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RESEARCH ARTICLE

A cellular automaton-based model of ship traffic flow in busy waterways

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Abstract
In busy waterways, spatial-temporal discretisation, safe distance and collision avoidance timing are three of the core components of ship traffic flow modelling based on cellular automata. However, these components are difficult to determine in ship traffic simulations because the size, operation and manoeuvrability vary between ships. To solve these problems, a novel traffic flow model is proposed. Firstly, a spatial-temporal discretisation method based on the concept of a standard ship is presented. Secondly, the update rules for ships' motion are built by considering safe distance and collision avoidance timing, in which ship operation and manoeuvrability are thoroughly considered. We demonstrate the effectiveness of our model, which is implemented through simulating ship traffic flow in a waterway of the Yangtze River, China. By comparing the results with actual observed ship traffic data, our model shows that the behaviours and the characteristics of ships' motions can be represented very well, which also can be further used to reveal the mechanism that affects the efficiency and safety of ship traffic.

1. Introduction

Maritime shipping occupies a crucial and significant place in global transportation. The *50 Years of Review of Maritime Transport, 1968–2018* noted that '. . . Shipping carries the vast majority of international trade with its share ranging between 80 and 90 per cent of trade. . . . In terms of trade value, of course, the shipping share is around 60 to 70 per cent of trade' (UNCTAD, 2018; Qi and Ji, 2020). However, maritime transport has always faced environmental pollution, transportation efficiency, navigation safety and other issues (Chen et al., 2019a, 2019b). In order to solve or relieve the negative consequences of these issues, researchers and engineers have been continuously developing new techniques and methods for years (Bell and Meng, 2016; Hua et al., 2020). With the development of e-Navigation, SMART-Navigation and intelligent navigation, the microscopic behavioural characteristics of ships and their influences on the whole marine traffic system are becoming a research hotspot, especially in the area of ports, waterways and other congested areas. One of the main and effective methods to study the above topics is to build a model and simulate ship traffic.

Cellular automata (CA) was systematically studied in the 1980s; it was pointed that, based on CA models and a series of related rules, complicated phenomena could be simplified and simulated (Wolfram, 1983; 1984a, 1984b; Wolfram and Mallinckrodt, 1995). The Nagel–Schrekenberg (NaSch) model, which was proposed in 1992, began the period when CA models attracted more and more attention from researchers in the field of transportation; and from then on, many improved traffic flow models based on CA were proposed (Nagel and Schreckenberg, 1992). Due to improvements in computing capability, the method of CA microscopic simulation was successfully used for modelling traffic flows (Biham et al., 1992; Takayasu and Takayasu, 1993; Kerner et al., 2002). One of the most favourable aspects of CA simulation is that it can extract the features from complex systems and then represent the systems using abstract forms for subsequently analysing and solving the relevant problems (Chowdhury et al., 2000; Helbing, 2001; Chen and Wang, 2015, 2016; Bao et al., 2018; Yang et al., 2019). The applications of CA modelling are very diverse in transportation fields ranging from motor vehicles, bicycles, pedestrians, trains, airplanes and ships (Naito and Nagatani, 2012; Rahman et al., 2013; Chen et al., 2019c; Yi et al., 2020), but research on ship traffic flow based on CA modelling is in its infancy and there have so far been very few research achievements. However, the related theories and applications have developed rapidly (Huang et al., 2019; Zhou et al., 2019).

There are three types of ship traffic flow models based on CA. The first one is the *single-lane ship traffic model*. A CA-based model combined with queuing theory and the Wolfram 184 rule was presented for simulating ship traffic flow at a harbour (Chen et al., 2009). Then this model was improved by considering the characteristics of ship traffic flow (Liu et al., 2010). A single-lane model on the basis of the NaSch model was used to simulate the traffic situation around ports (Xiao, 2011). The ship following behaviour was considered in single-lane CA modelling for inland waterways (Ke, 2010). A specific CA model was presented for ship traffic in the 'Xiazhimen' waterway, the shape of which is very narrow compared with the whole routes, and in this model the ship's domain, acceleration and deceleration were taken into account (Xin et al., 2019).

The second model is the *multi-lane ship traffic model*. Different from the previous single-lane CA models, the multi-lane CA model considered lane-changing rules (Ding et al., 2009; Ke, 2010). From 2013 to 2016, several two-lane or multi-lane CA models were proposed for ship traffic flow in harbours or inland canals (Feng, 2013; Feng et al., 2014a, 2014b; Sun et al., 2015; Tang, 2016). Then a multi-lane CA model with added regulations for preventing collisions and achieving a safe distance was proposed for the traffic flow around a port (Rong, 2016). A multi-lane model for ship traffic in the main fairway of Xiamen port was built (Zhao, 2017). In 2017, two CA models to solve the problems of spatial discretisation of waterways and the change of ship's velocity caused by the weather and sea conditions were proposed (Qi et al., 2017a, 2017b). The minimum safe distance in a two-lane waterway traffic model was discussed (Liao et al., 2019; Yang et al., 2020).

The third one is the *other type of ship traffic model*, which could not be classified into the above two types. In 2012, the CA-based model that was proposed to simulate the ship traffic flow in the Singapore Strait did not consider the lane-changing rules but instead decomposed the ship velocity direction into two components to simulate ship movements (Qu and Meng, 2012). The model, which was built by combining the multi-agent model and CA model, was proposed for marine traffic flow (Yan et al., 2009; Wang, 2011; Yu et al., 2014). A traffic flow model for simulating ships' motion in a grade roundabout crossing part of marine waterways was built (Blokus-Roszkowska and Smolarek, 2013). And research on marine traffic in Arctic waters was conducted (Khan et al., 2019).

Ship traffic flow has some unique characteristics, and therefore models based on motor vehicles, bicycles or pedestrians cannot be directly used for the modelling of ship traffic flow. These characteristics should be taken into account for a CA-based ship traffic flow model (Xu et al., 2014; Sun et al., 2015; Zhou et al., 2019). Some of the characteristics have been considered; for example, the ratio of the width of a waterway to the width of a ship is relatively larger than the ratio of a roadway to that of a vehicle, the navigation of a ship is greatly affected by meteorological and hydrological conditions, etc. Some other characteristics, e.g. ships' hydrodynamic characteristics, the difference in size between ships, and the operation and manoeuvrability difference between ships, should be considered in CA modelling for ship traffic flow.

In this paper, the research is focused on the ship's safe distance and collision avoidance timing in the CA model of ship traffic flow, by considering some unique characteristics of ship traffic in busy waterways. Based on the standard ship, ship domain and manoeuvring characteristics of the ships, a novel model suitable for busy waterways is proposed in this paper.

The structure of the rest of the paper is as follows. Section 2 states the methodology of the modelling. Section 3 shows the tests and analyses the performance of the proposed model. Section 4 concludes the main contribution of this paper and looks at the prospects for future study.

2. Methodology

In this section, the spatial-temporal discretisation method based on the standard ship, the ship safe distance based on ship domain, and the collision avoidance timing based on ship manoeuvrability are introduced. Then, based on the above research results, the new update rules for ship motion are built.

2.1. *Spatial-temporal discretisation*

For vehicle traffic flow modelling, one needs to do the spatial-temporal discretisation first. The space of the road is divided into many small cells, the length of each cell generally being taken as equivalent to the length of a vehicle. The update time is discretised, and the time step is usually 1 s. This is because when the traffic is congested, the distance between two vehicles can be very small, which means that the space headway between two adjacent vehicles is approximately equal to the length of one vehicle. Because a vehicle's velocity is relatively higher than a ship's, multiple cells can be crossed in 1 s. Assuming the length of a cell is 5 m and the velocity of the vehicle ranges from 0 km/h to 100 km/h, the number of cells crossed by the vehicle in one time step is about 0 to 6 cells, which is feasible for vehicle traffic simulation.

However, this is inapplicable to ship traffic, because the sizes of different ships could vary considerably, and it is necessary to maintain a large distance between ships for safety. Therefore, the unit for ship's length should be determined first. In marine traffic engineering, due to the different size and tonnage of ships, in order to achieve a scientific and rational representation of the traffic volume in waterways, the *standard ship* is used to normalise ships of different sizes (Wu and Zhu, 2004). Therefore, the length of a standard ship is used as the minimum unit to describe the length of ships in a waterway, which can be denoted by the symbol L_s. The lengths of other ships are integral multiples of the standard ship length, denoted by nL_s, where n is a positive integer coefficient. In this paper, the standard ship length L_s is used as the size of a cell along the direction of traffic flow.

In addition, different from the concept of lanes in road traffic, there is no further division in a waterway for the route on which a single ship should sail, and it can be seen from the ships' trajectories distribution that ships do not follow a specific lane in a waterway. However, the rules for the navigation of ships in the waterway are usually enacted, like the maximum velocity allowed for a ship, and whether a ship can be overtaken by other ships. If a ship is not allowed to overtake its preceding ship, the waterway can be considered as a single lane. Otherwise, the waterway can be considered as a multi-lane. Generally, the number of lanes can be two or more, which is determined by the width of the waterway and the lateral safe distance between ships. But in busy waterways the number can also be determined by observing how many ships at most are in parallel.

In the CA model, the temporal discretisation is often performed by the equal interval discretisation method, so the time step Δt needs to be determined first, which affects the accuracy of the simulation. The time step can be obtained by Equation (1):

$$\Delta t = kL_s/v_0, \tag{1}$$

where v_0 is the minimum integer value of a ship's speed, such as 1 kn (the unit of ship's velocity, one knot, 1 kn ≈ 1·852 km/h). In Equation (1) k is a positive integer coefficient, which is used to adjust the simulation step. When $v_0 = 1$ kn, the distance that the ship sails forward in time Δt is the length of k

cells, that is, kL_s. Thus k determines the simulation accuracy: the smaller k is, the smaller the time step is, the higher the simulation accuracy is, and, accordingly, the more computing resources are consumed.

2.2. *Ship safe distance*

The surrounding safe area of a ship is the *ship domain* (Fujii and Tanaka, 1971; Goodwin, 1973). The shape of the ship domain can be oval, rectangular or others, and the main parameters are the lateral size and the longitudinal size (Lamb, 1983; Zhao et al., 1993). Since in Subsection 2.1 the waterway was divided into several lanes, which has already taken the lateral safe distance into account, this section only deals with the longitudinal safe distance between ships in the same lane. Most of the research results show that the longitudinal size of the ship domain is roughly proportional to the length of the ship (Liu et al., 2011; Qi et al., 2011; Hansen et al., 2013; Liu et al., 2016; Hörteborn et al., 2019; Zhou and Zheng, 2019). As mentioned above, the length of a ship can be denoted by nL_s; then, based on the ship domain, the safe distance between a ship and its preceding ship in the same lane can be calculated by Equation (2):

$$D_{\text{safe}} = mnL_s, \tag{2}$$

where m is the multiple of safe distance relative to ship length. The value of m is related to the selected ship domain model, and it can also be obtained by ship traffic data statistics.

2.3. *Collision avoidance timing*

In a waterway, when a ship finds itself in collision danger with its preceding ship, it will choose a timing to change its action to avoid the potential risk (Zhuo and Tang, 2008; Chen and Huang, 2012). The *timing when a ship takes action to avoid collision* can be expressed by the time left before the collision, i.e. $T_{\text{act}} = \Delta d/\Delta v$, which is also called the time to closest point of approach (TCPA) (Erwin, 2012) in nautical navigation. Here Δd is the distance between two adjacent ships in the same lane, which is equal to the distance at closest point of approach (DCPA). The ship's location, which is used to calculate the value of Δd, is in the centre of the ship; and Δv is the relative velocity of two adjacent ships (Zhao et al., 1995; Kang et al., 2019). It is generally believed that T_{act} is relevant to the manoeuvrability of the ship, and the manoeuvrability is relevant to the ship's size and velocity (Bi et al., 2004a, 2004b). Therefore, the collision avoidance timing for ships can be expressed by Equation (3):

$$T_{\text{act}} = f_2(nL_s, v), \tag{3}$$

where nL_s represents the length of the ship, and v represents the velocity of the ship. Here f_2 represents the functional relationship between collision avoidance timing and the ship's length and velocity.

In addition, the ship density (ρ) and environmental factors (e) in the waterway can affect the collision avoidance behaviour of the ship (Wu and Zhu, 2004). Therefore, these factors can also be taken into account, so the collision avoidance timing can be expressed as

$$T_{\text{act}} = f_3(nL_s, v, \rho, e, \ldots). \tag{4}$$

However, the relationship between T_{act} and the parameters nL_s, v, ρ and e is very complicated, and the specific form of f_3 has not been found in related research literature. Specific and simplified forms can be expressed according to the specific application scenarios.

2.4. *Update rules*

Because the model studied in this paper is applicable to a busy waterway in which a ship is allowed to overtake its preceding ship, it is necessary to consider lane-changing behaviour. In addition, when slow ships occupy all the lanes and cause traffic congestion, the following ships can contact a slow ship by very-high-frequency radiotelephone (VHF-RT) to ask the slow ship to give way to them. This is similar to the honk behaviour of a fast vehicle in road traffic, which will be called the *VHF-RT effect* for the ship traffic in this paper. If the study of this paper needs to be applied to a single-lane waterway, just set all the ships to be not qualified for the lane-change condition in any case.

We use $v_i(t)$ to represent the velocity of ship i at time t. The length of ship i is $n_i L_s$, and the maximum velocity of ship i at time t is $V_{\max,i}(t)$; the preceding ship of i in the same lane is expressed by j.

Safe distance: According to Equation (2) in Subsection 2.2, the safe distance between ships i and j is mnL_s, where the value of L_s is the same as the value of the cell size. Therefore, the safe distance between i and j can be expressed by mn. Let $n_i L_s$ be the length of ship i. The safe distance is

$$D_{\text{safe},i} = mn_i. \tag{5}$$

Action distance: According to Equation (4) in Subsection 2.3, when ship i is in collision danger with its preceding ship j, the action timing of ship i, which is $T_{\text{act},i}$, can be calculated. Let the velocity of ship j be $v_j(t)$, and $\Delta v_{ij}(t) = v_i(t) - v_j(t)$, with $v_i(t) > v_j(t)$. The action distance from ship i to ship j is

$$D_{\text{act},i}(t) = T_{\text{act},i}\Delta v_{ij}(t). \tag{6}$$

Lane-change condition: When the ship that needs to change lane is in a new lane, all the other ships should not be in collision danger with it or no ship needs to take action to avoid collision at that time.

The *update rules* can be described as follows:

(i) Acceleration: Let $\text{gap}_i(t)$ denote the distance from i to j at time t. If $\text{gap}_i(t) > D_{\text{act},i}(t)$, then

$$v_i(t) \longrightarrow \min[v_i(t) + 1, V_{\max,i}(t)]. \tag{7}$$

(ii) Lane-change: If $gap_i(t) \le D_{\text{act},i}(t)$, and all the other ships in the neighbouring lane are far away from i, i.e. the distances are all greater than $D_{\text{act},i}(t)$, i should change to the neighbouring lane, and update the velocity of i by Equation (7).

(iii) VHF-RT effect: If $\text{gap}_i(t) \le D_{\text{act},i}(t)$, but there is a ship in the neighbouring lane and its distance to i is less than $D_{\text{act},i}(t)$, so i cannot change lane, then the VHF-RT effect needs to be considered, and j should try to give way to i. If j is qualified for the lane-change condition, j should change to another lane. Then, find out whether there is another ship in front of ship i. If there is such a ship, the front ship should be named as ship j, and recalculate the motion relationship between i and j, and go back to item (i). Otherwise, directly update the velocity of i by Equation (7). If j is not qualified for the lane-change condition, i should follow j; then go to the next item.

(iv) Deceleration: If $\text{gap}_i(t) \le D_{\text{act},i}(t)$, and i cannot overtake j, and j cannot give way to i, then i must decelerate to follow j, so

$$v_i(t) \longrightarrow \min[v_i(t), \text{gap}_i(t) - D_{\text{safe},i}]. \tag{8}$$

(v) Update velocity $v_i(t+1) = v_i(t)$, location $x_i(t+1) = x_i(t) + v_i(t+1)$ and maximum velocity $V_{\max,i}(t+1)$ by referring to the previous research of Qi et al. (2017b).

In addition, if a ship is not allowed to overtake other ships by the traffic rules, in the situation of item (ii) and item (iii), i must follow j and update its velocity by Equation (8).

3. Test and simulation results

In this section, the performance of the proposed model is tested. Firstly, the statistics and analysis of the ship traffic data in a waterway of the Yangtze River are introduced. Secondly, the results of a ship traffic simulation based on the model are analysed.

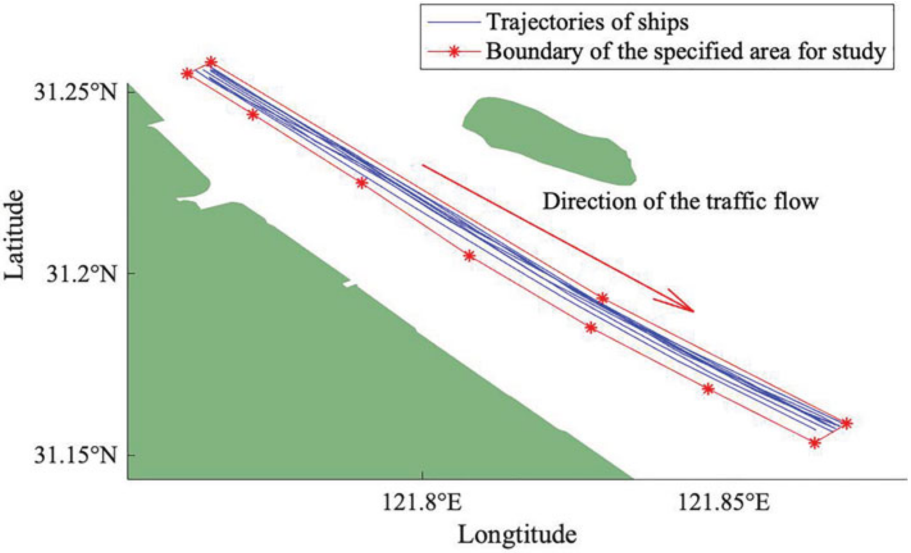

Figure 1. *The map of a segment of waterway in Yangtze River.*

3.1. Statistics and analysis of ship traffic

The ship traffic data were collected by the Automatic Identification System (AIS). The sample data are from the AIS message records of the down-bound ships in a segment of Nancao Waterway at the estuary of the Yangtze River, which is one of the busiest water shipping areas in China. Part of the ships' trajectories from the AIS data are shown in Figure 1. The parameters of the traffic flow are: 0·4 n mile (width) and 8 n miles (length), southeast (direction). Because the ships should keep a lateral safe distance between each other and only at most three ships are found sailing side by side in the waterway, the number of lanes in the CA model can be set to three.

The ships' length, which is a very important parameter as mentioned in Section 2, should be analysed for the traffic simulation. Figure 2(a) shows the statistical result of the length of the ships sailing through the waterway. The ships' length is generally consistent with the generalised Gaussian distribution, and ships of around 100 m account for the largest proportion. The minimum length of the ships is around 30 to 50 m, and the maximum length of the ships is around 320 to 370 m. According to the definition of standard ship length in Subsection 2.1, the value of L_s could be set to 30 m, which is also the cell size along the direction of traffic flow. By referring to the research of Fujii and Tanaka (1971) for ship traffic in a river, the value of m can be 8.

Figure 2(b) shows the statistical result of the velocity of the ships, which is also generally consistent with the generalised Gaussian distribution. The velocity of most ships ranges from 3 to 15 kn, with a very small number of ships occasionally exceeding 15 kn. The mean velocity of all the ships is around 10 to 11 kn. According to the update rules analysed in Subsection 2.4, the velocity of ships changes with the influence of the meteorological and hydrological conditions, so the velocity–time curves of ships are analysed and shown in Figure 2(c). The change cycle of ship's velocity is approximately 12.4 h, and the amplitude of the regular change is about 6 kn per cycle; the random change is less than 1 kn. In addition, the time interval should be set for generating ships' simulation traffic data, which can be approximately equivalent to the interval time of arrival of ships. The distribution of interval time of ships' arrival is shown in Figure 2(d), which is almost consistent with the exponential distribution.

According to Subsection 2.3, the collision avoidance timing T_{act} is related to the parameters nL_s, v, ρ and e, and is very complicated. But in this test, Equation (4) can be simplified. Because the environmental factor has been considered above, as shown in Figure 2(c), and the ship density does not change very much during the simulation, ρ and e can be ignored in Equation (4). Because of the ships'

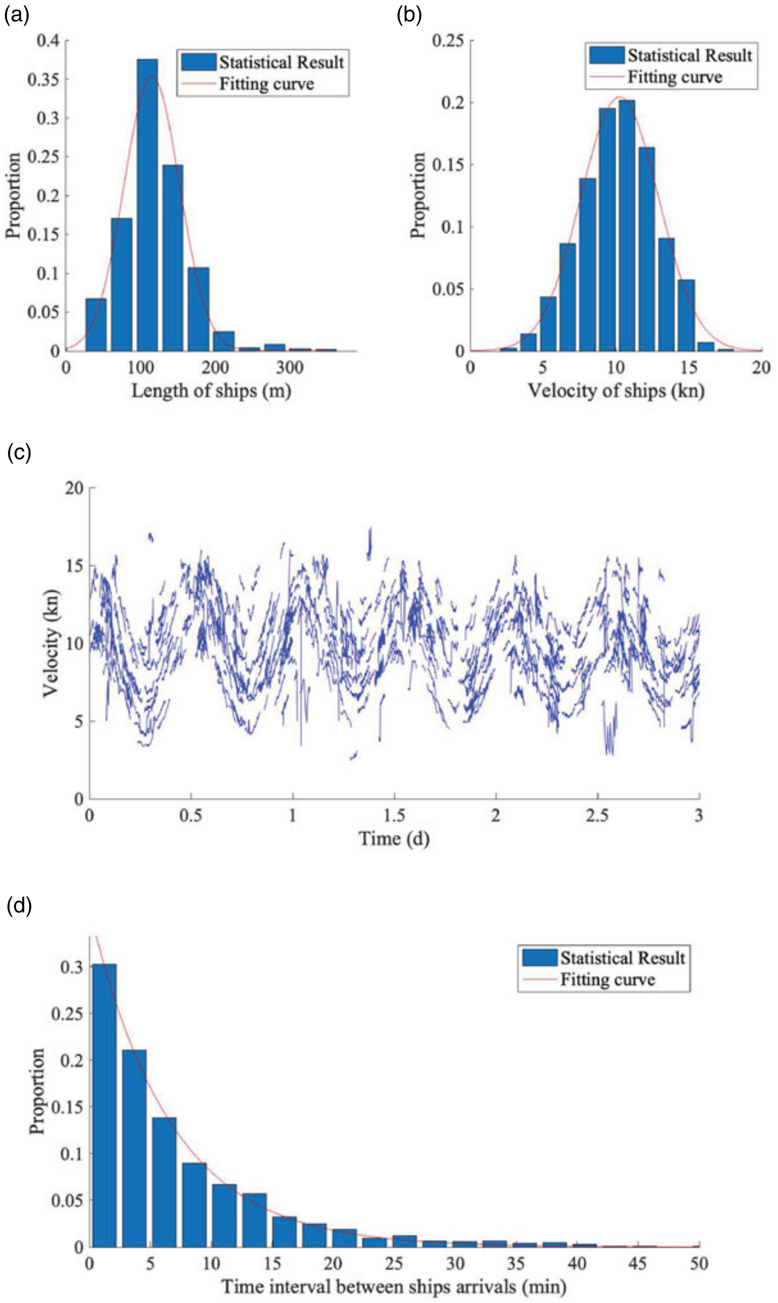

Figure 2. *Statistical results of one segment in the waterway of Yangtze River from AIS data: (a) distribution of ship lengths and its fitting curve; (b) distribution of ship velocities and its fitting curve; (c) the velocity–time curves of ships; and (d) distribution of time intervals between arrival of ships and its fitting curve.*

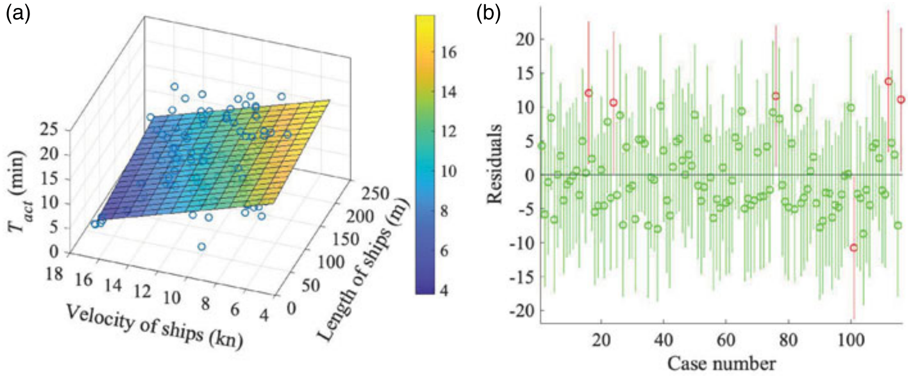

Figure 3. *The relationship between T_{act}, ships' velocity and ships' length: (a) the sample points and fitting surface by the regression; and (b) the confidence intervals on the residuals from the regression.*

hydrodynamic characteristics, the larger the ship is, the worse the ship's manoeuvrability will be, which needs a longer time to take action to avoid collision, and vice versa. Therefore, Equation (4) can be simplified to $T_{\text{act}} = k_1 nL_s - k_2 v + k_3$, where k_1 and k_2 reflect the influence of a ship's length and speed on the collision avoidance timing; here k_3 is a harmonic constant.

In order to determine the parameters k_1, k_2 and k_3, the avoidance actions of the ships in the waterway are observed; then the action timing, velocity and length of the ship are recorded at each sample point. The data samples were fitted based on a regression method, with $k_1 \approx 0{\cdot}0174$, $k_2 \approx 0{\cdot}8944$ and $k_3 \approx 18{\cdot}2821$. The sample points and fitting surface are shown in Figure 3(a). Figure 3(b) shows the confidence intervals on the residuals from the regression. During the simulation, if the position, length and velocity of two adjacent ships are known, as T_{act} can be calculated, the action distance D_{act} can be calculated according to Equation (6) in Subsection 2.4, which is a very important dynamic variable in update rules.

3.2. Analysis of simulation results

In this subsection, the simulation results are compared with the real ships' trajectories data in the waterway; then the performance of the proposed model is analysed.

Because the ship traffic flow is modelled mainly by considering the safe distance and collision avoidance, the lane-changing actions for a ship to overtake its preceding ship or to give way to its following ship, and the deceleration behaviour, are analysed. In order to analyse the characteristics of these three types of ships' collision avoidance phenomena, it is necessary to combine the ships' trajectories map with the ships' spatial-temporal diagram. The trajectories map can describe the position change of the ships during movement, and the spatial-temporal diagram can reflect the change of the ships' velocity and the positional relationship between the ships. Therefore, based on Figure 1, the time axis is added, and the ships' three-dimensional spatial-temporal trajectories are drawn to analyse these three types of ships' collision avoidance phenomena. The three coordinate axes are longitude, latitude and time.

In order to analyse the phenomenon of a fast ship overtaking its preceding slow ship by lane-changing, the three-dimensional spatial-temporal trajectories of ships is drawn, as shown in Figure 4(a). The projection of the three-dimensional trajectories on the latitude–longitude plane is the two-dimensional trajectories of the ships on a map. It can be seen from Figure 4(a) that a faster ship i_1 overtook its preceding ship j_1. The trajectories of the ships during the overtaking action is indicated with broken lines, as shown on the latitude–longitude plane in Figure 4(a). Figure 4(b) shows the trajectories in the selected area. Ship i_1 sailed on the left side of the waterway at first, and then sailed to the middle of the waterway in order to overtake ship j_1. Figure 4(c) shows the overtaking action from simulation results. Ship i_1' overtook ship j_1'. As shown in Figure 4(d), ship i_1' sailed in lane 2 at first, and then, in

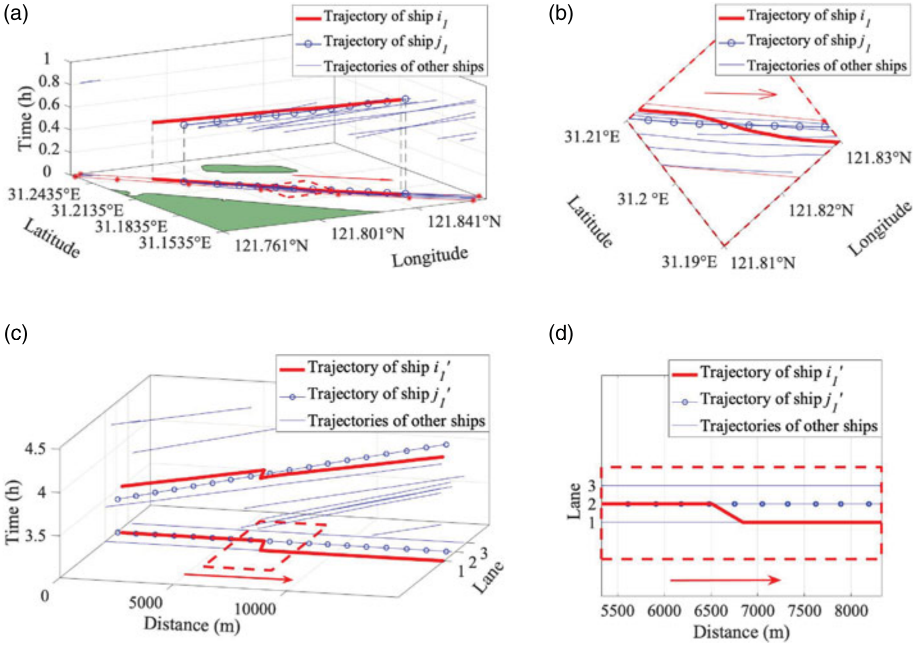

Figure 4. *The phenomenon of a fast ship overtaking its preceding slow ship by lane-changing: (a) the three-dimensional spatial-temporal trajectories of ships in the waterway; (b) the trajectories of ship* i_1 *overtaking its preceding ship* j_1*; (c) the three-dimensional spatial-temporal trajectories of ships in the simulation; and (d) the trajectories of ship* i_1' *overtaking its preceding ship* j_1'*.*

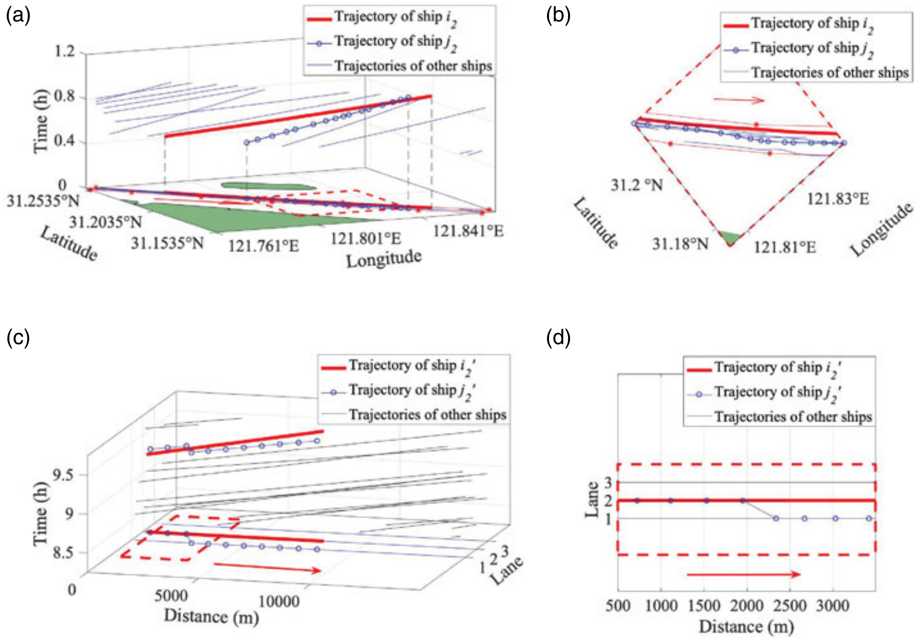

Figure 5. *The phenomenon of a slow ship giving way to its following fast ship by lane-changing: (a) the three-dimensional spatial-temporal trajectories of ships in the waterway; (b) the trajectories of ship* j_2 *giving way to its following ship* i_2*; (c) the three-dimensional spatial-temporal trajectories of ships in the simulation; and (d) the trajectories of ship* j_2' *giving way to its following ship* i_2'*.*

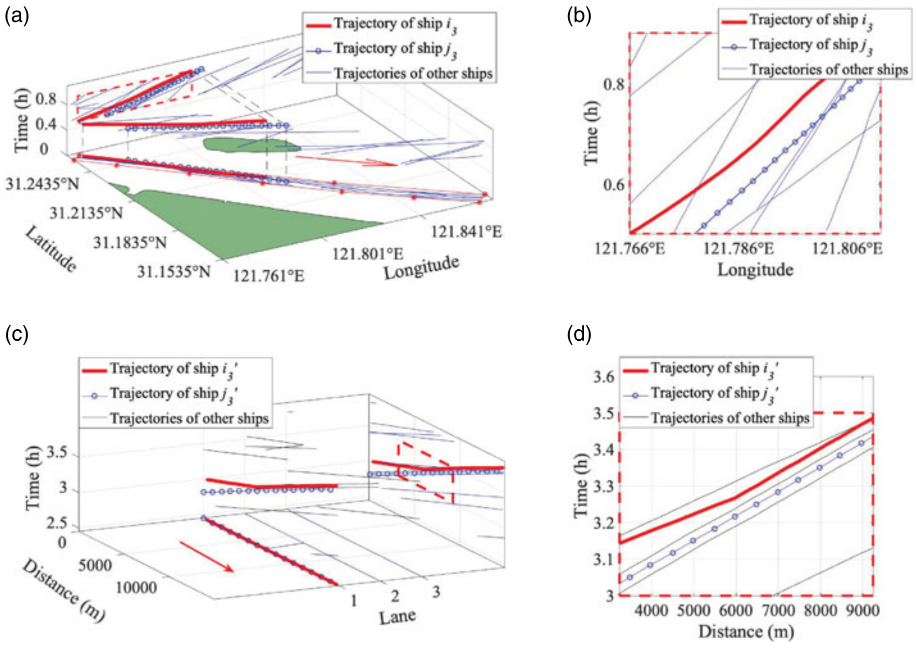

Figure 6. *The phenomenon of a fast ship following its preceding slow ship by deceleration: (a) the three-dimensional spatial-temporal trajectories of ships in the waterway; (b) the trajectories of ship* i_3 *following its preceding ship* j_3*; (c) the three-dimensional spatial-temporal trajectories of ships in the simulation; and (d) the trajectories of ship* i_3' *following its preceding ship* j_3'*.*

order to overtake ship j_1', it changed to lane 1 and overtook ship j_1'. Compared with Figures 4(a) and 4(b), respectively, the simulation results in Figures 4(c) and 4(d) are consistent with the observed ship lane-changing behaviour, which shows that the model can simulate the overtaking phenomenon very well.

In order to analyse the phenomenon of a slow ship giving way to its following ship, the three-dimensional spatial-temporal trajectories of ships is drawn, as shown in Figure 5(a). The velocity of ship i_2 was faster than that of its preceding ship j_2. When ship i_2 overtook ship j_2, ship j_2 gave way to ship i_2. As can be seen from Figure 5(b), ship j_2 was near the left side of the waterway at first, and then sailed to its right to give way to the following ship i_2, which is called the VHF-RT effect, as mentioned above. Figure 5(c) shows the process of giving way action from the simulation results. The slow ship j_2' gave way to the fast ship i_2'. As shown in Figure 5(d), ship j_2' sailed in lane 2 at first, and then, in order to give this lane to ship i_2', it changed to lane 1. Compared with Figures 5(a) and 5(b), respectively, the simulation results in Figures 5(c) and 5(d) are consistent with the observed ship lane-changing behaviour, which shows that the model can simulate the giving way phenomenon very well.

In order to analyse the phenomenon of a fast ship following its preceding slow ship by deceleration, the three-dimensional spatial-temporal trajectories of ships is drawn, as shown in Figure 6(a). The velocity of ship i_3 was faster than that of its preceding ship j_3. When ship i_3 sailed near ship j_3, there was traffic congestion; ship j_3 could not give way to ship i_3. Ship i_3 had to follow j_3 by deceleration. In order to show the deceleration of ship i_3, the projection of the three-dimensional trajectories on the latitude–longitude plane is drawn, as shown in Figure 6(a). Figure 6(b) shows the trajectories in the selected area with broken lines in Figure 6(a). The velocity of ship i_3 was fast at first, but when it sailed near ship j_3, its velocity slowed down, to be similar to the velocity of ship j_3. Figure 6(c) shows the process of the following action from simulation results. The fast ship i_3' followed its preceding slow ship j_3' in lane 3 by deceleration, because there were ships in the other two lanes, lanes 1 and 3, which resulted in traffic congestion. As shown in Figure 6(d), the velocity of ship i_3' was faster than that of

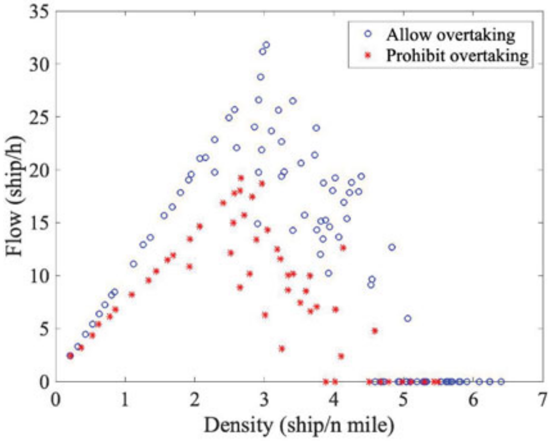

Figure 7. *The simulation results of ship traffic flow at different ship densities under the conditions when overtaking is allowed or prohibited in the waterway.*

ship j_3', but when ship i_3' sailed near ship j_3', its velocity slowed down. Compared with Figures 6(a) and 6(b), respectively, the simulation results in Figures 6(c) and 6(d) are consistent with the observed ship deceleration behaviour, which shows that the model can simulate the following phenomenon very well.

To study the traffic capacity of the waterway under conditions when overtaking is allowed or prohibited, simulations of ship traffic flow under these conditions were conducted. Ship traffic flow under different traffic densities of the waterway are statistically analysed, and the results are presented in Figure 7. When overtaking action is allowed in the waterway, the ship traffic capacity is larger than it is under the condition that overtaking action is prohibited. This illustrates that when the fast ship is prohibited to overtake its preceding slow ship by lane-changing, the speed of the ships in the waterway is greatly constrained by the slow ships, and the capacity of the waterway declined significantly in this situation.

4. Conclusions and prospects

In this paper, a cellular automaton-based model of ship traffic flow in busy waterways is proposed. In this model, the spatial-temporal discretisation for ship traffic flow and update rules for ships' motion have been studied by considering the unique characteristics of ship traffic flow.

Firstly, by studying the characteristics of the ships' length and velocity distribution, a new spatial-temporal discretisation method is proposed. By introducing the concept of a standard ship, this method solves the spatial-temporal discretisation problem caused by the size difference between ships.

Secondly, the update rules for the three typical collision avoidance behaviours of ships in busy waterways, i.e. overtaking, giving way and following, have been built. The safe distance and collision avoidance timing of ships in a busy waterway have been studied, based on which the rules for ships' overtaking and following action are built. In addition, the VHF-RT effect, which is similar to the honk effect in motor vehicle traffic flow, has been studied to build rules for the action of ships giving way.

Simulations of ship traffic in the busy waterway of the Yangtze River have been conducted. The results show that the traffic flow model proposed in this paper can successfully simulate the collision avoidance behaviours of ships in the waterway, which are consistent with the actual ships' behaviours. Besides, the effect of the overtaking rules on the traffic capacity of the waterway has been studied. The results show that the traffic capacity of the waterway declined significantly when overtaking is prohibited.

Next, the influences of different ship traffic organisation plans on the microscopic behaviours, and the influences of ships' microscopic behaviours on the whole traffic flow, need to be studied, so as to reveal the influence mechanism of different traffic organisation plans on ship traffic safety and efficiency.

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