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Review

Modelling of marine traffic flow complexity

Yuanqiao Wen [a,b], Yamin Huang [a,c], Chunhui Zhou [a,b,*], Junlan Yang [a], Changshi Xiao [a,b], Xiaochun Wu [a,b]

[a] School of Navigation, Wuhan University of Technology, 122 Luoshi Road, Wuhan, Hubei 430070, China
[b] Hubei Key Laboratory of Inland Shipping Technology, Wuhan, 430063, China
[c] Safety and Security Science Group, Faculty of Technology, Policy and Management, Delft University of Technology, Delft, 2628BX, The Netherlands

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ABSTRACT

Recent increases in the number of high-speed, large-scale, and heavy-load vessels have made marine traffic more complex. Traffic situations are more difficult to manage as a result because of the rapid increase in the traffic density and the development of ship encounter situations. Here, we introduce a marine traffic complexity model to evaluate the status of traffic situation, use the complexity to investigate the degree of crowding and risk of collision, and support mariners and traffic controllers to get the traffic situation awareness. The traffic unit complexity model is constructed using pair-wise ship traffic characteristics such as the relative distance, relative speed, and intersecting trajectory. This model is extended to an area traffic complexity model through interpolation post-processing. We show that a higher complexity corresponds to more crowding and dangerous traffic in which the traffic situation should be carefully managed. Simulated data from the Shenzhen West Sea are employed to demonstrate the model and construct a map of the spatial distribution of the marine traffic complexity. The complexity model is shown to be effective in indicating different traffic situations.

Contents

1. Introduction

Situation Awareness (SA) is aware of the environmental situation by collecting and interpreting information (Van de Laar et al., 2013). Being aware of traffic situation is a prerequisite for mariners and traffic controllers to low accident probability, make informed decisions, and

* Corresponding author. Tel.: +8615827445246.
E-mail addresses: huangyamin2012@gmail.com, y.huang-3@tudelft.nl (C. Zhou).

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List of symbols

VC_{ij}	the basic traffic unit which is consisted of ships i and j
l_{upper}	the distance boundary of VC_{ij}
l_{lower}	the radius of a rounded ship domain in this paper
l_{middle}	the distance boundary which both ships take action to avoid a collision
den_{ij}	the complexity caused by the traffic density, also named as density complexity
ρ	a redefined density function
$\overrightarrow{P_i}$	position of ship i
$\left\lvert\overrightarrow{D_{ij}}\right\rvert$	the distance between ship i and j in VC_{ij}: $\left\lvert\overrightarrow{D_{ij}}\right\rvert = \left\lvert\overrightarrow{P_j} - \overrightarrow{P_i}\right\rvert$, (see in Fig. 3)
R_{ij}	the minimum safe distance between the two vessels in the VC_{ij}
α	a internal parameter for fitting the model to the different water areas
λ	a internal parameter for fitting the model to the different water areas
$conf_{ij}$	the complexity caused by the traffic situation, also named as the conflict complexity
θ	the track-crossing angle, also known as collision angle.
$\overrightarrow{v_{ij}}$	the relative velocity between ship i and j in VC_{ij}: $\overrightarrow{v_{ij}} = \overrightarrow{v_j} - \overrightarrow{v_i}$
$angle_{ij}$	the complexity caused by the track-crossing angle, also named as the angle complexity
$g1$	an adjustment function when $\left\lvert\overrightarrow{D_{ij}}\right\rvert \in (l_{lower}, l_{middle}]$
$g2$	an adjustment function when $\left\lvert\overrightarrow{D_{ij}}\right\rvert \in (l_{middle}, l_{upper}]$
$Conv_{ij}$	the complexity caused by the relative motion, also named as the convergence complexity
$Complexity_{ij}$	the total complexity in VC_{ij}
$C(i)$	the total complexity from ship i's view
N	the number of ships in the area
L	the length of the ship
B	the width of the ship

take appropriate actions. To get traffic situation awareness has three phases: perception of ships in the environment; comprehension of traffic situation; projection of future states of traffic situation.

As so far, various kinds of equipment/systems, such as: land- or ship-radar, Vessel Monitoring Systems (VMS) and Automatic Identification System (AIS), etc., have been engaged (Fefilatyev et al., 2012) and numerous traffic data, like: ships' location, size, type, and destination, can be collected to help the traffic controllers know about traffic. Which means it's easy for mariners and traffic controllers to get the perception of elements in that way.

However massive traffic data do not always help traffic controllers or mariners to understand the traffic situation. On the contrary, too many irrelative data may decrease the cognition of other important information. Therefore, how to draw useful massage from the massive data to describe traffic situation is becoming a hot topic. Looking into existing research, currently, there are three main methods to show traffic situation.

Traffic statistics is the most popular way to describe traffic situation. The average speed, quantity of traffic flow, traffic distribution, the types of ship and et al. are treated as the basic features of the traffic system. Some researchers focus on finding the relationship between them and traffic situation, and then exhibit the long-term traffic situation (Weng et al., 2012) (Balmata et al., 2009). Whereas, others built traffic simulation model (Goerlandt and Kujala, 2011; Goerlandt et al., 2012) based on the traffic statistics data and evaluate the marine traffic situation in the traffic simulation systems (Blokus-Roszkowska and Smolarek, 2014). These kinds of researches are usually used to evaluate the long-term traffic situation, but they cannot meet the demands to estimate the real-time traffic situation. Traffic controllers have to judge the current traffic situation on the basis of long-term ones by their experience.

Traffic flow theory has been widely used in road traffic field. Because of the similarities between road traffic and marine traffic, it is introduced to research marine traffic in recent years (Shao and Fang, 2002; Yip, 2013). In their researches, the macro traffic flow is treated as a continuum model. In road traffic field, scientists used the traffic statistics variables: flow rate, density, and speed to plot the traffic fundamental diagram which can indicate the traffic status: free flow, synchronized flow, and wide moving jam (Kerner, 2009). However, in marine traffic field, these features haven't been verified.

Recently, researchers tried to visualize the AIS trajectory and draw a traffic density map to show the traffic situation (Willems et al., 2013). In this way, mariners and traffic controllers can get a direct cognition of traffic. Whereas, traffic conflict is not considered in their research. As a consequence, the traffic situation information provided in their map is limited.

Above all, present researches rarely focus on quantitatively describing the real-time traffic situation, which is important to inform mariners and traffic controllers the comprehension of traffic situation. Hence we formulate a new method based on the research of air traffic complexity.

Over viewing the development of the air traffic complexity, it is developed to estimate traffic controllers' workload at beginning. With the research goes on, the traffic complexity is applied to describing traffic situation. The air traffic complexity researches contain three stages till now.

Initially, the density of aircraft is the only factor to indicate the traffic complexity (Hilburn, 2004), i.e. the more aircrafts in certain section, the more complex it is. It is the basic of the traffic management, especially in US and Europe, but scientists found it's not precise. Low traffic density can also lead to a seriously complex traffic situation and need to be paid more attention to Masalonis et al. (2003). To solve this issue, some researchers brought out the dynamic density (DD) to indicate the complexity. The DD is regarded as a multidimensional index that reflects the change in the complexity. It contains some measurable index extracted from traffic flow, such as: the numbers of flights, the head changing rate, the altitude changing rate and so on (Wang et al., 2013). With these indexes, Laudeman et al. (1998) constructed a linear DD model to calculate the complexity of a flight sector, and Chatterji and Sridhar (2001) later pointed out the limitations of the linear model and proposed a nonlinear method to analyse the relationship between complexity factors.

In recent decade, some researchers believe that workload and traffic situation are only related to traffic intrinsic features (like: location and motion) (Lee, 2008). They used aircrafts' location and motion as the basic index to build complexity model. Delahaye et al. (2000, 2002) have used two approaches to define the airspace complexity; the first described an air traffic complexity indicator based on the geometry of the traffic, while the second was based on dynamic systems theory and used the Kolmogorov entropy to measure the global disorder of the system as it evolves over time. Lee (2008) proposed a way to analyse the airspace when an intruder aircraft crosses a sector boundary and presented a complexity map to describe response in the airspace to a set of disturbances. Zhang et al. (2009) analysed the intrinsic relationship between the airspace and air traffic, established an air traffic complexity metric through geometric attributes of the aircraft, analysed the pair-wise interactions between aircraft, and characterized the general features of the traffic. Ye et al. (2012) built a traffic complexity model based on the traffic structure that reflected the influence of the geometrical features on the traffic complexity.

The complexity has been shown to be an important index to show the traffic controllers' workload and traffic situation, gradually. To describe the traffic situation better and support the mariners and traffic controllers to get the traffic situation awareness, we employ the intrinsic complexity to build the marine traffic complexity model. However, the difference between marine traffic complexity and air traffic complexity definitions are obvious.

The aims of the researches are different. From the most air traffic complexity definitions (Xing and Manning, 2005; Lee, 2007, 2008), the main purpose of air traffic complexity researches is evaluating the traffic controllers' workload. While in this paper, marine traffic complexity is employed to describe the traffic situation, focuses on digging the traffic data (like: vessel locations and motions) and provide the traffic information which can be used to support the decision making.

The remainder of the paper is structured as follows. The model development is presented in Sections 2 and 3 describes the general setting for the model. In Section 4, a case study, simulated traffic data in the Shenzhen West Sea are used to demonstrate the complexity model and analyse the velocity and complexity fields. The findings and proposals for future work are included in Section 5.

2. Model development

The traffic complexity indicates the degree of traffic situation, including the degree of crowding and the risk of collision. The degree of crowding influences the transportation efficiency and the risk of collision directly impacts traffic safety. The traffic complexity is thus closely related to the features of the traffic flow.

Definition: The marine complexity is an indicator to show the degree of crowding and the risk of collision in specific area.

Traffic features can be treated as macroscopic or microscopic characteristics, e.g. the traffic density, i.e. the number of the vessels, (macroscopic) and the geometric relationship among ships (microscopic). Both these characteristics are external features of the traffic and are easily measurable, as is done by the AIS that is used in most ports to collect information about the relative position, course, and speed of each ship. The traffic density and geometric relationship are used here to describe the traffic complexity.

Definition: The basic traffic unit is a vessel couple VC_{ij} consisting of ships i and j. The entire traffic flow is composed of basic traffic units.

We also make the following assumptions:

Assumption 1. The continuity of complexity. The complexity of VC_{ij} satisfies the continuity hypothesis, i.e. the complexity values change continuously with changes in the factors. The lower bound of the complexity is zero, while the upper bound is infinite.

Assumption 2. The homogeneity of vessels. To simplify the model, we assume that the vessels in VC_{ij} are homogeneous. Therefore, the complexity induced by different types of ships is not considered in this paper.

Assumption 3. Distance-based Collision Detection. We assume that VC_{ij} exists a distance boundary (l_{upper}). Only when the distance less than l_{upper} two vessels are in encounter situation.

Assumption 4. Ship domain. According to vessel safety domain theory, the ship domain is an area that rejects other ships (Toyoda and Fujii, 1971). The shapes of ship domains are various, such as: circular, elliptical or polygonal (Silveira et al., 2014). To simplify the model, in this paper, we suppose the ship domain is rounded and its radius is shown as l_{lower}. When other ships invade the own ship domain (relative-distance less than l_{lower}), then the complexity value is a maximum. The distance boundary which both ships take action to avoid a collision is expressed as l_{middle}.

2.1. Traffic density factor

The traffic complexity is closely related to the traffic density in that an increase in the traffic density will be reflected by a change in the complexity.

Definition: The density complexity den_{ij} is the complexity caused by the traffic density.

In Fig. 1, while the number of ships in (a) and (b) is the same, so that traffic density is the same, the relative distance between ships is smaller in (b) and so this situation has a larger complexity value. If the traffic density is defined as the number of ships per unit area, then the complexity cannot be expressed simply in terms of the traffic density. Thus, we redefine the traffic density.

Definition: The VC_{ij} traffic density, ρ, is a function of $\left|\overrightarrow{D_{ij}}\right|$, i.e. $\rho(\left|\overrightarrow{D_{ij}}\right|)$, and is equal to the density complexity (den_{ij}) (inspired by

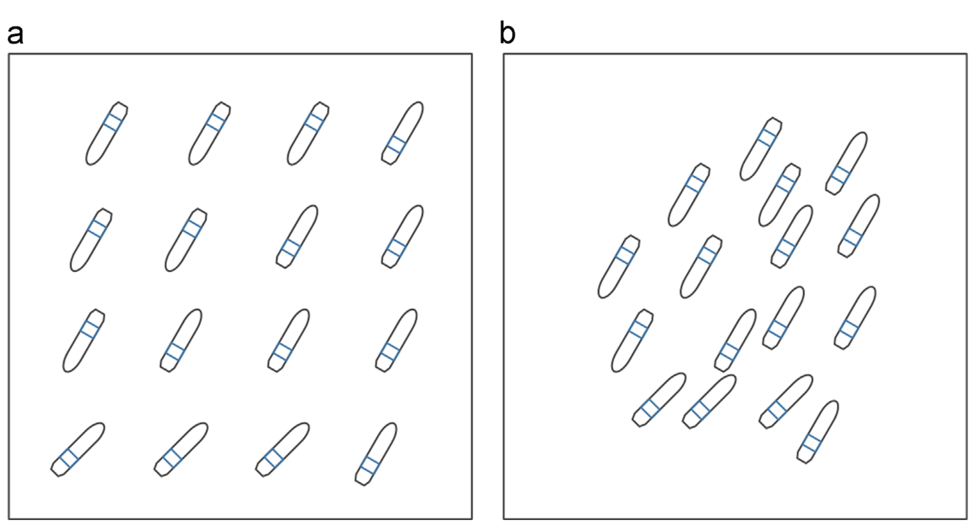


Fig. 1. Two situations with the same traffic density but (a) has a smaller complexity value than (b).

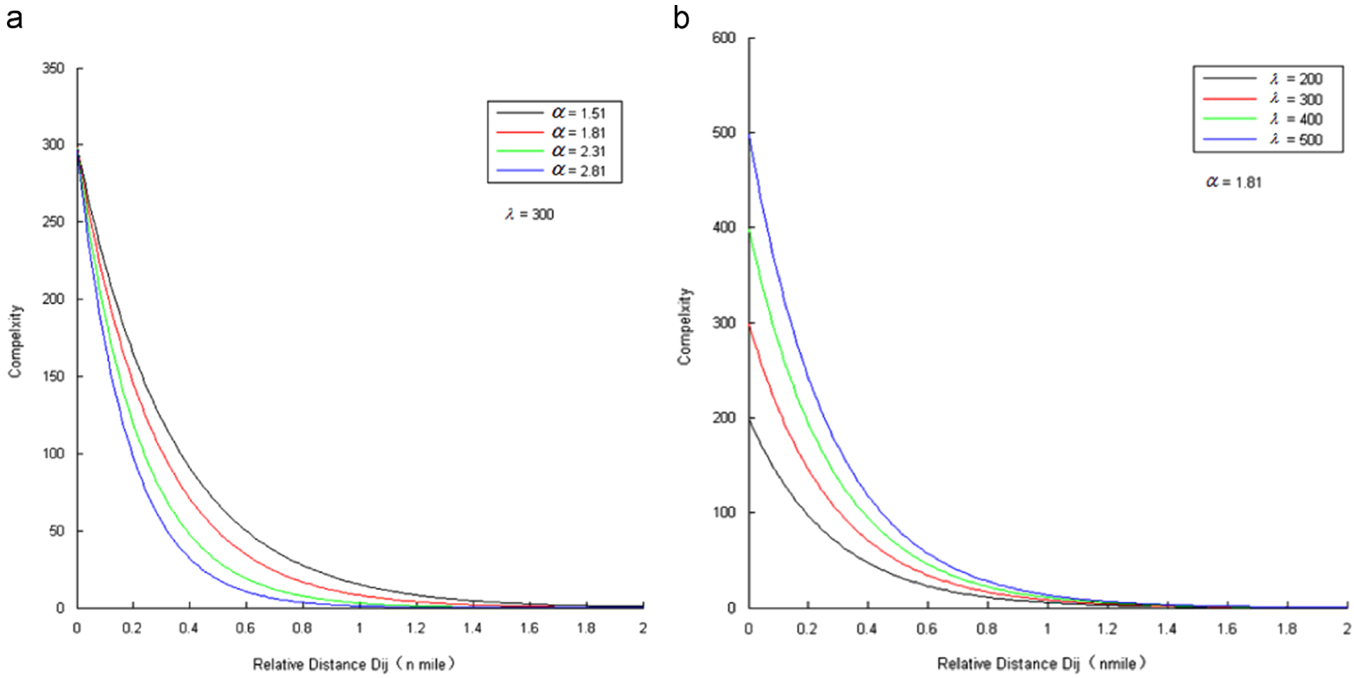


Fig. 2. Density complexity as a function of the relative distance for various values of α and λ.

Delahaye and Puechmorel (2000) and Ye et al.,(2012)):

$$den_{ij} = \rho(|\overrightarrow{D_{ij}}|) = \lambda \bullet e^{-\alpha \frac{|\overrightarrow{D_{ij}}|}{R_{ij}}}, \tag{1}$$

where α and λ ($\alpha > 0$, $\lambda > 0$) are correction parameters that depend on the navigation environment, and R_{ij} is the minimum safe distance between the two vessels in the VC_{ij}. The value of R_{ij} depends on the type of the ship and the navigation environment.

As $|\overrightarrow{D_{ij}}|$ decreases, the density complexity increases nonlinearly. For example, when the track-crossing angle and velocity are invariant, a shorter $|\overrightarrow{D_{ij}}|$ results in a higher traffic density (den_{ij}).

As shown in Fig. 2, for $R_{ij} = 0.5NM$ and $\lambda = 300$, a larger α value produces a faster change in $den_{ij}(|\overrightarrow{D_{ij}}|)$ with increasing $|\overrightarrow{D_{ij}}|$, while for $\alpha = 1.81$ and a varying λ value, a larger λ results in a smaller maximum $den_{ij}(|\overrightarrow{D_{ij}}|)$ value.

2.2. Traffic conflict factors

Definition: The conflict complexity $conf_{ij}$ is the complexity caused by the traffic conflict.

Not only will the density impact on ships traffic, but also the traffic conflict which is more directly and urgently. According to Assumption 3, as long as two ships encounter distance less than l_{upper}, they will have an encounter situation, meanwhile, the conflict complexity $conf_{ij}$ will emerge. Therefore, we need employ the traffic conflict factors to describe the encounter situation and construct the conflict complexity model.

All kind of factors have been proposed relative with traffic conflict, such as: the ship manoeuvrability, ship type, ship speed, encounter angle and other dynamic nature etc. (Montewka et al., 2012). In Zhang et al. (2015) research, they select distance, relative speed and encounter angle as factors. Tam and Bucknall (2013) introduce the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) (1972) into conflict risk estimate and emphasize the ships' relative location impact on the conflict risk evaluation.

In this paper, we combining the researches from Zhang et al. (2015) and Tam and Bucknall (2013), we choice the relative

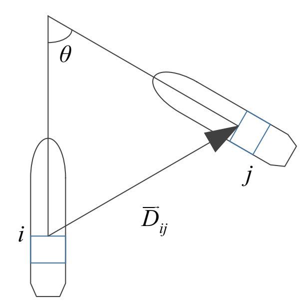


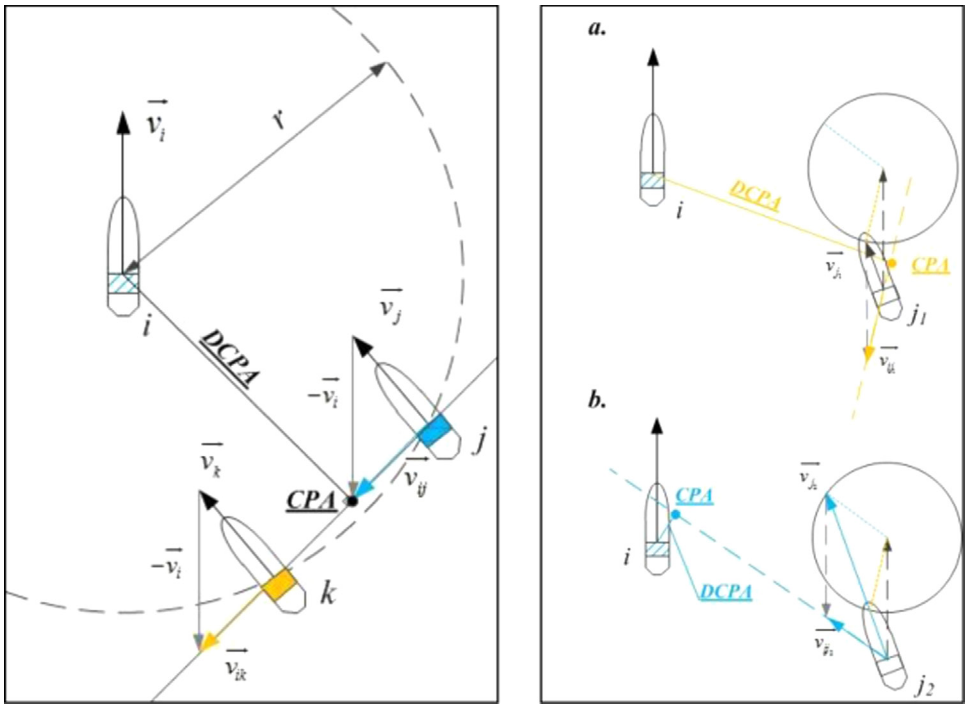
Fig. 3. Track-crossing angle θ.

distance (vector), relative speed (vector) and track-crossing angle (also named as encounter angle) as the basic factors.

Fig. 4(1) shows the impacts from different relative positions. From Fig. 4(1), in the perspective of ship i, we can see two target ships: ship j and ship k which are totally the same, such as distance, relative speed and encounter angle. The only differences of ship j and ship k are the relative positions with respect to ship i. So, in the perspective of ship i, we can see the different motion-trends: ship j is moving to the CPA (Closest Point of Approach); ship k is moving away from CPA. That means the conflict threats from various relative positions are different, even they have same distance, relative speed and encounter angle. Therefore, the relative distance vector is an essential factor.

Fig. 4(2) shows the impacts from different directions of relative speed from the perspective of ship i. Fig. 4(2) (a) and (b) have almost the same encounter situation, the ship j_1 and ship j_2 have the same relative position, distance and encounter angle. Although the speeds of ship j_1 and ship j_2 are different, the scalars of relative speed $|\overrightarrow{v_{ij_1}}|$ and $|\overrightarrow{v_{ij_2}}|$ are the same. However, the directions of relative speeds are different, which make ship j_1 and ship j_2 have different motion-trends: In Fig. 4(2) (a) ship j_1 is moving away from CPA; in Fig. 4(2)(b), ship j_2 is getting close to CPA. That means the conflict threats from ship j_1 and ship j_2 are different. Therefore, the relative speed vector is an essential factor.

From these two cases, we can find that the direction of relative movement strongly impact on conflict risk evaluation. To indicate the



(1) Different relative locations (2) The same scalar of relative speed but in different directions

Fig. 4. The relative distance and relative speed impact on conflict risk. (1) Different relative locations (2) The same scalar of relative speed but in different directions.

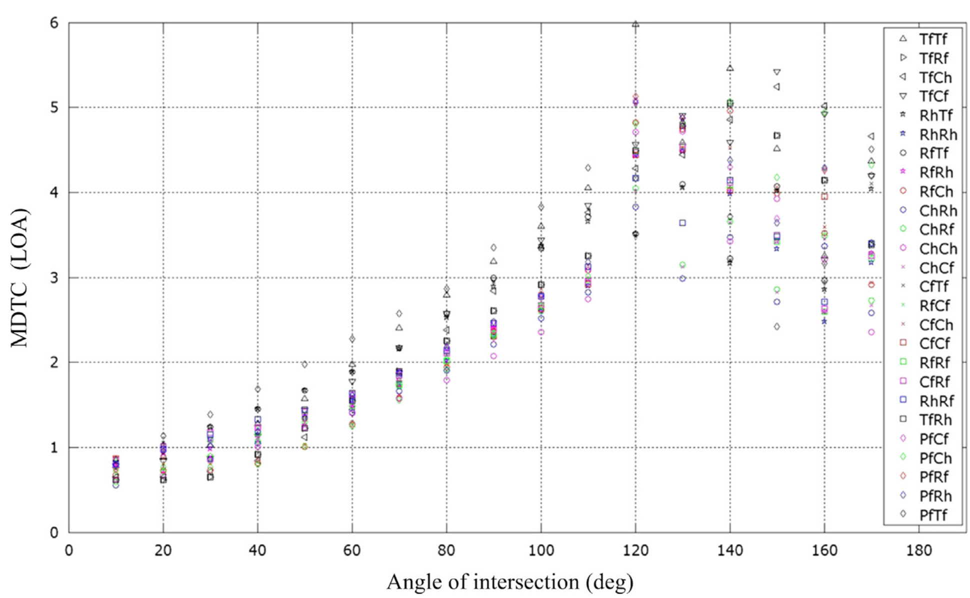


Fig. 5. Ships' MDTC values for different ship type (Montewka et al., 2012).

influence from that, the relative distance vector ($\overrightarrow{D_{ij}}$) and the relative speed vector ($\overrightarrow{v_{ij}}$) will be involved in Section 2.2.2. The impact from track-crossing angle (the angle θ is shown in Fig. 3) will be shown in Section 2.2.1. Thus, the conflict complexity can be expressed as

$$conf_{ij} = \psi(\overrightarrow{D_{ij}}, \overrightarrow{v_{ij}}, \theta), \tag{2}$$

where $\overrightarrow{v_{ij}}$ is the relative velocity ($\overrightarrow{v_{ij}} = \overrightarrow{v_j} - \overrightarrow{v_i}$).

2.2.1. Track-crossing angle factor

In navigation, the conflict is not a monotonous function of the track-crossing angle θ and relative-distance. However the precondition of $conf_{ij}$ is risk of collision in V_{ij} (the relative-distance less than l_{upper}), specific situations and responses are determined by the track-crossing angle.

To describe the complexity in different track-crossing angle, we adopt the MDTC (Minimum Distance To Collision) in Montewka et al. (2012) research. The MDTC indicates the minimum distance to collision avoidance, and it just likes a threshold for collision avoidance. The precondition for calculate the MDTC is that two ships are converging. In this situation, in different track-crossing angle, the MDTC will be different. If the MDTC is longer, that means the ships should take the evasive action earlier to collision avoidance. Therefore, the longer MDTC in certain track-crossing angle indicates the more dangerous situation than others track-crossing angles.

In Fig. 5, Montewka et al. (2012) shown the relationship between MDTC and θ. When θ is lower than 20 degree, the MDTC is shorter and ships have more time to take evasive action. Hence, the situation is more safety than others'. In fact that, when θ is lower than 20 degree, two ships have a lower relative velocity, and then the traffic situation would not change rapidly.

When θ is around 180 degree, the MDTC is greater than 20 degree's, but not the longest one. Hence, this situation is medium. In fact that, when θ is 180 degree (in the condition of converging), two ships will be in the head-on situation. Although the ships have largest relative velocity, they have clear responsibility from Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) (1972). Therefore they are not the most dangerous situation.

When θ is around 120 degree, the MDTC get longest and ships should take action earlier. Which means the situation is the most dangerous. In fact that, when θ is around 120 degree and two ships are converging, the ships have a higher velocity and the ship's actions are more complex.

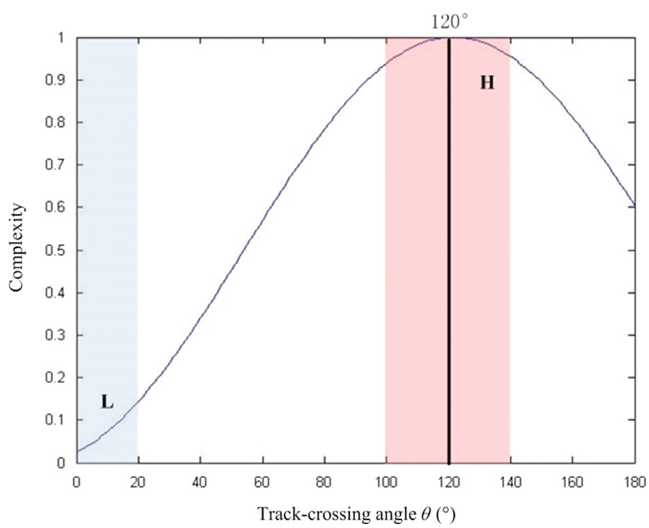


Fig. 6. Angle complexity as a function of θ. ("*H*" means high angle complexity and "*L*" means low $angle_{ij}$).

Therefore, we normalized the MDTC and draw the complexity line caused by θ shown in Fig. 6.

Definition: The angle complexity $angle_{ij}$ is the complexity caused by the track-crossing angle.

As shown in Section 2.1, the complexity increases nonlinearly with decreasing $\left|\overrightarrow{D_{ij}}\right|$, and based on Assumption 3, the complexity is set to a minimum if $\left|\overrightarrow{D_{ij}}\right|$ exceeds l_{upper}. In a similar manner, from Assumption 4, the complexity is a maximum when $\left|\overrightarrow{D_{ij}}\right|$ is less than l_{lower}. Thus, $\left|\overrightarrow{D_{ij}}\right| = l_{middle}$ defines the condition of the median complexity that changes nonlinearly as a function of θ (Fig. 6). The median complexity is given as:

$$f(\theta) = \frac{1}{2} \bullet \left\{ 1 - \cos\left[\left(\frac{180}{67.5} \right) \bullet \frac{\theta}{2} \bullet \frac{\pi}{180} + \frac{\pi}{10} \right] \right\} \tag{3}$$

We see that the complexity is a maximum for $\theta = 120^\circ$ and a minimum for $\theta = 0^\circ$. In determining the complexity, we consider two separate cases.

(1) $\left|\overrightarrow{D_{ij}}\right| \in (l_{lower}, l_{middle}]$

The complexity is a maximum when $\left|\overrightarrow{D_{ij}}\right| = l_{lower}$ and is given by Eq. (3) when $\left|\overrightarrow{D_{ij}}\right| = l_{middle}$. Assumption 4 makes it necessary to introduce an adjustment to the amplitude of the complexity curve so that there is a smooth decrease between $\left|\overrightarrow{D_{ij}}\right| = l_{middle}$ and $\left|\overrightarrow{D_{ij}}\right| = l_{lower}$. The adjustment function g_1 is given by

$$g_1\left(\left|\overrightarrow{D_{ij}}\right|\right) = \frac{\left|\overrightarrow{D_{ij}}\right| - l_{lower}}{l_{middle} - l_{lower}}. \tag{4}$$

Then complexity $angle_{ij}$ is then expressed as Eq. (5), and is shown in Fig. 7(a). Complexity $angle_{ij}$ grows with the growth of $\left|\overrightarrow{D_{ij}}\right|$.

$$angle_{ij} = f(\theta) \bullet g_1\left(\left|\overrightarrow{D_{ij}}\right|\right), \quad \left|\overrightarrow{D_{ij}}\right| \in (l_{lower}, l_{middle}], \tag{5}$$

(2) $\left|\overrightarrow{D_{ij}}\right| \in (l_{middle}, l_{upper}]$

In a similar manner an adjustment is introduced based on Assumption 3 to ensure a smooth increase between $\left|\overrightarrow{D_{ij}}\right| = l_{middle}$

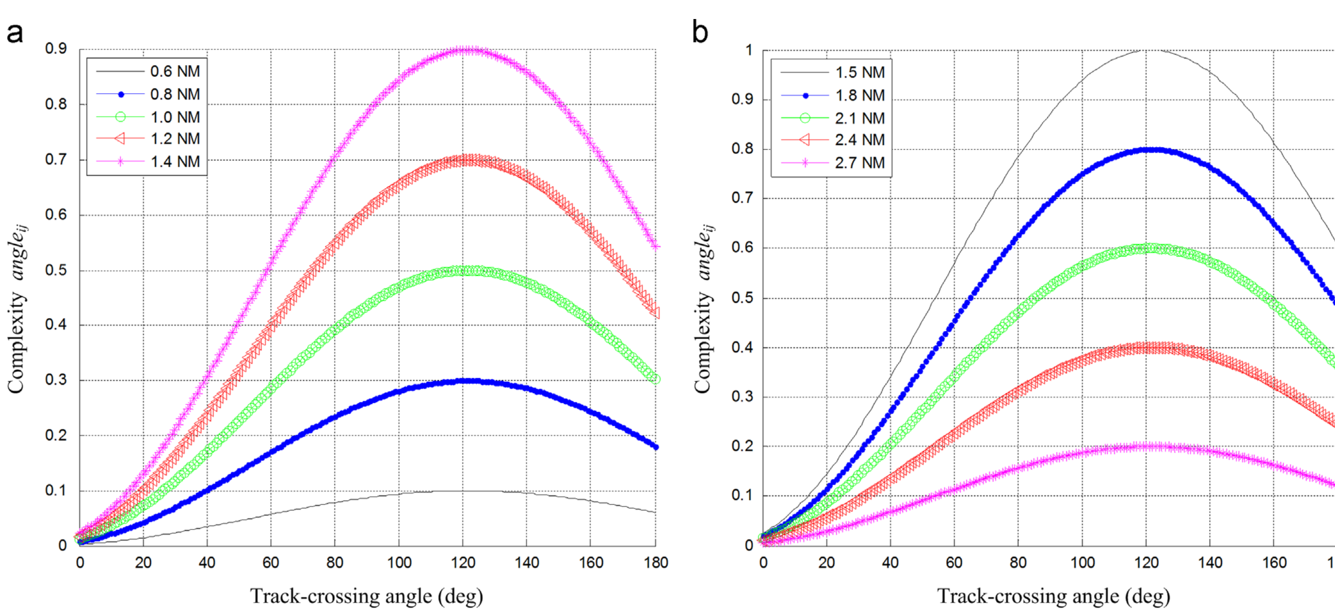


Fig. 7. Angle complexity curves for specific relative distances, the $\left|\overrightarrow{D_{ij}}\right|$ in (a) belong to $(0.5, 1.5]NM$ (*nautical mile*), (b)'s belong to $(1.5, 3]NM$. (Assume that $l_{lower} = 0.5NM$, $l_{middle} = 1.5NM$, $l_{upper} = 3NM$).

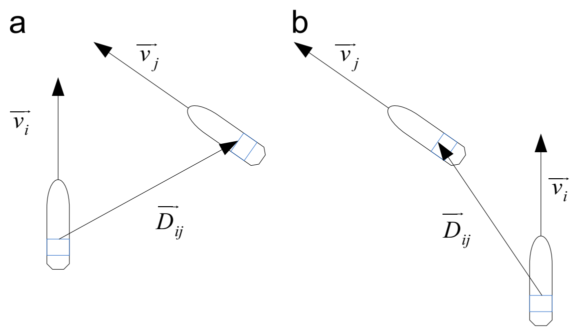


Fig. 8. Different relative motions.

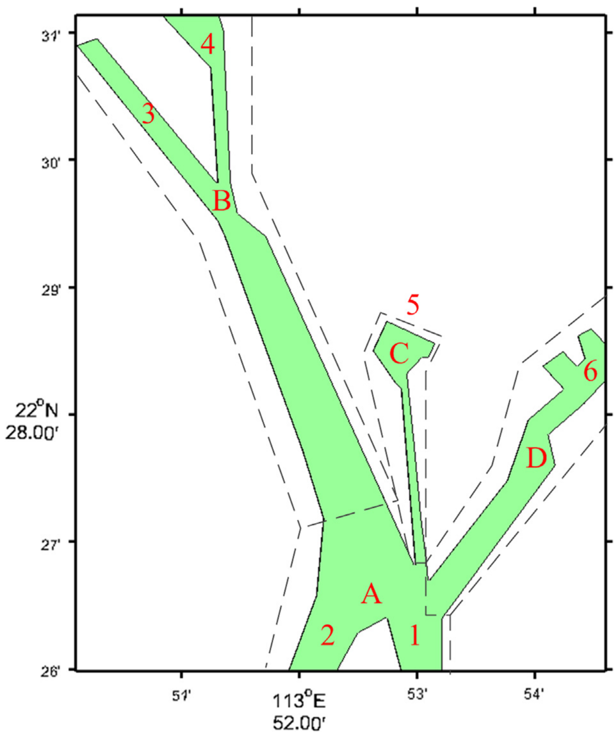


Fig. 9. Four sectors (A–D) in the Shenzhen West Sea. There are two entrances (1 and 2) and four exits (3–6).

and $\left|\overrightarrow{D_{ij}}\right| = l_{upper}$. The adjustment function g_2 is

$$g_2\left(\left|\overrightarrow{D_{ij}}\right|\right) = \frac{l_{upper} - \left|\overrightarrow{D_{ij}}\right|}{l_{upper} - l_{middle}}. \tag{6}$$

The complexity $angle_{ij}$ (the complexity causes by the track-crossing angle) is

$$angle_{ij} = f(\theta) \bullet g_2\left(\left|\overrightarrow{D_{ij}}\right|\right), \quad \left|\overrightarrow{D_{ij}}\right| \in \left(l_{middle}, l_{upper}\right], \tag{7}$$

According to Eq. (7), the different $\left|\overrightarrow{D_{ij}}\right|$ will make up a family curve shown in Fig. 7(b), it means that with the growth of $\left|\overrightarrow{D_{ij}}\right|$, the complexity caused by track-crossing angle is smaller.

2.2.2. Relative motion factor

The relative motion of the VC_{ij} affects the situation of traffic conflict, as seen in Fig. 8(a) and (b), where the track-crossing angles are the same but the relative motions are different: the two ships in (a) are converging, while those in (b) are diverging.

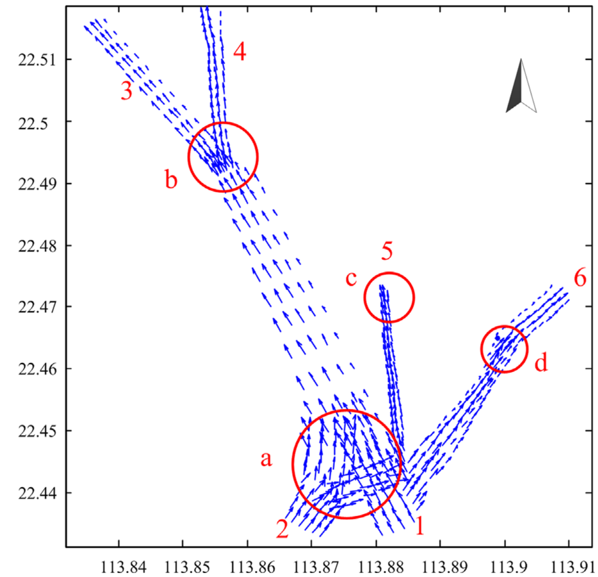


Fig. 10. Calculated velocity field of the Shenzhen West Sea channel.

Definition: The convergence complexity $Conv_{ij}$ is the complexity caused by the relative motion. If vessels are diverging, then $Conv_{ij}=0$, whereas if the vessels are converging, $Conv_{ij}$ is a function of the relative speed.

The relative motion of two vessels can be determined as

$$\frac{d\left|\overrightarrow{D_{ij}}\right|}{dt} = \frac{\overrightarrow{D_{ij}} \bullet \overrightarrow{v_{ij}}}{\left|\overrightarrow{D_{ij}}\right|} = \left|\overrightarrow{v_{ij}}\right| \bullet \cos\left(\overrightarrow{v_{ij}}, \overrightarrow{D_{ij}}\right), \text{(Delahaye and Puechmorel, 2000)} \tag{8}$$

such that $\frac{d\left|\overrightarrow{D_{ij}}\right|}{dt} > 0$ defines diverging vessels, and $\frac{d\left|\overrightarrow{D_{ij}}\right|}{dt} < 0$ defines converging vessels. The complexity $Conv_{ij}$ is then given as

$$conv_{ij} = l_{R^+}\left\{\frac{d\left|\overrightarrow{D_{ij}}\right|}{dt}\right\} = \begin{cases} \left|\frac{d\left|\overrightarrow{D_{ij}}\right|}{dt}\right| & \frac{d\left|\overrightarrow{D_{ij}}\right|}{dt} < 0 \\ 0 & \frac{d\left|\overrightarrow{D_{ij}}\right|}{dt} > 0 \end{cases}. \tag{9}$$

Thus, the conflict complexity (caused by traffic conflict) is

$$conf_{ij} = \psi\left(\left|\overrightarrow{D_{ij}}\right|, \overrightarrow{v_{ij}}, \theta\right) = conv_{ij} \bullet angle_{ij} \tag{10}$$

When the track-crossing angle is invariant and the traffic is diverging, $Con_{ij}=0$, whereas for converging traffic, $conf_{ij} = \left|\frac{d\left|\overrightarrow{D_{ij}}\right|}{dt}\right| \bullet angle_{ij}$. If the traffic is invariant, then the change in $conf_{ij}$ obeys Eqs. (3)–(7); it depends on the change in the track-crossing angle and the relative distance.

2.3. Traffic complexity modelling

For a basic traffic unit VC_{ij}, the total complexity: $complexity_{ij}$ is a sum of the first (den_{ij}) and second ($conf_{ij}$) complexities:

$$complexity_{ij}\left(\overrightarrow{D_{ij}}, \overrightarrow{v_{ij}}, \theta_{ij}\right) = den_{ij}\left(\left|\overrightarrow{D_{ij}}\right|\right) + conf_{ij}\left(\overrightarrow{D_{ij}}, \overrightarrow{v_{ij}}, \theta_{ij}\right)$$

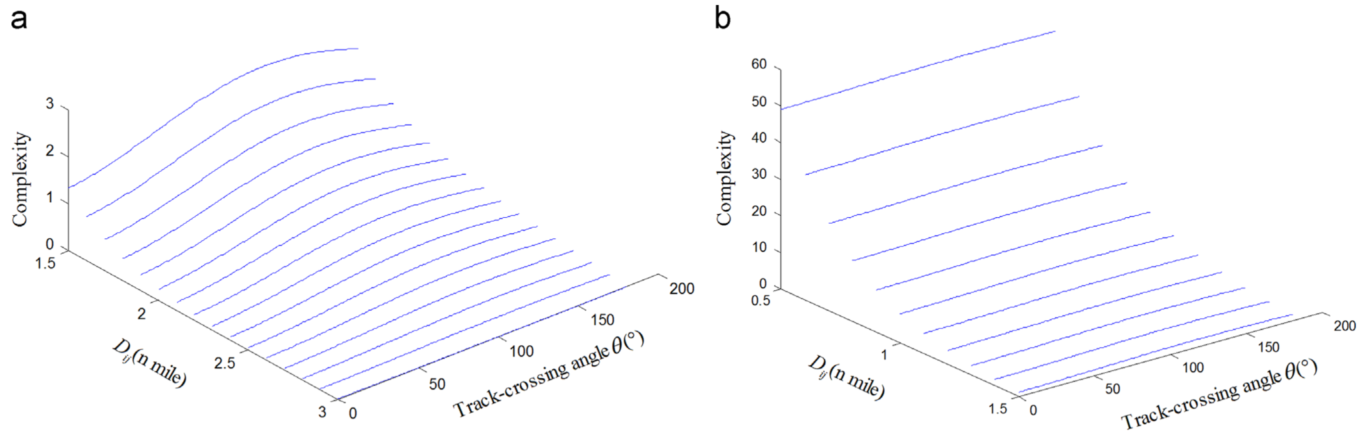


Fig. 11. Traffic complexity curves for specific relative distances. (a) $\left|\overrightarrow{D_{ij}}\right| \in (1.5, 3]NM$ (b) $\left|\overrightarrow{D_{ij}}\right| \in (0.5, 1.5]NM$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

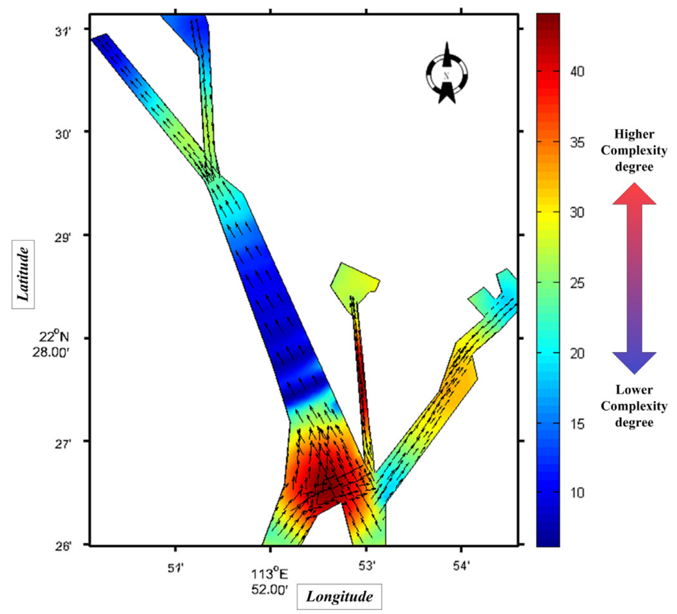


Fig. 12. Spatial distribution of the traffic complexity in the Shenzhen West Sea.

$$= \begin{cases} \lambda \bullet e^{-\alpha \frac{\left|\overrightarrow{D_{ij}}\right|}{R_{ij}}}, \left|\overrightarrow{D_{ij}}\right| \in (0, l_{lower}] \cup (l_{upper}, +\infty) \\ \lambda \bullet e^{-\alpha \frac{\left|\overrightarrow{D_{ij}}\right|}{R_{ij}}} + l_{R^+}\left\{\frac{d\left|\overrightarrow{D_{ij}}\right|}{dt}\right\} \bullet f(\theta_{ij}) \bullet g_1(\left|\overrightarrow{D_{ij}}\right|), \left|\overrightarrow{D_{ij}}\right| \in (l_{lower}, l_{middle}] \\ \lambda \bullet e^{-\alpha \frac{\left|\overrightarrow{D_{ij}}\right|}{R_{ij}}} + l_{R^+}\left\{\frac{d\left|\overrightarrow{D_{ij}}\right|}{dt}\right\} \bullet f(\theta_{ij}) \bullet g_2(\left|\overrightarrow{D_{ij}}\right|), \left|\overrightarrow{D_{ij}}\right| \in (l_{middle}, l_{upper}] \end{cases} . \tag{11}$$

The total complexity of ship i $C(i)$ is the sum of all the complexities of the related basic traffic units. But to eliminate the impact comes from the number of ships, we get the sum of all the complexity over the number of units N:

$$C(i) = \frac{1}{N}\sum_{j=1}$$

$$j \neq i^N complexity_{ij}(\overrightarrow{D_{ij}}, \overrightarrow{v_{ij}}, \theta_{ij}). \tag{12}$$

This equation forms the basis for producing spatial distribution maps of the traffic complexity.

3. The general settings

According to Eq. (11), there are 5 parameters should be define before the model work. There are: l_{upper}, l_{middle}, l_{lower}, α and λ.

l_{upper} is the upper distance boundary for two ships. If the relative distance of two ships greater than l_{upper}, then own ship can ignore the other ship in VC_{ij}. However different mariners have different sense about the dangerous, so the upper distance boundaries are different. It also depends on the environment ship sailing. Each mariners or traffic controllers can set l_{upper}'s value by their experience.

l_{middle} is the distance boundary which both ships should take action to avoid a collision. l_{middle} is related with the mariners' manoeuvring habits and the performance of ship. Mariners or traffic controllers can set l_{middle} 's value by the ship performance.

l_{lower} is the radius of the ideal ship domain. In classical ship domain theory, the ship domain is an ellipse with a long axis that is close to 8 times the length of the ship and a short axis of approximately 3.2 times the length of the ship (Toyoda and Fujii, 1971). Therefore, a discomforting danger situation is recognized when D_{ij} is smaller than the semi-major axis length and the complexity value is a maximum. Above all, we have $l_{lower} = 8L/2$ (L is the length of the ship).

α and λ are the intermediate parameters, which have no physical meaning. To obtain the value of α and λ, we need some more information from mariners and traffic controllers. For instance, the comparison of complexity in different situation (different locations). These information can be acquired from questionnaire survey. Applying these information to Eq. (12), we can calculate the value of α and λ.

4. A case study

4.1. Scenario

Shenzhen is the one of the busiest container ports in the world. In this paper, the main channel intersection in Shenzhen West Sea is set as the scenario background. The Structure of the channel is shown as Fig. 9. Entrances to the channel are indicated by the numbers 1 and 2, while numbers 3 to 6 indicate exits. Vessels from entrances 1 and 2 converge in area A and proceed to areas B, C, and

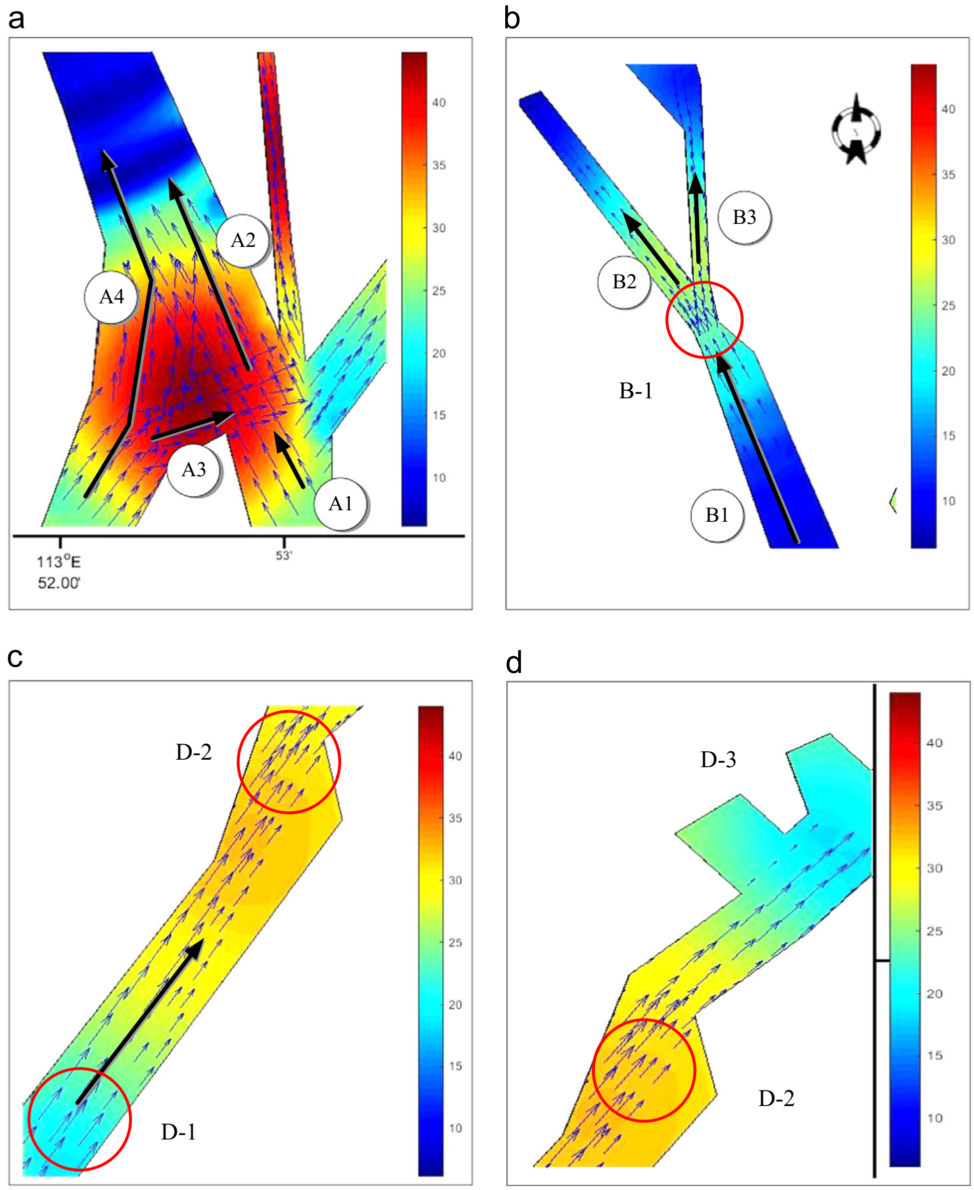


Fig. 13. Details of the complexity in the Shenzhen West Sea (a) in area A, (b) in area B, and (c) and (d) in area D.

D. Area B area is a 'Y'-type channel, area C is a narrow approach channel, and area D is a curing channel.

According to "Assumption 2", the vessel can be treated as a standard vessel in a Chinese port, like: 70,000-deadweight-tonnage bulk carrier, 230 m in length with a moulded breadth of 32.3 m (Du, 2008).

The velocity field calculated with the simulated data from the Shenzhen West Sea is shown in Fig. 10. There is a complex traffic situation in the subarea a of area A due to both the dense traffic and the number of track crossings; traffic from entrance 1 heading to area D has to cross traffic from entrance 2 heading to area B, and traffic from entrances 1 and 2 has to merge to enter area B.

4.2. Parameter settings

As the previous section said, we have ship size: $L = 230$ m; $B = 32.3$ m. Then $l_{lower} = 4L \approx 0.5NM$. According to the navigation habits in simulated area, we found that vessels always take actions when relative-distance less than $3NM$ (*Nautical Mile*). So we have $l_{upper} = 3NM$. When the relative-distance smaller than $1.5NM$, all the ships in VC_{ij} will take operations. So we have $l_{middle} = 1.5NM$.

The parameters α and λ come from the traffic controller's assessment via questionnaires, are set: the complexity when $\left|\overrightarrow{D_{ij}}\right| = 0.2NM$ is 3 times as large as that when $\left|\overrightarrow{D_{ij}}\right| = 0.5NM$; when $\theta = 0^\circ$, the complexity when $\left|\overrightarrow{D_{ij}}\right| = 0.5NM$ is 15 times as large as that when $\left|\overrightarrow{D_{ij}}\right| = 1.5NM$; and when $\left|\overrightarrow{D_{ij}}\right| = 3NM$, the complexity is equal to 0. With these simultaneous equations, $\alpha = 1.81$ and $\lambda = 300.21$ can be calculated.

Fig. 11 shows a 3D surface plot of traffic complexity for $\left|\overrightarrow{D_{ij}}\right| \in (1.5, 3]NM$ and $\left|\overrightarrow{D_{ij}}\right| \in (0.5, 1.5]NM$ when the relative motion is ignored, i.e. $l_{R^+}\left\{\frac{d\left|\overrightarrow{D_{ij}}\right|}{dt}\right\} = 1$. Fig. 11(a) and (b) are the partial magnifications for $\left|\overrightarrow{D_{ij}}\right| \in (0.5, 3]NM$; the x-axis is track-crossing angle from 0 to 180; the y-axis is relative distance between ships; the z-axis shows the complexity in different θ and $\left|\overrightarrow{D_{ij}}\right|$.

The curves in Fig. 11(a) and (b) are the family curves for track-crossing angle and complexity in different relative distance. When the $\left|\overrightarrow{D_{ij}}\right|$ is invariant, the curve in Fig. 11 is resemble to Fig. 6, which is influenced by the track-crossing angle mainly; When the θ is invariant, the complexity becomes a decreasing function of $\left|\overrightarrow{D_{ij}}\right|$, which the principal factor is relative distance.

4.3. Traffic flow complexity map

The traffic complexity of each ship calculated using Eq. (12) is used to construct the spatial distribution of the traffic complexity by interpolation, as shown in Figs. 12 and 13. The velocity field, indicated by the arrows, is also shown for reference. The complexity is a maximum along the channel in area C, and the complexity in area A is higher than that in areas B and D. Note that the traffic flow in areas B and C are the same but that the distances between vessels are much smaller in area C (most are less than 0.5*NM*), which is the reason for the higher complexity.

Fig. 13(a) shows that the traffic denoted by A1 crosses that denoted by A3 at a large angle and that traffic denoted by A4 and A2 merge. Thus, the complexity between A1 and A3 has a high value of 40–50 and is consistent with the velocity field in the same area (Fig. 10). The complexity between A4 and A2 takes a relatively lower value of between 25 and 30.

In area B (Fig. 13(b)), the traffic structure is such that the traffic (B1) is divided into two parts (B2 and B3). The interval between vessels in the B1 traffic is relatively large and their courses are relatively coherent, resulting in a low complexity (10 to 15). The complexity increases to 20–30 in the crossing area (B-1) as the interval between vessels decreases and the number of crossing increase before the traffic is split into the two narrow channels. The complexity then decreases as the traffic moves away from area B-1.

We see in Fig. 13(c) and (d) that the wide channel in area D is associated with a low complexity value of 20 (in area D-1). The complexity increases to 30 at the channel kink (area D-2) because the intervals between vessels decrease and there are a number of vessel crossings. We also see that the complexity decreases when the traffic density is low (area D-3).

The spatial distribution of the traffic complexity is in agreement with the velocity field of the traffic and reflects the traffic situation. Compares with the velocity field, the complexity map has some advantages as follows:

(1) More information
The complexity map displays more traffic information than the velocity field, not only the basic information, like geo-location information and velocity information of ships, but also the traffic evolution information. The relative motions of vessels, converging or diverging, are shown clearly in the map by different colours, which provide supports for the traffic controllers to identify the urgent traffic situation.

(2) More quantitative
The velocity field describes the traffic situation qualitatively. That is to say, it is easy to identify the complicated and uncomplicated traffic, but difficult to distinguish the difference in the complicated traffic situations. The complexity map is based on the complexity metric model which provides quantitative values to describe the traffic situation. As a consequence, the spatial distribution of the complexity can be employed to allocate the management resource optimally.

5. Conclusions

We have examined the spatial distribution of the complexity by analysing the characteristics of the traffic. After referring to airspace complexity analysis studies, the traffic density and traffic conflict were chosen as complexity factors to build a model of marine traffic flow complexity. We have demonstrated that the model shows the spatial distribution of the marine traffic complexity, the results can exhibit the real-time traffic situation directly, and the complexity map can help mariners and traffic controllers get the traffic situation awareness.

In aspect of the modelling process, the current complexity model is composed of the traffic density factor and conflict factor linearly. While the linear relationship between traffic density factor and conflict factor need further verify and the others relationship should be comparative analysed in the future.

In aspect of the assumptions, the homogeneity of vessels condition simplifies the current model. However, the ship type, size, and performance are totally different in real traffic flow. Generally, vessels in VC_{ij} are different, which means for every VC_{ij}, it has its own parameters: l_{upper}, l_{middle}, l_{lower}. Thus, how to obtain these parameters rapidly, accurately, and objectively is the main problem in the future work. Furthermore, the real traffic data based verification should be taken after these problems address.

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References

Balmata, J., Lafonta, F., Maifretb, R., Pessela, N., 2009. MAritime RISk assessment (MARISA), a fuzzy approach to define an individual ship risk factor. Ocean Eng. 36, 1278–1286.
Blokus-Roszkowska, A., Smolarek, L., 2014. Maritime traffic flow simulation in the intelligent transportation systems theme. In: Safety and Reliability: Methodology and Applications—Proceedings of the European Safety and Reliability Conference (ESREL 2014), Sep. 14–18, 2014, WROCLAW, POLAND.
Chatterji, G.B., Sridhar, B., 2001. Measures for air traffic controller workload prediction. In: Paper Presented at the First Aircraft, Technology Integration, and Operations Forum, Oct. 16–18, 2001, Los Angeles, CA. doi:10.2514/6.2001-5242.
Convention on the International Regulations for Preventing Collisions at Sea (COLREGs), 1972. The International Maritime Organisation (IMO).
Delahaye, D., Puechmorel, S., 2000. Air traffic complexity: towards intrinsic metrics. In: Paper Presented at the third US/Europe Air Traffic Management Research & Development Seminar, June 3–6, Napoli, Italy.
Delahaye, D., Paimblanc, P., Puechmorel, S., Histon, J.M., Hansman, R.J., 2002. A new air traffic complexity metric based on dynamical system modelization. In: Proceedings of the 21st Digital Avionics Systems Conference, Oct 27–31, Irvine, CA, p. 4A2-1–4A2-12.
Du, A., 2008. Study on Port Fairway Capacity Based on Standard Vessels Master's Thesis. Dalian University of Technology, Dalian [in Chinese.
Fefilatyev, S., Goldgof, D., Shreve, M., Lembke, C., 2012. Detection and tracking of ships in open sea with rapidly moving buoy-mounted camera system. Ocean Eng. 54, 1–12.
Goerlandt, F., Kujala, P., 2011. Traffic simulation based ship collision probability modelling. Reliab. Eng. Syst. Saf. 96, 91–107.
Goerlandt, F., Stahlberg, K., Kujala, P., 2012. Influence of impact scenario models on collision risk analysis. Ocean Eng. 47, 74–87.
Hilburn, B., 2004. Cognitive Complexity in air Traffic Control: A Literature Review. Eurocontrol, Brussels, Belgium, Tech. Rep. 04/04.
Kerner, B.S, 2009. Introduction to Modern Traffic Flow Theory and Control. Springer-Verlag, Berlin Heidelberg.
Laudeman, I.V., Shelden, S.G., Branstrom, R., Brasil, C.L., 1998. Dynamic Density: An Air Traffic Management Metric. National Aeronautics and Space Administration Ames Research Center (US), Moffet Field, NASA.TM-1998-112226.
Lee, K.J., Feron, E., Pritchett, A., 2007. Air traffic complexity: an input–output approach. In: Proceedings of the 2007 American Control Conference, July 9–13, New York, U.S.
Lee, K.J., 2008. Describing Airspace Complexity: Airspace Response to Disturbances (dissertation). Georgia Institute of Technology, Atlanta.
Masalonis, A., Callaham, M., Wanke, C., 2003. Dynamic density and complexity metrics for real-time traffic flow management. In: Proc. Fifth USA/Eur. Air Traffic Manag. Semin., Budapest, Hungary.

Montewka, J., Goerlandt, F., Kujala, P., 2012. Determination of collision criteria and causation factors appropriate to a model for estimating the probability of maritime accidents. Ocean Eng. 40, 50–61.
Shao, C., Fang, X., 2002. Fluid mechanics model for vessel traffic flow 28, 52–55 [in ChineseJ. Dalian Marit. Univ. 28, 52–55 [in Chinese.
Silveira, P., Teixeira, A.P., Soares, C.G., 2014. Assessment of ship collision estimation methods using AIS data, Maritime Technology and Engineering. CRC Press, pp. 195–204.
Tam, C., Bucknall, R., 2013. Cooperative path planning algorithm for marine surface vessels. Ocean Engineering 57, 25–33.
Toyoda, S., Fujii, Y., 1971. Marine traffic engineering. J. Navig. 24, 24–30.
Van de Laar, P., Tretmans, J., Borth, M., 2013. Situation Awareness with Systems of Systems. Springer.
Weng, J., Meng, Q., Qu, X., 2012. Vessel Collision frequency estimation in the Singapore strait. J. Navig. 65, 207–221.
Wang, Y., Vormer, F., Hu, M., Duong, V., 2013. Empirical analysis of air traffic controller dynamics. Transp. Res. C—Emerg. 33, 203–213.
Willems, N., Scheepens, R., van de Wetering, H., van Wijk, J.J., 2013. Visualization of vessel traffic, Situation Awareness with Systems of Systems. Springer, New York, pp. 73–87.
Xing, J., Manning, C.A., 2005. Complexity and Automation Displays of air Traffic Control: Literature Review and Analysis. Office of Aerospace Medicine, Federal Aviation Administration, Washington. DOT/FAA/AM-05/4.
Ye, B., Hu, M., Zhang, C., Zhang, J., 2012. Traffic structure-based air traffic complexity modeling. J. Transp. Syst. Eng. Inf. Technol. 12, 166–172 [in Chinese.
Yip, T.L., 2013. A marine traffic flow model. J. TransNav 7 (1), 109–113.
Zhang, C., Zhang, J., Hu, M., 2009. Air traffic complexity based on alliance effects. In: Proceedings of 28th Digital Avionics Systems Conference, Oct 25–29, 2009, Orlando, U.S.A., p. 7.A.1-1–7.A.1-9.
Zhang, W., Montewka, J., Goerlandt, F., 2015. Semi-qualitative method for ship collision risk assessment. In: Nowakowski, M. (Ed.), Safety and Reliability; Methodology and Applications. Taylor and Francis Group, London, pp. 1563–1572.