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MANOEUVRABILITY-BASED CRITICAL TIME FOR PREVENTING CLOSE-QUARTERS SITUATIONS

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Key words: collision avoidance, close-quarters situation, COLREGS.

ABSTRACT

This paper deals with the COLREGS-complaint actions and the critical time for preventing close-quarters situations, from the viewpoint of a stand-on vessel. A model based on the dynamic game of complete information (DGCI) is formulated for three collision situations, and the COLREGS-complaint actions are obtained. The critical time is then composed by the alteration time and the physical time delay. The alteration time is determined by using analytic geometry with relative motion. Considering manoeuvrability of the vessels, an equation to estimate the physical time delay is derived from the *MSC.137(76) Standards for Ship Manoeuvrability*. Then, the critical time can be determined by correcting the physical time delay. Finally, three real cases are analysed to validate the proposed results and demonstrate that they can provide criteria to ensure navigation safety for practical applications.

I. INTRODUCTION

Collision avoidance can be regarded as a process wherein the officers of the watch (OOWs) take proper actions in ample time, based on the rules of the road, so that two vessels can pass at a safe distance. The rules of the road–*International Regulations for Preventing Collisions at Sea, 1972*, or COLREGS–serve as a guidance for the process. However, some critiques of the COLREGS, such as their qualitative nature and unnecessary complication, have been presented (Weber, 1995; Stitt, 2002). These disadvantages lead to divergent interpretations of the rules by different individuals. In such cases, subjective judgments based on the experiences of the OOWs are usually adopted to deal with these situations, rather than bureaucratically following prescriptive rules (Belcher, 2002). Uncertainties in collision situations may arise (Wu, 1984; Taylor, 1990; James, 1994). Therefore, a further step to ensure safety would be a formalisation of criteria for practical applications–which is the motivation of this research.

Close-quarters situation (CQS) is one of the qualitative terms needing clarification, although the objective of the COLREGS is to prevent the development of such critical situation (Zhao, 2008). Considering the condition of being in sight of one another, the process of a collision may be divided into four stages based on the obligations of the give-way and stand-on vessels, as follows: free manoeuvre, action required by the give-way vessel, action required by the stand-on vessel and the CQS (Cockcroft and Lameijer, 1996). In this regard, a CQS can be viewed as a situation where it is impossible for one vessel manoeuvring alone to avoid the other by a substantial alteration of course (Mankababy, 1987). The give-way vessel is required to manoeuvre in the second stage, namely action required by the give-way vessel, when the rules begin to apply (Zhao, 2008). However, some critical occasions arise if the give-way vessel neglects to keep a proper lookout (Wu, 1984); the stand-on vessel then has to manoeuvre alone under *Rule 17(a)(ii)* before the last moment to prevent the development of a CQS. In such cases, how and when to manoeuvre by herself alone become an urgent task for the stand-on vessel. Therefore, analysis of the COLREGS-complaint actions and determination of the critical time for preventing a CQS from the viewpoint of the stand-on vessel are necessary for maritime safety, and are the main goals of the present effort.

The relevant literature is divided into two categories: analysis of the COLREGS-complaint actions, and determination of the critical time or distance. To analyse the COLREGS-complaint actions, a static game of complete information was first adopted by Cannell (1981); Tsai et al. (2014) then proposed a model based on a dynamic game of complete information (DGCI) to reflect the dynamic nature of collision avoidance. These qualitative researches interpreted the COLREGS in strategic and formalised manners and obtained the COLREGS-compliant actions for the second stage. However, actions and critical time to prevent a CQS for the stand-on vessel if the give-way vessel neglects to fulfill her obligation are not addressed. As for determining the critical distance, there are three types of research: rules of thumb, descriptive models, and prescriptive models. As a rule of thumb, Cockcroft and Lameijer (1996) suggested that the boundary of the CQS be considered one nautical mile (nm) for vessels in sight

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of one another and 2 to 3 nm in restricted visibility. However, this simple concept fails to take into account the various sizes, characteristics and speeds of the vessels, as stated by Mr. Justice Willmer in the case of *Grepa/Verna* (Cockcroft and Lameijer, 1996).

Descriptive models are constructed based on statistical analyses. Davis et al. (1980) proposed a concept of the arena, in which the OOWs would start to take action to avoid a CQS, based on the questionnaires and analysis of the average patterns. Habberly and Taylor (1989) designed a simulation and analysed the alteration distances made by the subjects. Taylor (1990) and James (1994) subsequently provided probability distributions of the alteration distance based on simulation data collected by Habberly and Taylor (1989). These descriptive models can calculate the alteration distance within which manoeuvres are initiated, but are unable to take into account the delay distance or time as affected by the manoeuvrabilities of the vessels.

Finally, prescriptive models are constructed by using mathematical concepts. Hilgert (1983) defined the critical distance for preventing a CQS as that distance at which a crashing stop is made by both vessels. However, this model subsequently proved ineffective in avoiding a CQS if the manoeuvre is made by one vessel alone (George, 1984). Colley et al. (1983) and Wu (1984) both developed equations for the distance of last-minute action (LMA). However, the former equation can only determine the distance in a head-on situation, and the latter is too risky due to its assumption that the initial distance to closest point of approach (DCPA) and the final passing distance of the vessels both equal zero.

Based on the definition of a CQS, this paper attempts to formalise the safety criteria of how and when to manoeuvre for the stand-on vessel if the give-way vessel neglects to fulfill her obligation. The COLREGS-complaint actions in overtaking, head-on and crossing situations are first analysed by a DGCI, which deals with sequential processes in which thinking people interact with each other (Fudenberg and Tirole, 1991; Gibbons, 1992; Montet and Serra, 2003; Rasmusen, 2005). Then, the critical time for the stand-on vessel to prevent a CQS is considered. The alteration time is determined by the analytic geometry with relative motion. Since relative motion is unable to take into account the effect of manoeuvrability, the parameters of *MSC.137(76) Standards for Ship Manoeuvrability* (IMO, 2002) are adopted to serve as maximum limits and to derive an estimated equation of the physical time delay. So the alteration time can be corrected and the critical time for preventing the CQS can be determined, and the purpose of this research can be met.

This paper is organized as follows: Section 2 describes the DGCI and the analysis of the COLREGS-complaint actions. The theoretic background and procedure required to obtain the critical time for a CQS are presented in Section 3. In Section 4, three real accidents are analysed to demonstrate the feasibility of the proposed approach. Finally, conclusions are presented in Section 5.

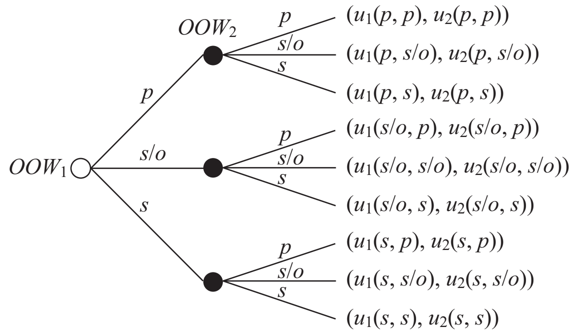


Fig. 1. Extensive-form representation of the collision game.

II. COLREGS-COMPLAINT ACTIONS FOR PREVENTING A CLOSE-QUARTERS SITUATION

In this section, a brief introduction of the DGCI is presented. Then, three collision situations are formalised and analysed by a DGCI, and the COLREGS-complaint actions are obtained. Finally, the actions required by the stand-on vessel in the case of negligence of the give-way vessel are discussed.

1. Dynamic Game of Complete Information

Game theory is a strategic-thinking approach that deals with real-life situations where thinking people interact with each other (Montet and Serra, 2003). That is, each individual's choice depends on what the others may do (Fudenberg and Tirole, 1991). The DGCI particularly concerns situations where individuals, who have full understanding of the situation, make choices in sequence (Gibbons, 1992; Rasmusen, 2005). It is adopted here to analyse the process of collision avoidance.

When one considers two vessels in a direct collision situation in the open sea with good visibility, alteration of course alone may be the most effective actions to avoid collisions. Therefore, the speeds of the vessels are assumed to be maintained at a safe level. Two OOWs of the vessels sequentially take actions in two stages before a CQS can develop. The framework of the collision game can be described by an extensive-form representation, as shown in Fig. 1. The basic elements constituting a DGCI, such as players, actions, payoffs, information and strategies, are defined as follows:

(1) The *players* who take actions to maximize their own payoffs are two OOWs for this case. They are represented by decision nodes from left to right in order of time, and denoted by OOW_i, $i = 1, 2$. It is noted that each decision node constitutes a subgame.
(2) An *action*, which is represented by a branch, is a choice the player can make. When we consider usual practice in open sea with good visibility, there are 3 actions can be chosen, including of altering course to port (p), standing on (s/o), and altering course to starboard (s). They are denoted by $a_i = \{p, s/o, s\}$ referring to OOW_i.
(3) The *payoffs* are utilities that respond to actions chosen by all OOWs and are denoted by u_i (a_1, a_2). In this case, the

payoffs for each OOW consist of two values. One is a state utility that corresponds to the effects of the actions, while the other is a penalty utility if either action violates the COLREGS.

(4) The *information* refers to the knowledge of this game. In particular, complete information means that the knowledge is possessed by each OOW. There is no probability distribution in the framework and the nodes are singleton.

(5) The *strategies* are full plans for each OOW reacting to each subgame at the time he makes a choice. In this regard, OOW_1 has only one decision node with three strategies as the actions he can choose. On the other hand, OOW_2 has three decision nodes so he has $3^3 = 27$ strategies denoted by ($p|p|p$, $p|p|s/o$, …, $s|s|s$). That is, for $p|p|p$, OOW_2 chooses p no matter what the OOW_1 chooses; for $p|p|s/o$, OOW_2 chooses p if OOW_1 chooses p or s/o, and chooses s/o if OOW_1 chooses s; … and so on.

The solution of the DGCI is named the subgame perfect Nash equilibrium (SPNE), which is composed of the best strategies for each OOW. It can be obtained by searching through all possible strategies; however, this is a complicated task. A convenient method referred to as backwards induction is adopted to achieve the result. Backwards induction represents a pattern of reasoning that starts from the time when OOW_2 makes a choice. In this regard, the question each OOW faces can be viewed as an optimization problem (Gibbons, 1992).

For each subgame, OOW_2 faces an optimization problem as follows,

$$\max_{a_2 \in A_2} u_2\left(a_1, a_2\right). \tag{1}$$

A set of best actions chosen by OOW_2 that would maximize his payoffs in each subgame, is denoted by a_2^*, also referred to as the best strategy for him. Working backwards to the time when OOW_1 makes a decision, he anticipates that OOW_2 will choose the set of best actions and face the other optimization problem as follows,

$$\max_{a_1 \in A_1} u_1\left(a_1, a_2^*\right). \tag{2}$$

OOW_1 would pick an action from a_1 based on the set of a_2^* to maximize his payoff. As mentioned above, this best action is also the best strategy for him. Thus the combination of these best strategies, the SPNE, from which the players have no incentive to deviate, is obtained.

2. COLREGS-Complaint Actions

Collision situations can be categorized into overtaking, head-on, and crossing situations, under *Rule 13. Overtaking*, *Rule 14. Head-on Situation*, and *Rule 15. Crossing Situation*, in the COLREGS. Assuming there is a vessel at the centre, the situation can be determined based on the region where the other vessel is coming up. Region "A" corresponds to an overtaking situation, region "B" to a head-on situation and regions "C" and "D" to crossing situations, as illustrated in Fig. 2. It is noted that the boundaries of region "B", namely head-on situation, are assumed to be 005° and 355° as categorised by Cockcroft (1982). The COLREGS-complaint actions for these situations can be analysed by collision games as follows:

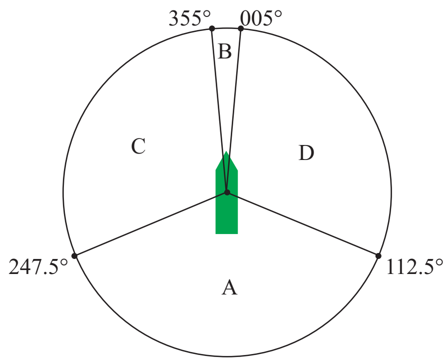


Fig. 2. Regions for determining collision situations.

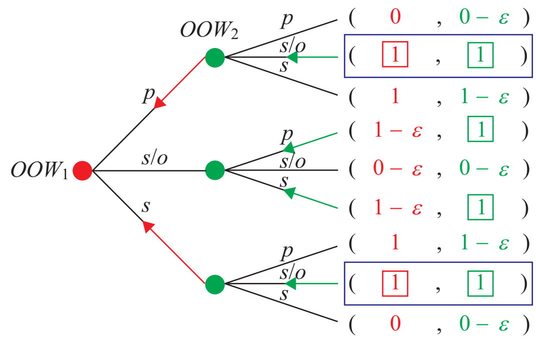


Fig. 3. The framework and the SPNE of the game for overtaking situation.

1) Game for Overtaking Situation

As shown in Fig. 2, the vessel coming from region "A" is the give-way vessel, which takes action first and is referred to as OOW_1, while the centre vessel is the stand-on vessel that takes its own action after observing give-way vessel's action, and is referred to OOW_2. The state utility is designated 0, indicating danger in the condition that both vessels choose the same actions. Otherwise, it is designated 1, connoting safety. The rules related to actions in this situation are *Rule 8. Actions to Avoid Collisions*, *Rule 13. Overtaking*, *Rule 16. Action by the Give-way Vessel* and *Rule 17. Action by the Stand-on Vessel*. The penalty utility, denoted by ε with a positive value between 0 and 1, corresponds to the actions that violate the Rules. These violations are: first, OOW_1 chooses the action s/o; second, OOW_2 chooses actions other than s/o if OOW_1 has given way; and third, OOW_2 chooses the action s/o if OOW_1 has chosen s/o. The framework and the SPNE are illustrated as Fig. 3.

Table 1. COLREGS-complaint actions for three collision situations.

Situation	Region	Obligation		Stage of give-way vessel		Stage of stand-on vessel
		The other	Centre vessel	The other	Centre vessel	Centre vessel
Overtaking	A	Give-way	Stand-on	***p*** or ***s***	***s/o***	***p*** or ***s***
Head-on	B	Both required to manoeuvre		***s***	***s***	***s***
Crossing	C	Give-way	Stand-on	***s***	***s/o***	***s***

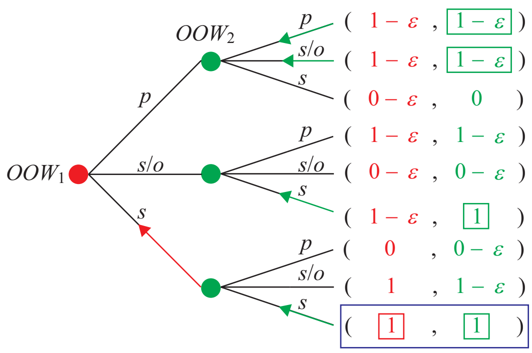


Fig. 4. The framework and the SPNE of the game for head-on situation.

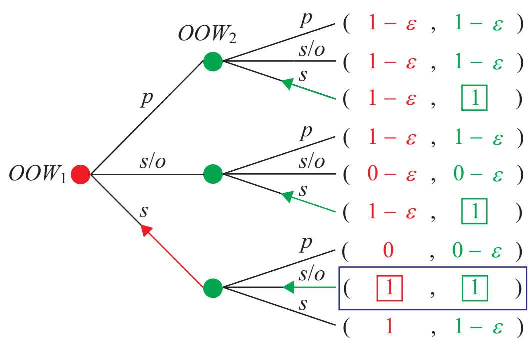


Fig. 5. The framework and the SPNE of the game for crossing situation.

The best strategies are (p) and (s) for OOW_1 and ($s/o|p|s/o$) and ($s/o|s|s/o$) for OOW_2. The SPNEs of the overtaking game are (p, ($s/o|p|s/o$)), (p, ($s/o|s|s/o$)), (s, ($s/o|p|s/o$)) and (s, ($s/o|s|s/o$)). The OOWs receive the same payoff of 1 which implies the actions are not only safe but comply with the COLREGS. That is, the COLREGS-complaint actions are altering course to port or starboard for the overtaking vessel and standing on for the overtaken vessel.

2) Game for Head-On Situation

This situation appears when one of the two vessels is coming from region "B" as illustrated by Fig. 2. The state utility is designated 0, indicating danger in the condition that both vessels choose s/o, or if they take opposite directions, i.e., p and s. Otherwise, it is designated 1, connoting safety. The only applicable rule in this situation is *Rule. 14 Head-on Situation*, which indicates that both vessels shall alter course to starboard. That is, the payoff would contain a penalty utility if either of them does not choose s. The framework and the SPNE are illustrated in Fig. 4.

The best strategies are (s) for the first mover and ($p|s|s$) and ($s/o|s|s$) for the other. The SPNEs are (s, ($p|s|s$)) and (s, ($s/o|s|s$)). The solution is precise in that both vessels have to alter course to starboard to ensure safety and comply with the COLREGS.

3) Game for Crossing Situation

A crossing situation occurs if the other vessel coming from region "C" or "D" in Fig. 2. For region "C", it is a stand-on case for the centre vessel, but for region "D" it is a give-way case. From the viewpoint of the stand-on vessel with the COLREGS, the former case is considered here. The order of play is that the other vessel, i.e., the give-way vessel referred to as OOW_1, makes a choice first. Then, the centre vessel, i.e., the stand-on vessel referred to as OOW_2, chooses an action. The state utility is designated 0, indicating danger if OOW_1 chooses s and then OOW_2 chooses p, or if both vessels choose the action of standing on. Otherwise, it is designated 1, which connotes safety. Considering *Rule 8. Actions to Avoid Collisions*, *Rule 15. Crossing Situation*, *Rule 16. Action by the Give-way Vessel* and *Rule 17. Action by the Stand-on Vessel*, the penalty utility is determined as follows: first, OOW_1 chooses p or s/o; second, OOW_2 chooses p or s/o if OOW_1 chooses p or s/o; and third, OOW_2 chooses p or s if OOW_1 chooses s. In this way, the game can be formalised, and the framework as well as the SPNE outcome are illustrated in Fig. 5.

The best strategies are (s) for the OOW of the give-way vessel and ($s|s|s/o$) for the OOW of the stand-on vessel. The SPNE is (s, ($s|s|s/o$)) and both OOWs obtain a payoff of 1. The COLREGS-complaint actions are altering course to starboard for the give-way vessel and standing on for the stand-on vessel.

3. Discussions on the COLREGS-Compliant Actions for Stand-On Vessels

The COLREGS-complaint actions in the second stage, namely action required by the give-way vessel, are summarised as follows. First, the give-way vessel shall alter course to either side while the stand-on vessel stands on in an overtaking situation. Second, both vessels have to alter course to starboard in a head-on situation. Third, the give-way vessel shall alter course to starboard while the stand-on vessel shall stand on in a crossing situation. However, some critical occasions arise in overtaking and crossing situations because the give-way vessel may neglect to keep a proper lookout. The process of a collision enters the next stage, namely action required by the stand-on vessel. The

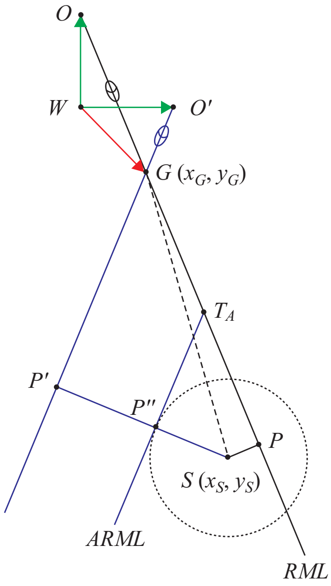


Fig. 6. The alteration time is determined by Scenario 1.

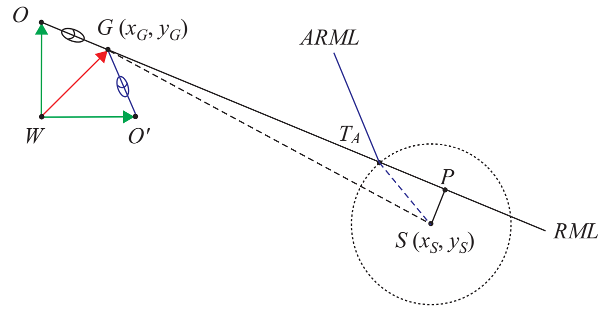


Fig. 7. The alteration time is determined by Scenario 2.

stand-on vessel must take action under *Rule 17(a)(ii)* before the last moment at which she can prevent a CQS by her manoeuvring alone. The actions complying with the COLREGS for stand-on vessels can be found in Figs. 3 and 5 and summarised in Table 1, which illustrate overtaking and crossing situations, respectively. In these cases, the stand-on vessel shall alter course to either side in an overtaking situation, or alter to starboard in a crossing situation. Thereafter, the most important issue turns to the question of when to manoeuvre, depending on the vessel's manoeuvrability. This is the critical time for preventing a CQS, that is to be resolved in the next section.

III. CRITICAL TIME FOR PREVENTING A CLOSE-QUARTERS SITUATION

As mentioned above, a CQS can be viewed as a situation wherein it is impossible for two vessels to pass at a safe distance by a substantial alteration of one vessel alone. Based on the viewpoint of the stand-on vessel, the COLREGS-complaint actions have been analysed in Section 2. Here the critical time, which consists of the alteration time and the physical time delay, is considered. The alteration time is calculated by using equations of analytic geometry with relative motion. To eliminate the disadvantage of relative motion being unable to take into account the manoeuvrability of the vessel, the *MSC.137(76) Standards for Ship Manoeuvrability* is adopted to derive an estimation equation of physical time delay. Through the correction of the physical time delay, the critical time can be obtained. In this procedure, a safe distance of 0.85 nm adopted from Goodwin (1975) in the open sea is assumed to ensure safety. Of course, a substantial alteration of course is assumed to be a course change of 90°. Besides, all the symbols used in the following are listed in Nomenclature for a quick reference.

1. Alteration Time

Given that the positions, courses and speeds of the vessels are known, equations of analytic geometry with relative motion are adopted. The position of the stand-on vessel is considered the reference point for relative motion. The alteration time is determined by an initial relative motion line (RML) and an altered RML. By searching for a point of alteration along the initial RML to yield a safe distance between the centre vessel and the altered RML, the alteration time can be determined. In particular, there are two scenarios for obtaining the alteration time depending on whether the direction difference between the initial and new RMLs is greater than 90° as shown in Figs. 6 and 7. The procedures are conducted as follows:

1) Obtaining the Distance, True Bearings and Relative Bearings

Given the positions of two vessels, (x_S, y_S) for the stand-on vessel and (x_G, y_G) for the give-way vessel, the differences between the x- and y-coordinates of the positions can be determined first, i.e., Δx and Δy. The distance between two vessels and the true bearings from one vessel to the other are consequently determined as follows:

$$D_{SG} = \sqrt{\Delta x^2 + \Delta y^2}\ , \tag{3}$$

$$TB_{SG} = \begin{cases} \tan^{-1}\dfrac{\Delta x}{\Delta y}, & \text{if } \Delta y > 0,\quad \Delta x \geq 0 \\ \tan^{-1}\dfrac{\Delta x}{\Delta y} + 180°, & \text{if } \Delta y < 0 \\ \tan^{-1}\dfrac{\Delta x}{\Delta y} + 360°, & \text{if } \Delta y > 0,\quad \Delta x < 0\ , \\ 90°, & \text{if } \Delta y = 0,\quad \Delta x \geq 0 \\ 270°, & \text{if } \Delta y = 0,\quad \Delta x < 0 \end{cases} \tag{4a}$$

$$TB_{GS} = \begin{cases} TB_{SG} + 180°, & \text{if } TB_{SG} \leq 180° \\ 360° - TB_{SG}, & \text{if } TB_{SG} > 180° \end{cases}. \tag{4b}$$

Subsequently, the relative bearings for both vessels can be yielded as:

$$RB = TB - C\,, \tag{5a}$$

$$RB_{SG} = \begin{cases} TB_{SG} - C_S, & \text{if } TB_{SG} - C_S \geq 0° \\ (TB_{SG} - C_S) + 360°, & \text{if } TB_{SG} - C_S < 0°, \end{cases} \tag{5b}$$

$$RB_{GS} = \begin{cases} TB_{GS} - C_G, & \text{if } TB_{GS} - C_G \geq 0° \\ (TB_{GS} - C_G) + 360°, & \text{if } TB_{GS} - C_G < 0°. \end{cases} \tag{5c}$$

2) Initial Relative Motion

The relative motion can be derived by vectors analysis. The x- and y-components of the initial relative motion is yielded as:

$$\Delta R_x = V_G \sin C_G - V_S \sin C_S\,, \tag{6a}$$

$$\Delta R_y = V_G \cos C_G - V_S \cos C_S\,. \tag{6b}$$

By using ΔR_x and ΔR_y, the slope of the initial RML can be obtained as:

$$m_{RML} = \frac{\Delta R_y}{\Delta R_x}\,. \tag{7}$$

Based on the point-slope form of a line equation, the equation of the initial RML is derived as:

$$m_{RML} x - y + (-m_{RML} x_G + y_G) = 0\,. \tag{8}$$

On the other hand, the magnitude and direction of the initial relative motion, i.e., V_{RM} and C_{RM}, can be solved by substituting ΔR_x and ΔR_y for Δx and Δy in Eqs. (3) and (4a) where the time scale of V_{RM} is further transformed to be minutes.

Using the formula for the distance from a point to a line, the DCPA is yielded as:

$$D_{CPA} = \frac{|m_{RML} x_G - y_G|}{\sqrt{m_{RML}^2 + 1}}\,. \tag{9}$$

The time to closest point of approach, TCPA, can be subsequently yielded by dividing the distance from point "G" to point "P" by magnitude of the relation motion can be illustrated as:

$$T_{CPA} = \frac{\sqrt{D_{SG}^2 - D_{CPA}^2}}{V_{RM}}\,. \tag{10}$$

3) Altered Relative Motion

By a substantial alteration of course the differences of the x- and y-components of the altered relative motion are expressed as following equations:

$$\Delta R_x' = V_G \sin C_G - V_S \sin(C_S \pm 90°)\,, \tag{11a}$$

$$\Delta R_y' = V_G \cos C_G - V_S \cos(C_S \pm 90°)\,. \tag{11b}$$

Here the "±" term is used to indicate direction of the alteration: "+" for a starboard turn or "–" for a port turn.

The course of the altered relative motion, i.e., C_{ARM}, can be obtained by substituting Δx in Eq. (4a) with $\Delta R_x'$ and Δy with $\Delta R_y'$. Likewise, the slope m_{ARML} can be determined by substituting ΔR_x in Eq. (7) with $\Delta R_x'$ and ΔR_y with $\Delta R_y'$. The line equation of the altered RML can also be formalised by substituting m_{ARML} for m_{RML} in Eq. (8).

4) Obtaining Alteration Time

Given that the course of the altered RML may be toward or away from the reference point, the alteration time can be obtained in two different ways. The criterion is whether the difference of direction between the two RMLs is greater than 90°.

Scenario 1. The course of altered relative motion is toward the centre vessel.

As shown in Fig. 6, in this case the difference of direction between the two RMLs is less than or equal to 90°. Adopting the formula for the distance from a point to a line, the new DCPA results from a substantial alteration of course is obtained as:

$$D_{ACPA} = \frac{|m_{ARML} x_G - y_G|}{\sqrt{m_{ARML}^2 + 1}}\,. \tag{12}$$

Since the distance to alteration ($\overline{GT_A}$) is the projection of the difference between the new D_{CPA} ($\overline{SP'}$) and the safe distance ($\overline{SP''}$) on the initial RML, the alteration time can be calculated by dividing $\overline{GT_A}$ by the magnitude of initial relative motion as determined in following equation:

$$T_A = \frac{(D_{ACPA} - D_S)}{V_{RM} \sin(|C_{RM} - C_{ARM}|)}\,. \tag{13}$$

Scenario 2. The course of altered relative motion is away from the centre vessel.

In this case, the point of alteration, T_A, is the intersection of the initial RML and the circle of safe distance as illustrated in Fig. 7. Because the $\Delta T_A PS$ is a right-angled triangle, the distance of $\overline{T_A P}$ can be easily obtained by the safety distance ($\overline{T_A S}$) and DCPA ($\overline{SP}$). Once the TCPA and time required for $\overline{T_A P}$ are obtained, the alteration time can consequently be determined as:

$$T_A = T_{CPA} - \frac{\sqrt{D_S^2 - D_{CPA}^2}}{V_{RM}}\,. \tag{14}$$

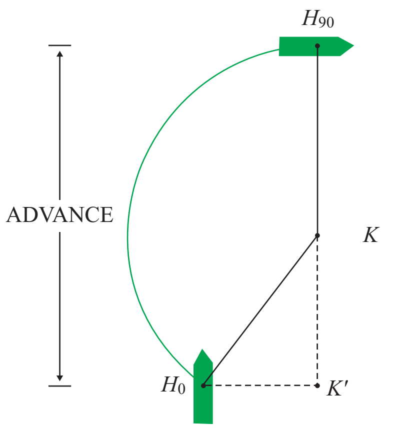


Fig. 8. The physical time delay.

2. Physical Time Delay

Since relative motion has a major disadvantage of failing to account for manoeuvrability, the physical time delay is introduced to resolve this problem. According to *5.3.1 Turning ability* of the *Resolution MSC.137(76) Standards for Ship Manoeuvrability*, it is assumed that the vessel makes a turning circle manoeuvre at a point, i.e., H_0, around a circle as illustrated in Fig. 8. The track of the manoeuvre arrives at the point H_{90} when the course change is 90°. Considering that the physical time delay occurs along the arc from H_0 to H_{90}, a diameter of 5 ship lengths (L) and an advance of 4.5 L is adopted to approach the result. Here $\overline{KH_0}$ and $\overline{KH_{90}}$ represent the radius of 2.5 L while $\overline{K'H_{90}}$ represents the advance of 4.5 L. The angle $\angle H_0KH_{90}$ of 143.13° can be calculated by:

$$\overline{K'H_{90}} = \overline{KH_0}\cos\left(180° - \angle H_0KH_{90}\right) + \overline{KH_{90}}\,. \qquad (15)$$

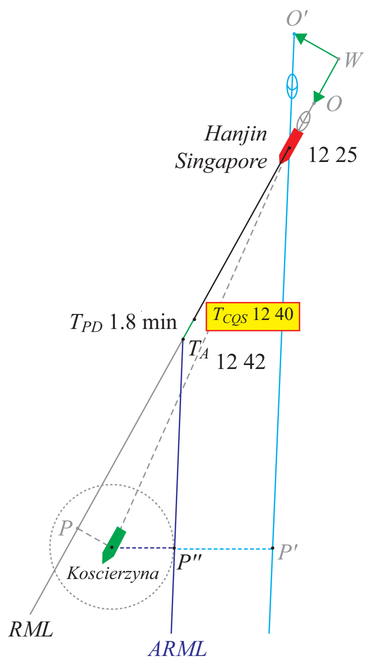
Then $\overset{\frown}{H_0H_{90}}$ of 6.245 L which represents the delay distance for a vessel making a course change by 90° can be determined accordingly. Thus, the physical time delay can be obtained by $\overset{\frown}{H_0H_{90}}$ and speed of the vessel. After converting the units of ship length and speed, the equation of the physical time delay can be yielded as:

$$T_{PD} = 3.372 \times 10^{-3}\,\frac{L}{V_S}\,. \qquad (16)$$

3. Critical Time for Preventing a CQS

By considering the vessel's manoeuvrability, the critical time for preventing a CQS can be determined by the alteration time and physical time delay as shown in following equation:

$$T_{CQS} = T_A - T_{PD}\,. \qquad (17)$$



	Koscierzyna	*Hanjin Singapore*
Position at 12 25	(0, 0)	(2.4, 5.5)
Course (°)	209°	209°
Speed (kts)	10.5	21.0
LBP (m)	95.0	
Situation	overtaking	
Obligation	stand-on	give-way

Preventing a CQS	A/C to starbord and port are permitted
Physical time delay (min)	1.8
Alteration time (min)	17.3 (s/b)/29.3 (p)
Critical Time (min)	15.5 (s/b)/27.4 (p)
Critical Time at GMT	12 40 (s/b)/12 52 (p)

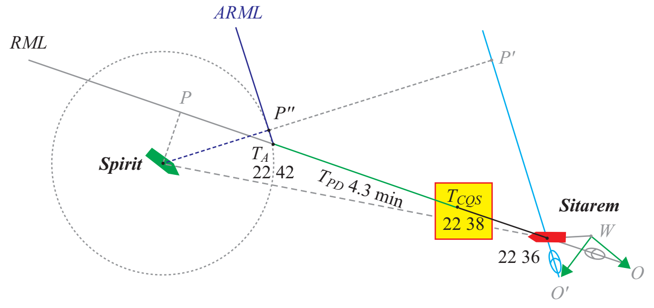
Fig. 9. COLREGS-complaint action and critical time for *Koscierzyna*.

IV. CASE STUDIES

Three real collision cases are discussed to validate the proposed approach. In the case of *the Koscierzyna and Hanjin Singapore* (LLR, 1996), an overtaking situation where the alteration time is determined by Scenario 1 is demonstrated. Second, a crossing situation where the alteration time is determined by Scenario 1 is revealed in the case of *the Spirit and Sitarem* (LLR, 2001). Finally, the case of *the Hyundai Dominion and Sky Hope* (MAIB, 2004) is adopted to demonstrate the critical time for a crossing situation with Scenario 2.

1. The *Koscierzyna* and *Hanjin Singapore*

The collision occurred on Sept. 15, 1991, at 1300 GMT in the open sea where the visibility was clear for at least 4 miles. The *Koscierzyna* was 95 metres in length. She was sailing on a course of 209° (T) and making a speed of 10.5 kts. The *Hanjin Singapore* was 242 metres in length. She was steering a course of 209° (T) and making a speed of 21 kts. The *Koscierzyna* was overtaken by the *Hanjin Singapore*. The analysis is grounded by



	Spirit	Sitarem
Position at 22 36	(0, 0)	(2.9, -0.6)
Course (°)	126°	268°
Speed (kts)	12.0	10.0
LBP (m)	253.0	
Situation	crossing	
Obligation	stand-on	give-way

Preventing a CQS	A/C to starbord is permitted
Physical time delay (min)	4.3
Alteration time (min)	6.4 (s/b)
Critical Time (min)	2.1 (s/b)
Critical Time at ZT	22 38 (s/b)

Fig. 10. COLREGS-complaint action and critical time for *Spirit*.

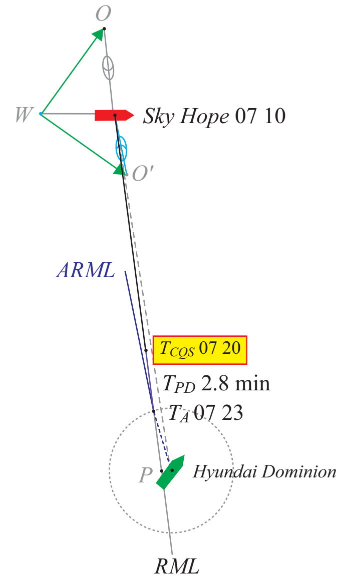
the fact that *Koscierzyna* was at about 5° on the port bow of *Hanjin Singapore* at a distance of about 6 miles at 1225 GMT. Based on this information and from the perspective of the *Koscierzyna*, the COLREGS-complaint actions and the critical time for preventing a CQS can be determined and are shown in Fig. 9.

As a result, a substantial alteration either to starboard or to port of the *Koscierzyna* is permitted. The alteration times are 17.3 and 29.3 minutes for substantial alterations to starboard and port, respectively. Considering her manoeuvrability, the estimation of physical time delay is 1.8 minutes. In this scenario, the critical time for preventing a CQS is 15.5 minutes after 1225 GMT, i.e., 1240 GMT, if a substantial alteration to starboard is made. Otherwise the critical time is 27.4 minutes after 1225 GMT, i.e., 1252 GMT, if a substantial alteration to port is made.

2. The *Spirit* and *Sitarem*

On March 12, 1996 at 2245 zone time (ZT), a collision occurred between the VLCC *Spirit* and the coaster *Sitarem* in open sea with good visibility. The *Spirit* was 253 metres in length. She was the stand-on vessel proceeding on a course of 126° (T) at a speed of 12 kts. The *Sitarem* was 87.81 metres in length. She was the give-way vessel sailing on a course of 268° (T) and making a speed of 10 kts. The available grounds for this determination are that the *Sitarem* was first seen at a distance of about 3 miles, bearing about 25° on the port bow of *Spirit*. It is assumed that the observation was made at 2236 ZT, according to the time of collision and the TCPA. Based on this information, the determination is conducted as shown in Fig. 10.

A substantial alteration to starboard by the *Spirit* is permitted. The alteration time is 6.4 minutes for substantial alterations to starboard. Considering her manoeuvrability, the estimation of physical time delay is 4.3 minutes. Thus, the critical time for preventing a CQS is 2.1 minutes after 2236 ZT, i.e., 2238 ZT, if a substantial alteration to starboard is made.



	Hyundai Dominion	Sky Hope
Position at 07 10	(0, 0)	(-0.8, 4.9)
Course (°)	036°	091°
Speed (kts)	22.0	15.3
LBP (m)	303.8	
Situation	overtaking	
Obligation	stand-on	give-way

Preventing a CQS	A/C to starbord is permitted
Physical time delay (min)	2.8
Alteration time (min)	13.7 (s/b)
Critical Time (min)	10.9 (s/b)
Critical Time at ZT	07 20 (s/b)

Fig. 11. COLREGS-complaint action and critical time for *Hyundai Dominion*.

3. The *Hyundai Dominion* and *Sky Hope*

The collision case happened on June 21, 2004, at 0738 ZT in open sea with good visibility. The *Hyundai Dominion* was 303.83 metres in length. She was the stand-on vessel steering a course of 036° (T) and making a speed of 22 kts.The *Sky Hope* was 120.84 metres in length. She was the give-way vessel sailing on a course of 091° (T) with a speed of 15.3 kts. The two vessels encountered each other in a crossing situation. The available grounds to be taken into account are that the *Sky Hope* was first seen by OOW on board *Hyundai Dominion* on the port bow at 45° and at a distance of 5 nm at about 0710. Based on this information, the determination is conducted as shown in Fig. 11.

A substantial alteration to starboard of the *Hyundai Dominion* is permitted. The alteration time is 13.7 minutes for the substantial alterations to starboard. Considering her manoeuvrability, the estimation of physical time delay is 2.8 minutes. Thus, the critical time for preventing a CQS is 10.9 minutes after 0710 ZT, i.e., 0720 ZT, if a substantial alteration to starboard is made.

V. CONCLUSIONS

This paper has successfully proposed the COLREGS-complaint actions and determined the critical time for preventing a CQS based on the viewpoint of a stand-on vessel. Aimed at to get rid of the ambiguity of the COLREGS, a DGCI is adopted to analyse three collision situations such that the precise COLREGS-complaint actions can be obtained. To take a substantial action in ample time for preventing a CQS, the alteration time is first determined by analytic geometry with relative motion and then is corrected by the physical time delay with consideration of manoeuvrability of the stand-on vessel. Three real cases are conducted as well as analysed to demonstrate that the proposed approach is effective for practical application.

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NOMENCLATURE

S the position of the stand-on vessel
G the position of the give-way vessel
C_S the course of the stand-on vessel
C_G the course of the give-way vessel
C_{RM} the course of the initial relative motion
C_{ARM} the course of the altered relative motion
V_S the speed of the stand-on vessel
V_G the speed of the give-way vessel
V_{RM} the magnitude of the relative motion
L the length of the vessel
x_S the x-coordinate of the stand-on vessel
x_G the x-coordinate of the give-way vessel
y_S the y-coordinate of the stand-on vessel
y_G the y-coordinate of the give-way vessel
Δx the difference between x-coordinate of the points
Δy the difference between y-coordinate of the points
TB_{SG} the bearing of give-way vessel from the view of stand-on vessel
TB_{GS} the bearing of stand-on vessel from the view of give-way vessel
RB_{SG} the relative bearing of give-way vessel from view of stand-on vessel
RB_{GS} the relative bearing of stand-on vessel from view of give-way vessel
ΔR_x the x-component of the initial relative motion
$\Delta R_x'$ the x-component of the altered relative motion
ΔR_y the y-component of the initial relative motion
$\Delta R_y'$ the y-component of the altered relative motion
m_{RML} the slope of the initial relative motion line
m_{ARML} the slope of the altered relative motion line
D_{SG} the distance between the give-way and the stand-on vessels
D_S the safety distance of 0.85 nm
D_{CPA} the initial DCPA
D_{ACPA} the new DCPA results from a substantial alteration of course
T_A the alteration time
T_{PD} the physical time delay
T_{CQS} the critical time for preventing a close-quarters situation
K the centre of turning circle
H_0 the starting point of turning circle manoeuvring
H_{10} the point of course changed by 10°
H_{90} the point of course changed by 90°

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