Multi-vessels encounter based on AIS data*

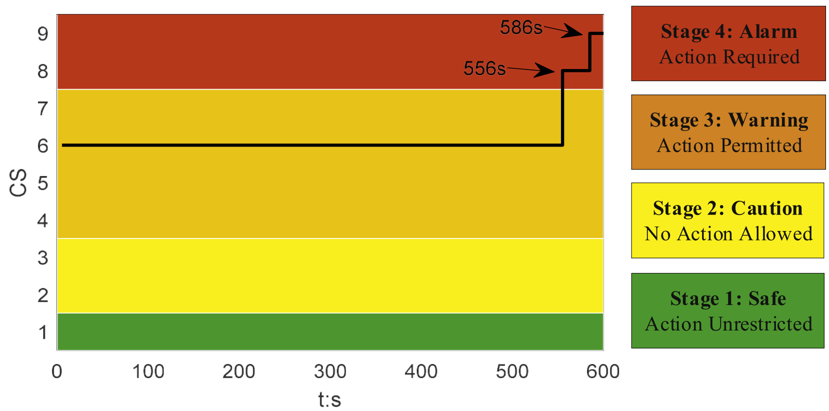
4.2.1. *Encounter scenario description*

Fig. 12 visualizes the ship trajectories involved in a multi-vessels encounter, which was happened in the North Atlantic (Du et al., 2020a). Ship1 is a smaller oil tanker with 96m in length. Its trjectory is marked in blue in Fig. 12. Ship2 is a fishing vessel with 23m in length, with its trajectory marked in red. Ship3 is a larger oil tanker with 171m in length, its trajectory being marked in black. The discrete points indicate the historical trajectories of these three ships, based on historic AIS data after processing. The lines linking these points are the ship trajectories after linear interpolation based on the AIS data.

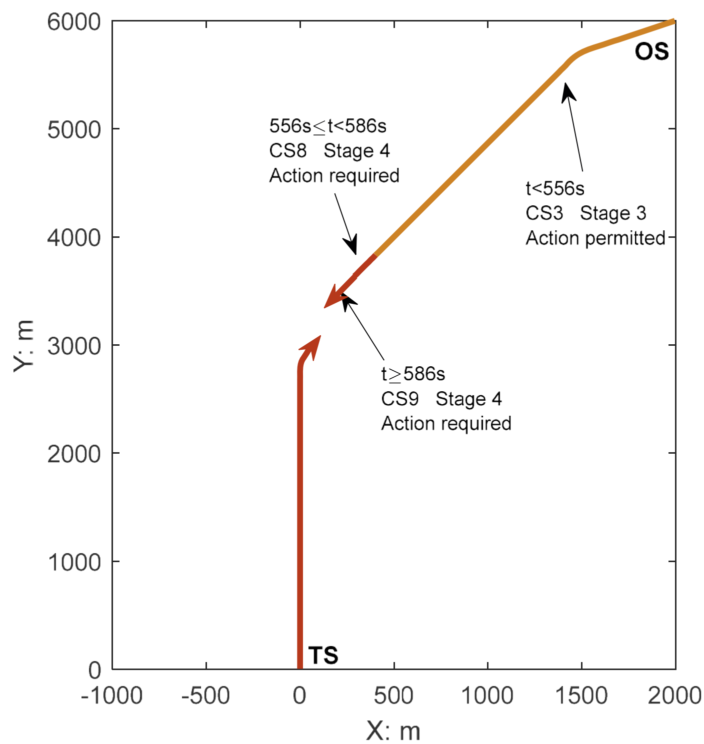
4.2.2. *Results*

Fig. 13 illustrates the time periods during a conflict exists between each ship-pair. For the encounter between Ship1 and Ship2, there are two periods in which a conflict exists, ranging from 661s to 721s and from 881s to 911s. Similarly, the collision risk for the encounter between Ship1 and Ship3 exists between 501s and 531s, and between 931s and 941s. The time of collision risk existing between Ship2 and Ship3 is also not consecutive, containing four periods (from the start to 31s, from 431s to 481s, from 521s to 591s, and from 821s to 1391s).

The results of ship conflict analysis between different ship-pair in multi-vessel encounter scenario are elaborated in Section 4.2.2.1, 4.2.2.2 and 4.2.2.3 respectively. The thick line is the trajectory of the OS and the thin line is that of the TS. The different colours on the OS's trajectory indicate different levels of alert during different encounter stages, which are consistent with the color set in Table 1 and Fig. 5. The



(a) The determination of the encounter stage and the level of conflict severity in temporal scales



(b) The OS's obligation at different encounter stage in spatial scales

Fig. 11. Visualization of ship conflict analysis in Scenario 4, as per Table 2.

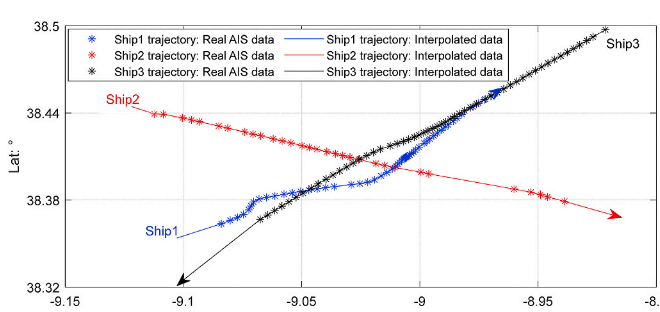


Fig. 12. Ship trajectories in a multi-vessel encounter scenario (Du et al., 2020a).

color on the TS's trajectory is the same as that on the OS to indicate their relative position.

4.2.2.1. Ship-pair encounter berween Ship1 and Ship2. Ship2 is the stand-on ship according to Rule 18 in the COLREGs. The Ship2 is set as OS. The results are illustrated in Fig. 14.

Before 661s, there is no conflict between Ship1 and Ship2, see Fig. 14. The conflict severity is CS1 in Stage 1. Hence, the FLoD, SLoD and TLoD are inactive. The OS can move unrestricted and the alert level is 'safe'. However, due to the TS's action during this period, such as at 441s and 521s for the conflict between TS and Ship3, a conflict between OS and TS is generated from 661s.

Afterwards, TS's evasive action between 661s and 671s is positive. However, this evasive action violates the COLREGs, so that the conflict severity is CS4 in Stage 3. During this period, FLoD and SLoD are activated. Therefore, that OS's obligation is 'action permitted' and the alert level is 'warning'.

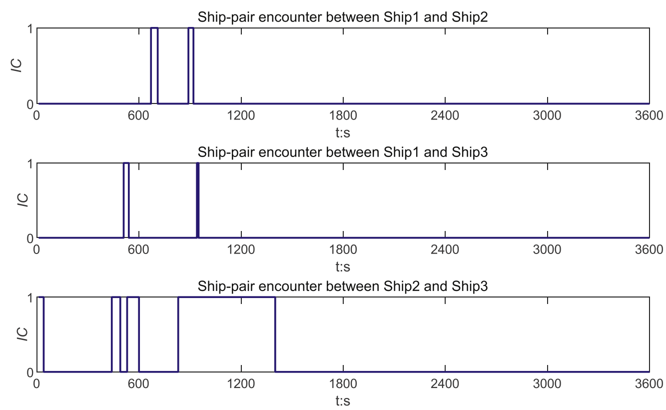


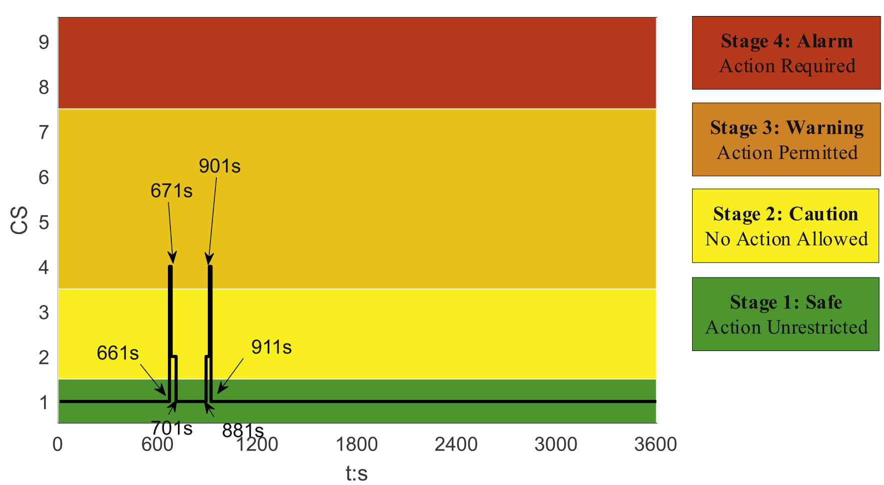
Fig. 13. The result of conflict detection between the ship pair in a multi-vessel encounter scenario.

As the TS takes positive and legal evasive action from 671s to 701s, the conflict severity decreases to CS2 and only FLoD is activated. Hence, the OS's obligation is 'action not allowed' and the alert level is 'caution'. Finally, with the TS's continous evasive action, the conflict between the OS and TS is eliminated already from 701s. The conflict severity between 701s and 881s is CS1 in Stage 1. The OS can move unrestricted, and the alert level is 'safe'.

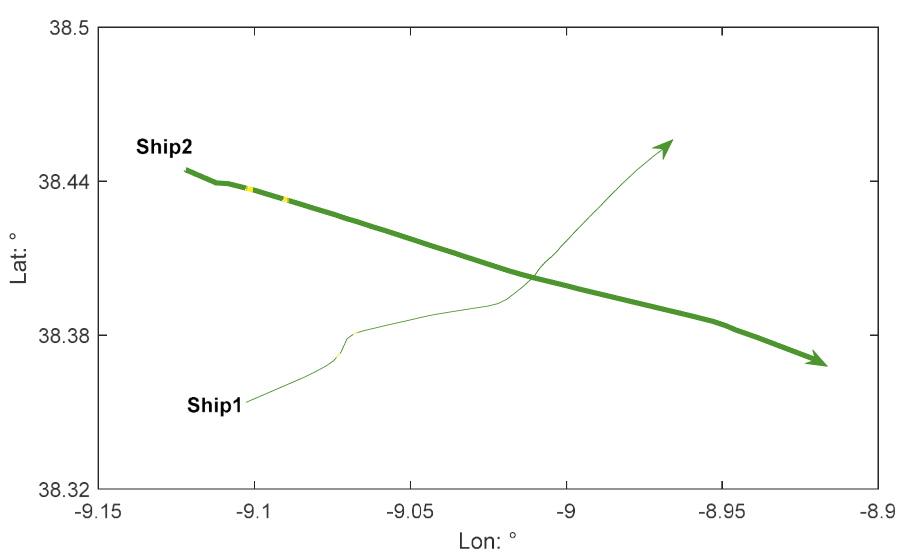
The TS turns to starboard to return to her planned trajectory during this period from 701s to 881s, which re-generates a conflict between OS and TS. This action leads the TS to pass the OS ahead of its bow. Therefore, the conflict severity increases to CS4 at 901s and this stage remains until 911s. Both FLoD and SLoD are activated. Hence, the OS's obligation is 'action permitted' and the alert level is 'warning'.

There is no conflict between the OS and the TS after 911s. The TS passes the OS ahead of its bow around 2000s. None of the FLoD, SLoD and TLoD are activated. The OS has no action restriction and the alert level is 'safe'.

4.2.2.2. Ship-pair encounter berween Ship1 and Ship3. Ship3 is the stand-on ship according to Rule 15 and Rule 18 in the COLREGs. The Ship3 is

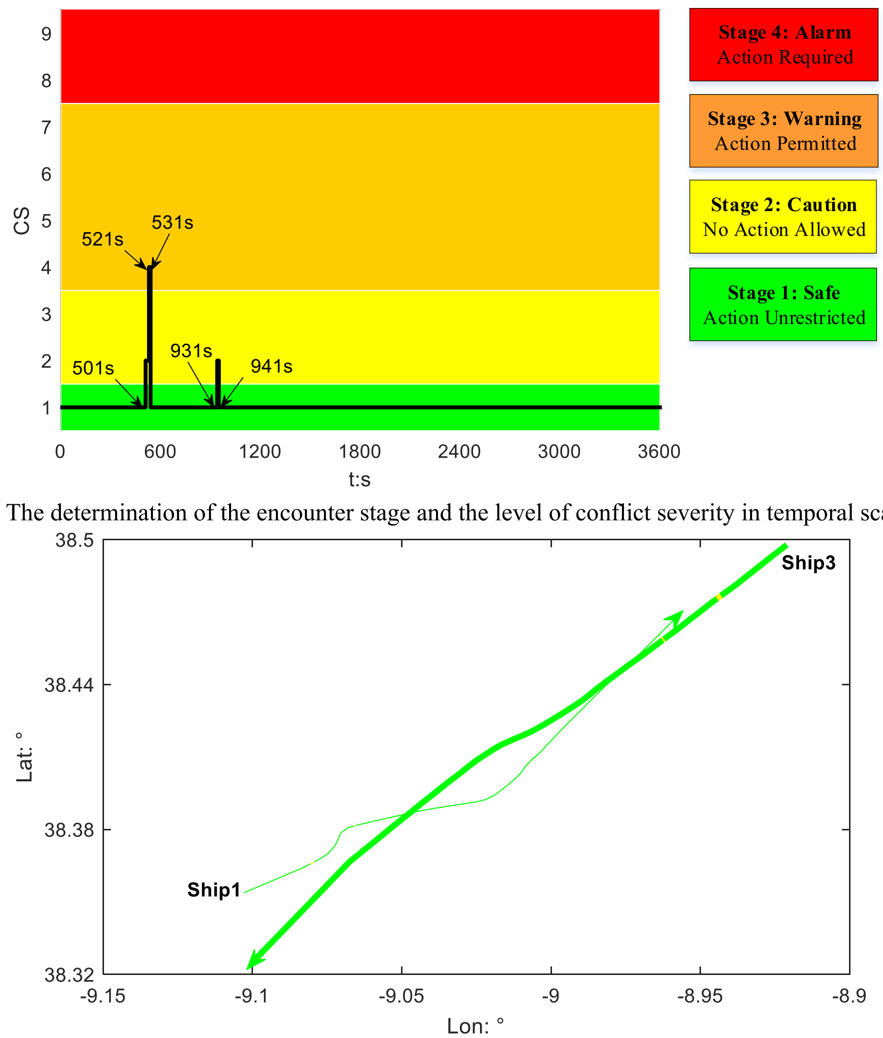


(a) The determination of the encounter stage and the level of conflict severity in temporal scales



(b) The OS's obligation at different encounter stage in spatial scales

Fig. 14. Visualization of ship conflict analysis between Ship1 and Ship2 in multi-vessel encounter scenario and Ship2 is OS.



(a) The determination of the encounter stage and the level of conflict severity in temporal scales

(b) The OS's obligation at different encounter stage in spatial scales

Fig. 15. Visualization of ship conflict analysis between Ship1 and Ship3 in multi-vessel encounter scenario and Ship3 is OS.

set as OS. The results are shown in Fig. 15.

No conflict exists between OS and TS before 501s. The conflict severity is CS1 in Stage 1. The FLoD, SLoD and TLoD are inactive. Hence, the OS can move unrestricted and the alert level is 'safe'.

Due to the course change of TS, the conflict between OS and TS occurs from 501s. The TS acts positive and legal so that the existing conflict is expected to be eliminated by the TS's action alone. The level of conflict severity is CS2, where only the FLoD is activated. The OS is not allowed to act and the alert level is 'caution'. This state remains until 521s.

From 521s to 531s, the TS turns to port and the TS's action violates the Rule 15 in the COLREGs. The conflict severity increases to CS4 in Stage 3. The FLoD and SLoD are activated. The alert level is 'warning', with the OS being permitted to act.

From 531s to 931s, there is no conflict. The level of conflict severity returns to CS1 in Stage1, so the OS has no action restriction and the alert level is 'safe'. During this period, the TS turns to starboard to return its original trajectory, which results in the conflict regeneration from 931s to 941s. The period between 931s and 941s is in Stage 2 with a conflict severity of CS2. The TS takes positive and legal evasive action so that the existing conflict is expected to be eliminated by TS's action alone. Only the FLoD is activated. The OS is not allowed to act and the alert level is 'caution'.

The conflict is eliminated at 941s. Afterwards, the OS has no action restrictions. This is in Stage 1, with a conflict severity of CS1. None of the FLoD, SLoD and TLoD are activated. The alert level is 'safe'.

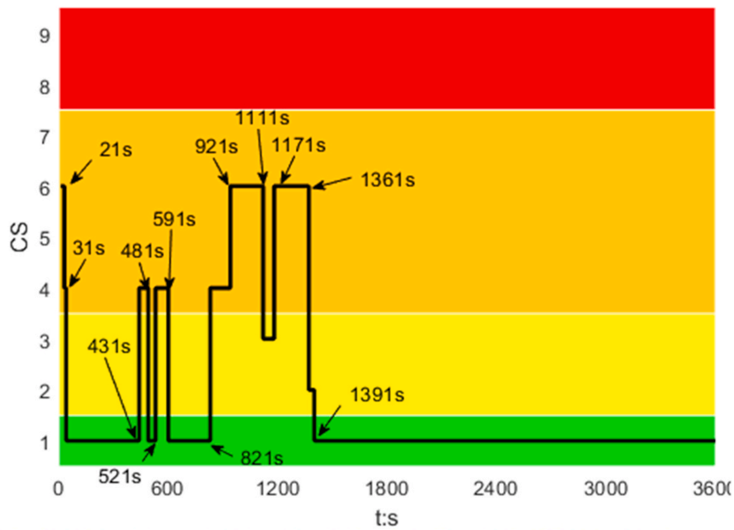
4.2.2.3. Ship-pair encounter berween Ship2 and Ship3. Ship2 is the stand-on ship according to Rule 15 in the COLREGs. The Ship2 is set as OS. From Fig. 16(a), it is seen that TS's action is more complicated.

The conflict occurs from the beginning. Because the TS does not act and the OS's AMM is high, the conflict severity is CS6 in Stage 3 before 21s. The FLoD and SLoD are activated. The OS's obligation is 'action permitted' and the alert level is 'warning'.

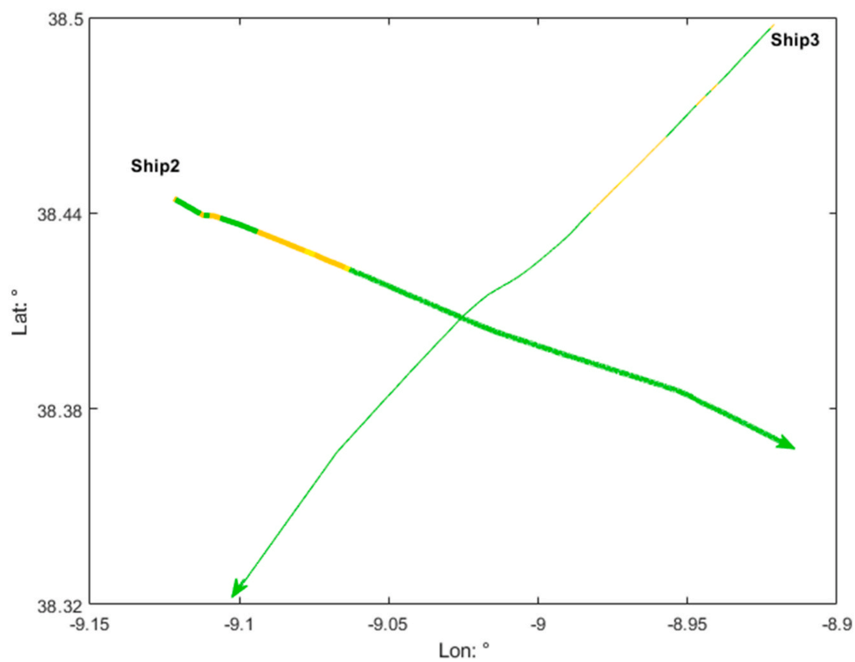
The TS is aware of the existing conflict and starts to act from 21s. From 21s to 31s, the TS's action is positive and sufficient to eliminate the existing conflict. However, this action is illegal in the sense that the TS is expected to pass the OS ahead of its bow. The conflict severity in this period is CS4 in Stage 3. The FLoD and SLoD are activated. Hence, the OS is permitted to act and the alert level is 'warning'.

With the continuous evasive action of the TS, the conflict is eliminated from 31s. From 31s to 431s, the conflict severity decreases to CS1 in Stage 1, with the FLoD, SLoD and TLoD all inactivated. The OS has no action restriction. If the TS keeps her current velocity and course, she is expected to safely pass the OS's bow. The alert level is 'safe'.

To comply with the COLREGs to pass the OS by its abaft, the TS turns to starboard, which generates the conflict from 431s. Afterwards, the TS turns to starboard intermittently, which makes the encounter stage



(a) The determination of the encounter stage and the level of conflict severity in temporal scales



(b) The OS's obligation at different encounter stage in spatial scales

Fig. 16. Visualization of ship conflict analysis between Ship2 and Ship3 in multi-vessel encounter scenario and Ship2 is OS.

changes. The TS acts continuously from 431s to 481s, and from 521s to 591s, leading the TS to pass the OS safely ahead of its bow. The conflict severity during this action period is CS4, which implies that the OS is permitted TS to act, with an alert level 'warning'. There is no conflict between 481s and 521s, and between 521s and 821s, which is CS1 in Stage 1. During these two periods, the FLoD, SLoD and TLoD all inactivated. The OS has no action restriction and alert level is 'safe'.

TS's intermittent action from 591s to 821s regenerates the conflict since 821s. Before 921s, TS's action is positive but illegal, so the conflict severity during this action period is CS4 in Stage 3. OS is allowed to act and the alert level is 'warning'.

There is no action taken by TS between 921s and 1111s. However, the OS's AMM is high during this period. Therefore, the conflict severity is CS6 in Stage 3, and the FLoD and SLoD are activated. The OS is allowed to act. The alert level is 'warning'. From 1111s to 1171s, the conflict severity decreases to CS3 as TS's action is negative but OS's AMM is high. OS is not allowed to act during this period and the laert level is 'caution'. The situation in the period between 1171s and 1361s is similar to that between 921s and 1111s.

The TS's turning to starboard at 1361s is positive and complies with COLREGs. The TS is expected to pass abaft the OS's abaft with current velocity unchanged. During the period from 1361s to 1391s, the conflict severity is CS2, which is in Stage2 and only the FLoD is activated. The OS is not allowed to act. The alert level is 'caution'.

The conflict is completely eliminated from 1391s onwards and the TS's action is legal due to her cultivated turning to starboard. The TS passes abaft the OS's stern around 2550s. Afterwards, the conflict severity is CS1 in Stage 1. None of the FLoD, SLoD and TLoD are activated. The OS has no action restriction and the alert level is 'safe'.

5. Discussion

5.1. Features of the proposed method

The proposed CAS from the stand-on ship's perspective aims at refining the terms of the COLREGs regarding the stand-on ship's action obligation. Our method can (1) classify the conflict levels (from stage 1 to Stage 4), (2) reveal the cause leading to the current encounter situation (from CS1 to CS9, such as give-way ship's positive but illegal evasive action), and (3) clarify the stand-on ship's action responsibilities (from action unrestricted to action required). This work helps support this ship's active involvement in conflict elimination through appropriately anticipating the developing situation. Improved situational awareness and better anticipation of developing dangerous situations may be conductive to reduce the probability of ship collision caused by the misinterpretations of the COLREGs rules by navigators of the stand-on ship.

The proposed method of CAS from the stand-on ship perspective has the following features.

First, this work quantifies the terms of the COLREGs regarding the stand-on ship's action obligation. According to the different action responsibilities for each ship as specified in COLREGs, the encounter stage is divided in 4 stages. Correspondingly, the conflict severity is subdivided into 9 levels to signify different cases. Apart from the regulation specified in COLREGs, the classification of conflict severity is also determined with reference to the following two principles. The first principle is that the situation is worse when the target ship is not aware of the existing risk, compared with that when the ship is aware of it. For instance, CS9 is more dangerous than CS8. This can be supported by the evidence that a lack of situational awareness has been identified as a main contributing factor in ship collisions (Liu and Wu, 2004; Gale and Patraiko, 2007). The second principle is that the risk is more serious when the ship has a limited number of maneuvering options for the navigator to eliminate the existing risk (Huang and van Gelder, 2019c). Hence, the conflict severity of CS5 is higher than CS3. Based on these, subdividing the conflict severity into 9 levels is reasonable. These 9 levels of encounter severity are made to distinguish cases in the calculation scheme, to account for differences in situations. Afterwards, these 9 levels of conflict severity are used to the division of alert levels. This is to simplify the information to support the navigators to make action decision. The output of this CAS from the stand-on ship perspective is the encounter stage, the action obligation of the OS in the stand-on position, and the alert level. This information can help the navigator onboard the stand-on ship compensates the give-way ship's lack of or incorrect action in response to an evolving dangerous situation.

Second, the dynamic and uncertain nature of the action by the TS are considered in the conflict detection. This work adopts the NL-VO algorithm to detect the conflict between OS and TS. This is done instead of making the commonly made assumption that ships sail in a straight line with constant speed. The determination of risk fully considers the influence of the OS on the decision of the TS. Hence, the application of the NL-VO algorithm makes the conflict assessment more realistic and accurate (Du et al., 2020a). Further, the TS's action uncertainty is also considered. In principle, all possible give-way ship's actions should be determined in making the stand-on ship's conflict assessment. This paper assumes that the give-way ship adopts a course alteration strategy for eliminating the encounter risk. This is in accordance with the observation done by Baldauf et al. (2017). Therefore, the reachable velocity of OS is utilized to measure TS's action uncertainty.

Third, the AMM of the OS are considered when determining the conflict severity. Navigators with a risk-taking attitude might accept some risky scenarios and act relatively late (Huang et al., 2020), but this situation leaves a limited number of maneuvering options for the navigator. However, some navigators on board a stand-on ship may illegally act to master the situation when the rule requires the ship to keep her course and speed (Chauvin and Lardjane, 2008), which leaves sufficient maneuvering options for the navigator but violates the Rule 17 in COLREGs. Hence, a lack of understanding of the AMM of the ship to eliminate the risk may lead to inaccurate detection of a dangerous situation (Huang and van Gelder, 2019b). Therefore, when determining the conflict severity, the ease of eliminating the conflict should also be considered. The AMM of OS is utilized to measure the capability of OS to prevent collision. For this reason, the accuracy of ranking the conflict severity is improved.

5.2. Applications of the proposed method

This work has the potential to be applied for various purposes under different encounter scenarios.

Firstly, it contributes to the autonomous shipping development. Autonomous ships need to be as safe as a manned counterpart operating in similar circumstances (Maritime UK, 2018; Xue et al., 2019a, b; Fan et al., 2020). Two reasons demonstrate this. One is that this proposed method takes the COLREGs into consideration. This helps the autonomous ship to understand the conventional ships' action. Moreover, the rules for autonomous ships need to be merged with COLREGs (Du et al., 2020a). Second is that the AMM of the OS is considered. The autonomous ship can accurately grasp not only the dangerous level of the approaching ships but also the difficulty of avoiding collisions. Having adequate information about navigational safety, including the current encounter stage and her action obligation, is important for the autonomous ships to make correct action-decision for a safe pass.

Secondly, it can be applied in ship-pair encounter scenarios and multi-vessels encounter scenarios. For a ship-pair encounter, the proposed CAS from the stand-on ship perspective can help OS understand the encounter stage and clarify her action obligation. The results of the case study in Section 4 can demonstrate this. However, for a multi-vessel encounter, the collision avoidance between target ships may lead to own ship's inaccurate estimation of the target ship's intention. Performing AQ assessment of TS1 (Step 3 in Fig. 4) can help reduce the impact on the accuracy of risk assessment that caused by this inaccurate ship intention estimation (Step 2 in Fig. 4), which is one of the focus of this work, see Fig. 4. Taking a three-vessel encounter as an example, including OS, TS1 and TS2, see Fig. 3(a). OS has the collision risk with TS1, and the collision risk between TS1 and TS2 exists. OS is the stand-on ship. If TS1 changes her action for the collision avoidance with TS2, the intention estimation of TS1 from OS perspective is that TS1 is aware of the exiting conflict with OS. In this work, there is an assumption that the intention of the action will affect the effect of avoiding collisions that produced by adopted action. If TS1 is aware of the collision hazard but TS1's AQ is negative, the conflict severity is CS5. If TS1 is not aware of the collision hazard and TS1's AQ is negative, the conflict severity is CS6 or CS7, see Table 1. CS5, CS6 and CS7 are in the Stage 3 that alert levels are warning. Hence, the impact on the accuracy of risk assessment that caused by this inaccurate ship intention estimation is minor. For the condition that TS1's AQ is positive, TS1's action helps collision avoidance with OS. It is reasonable to estimate that TS1 is aware of the collision risk with OS and acts for it as we value TS's AQ more. Therefore, the collision risk still can be correctly assessed and classified by this proposed method.

Thirdly, the method can also be used to determine the alert levels in historic AIS data, which can be used to obtain further insight in the risk levels in waterways. Accurate ranking of traffic encounters through a conflict severity hierarchy contributes to the detection of high-risk areas with a high occurrence frequency of near miss. A near miss is a situation which did not lead to an accident but where an accident was narrowly avoided (Zhang et al., 2015, 2016; 2017; Du et al., 2020b). The focus of these detected near miss is effective in reducing the number of encounters requiring further examination by experts, such as the VTS operator. Besides, the knowledge extracted from the analysis of historical waterway traffic risks can support the VTS operators to manage waterway traffic and provide guidance to navigators.

5.3. Limitations and future research

5.3.1. Parameters determination

First, the elliptical domain is selected as a basis of the current work as it is the most realistic one based on empirical data (Hansen et al., 2013). However, the elliptical domain still has many limitations (Szlapczynski and Szlapczynska., 2017b) that may undermine the accuracy of ship collision risk classification. This issue could be overcome by the adoption of more advanced ship domain models, such as knowledge-based ship domain (Zhu et al., 2001; Pietrzykowski and Uriasz, 2009) or a model-based ship domain (Rawson et al., 2014; Krata and Montewka, 2015). Further, the shape, traffic density and traffic patterns of different sea and waterway regions are known to have an impact on the shape and size of the ship domain. Ship domains specified to open water (Pietrzykowski and Uriasz, 2009), restricted water (Hansen et al., 2013; Wang and Chin, 2016; Pietrzykowski, 2008) and ice-covered water in convoy operations (Goerlandt et al., 2017) are different. A balance should be achieved between precisely defining the shape and dimensions of the ship domain and simplifying the computations. Ultimately, the choice of domain is less important than the accuracy of the output level of the CAS. In the proposed CAS method, the elliptical domain is only used to help the stand-on ship correctly understand the rules and to fulfil her duties. The ship domain is only a means to that end, instead of a focus. Therefore, if other ship domain, such as the fuzzy ship domain, proves to be better under other encounter scenarios, the proposed approach can be further applied to improve the CAS further.

Second, the conflict evolution analysis, including the TS's AQ assessment and the OS's AMM calculation, is performed based on the assumption that the motion state of the TS remains constant within a certain time. For the condition that the TS is aware of the existing conflict, the TS is assumed to alter course with a constant *ROT* within a short period, which is observed by the OS. There are two challenges of using *ROT* as an indicator to do the conflict evolution analysis. One challenge is that *ROT* is currently not a reliable parameter due to the fact that *ROT* indicator is usually not connected to the AIS transponder (Mestl et al., 2016). The second challenge is the quality represented in AIS data. In this work, *ROT* is calculated from the course in AIS data. Due to the influence of the external environment, such as the wind and current, a change of TS's course may be not for conflict elimination. A more reliable method of the reconstruction of *ROT* from the ship's heading is needed.

Third, the threshold τ_1 and τ_2 to divide the different levels of OS's AMM are set as 80% and 60% respectively, which is however subjective. Higher thresholds lead to more frequent alerts including many unnecessary or false alerts. Lower thresholds however may omit some important alerts. Therefore, the determination of thresholds for the division of the different levels of OS's AMM still needs to be more precise. Many risk indicators analysis methods can help this (Goerlandt and Kujala, 2014; Zhang et al., 2019, 2020). This is also a direction for future work.

Finally, the proposed CAS has only been demonstrated in a limited number of test scenarios, to show its rationale and feasibility. More elaborate testing, both with simulated scenarios, encounters from historic AIS data, and ultimately in realistic environments with human operators, should be performed. This is essential for instance to determine the appropriate domain sizes and threshold settings, striking a balance between the number of alerts and their actually perceived need.

5.3.2. Rule conflict in the multi-vessel encounter

The threat of the OS's ship domain being violated is possible from more than one ship in high traffic density areas. However, most of the existing research about conflict elimination focuses only two-ship encounter scenario (Huang and van Gelder, 2019c). The multi-vessel encounters are usually regarded as a linear superposition of multiple ship-pair encounters. For instance, many works have been done to help the own ship to detect the most immediate danger ship (Brcko, 2018), and determine the optimal course alteration maneuver (Szlapczynski, 2007, 2008). Further, the multi-vessel encounter situation is not directly included in the COLREGS rules, but relies on the knowledge and experience of the navigator in interpreting the situation based on the COLREG rules for pairwise encounters (Brcko, 2018). Some work utilizes a traffic complexity (van Westrenen and Ellerbroek, 2015) or cooperative game approach (Liu et al., 2019) to measure the global collision risk in multi-vessel encounters. However, none of these considers the COLREGs.

Nevertheless, two critical issues in the multi-vessel encounter situation need future work.

First, the conflict between the own ship and other target ships are assessed separately, while the conflict between target ships are currently not considered. This issue may lead to an inaccurate understanding of the action intention of the target ship. Ship 1's abnormal action in multi-vessel encounter scenario in Section 4.2 reveals this issue. For the ship-pair encounter between Ship1 and Ship2, there is no conflict between Ship1 and Ship2 at the beginning, while Ship1's turning to port causes a conflict. The motivation of this apparently abnormal action from Ship1 can be interpreted by also considering the conflict between Ship1 and Ship3. From this, it can be understood that the action by Ship 1 aims to eliminate the conflict with Ship3. The maritime traffic system is characterized by a complex interaction between ship, human and environment, and therefore the multi-vessel encounter needs to be considered as a whole.

Second, little of research considers the rule conflicts, where a vessel can have two identities simultaneously, e.g. stand-on and give-way vessel for different vessels in a multi-vessel encounter situation. However, in dense traffic areas, this issue is not rare. For the multi-vessel encounter scenarios as described in Section 4.2, Ship3 is the stand-on ship for the encounter with Ship1, and Ship3 is the give-way ship for the encounter with Ship2. From Fig. 16, it is seen that Ship3's actions are more complicated. Ship3 acts more frequently and takes a longer time to eliminate the conflicts. Ship 3's action needs to comply with the COLREGs. Hence, Ship3 should not only give way to Ship2 but also needs to fulfil her action obligation as a stand-on ship to Ship1. Further, Ship3's action should avoid making the situation worse. Ship3's uncoordinated action may make Ship1's evasive actions ineffective. However, this work does not directly provide collision avoidance solutions in current circumstance. The related information of rule conflict is notified to the OS in the stand-on position, while the solution of which still needs navigator's decision. Consequently, it is important to conduct an analysis of rule conflict to further improve the possibility of ships passing safely with each other.

6. Conclusions

The effective response from the stand-on ship helps prevent the occurrence of dangerous encounters and even ship collision when the give-way ship does not act properly. However, the COLREGs rules do not provide specific guidance for the stand-on ship. Although ship collision alert is a plausible way to alert the ship of a collision hazard in a timely fashion by reminding the ship operator of her action duties, there is a lack of research focusing on alerting the stand-on ship to compensate the give-way ship's inappropriate actions.

Therefore, this article has proposed a CAS from the stand-on ship perspective to trigger the stand-on ship's involvement in the conflict elimination by quantifying the terms of the COLREGs regarding the stand-on ship's responsibility for conflict elimination. The conflict severity is divided into 9 classes with the OS's AMM considered. These classes are linked with the 4 stages of the encounter process and 4 alert levels. This helps the stand-on ship accurately understand her action responsibilities and clarify the corresponding alert level.

The results of several case studies demonstrate that the proposed method is feasible to support the stand-on ship in making action decisions for conflict elimination. This may contribute to the reduction of collisions caused by misinterpretations of the COLREGs by navigators. The dynamic nature and uncertainty of ship actions are also considered in this proposed method to make the conflict assessment more accurate and reliable.

Nonetheless, several issues require further improvement. The first is the determination of several critical parameters, including the shape and size of ship domain, *ROT*, and threshold between different levels of OS's AMM. These require further research to increase the universality and reliability of this proposed method. The second is that multi-vessel encounters need to be considered as a whole rather than a linear superposition of multiple ship-pair encounters. In particular, rule conflicts where vessels can have two identities and opposing action requirements simultaneously is not rare especially in density water area. This issue requires new research to find new alternatives for improving the possibility of ships passing safely with each other.

CRediT authorship contribution statement

Lei Du: Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing, Visualization, Formal analysis. **Osiris A. Valdez Banda:** Supervision, Writing - review & editing, Investigation. **Floris Goerlandt:** Writing - review & editing, Supervision, Investigation. **Yamin Huang:** Conceptualization, Writing - review & editing, Formal analysis. **Pentti Kujala:** Supervision, Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table 1
List of Abbreviations

AMM	Available Maneuvering Margin	MMG	Maneuvering Modeling Group
AQ	Action Quality	MSA	Maritime Safety Administration
CAS	Collision Alert Systems	NL-VO	Non-Linear VO
COLREGs	Convention on the International Regulations for Preventing Collisions at Sea	OS	Own Ship
CS	Conflict Severity	ROT	Rate of Turn
FLoD	Give-way ship as First Line of Defense	SD	Ship Domain
LLoD	Last Line of Defense	SLoD	Stand-on Ship as Second Line of Defense
LTTA	Last Time to Take Action	TLoD	Both Ships as Third Line of Defense
MAIB	Maritime Accident Investigation Branch	TS	Target Ship
MDTC	Minimum Distance to Collision	VO	Velocity Obstacles

Table 2
List of notations

AMM	AMM calculation	$PT_{OS}(x,y,t)$	planned trajectory of the OS
AQ	AQ assessment	r	yaw rate
Col	COLREGs scrutiny	ROT	course change rate
C_{OS}	course of the OS	RV	reachable ship velocity
C_{TS}	course of the TS	t_{TP}	designed turning time
C_0	initial course of the ship	S_{NL_VO}	velocity obstacle zone at in TS's velocity space
C_{TP}	course change at the turning point	T	turning lag index
Dis	relative distance between a ship pair	t_0	current moment
IC	conflict index	V_{OS}	velocity of the OS
Int	ship action intention index	V_{TS}	velocity of the TS
K	turning ability index	$\|V_{TS}\|$	magnitude of the TS's speed
$\min Dis$	minimum distance between two ship trajectories	ΔC_{TS}	course change of the TS
$\tilde{p}_{TS}$	TS's predicted trajectory	δ	demanded rudder angle
P_0	initial position of the ship	Δt	time interval of simulation
P_{OS}	OS's trajectory	ϕ_δ	change of ship course
$P_{TS}(x,y,t)$	position of the TS		

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