Risk-Based Ship Collision-Avoidance Maneuvers Accounting for Optimal Bunker Consumption

(TRB 16-4623)

Kang Zhou (Corresponding Author)
Ph.D. Student
Department of Civil and Environmental Engineering
Rutgers, The State University of New Jersey
96 Frelinghuysen Road, Piscataway, NJ 08854-8018
Tel: 732-319-5177; Email: kang.zhou@rutgers.edu

Jihong Chen, Ph.D.
Associate Professor
Shanghai Maritime University
&
Visiting Scholar
Rutgers, The State University of New Jersey
96 Frelinghuysen Road, Piscataway, NJ 08854-8018
Tel: 732-912-9731; Email: jihongchen2015@gmail.com

Xiang Liu, Ph.D.
Assistant Professor
Department of Civil and Environmental Engineering
Rutgers, The State University of New Jersey
96 Frelinghuysen Road, Piscataway, NJ 08854-8018
Tel: 848-445-2868; Email: xiang.liu@rutgers.edu

5,489 Words + 8 Tables and Figures = 7,489 words

November 15, 2015

ABSTRACT

This paper optimizes ship collision-avoidance maneuvers accounting for both accident risk and fuel use. The model determines the optimal timing of turning, the turning angle, the timing of the ease rudder, and the angle of the rudder for course reorientation, while still minimizing fuel use. First, critical factors of ship collision avoidance are identified. Then, an optimization model is developed to minimize fuel consumption while assuring ship operational safety. To address complex ship navigation procedures, an enumeration algorithm is used to determine when to take actions to avoid a collision, how to change course, and what rudder angles are needed. A quantitative navigation simulation is developed to illustrate the model application. The methodology can be further developed to guide practical ship collision-avoidance maneuver decision making. In the era of intelligent navigation, this research can contribute to the development of computer-aided collision-avoidance operations to improve the safety and energy efficiency of maritime transportation.

1 INTRODUCTION

The rise of maritime trade in global commerce and the use of larger ships leads to increasing ship traffic density and correspondingly accident risk, particularly during coastal navigation. The historical accident data show that human error accounts for 80% of ship collisions (*1*). Technological advances and new maritime regulations demand more novel nautical marine instruments to be installed on the bridge to enhance the accuracy of navigational information, which complicates on-duty officers' decisions. The concept of E-Navigation was introduced by the International Maritime Organization (IMO) and the International Association of Lighthouse Authorities (IALA) for intelligent maritime safety operations decision support (*3-4*). According to the IALA's E-Navigation Committee, "E-Navigation is the collection, integration and display of maritime information onboard and ashore by electronic means to enhance berth-to-berth navigation and related services, safety and security at sea and protection of the marine environment." The computer-aided system integrates complex navigation information to reduce human error and improve the safety of marine operations (*2*).

The information needed for effective collision avoidance is obtained by combining the data of electronic equipment such as ARPA (Automatic Radar Plotting Aids), GMDSS (Global Maritime Distress & Safety System), GPS (Global Positioning System) and ECDIS (Electronic Chart Display and Information System). Using ARPA, on-duty officers can acquire the relative bearing of two ships on an intersecting course to estimate the encounter situation. DCPA (Distance to Closest Point of Approaching) and TCPA (Time to Closest Point of Approaching) are two important factors that aid in analyzing the collision risk and necessity of collision avoidance maneuvering. Officers also can obtain the DCPA and TCPA data from ARPA. GPS can provide positions (latitude and longitude), courses, and velocities for relevant objects. ECDIS can display the past trajectories in order to deduce whether either object has adjusted course and/or speed. If either object changes course or speed during an encounter situation, the collision risk can then be reappraised.

The collision-avoidance maneuvering is a real-time decision-making process which contains five procedures:

1) **When to act**. This procedure addresses the required time to the turning point. In other words, decision makers need to judge the relative bearing and distance at which they need to act.
2) **What actions to take**. This step addresses the required rudder angle for the ships in question to pass each other at a safe distance.
3) **What new navigation courses to adopt**. This stage tackles the necessary course change that the give-way ship should take. The extent of the course change determines whether it will leave the safety domain of the target ship.
4) **When to correct heading to restore original course. This stage determines** when the give-way ship passes the closest point to the target ship.
5) **New course that the give-way ship adopts to return to the original route**. The new

course determines the navigational length before returning to the original route.

Different decisions for the five procedures results in different collision-avoidance trajectories as for the give-way ship. These decisions also can affect bunker consumption per nautical mile, which is approximately proportional to the second power of sailing speed (*5*). Therefore, making an optimal real-time decision for each encounter situation can reduce the total operating cost while assuring safety.

2 LITGERATURE REVIEW

There have been many studies on ship navigation (*2, 6-12, 31*). Previous analytical methods include 1) fuzzy neural networks (*13*) that uses fuzzy rules to make inferences about the static and dynamic degrees of danger; 2) fuzzy logic (*14-16*) that describes the operator's recognition rules for collision avoidance; and 3) optimization method (*18-20*) that addresses the complex relationship between navigational safety and operational and environmental factors. However, most previous studies either entirely focused on the shortest distance in the navigation or did not explicitly account for fuel use during the navigation. According to the speed-loss and the change of bunker consumption during ship turning, the shortest route may not represent the most energy-saving route, accounting for speed, sea state, wind and other factors. Table 1 summarizes previous relevant studies.

TABLE 1 A review of previous navigation models

Model	Merit	Limitation
Safety as the only goal (*1*)	Ensure that ships pass each other safely	No consideration of bunker consumption
The shortest route in collision-avoidance maneuvering (*13*)	Avoids the give-way ship deviate too much from the original route	Assume constant speed during turning; No consideration of the bunker consumption
Collision risk degree (*7*)	Analyze the necessity of maneuvering at a certain relative distance	Does not account for optimal maneuvers during the whole collision-avoidance process
Turning to a required angle for collision avoidance (*2,6*)	Accounts for the realistic response of the rudder to the order	Complicated and not easy to simulate and implement
Turning with constant speed model (*12,14*)	Simplifying model, easy to simulate	Due to the speed-loss effect during turning, the speed will decrease and the bunker consumption will be influenced accordingly
Optimum steering for maneuvering (*30)*	Considering environmental factors	Not focused on collision risk

3 RESEARCH OBJECTIVES AND SCOPE

The International Collision Regulations (COLREGS) proposed quantitative interpretations of widely adopted concepts such as "safe passing distance," "early" action, etc. (*21*). In addition, fuel use is a principal cost component in maritime transportation. The primary goal of this research is to develop an optimization framework for collision-avoidance maneuvers to minimize energy use, while maintaining a satisfactory safety level.

The remainder of this paper is organized as follows. Section 4 introduces general encounter situations. Section 5 determines the range of collision-avoidance timing and actions. Section 6 models bunker consumption as a function of speed, accounting for the loss of ship speed at sea. Section 7 develops a risk-based bunker consumption optimization model. Section 8 illustrates the application of the methodology through a simulation study. Section 9 presents findings, conclusions and possible future research directions.

4 INTELLIGENT SHIP COLLISION AVOIDANCE

This paper uses terminology in accordance with the literature and practice. The vessel with the responsibility for collision-avoidance maneuvers is called "own ship," and the ship that needs to be avoided as the "target ship." COLREGS specifies three encounter situations (*1*, *7*):

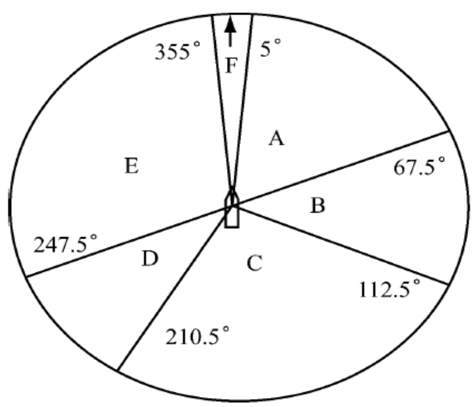

Figure 1 Encounter bearing distribution

Scenario 1 (head-on collision): target ship approaching from Region E

In a head-on situation, the own ship and the target ship are approaching each other on reciprocal or near-reciprocal courses. Both ships should alter their courses to starboard in order to pass each other port-to-port.

Scenario 2 (overtaking): target ship approaching from Region C

A ship shall be deemed to be overtaken when another ship is approaching from a direction more than 22.5 degrees abaft her beam. If the overtaking ship is on the starboard quarter of the overtaken ship, she should alter her course to starboard. If the overtaking ship is on the port quarter of the overtaken ship, it should alter its course to port. The overtaken ship should keep its course and speed.

Scenario 3 (Crossing): target ship approaching from Region A, B, D
Two ships are crossing each other's intended courses. The COLREGS requires a ship to yield to the other ship on the starboard side and avoid crossing in front of the other ship. The ship that does not need to take collision-avoidance action should maintain its course and speed.

Depending on the encounter situation, the rights and responsibilities of the two ships differ. For illustrative convenience, this paper considers the encounter situations in which only one ship is responsible for collision avoidance. Due to content limit, this paper focuses on crossing situation. Future research can account for other types of scenarios. In the maritime field, the ship taking action to avoid collision is called the "give-way" ship and the ship maintaining course and speed is called the "stand-on" ship.

As for collision-avoidance maneuvers, course change is the primary consideration for the avoidance of collisions. Only when the environment does not allow a course change should the ship's speed be changed. Fagerholt et al. (*28*) concluded that reducing or increasing speed is not very effective for collision avoidance because of the momentum of a power-driven ship. Hence, this paper focuses on course alteration as the crucial collision-avoidance maneuver.

5 COLLISION RISK MODEL

Whether a ship shall take collision-avoidance maneuvers depends on the collision risk in an encounter situation. Some collision risk evaluation methods have been proposed by existing studies based on traffic flow theory or fuzzy synthetic assessment. The collision risk should depend on many factors, such as ship type, size, speed and so on. Ship domains play a very important role in collision risk evaluation and optimal trajectory planning. Goodwin defines ship domain as that area which "most of the navigators wish to keep free with respect to ships and other stationary objects" (*22*). Expanding on the concept, some researchers have also presented various ship domains with different shapes and sizes taking into account different factors affecting the domain parameters such as the maneuvering capability, dimensions, courses and speeds of the encountered ships (*25-26*). In order to satisfy practical applications, a fuzzy quaternion ship domain (FQSD) with fuzzy boundaries has been developed by Wang (2010b) using fuzzy sets. In ordinary set theory, elements either belong or do not belong to a particular set. For example, an approaching vessel is regarded either as a threat or as completely safe, without any intermediate degree of safety or threat. Fuzziness is introduced by generalizing the membership function so that it can assume any value in the closed interval [0, 1]. This paper will adopt the FQSD model to acquire the minimum DCPA based on collision risk. Table 2 presents the mathematical notations used in our following analyses.

TABLE 2 Mathematical notations

Notation	Definition	Notation	Definition
$R_{fore}(r)$ $R_{aft}(r)$ $R_{starb}(r)$ $R_{port}(r)$	safe radius for the ship's fore, aft, starboard and port side in terms of collision risk index r	DCPA	distance between two encountered ships to the closest point of approaching
Br	Relative bearing between own ship and target ship	TCPA	time to the closest point of approaching
R_t	turning radius	(x_0, y_o)	initial coordinates of own ship
D_r^0	relative distance when action	(x_t, y_t)	initial coordinates of target ship
v_o	own ship speed	(x_o^i, y_o^i)	coordinate of own ship in the end of step i
v_t	target ship speed	(x_t^i, y_t^i)	coordinate of target ship in the end of step i
C_O	own ship course	t_0	time period between initial and action
C_t	target ship course	φ_t	course change in turning
D_r	relative distance	δ_t	rudder angle in turning
l_{oi}	navigating range in step i	t_2	time period for navigating linearly in step 2
φ_r	course change for reorientation	δ_r	ruder change for reorientation

The FQSD model boundary can be formulated as follows:

$$FQSD(r) = \{(x,y) | f(x,y;Q(r)) \leq 1,\} \tag{1}$$

Where

$$f(x,y;Q(r)) = \left(\frac{2x}{(1+sgnx)R_{starb}(r)-(1-sgnx)R_{port}(r)}\right)^2 + \left(\frac{2y}{(1+sgny)R_{fore}(r)-(1-sgny)R_{aft}(r)}\right)^2 \tag{2}$$

$$Q = \{R_{fore}(r), R_{aft}(r), R_{starb}(r), R_{port}(r)\} \tag{3}$$

$$sgnx = \begin{cases} -1, \wedge\ x < 0 \\ 1, \wedge\ x \geq 0 \end{cases} \quad R_i(r) = \left(\frac{ln\frac{1}{r}}{ln\frac{1}{r_0}}\right)^{\frac{1}{2}} R_i, i \in \{fore, aft, starb, port\} \tag{4}$$

$$\begin{cases} R_{fore} = \left(1 + 1.34\sqrt{k_{AD}^2 + (k_{DT}/2)^2}\right)L \\ R_{aft} = \left(1 + 0.67\sqrt{k_{AD}^2 + (k_{DT}/2)^2}\right)L \\ R_{starb} = (0.2 + k_{DT})L \\ R_{port} = (0.2 + 0.75k_{DT})L \end{cases} \tag{5}$$

$$\begin{cases} k_{AD} = A_D/L = 10^{0.3591 logV_{own}+0.0952} \\ k_{DT} = D_T/L = 10^{0.5441 logV_{own}-0.0795} \end{cases} \tag{6}$$

Where parameter $r \in (0,1)$ represents the collision risk of the corresponding fuzzy boundary of the FQSD with the larger r, the smaller necessity of taking actions. Usually we set $r_0 = 0.5$. V_{own} is the own ship speed represented in knots, and L is the own ship length. In view of the FQSD model, we can observe that $FQSD(r) < 1$ means encountered ships are located in the relevant ship domain, and vice versa. We set r =0.5 and $FQSD(r) = 1$ if the two ships pass each other at the minimum DCPA. In this situation, $FQSD(r) > 1$ indicates that they pass each other at a distance larger than the minimum DCPA (*26*).

With respect to maneuvering timing, existing studies seldom model the point at which the give-way ship needs to initiate the collision-avoidance maneuvers or the final point at which collision can still be avoided. Zheng (*29*) proposed a collision risk membership function of objective distance for collision risk evaluation based on fuzzy logics. The membership function can be formulated as follows:

$$u(d_{rot}) = \begin{cases} 1 & d_{rot} \leq d_{risk} \\ (d_{safe} - d_{rot})/(d_{safe} - d_{risk}) & d_{risk} < d_{rot} \leq d_{safe} \\ 0 & d_{rot} > d_{safe} \end{cases} \quad (7)$$

Where $u(d_{rot}) \in (0,1)$ defines the collision risk degree. $u(d_{rot}) = 1$ means that the two encountered ships cannot avoid the collision . $u(d_{rot}) = 0$ denotes that it is not necessary for the give-way ship to take action. The relative distance between the two encountered ships is denoted by d_{rot}.

$$d_{risk} = C_{la} \cdot d_a(L_w, v_r) \cdot [1 + 0.2(sinT_b)] \cdot [1 + K_{la}(cosT_{sb})^6] \quad (8)$$
$$d_{safe} = C_{ma} \cdot d_a(L_k, v_s) \cdot [1 + K_{ma}(cosT_{sb})^6] \quad (9)$$

Where d_{risk} and d_{safe} are obtained from the regression of the observational data. C_{la} and C_{ma} are the safety distance coefficient of starboard and port side respectively.

$$d_a(L_w, v_r) = exp[0.892ln(L_0 + L_t) + 0.631lnv_r - 0.0367] \quad (10)$$
$$d_a(L_k, v_r) = exp\left[0.892ln\sqrt{({L_0}^2 + {L_t}^2)/2} + 0.631lnv_r - 0.0367\right] \quad (11)$$
$$T_{sb} = T_s - T_b \quad (12)$$

Where L_0, L_t, v_s denote the own ship length, , the target ship length and the relative speed respectively. K_{la} and K_{ma} are coefficients with respect to C_{la} and C_{ma}. T_b and T_s represent the relative bearing and course of the target ship respectively.

Based on the collision risk membership of the relative distance between the two encountered ships we obtain a range (d_{risk}, d_{safe}) where the give-way ship should take action to avoid a potential collision.

6 BUNKER CONSUMPTION BY SPEED

Bunker consumption has a complex relationship with environmental elements (e.g., water flow and wind) and other external navigation parameters (trim, draft, displacement). As this research focuses on understanding the impact of navigation factors, we did not explicitly account for all possible environmental scenarios. Instead, we will use representative environmental conditions in our simulation-based quantitative study. Based on the literature, we assume that the daily bunker consumption Q (tons/day) and sailing speed v (knot) has the power relationship:

$$Q = a \times v^b \tag{13}$$

Where
a and b are coefficients to be calibrated from the observational data.

We assume that the daily bunker consumption is related to the power of sailing speed, based on the literature *(19)*:

$$Q = a \times v^3 \tag{14}$$

We denote by $g_i(v_i)$ the bunker consumption per nautical mile the speed v_i.

$$g_i(v_i) = \frac{av_i^2}{24} \tag{15}$$

When the ship needs to change course to avoid collision, it may not keep a fixed speed during ship turning. The ship will experience a speed-loss effect during a fixed throttle turn with no bunker consumption saving. Li (*27*) has proposed a mathematical model of speed-loss effect. We will introduce K and T as the ship maneuverability indices. K denotes the turning index and a larger K means a better turning ability. T represents the adherence index and a smaller one means a better initial turning ability.

K and T can be calculated as follows:

$$K' = \frac{L}{V}K \tag{16}$$

$$T' = \frac{V}{L}T \tag{17}$$

Above, L denotes the ship length and V denotes the ship speed.
With reference to Li (*27*), we can get

$$K' = 1.715 + 0.964\frac{L}{B} - 0.158\frac{Ld}{A_R} - 1.702C_b\frac{L}{B} + 0.262C_b\frac{Ld}{A_R} \tag{18}$$

$$T' = 4.664 + 0.716\frac{L}{B} - 14.491C_b - 0.033\frac{L}{B}\cdot\frac{Ld}{A_R} + 0.396C_b\frac{Ld}{A_R} \tag{19}$$

The ratio of the original speed V to the speed with loss is formulated as

$$\frac{V}{V_{loss}} = -8.697 + 6.361K' + 7.960C_N - 5.295K' \cdot C_N - 0.226C_N \cdot \frac{\varphi}{57.3} + 0.067(K')^2 + 0.028\left(\frac{\varphi}{57.3}\right)^2 \quad (20)$$

Based on the Joessel Equation (*30*), we obtain

$$C_N = \frac{0.311 sin\delta}{0.195+0.305 sin\delta} \quad (21)$$

Where δ is the rudder angle and φ denotes the course change.

So during ship turning, the bunker consumption per nautical mile can be formulated as follows:

$$g_{loss}(v_{loss}) = \frac{Q}{24 \cdot v_i} \times \frac{v_i}{v_{loss}} = \frac{a \cdot v_i^3}{24 \cdot v_{loss}} \quad (22)$$

7 MODELING COLLISION AVOIDANCE MANEUVERING

The ship collision-avoidance maneuvering process can be modeled in four steps. The trajectory draft is described in figure 2.

1) Ship turning for collision avoidance;
2) Ship navigating linearly on a new course;
3) Ship turning for reorientation;
4) Ship navigating directly to the original route.

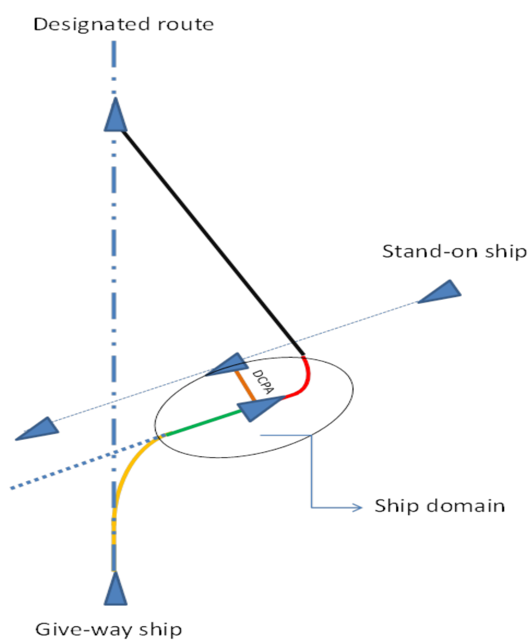

FIGURE 2 Collision-avoidance trajectories of two encountered ships

The research firstly establishes two x, y-coordinate systems: the Earth Reference Coordinate system (ERC) and the Own Ship Reference Coordinate system (ORC). The y-axis of the ERC indicates the direction of the initial speed v_o and the x-axis is perpendicular to it and positive to starboard. The ORC system is relative to the own ship with the gravity of the own ship as the origin, the y-axis in the direction of v_o and the x-axis perpendicular to it and positive to starboard. The initial coordinates of the own ship and the target ship in ERC are (x_o,y_o) and (x_t,y_t) respectively. The relative coordinates of the target ship are (x_r,y_r). The following sub-sections model each of the above-mentioned steps. For convenience, the own ship and target ship are denoted by OS and TS respectively.

Step 1: turning for collision avoidance

After a period time of t_0, the OS initiates the collision avoidance maneuvers. At this moment, the coordinates of the OS and TS with respect to the ERC system are (x_o^0,y_o^0) and (x_t^0,y_t^0). The relative distance between the two encountered ships reaches D_r^0 when the OS begins to take actions to change the speed course with a rudder angle $\delta_t \in \left(10^\circ, 30^\circ\right)$ according to the COLREGS. We denote by C_o^0 and C_t^0 the present speed courses of the own ship and the target ship, respectively.

$$x_o^0 = x_0 \quad (23)$$

$$y_o^0 = y_o + v_o t_0 \quad (24)$$

$$x_t^0 = x_t + v_t sin(C_t^0 - C_o^0) t_0 \quad (25)$$

$$y_t^0 = y_t + v_t cos(C_t^0 - C_o^0) t_0 \quad (26)$$

$$D_r^0 = \sqrt{(x_t^0 - x_o^0)^2 + (y_t^0 - y_o^0)^2} \quad (27)$$

After time t_1 , the own ship reaches the required turning angle φ_t. The present coordinates of the own ship are (x_o^1,y_o^1), and the present coordinate of the target ship is (x_t^1,y_t^1). The relative distance between them is D_r^1. The new speed course of the own ship is denoted by C_o^1. Due to the speed-loss effect during ship turning, the speed of the own ship is decreasing according to a special principle to the velocity v_o^{loss1} until turning ends. To simplify the model, we will assume that during the turning, the own ship maintains the constant speed v_o^{loss1}.

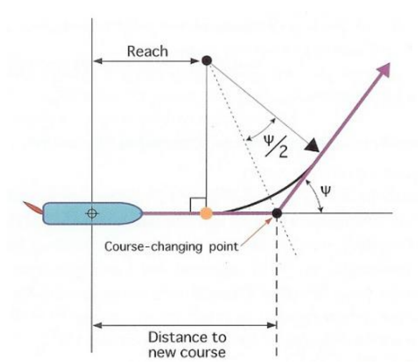

FIGURE 3 Schematic figure for ship turning

$$C_o^1 = C_o^0 + \varphi_t \tag{28}$$

The ship will be navigating in compliance with a circle with a special diameter D_t

$$D_t = \frac{2v_o^{loss1}}{K\delta_t} \tag{29}$$

The own ship navigates until reaching required angle l_{o1},

$$l_{o1} = v_o^{loss1}T + \frac{\varphi_t v_o^{loss1}}{K\delta_t} \tag{30}$$

$$t_1 = \frac{l_{o1}}{v_o^{loss1}} = T + \frac{\varphi_t}{K\delta_t} \tag{31}$$

$$x_o^1 = x_o^0 + (R_t - R_t cos\varphi_t) = x_o^0 + \frac{v_o^{loss1}}{K\delta_t}(1 - cos\varphi_t) \tag{32}$$

$$y_o^1 = y_o^0 + (v_o^{loss1}T + R_t sin\varphi_t) = y_o^0 + v_o^{loss1}T + \frac{v_o^{loss1} sin\varphi_t}{K\delta_t} \tag{33}$$

The turning angle $\varphi_t$is constrained by the minimum safe passing distance$DCPA_{min}$.

$$DCPA \geq DCPA_{min} \tag{34}$$
$$x_t^1 = x_t^0 + v_t t_1 sin(C_t - C_o) \tag{35}$$
$$y_t^1 = y_t^0 + v_t t_1 cos(C_t - C_o) \tag{36}$$

The relative coordinates of the TS position with respect to OS at the final situation is (x_r^1, y_r^1)

$$x_r^1 = (x_t^1 - x_o^1)cos\varphi_t - (y_t^1 - y_o^1)sin\varphi_t \tag{37}$$
$$y_r^1 = (x_t^1 - x_o^1)sin\varphi_t + (y_t^1 - y_o^1)cos\varphi_t \tag{38}$$

Step 2: Navigating linearly on a new course

The speed-loss effect due to resistance during turning will cease once the turning terminates. Engine power will restore the original speed prior to turning in a short time. We assume that the own ship is restored to v_o once the rudder angle is reset. To avoid collision, the own ship needs to navigate on the new course for a period of time to reach the closest point to the target ship on the course. The time to approach the closest point to the target ship is denoted by $TCPA$. When the own ship reaches the closest point, the coordinates of the own ship are $(x_o^{'}, y_o^{'})$, and the coordinates of the target ship are $(x_t^{'}, y_t^{'})$. The relative coordinates of the TS position with respect to the ORC system are $(x_r^{'}, y_r^{'})$. The own ship is navigating linearly during a period of

t_2, The own ship navigates until reorientation reaches angle l_{o2}. The coordinates of OS position with respect to the ERC system are (x_o^2, y_o^2)

$$t_2 \geq TCPA \tag{39}$$
$$l_{o2} = v_o t_2 \tag{40}$$
$$x_o^2 = x_o^1 + v_o sin\varphi_t t_2 \tag{41}$$
$$y_o^2 = y_o^1 + v_o cos\varphi_t t_2 \tag{42}$$

The relative speed of TS and OS with respect to the OS coordinate system is v_r^2. The relative heading of TS to the ORC system is $\theta_{r,2}^h$.

$$\theta_{r,2}^h = C_t - C_o - \varphi_t \tag{43}$$
$$v_{r,x}^2 = v_t sin\left(\theta_{r,2}^h\right) \tag{44}$$
$$v_{r,y}^2 = v_t cos\left(\theta_{r,2}^h\right) - v_o \tag{45}$$
$$TCPA = \frac{-\left(x_r^1 v_{r,x}^2 + y_r^1 v_{r,y}^2\right)}{\left(v_{r,x}^2\right)^2 + \left(v_{r,y}^2\right)^2} \tag{46}$$
$$x_r' = x_r^1 + v_{r,x}^2 TCPA \tag{47}$$
$$y_r' = y_r^1 + v_{r,y}^2 TCPA \tag{48}$$

The required collision-avoidance maneuvers should guarantee that the relative position of TS with respect to the ORC system should be outside the OS domain, which can be formulated as

$$f(x_r', y_r'; Q) \geq 1 \tag{49}$$

Based on practical experience and maneuvering simulation, we can determine that the optimal beginning of reorientation with consideration to bunker consumption is the moment when the two encountered ships reach the closest point of approaching. So we can define

$$t_2 = TCPA \tag{50}$$

Step 3: Turning for reorientation

The moment when the OS passes the closest point to the TS indicates the termination of the collision avoidance. So the OS can initiate reorientation operations to return to the original route. We denote the rudder angle of reorientation by $\delta_r \in (-30°, -10°)$. When the turning angle reaches φ_r, the ship can stop turning. The own ship also suffers from speed-loss effect and turns with a speed of v_o^{loss2}. The coordinates of the OS with respect to the ERC system are (x_o^3, y_o^3).

$$D_r = \frac{-2v_o^{loss2}}{K\delta_r} \tag{51}$$

$$l_{o3} = v_o^{loss2} T + \frac{\varphi_r v_o^{loss2}}{K\delta_r} \tag{52}$$

$$x_o^3 = \left(\frac{v_o^{loss2}}{K(-\delta_r)}(cos\varphi_r - 1) + x_o^2\right) cos(-\varphi_t) - \left(\left(v_o^{loss2} T + \frac{v_o^{loss2} sin(-\varphi_r)}{K(-\delta_r)}\right) + y_o^2\right) sin(-\varphi_t) \tag{53}$$

$$y_o^3 = \left(\left(v_o^{loss2}T + \frac{v_o^{loss2}\sin(-\varphi_r)}{K(-\delta_r)}\right) + y_o^2\right)\cos(-\varphi_t) + \left(\frac{v_o^{loss2}}{K(-\delta_r)}(\cos\varphi_r - 1) + x_o^2\right)\sin(-\varphi_t) \qquad (54)$$

Step 4: Returning to the original route

The OS navigates linearly on the new course to the original route with a speed of v_o, and when the OS returns to the initial route, the coordinates of the OS with respect to the ERC system are (x_o^4, y_o^4). The relative heading of the OS with respect to the ERC system is C_o^r.

$$C_o^r = \varphi_t + \varphi_r \qquad (55)$$
$$x_o^4 = x_o^0 \qquad (56)$$
$$y_o^4 = y_o^3 + (x_o^0 - x_o^3)cot \qquad (57)$$
$$l_{o4} = (x_o^0 - x_o^3)csc(\varphi_t + \varphi_r) \qquad (58)$$

This paper uses intelligent navigation as the framework, proposing a collision-avoidance decision making process incorporating navigational practice. Because COLREGS is the general regulation for collision avoidance, all the decisions the model makes should comply with it. The process of collision-avoidance decision making is shown in Figure 4.

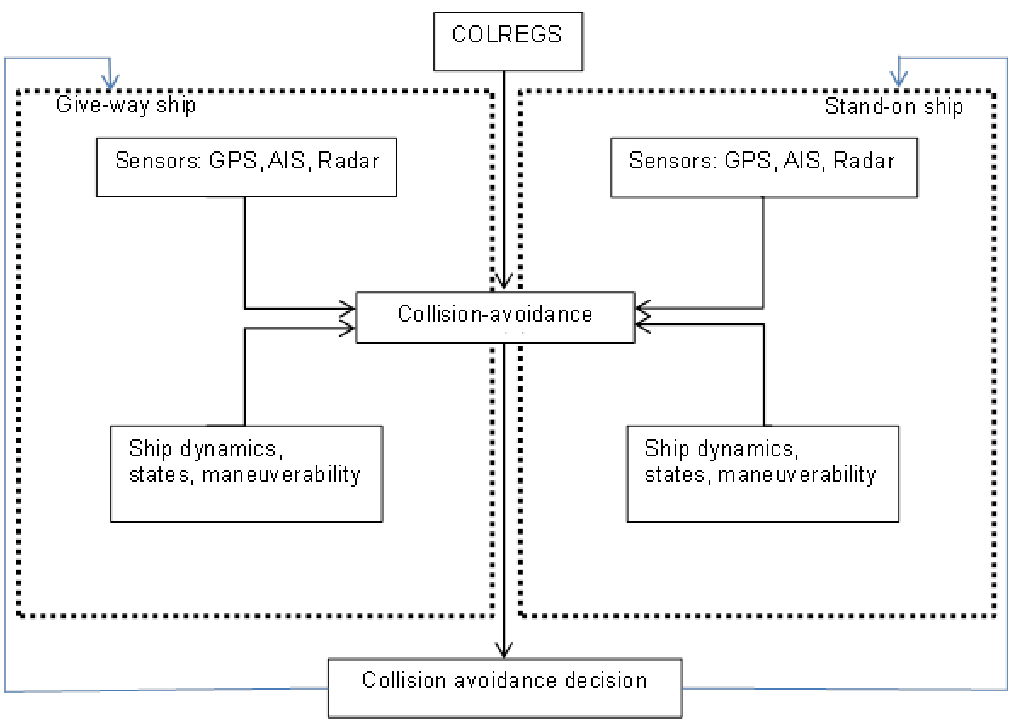

FIGURE 4 Collision-avoidance decision-making framework

8 Collision Avoidance Maneuver Optimization

The maneuvering optimization of ship collision avoidance problem can be stated as follows: Given a crossing situation with the own ship as the give-way ship and the target ship as the stand-on ship. The own ship speed is v_o, with a course of C_o. The target ship speed is v_t, with a course of C_t, the initial coordinates of own ship and target ship with respect to the ERC system are (x_o,y_o) and (x_t,y_t) respectively. With these information, we can determine optimal decision-making steps for each phase during collision avoidance in order to fulfill the navigational demand for safety while simultaneously minimizing bunker consumption.

The following assumptions were made in the model based on the literature and navigational practice:

- The rudder can turn to the required angle in a very short time.
- The tactical diameter equals the final diameter, which is the ship steady turning diameter.
- The ship returns to the original route after the collision avoidance procedure.
- No consideration need be made regarding collision avoidance maneuvers made by other ships when the own ship takes collision avoidance action.
- No consideration need be made of the effect of VHF (Very High Frequency) communication on the two ships' collision avoidance actions.

In the E-Navigation and intelligent collision-avoidance environment, the operation framework of collision-avoidance decision making is described Figure 5.

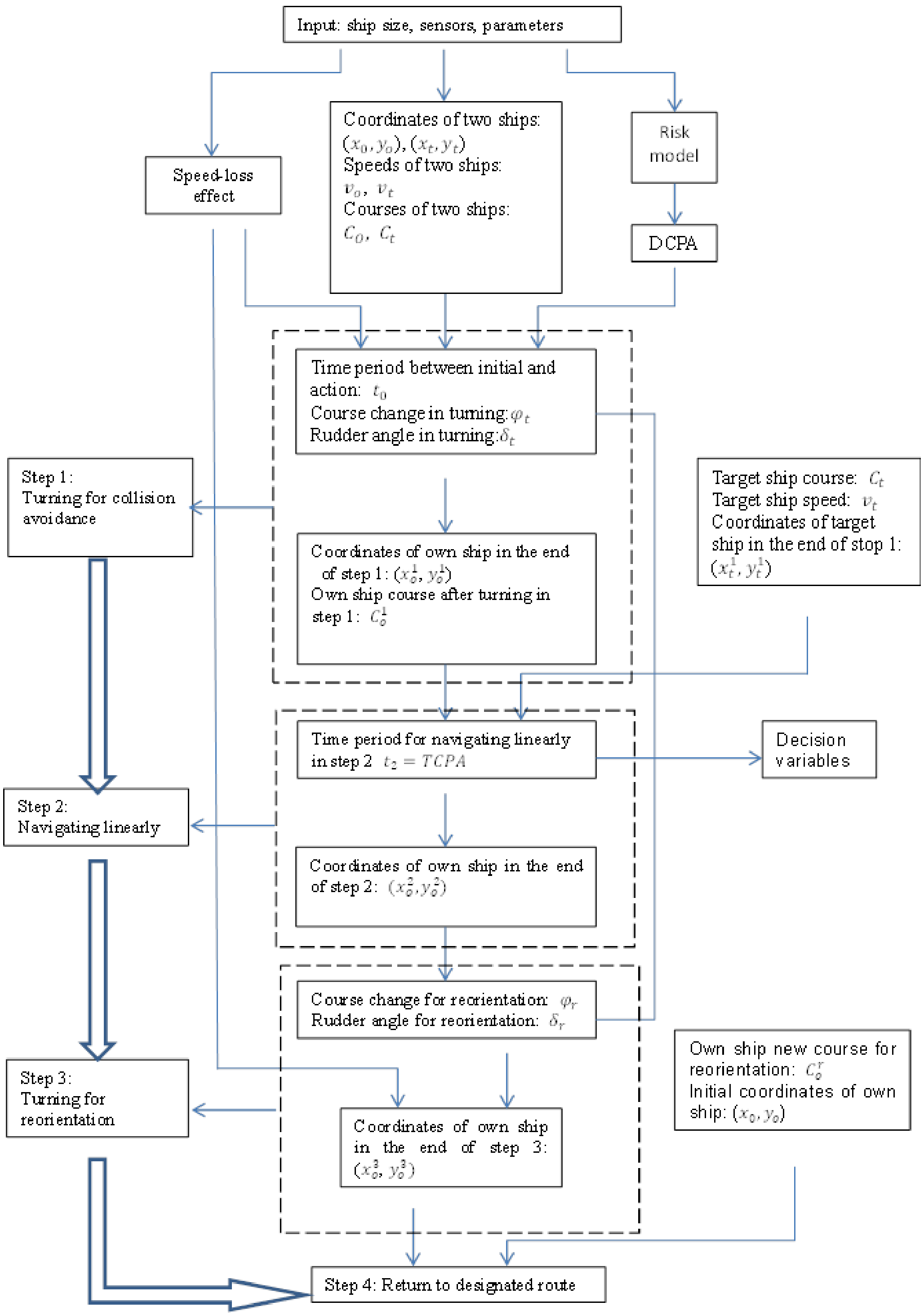

FIGURE 5 Intelligent navigation and collision avoidance analytical framework

The maneuvering optimization problem can be formulated as a mixed-integer nonlinear programming model:

$$\min \ Q_{min} = \sum_{i \in I_p} l_i g_i(v_i) - (y_o^4 - y_o^0) g_0(v_0) \tag{59}$$

$$I_p = \{o1, o2, o3, o4\} \tag{60}$$

Subject to

$$d_{risk} \leq D_r^0 \leq d_{safe} \tag{61}$$

$$f(x_r', y_r'; Q) \geq 1 \tag{62}$$

$$t_i \geq 0 i \in \{0,1,2,3,4\} \tag{63}$$

$$t_2 = TCPA \tag{64}$$

$$0 < \varphi_t \leq 90° \tag{65}$$

$$-180° \leq \varphi_r < 0 \tag{66}$$

$$10° \leq \delta_t \leq 30° \tag{67}$$

$$-30° \leq \delta_r \leq -10° \tag{68}$$

$$t_i, \varphi_t, \ \varphi_r, \ \delta_t, \ \delta_r \in Z \tag{69}$$

The objective function (59) minimizes the increased bunker consumption due to collision avoidance. The first term is the bunker consumption during the collision-avoidance process. The second term is the bunker consumption if no collision avoidance maneuvering exists. Constraint (61) defines the lower and upper bounds of the relative distance between the two encountered ships where the own ship should take actions. Constraint (62) ensures a safe passing distance at which the target ship is located outside the own ship's domain. Constraint (63) defines t_i as a non-negative variable. Constraint (64) enforces the time of the own ship's reorientation. Constraints (65) and (66) impose the ranges of two course changes. We define the change of course to starboard as positive and the change of course to port as negative. Constraints (67) and (68) define rudder angles for collision avoidance based on practical experience. The applied rudder angle during maneuvers should comply with the proposed COLREGS requirement that a collision-avoidance maneuver should be a 'large action.' Constraint (69) specifies the variable $t_i, \varphi_t, \ \varphi_r, \ \delta_t, \ \delta_r$ as an integer. The unit of $t_i$is measured in seconds.

Theoretically, these variables can be defined as continuous variables. However, according to navigational practice, the time period of collision-avoidance maneuvering can only realistically be controlled in terms of seconds. Meanwhile, course changes and rudder angles usually vary from one integer to another. Taking these practical factors into account, we treat certain decision variables as integers. The methodology can be adapted in the future, when a different data type is used.

9 NUMERICAL EXAMPLES

Due to the nonlinearity of constraints on the decision variables with trigonometric functions, as well as the interactive effects imposed on decision variables, an enumeration method implemented on a VB.NET platform is applied to obtain the optimal solutions. An enumeration is a complete, ordered listing of all the items in a set. If the set is finite, enumeration method will search the precise optimal solution satisfying the objectives while conforming to the specified constraints.

9.1 Data Source

The initial step to enumerate this ship maneuvering model for collision avoidance is to gather requisite data for encounter scenarios, including ship particulars and motion parameters. Due to the specificity of the collision avoidance situation in real navigational experiences, it is unrealistic to obtain suitable real-life scenario data. This paper uses the simulation data from maritime simulators at the Dalian Maritime University, China. In future, with the implementation of data sensors on the bridge, the required data in the scenarios can be obtained from real recorded data. The dimensions of the own ship can be cited directly from the particular ship's documents. The target ship's particulars can be gathered from ARPA (Automatic Radar Plotting Aids) or AIS (Automatic Identification System). Using a positioning system (GPS), we can get the coordinates and the motion parameters of the own ship. AIS data includes the motion parameters of the target ship. This is the general approach to obtain the required data and has been adopted by many existing studies for maritime transportation simulations. It is noted that AIS data might be subject to uncertainty under certain circumstances. In the age of E-Navigation, more electronic devices can be used to provide better information regarding maritime transportation. Our methodology shall be adapted to reflect additional information. This paper fixes the course of the own ship at 000, and adjusts the target ship's course. The domain of the own ship is not affected by the target ship's dimensions. The own ship's parameters are listed below:

- L(ship length) = 316.12(meter)
- B(ship width) = 60.0 (meter)
- D (ship draft)= 21.8 (meter)
- C_b (cube coefficient)= 0.8093
- $A_R(\text{Area of Rudder}) = 150.22(\text{square meter})$

In the numerical example, we consider the ship parameters for a typical VLCC (Very Large Crude Carriers). In addition, this paper focuses on collision avoidance at open sea. Future research can account for additional scenarios and ship operating characteristics.

9.2 Optimal Maneuver Strategies

Based on Zheng (2002)'s collision risk membership function of objective distance (*29*), we can calculate the range (d_{risk}, d_{safe}) where the own ship should take collision-avoidance maneuvers. To solve the optimization model, we transformed the distance range to the time range at which the own ship begins to act, measured in minutes. We analyzed the results of optimal maneuver strategies under different ship encounter scenarios (Table 3).

Table 3 Scenarios and results

Scenario	Input (scenario variable)					Output (Decision Variable)						
	v_o	v_t	C_t	D_r	B_r	t_0	D_r^0	φ_t	δ_t	t_2	φ_r	δ_r
1	15	14	240	10	030	535	6.2	14°	27°	720	15°	30°
2	15	14	240	8	030	300	6.0	8°	10°	718	9°	30°
3	20	18	240	15	030	840	7.5	12°	30°	729	13°	30°
4	20	15	270	10	030	710	5.1	1°	30°	390	2°	30°
5	15	17	330	10	090	2276	4.7	28°	10°	842	29°	30°
6	10	18	300	10	090	1140	5.2	39°	10°	641	40°	30°
7	15	12	330	10	060	3360	3.2	1°	30°	974	2°	30°

Note：As defined in Table 2, v_o*: own ship speed;* v_t*: target ship speed;* C_t *target ship course;* D_r*: initial relative distance;* B_r*: initial relative bearing;* t_0*: time period before action;* D_r^0*: relative distance when action;* t_2*: time period for navigating linearly in step 2;* φ_t*:course change in turning;* δ_t*: rudder angle in turning;* φ_r*: course change for reorientation;* δ_r*: rudder change for orientation.*

9.3 Observations from Simulation Analysis

Through the comparison of the simulation results from various encounter scenarios, we observed the following:

(1) The give-way ship should make as small a course change as possible for reorientation to the designated route in order to minimize the bunker consumption during collision avoidance. This finding conforms to traditional navigational practice.

(2) In terms of δ_r, all scenarios recommend a maximal rudder angle. It indicates that reaching the required course change as soon as possible through larger rudder angles can reduce bunker consumption.

(3) Through a comparison of the result of scenario 1 with scenario 3 with reference to the risk model, the two encountered ships with the same bearing and courses should need a larger D_r^0 (the relative distance when action is initiated) if their respective speeds are larger.

(4) The results of scenarios 6 and 7 reveal that the factor determining D_r^0 is not the absolute speed of the two ships, but rather their relative speed.

10 CONCLUSIONS

This paper develops an optimization framework to determine the optimal collision-avoidance maneuvers, while minimizing fuel use. The research investigates the optimal maneuvering strategies during each phase of collision avoidance. In the collision-avoidance decision model, the paper takes into account the speed-loss effect during the navigation. The model can ultimately be used to support the development of a computer-aided collision avoidance system in the age of intelligent navigation, to further improve the safety and efficiency of maritime transportation.

ACKNOWLEDGEMENT

The first author was funded by the Department of Civil and Environmental Engineering (CEE) through a research fellowship at Rutgers University. The second author was supported by the National Natural Science Foundation of China (Grant No. 51409157) and the Young Scholar Program of Humanities and Social Science of the Ministry of Education of China (14YJC630008). The third author was partially funded by the Department of Civil and Environmental Engineering and the School of Engineering, both at Rutgers University. However, the authors are solely responsible for all the views and analyses in this paper.

REFERENCES CITED

1. Tsou M.C., and C.K. Hsueh. The study of ship collision avoidance route planning by ant colony algorithm. Journal of Marine Science and Technology, Vol. 18, No.5, 2010, pp. 746-756.
2. Kwik K.H. Calculation of ship collision avoidance maneuvers: a simplified approach. Ocean Engineering, Vol. 16, No 5/6, 1989, pp. 475-491.
3. IMO. Development of an e-navigation strategy. Report of the correspondence group on e-navigation, NAV/53/13, 2007.
4. Perera L.P., V. Ferrari, F.P. Santos, M.A. Hinostroza, and C.G. Soares. Experimental evaluations on ship autonomous navigation and collision avoidance by intelligent guidance. Journal of oceanic engineering, Vol. 40, No. 2, 2015, pp. 374-387.
5. Ronen, D. The effect of oil price on the optima sped of ships. Journal of the Operational Research Society 33, 1982, pp. 1025-1040.
6. Sato Y., and H. Ishii. Study of a collision-avoidance system for ships. Control Engineering Practice 6, 1998, pp. 1141-1149.
7. Su C.M., K.Y. Chang, and C.Y. Cheng. Fuzzy decision on optimal collision avoidance measures for ships in vessel traffic service. Journal of Marine Science and Technology, Vol.20, No.1, 2012, pp. 38-48.
8. Kao S.L., C. Y. Cheng, and K. Y. Chang. A new method of collision avoidance for vessel traffic service. 2007 International Conference Maritime Technology.
9. Vincent T.L., E.M. Cliff, W.J. Grantham, and W.Y. Peng. A problem of collision avoidance. EES series Report No.39, University of Arizon, Tucson, U.S.A, 1972.
10. Merz A.W. Optimal evasive manoeuvres in maritime collision avoidance. Navigation, Washington DC 20, 1973, pp. 144-152.
11. Miloh T., and S.D. Sharma. Maritime collision avoidance as a differential game. 4th Ship Control Systems Symposium, The Hague, The Netherlands, 1975, pp. 27-31.
12. Wang Y., A.K. Debnath, and H.C. Chin. Modeling collision avoidance decisions in navigation. In Proceeding of 10th Asian Conference on Marine Simulation and Simulator Research, Taiwan, 2010.
13. Hiraga I., T. Furuhashi, Y. Uchikawa, and S. Nakayama. An acquisition of operator’s rules for collision avoidance using fuzzy neural networks. IEEE Transactions of Fuzzy systems, Vol.3, No.3, 1995, pp. 280-287.

14. Hammer A., and K. Hara. Knowledge acquisition for collision avoidance maneuver by ship handling simulator. Proc. MARSIM 4-ICSM'90 245-252, 1990.
15. Shimada K., S. Mabuchi, and K. Hara. Identification of operators' judgement rules of daner in collision avoidance maneuvering of ships. Proc. 7th Fuzzy Syst. Symp., 1991, pp. 509-512.
16. Zhao J., M. Tan, W.G. Price, and P.A. Wilson. DCPA simulation model for automatic collision avoidance decision making systems using fuzzy sets. Oceans'94, Vol.2, 1994, pp. 244-249.
17. Smierzchalshi R., and Z. Michalewica. Modeling of ship trajectory in collision situations by an evolutionary algorithm. IEEE Transactions on evolutionary computation, Vol.4, No.3, 2000, pp. 227-240.
18. Jansson J., and F. Gustafsson. A framework and automotive application of collision avoidance decision making. Automatica 44, 2008, pp. 2347-2351.
19. Wang S., and Q. Meng. Sailing speed optimization for container ships in a linear shipping network. Transportation Research 48E, 2012, pp. 701-714.
20. Wang S., and Q. Meng. Bunker consumption optimization methods in shipping: A critical review and extensions. Transportation Research Part E: Logistics and Transportation Review, 53, 2013, pp. 49-62.
21. Cockcroft A.N., and J.N.F. Lameijer. A guide to the collision avoidance rules. Elsevier Butterworth-Heinemann, Burlington, MA. USA, 2001.
22. Goodwin, E.M. A statistical study of ship domains. Journal of Navigation, 28,328, 1975.
23. Davis P.V., M.J. Dove, and C.T. Stockel. A computer simulation of marine traffic using domains and arenas. Journal of Navigation, 33(1), 1980, pp. 215-222.
24. Fujii Y., and K. Tanaka. Traffic Capacity. Journal of Navigation, Vol 24, 1971, 543-552.
25. Wang N., X. Meng, Q. Xu, and Z. Wang. A unified analytical framework for ship domains. Journal of Navigation (2009), 62, 2009, pp. 643-655.
26. Wang N. An intelligent spatial collision risk based on the quaternion ship domain. Journal of Navigation (2010), 63, 2010, pp. 733-749.
27. Li Z. Research on speed loss during ships' turning. master thesis: Dalian Maritime University.
28. Fagerholt K., S. Heimda, and A. Loktu. Shortest paths in the presence of obstacle: an application to ocean shipping. Journal of Operational Research Society, Vol.51, 2000, pp. 683-688.
29. Zheng D. A survey on ship collision risk evaluation. Journal of Dalian Maritime University, Vol.28, 2002, pp. 14-17.
30. Hong B., and L.Yang. Ship Handling. Dalian Maritime University Press, Dalian, China, 2012.
31. Amerongen J., and H.R. Nauta Lemke. Optimum steering of ships with an adaptive autopilot. the Fifth Ship Control Systems Symposium, 1978.