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EFFECT OF WATER FLOWS ON SHIP TRAFFIC IN NARROW WATER CHANNELS BASED ON CELLULAR AUTOMATA

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ABSTRACT

In narrow water channels, ship traffic may be affected by water flows and ship interactions. Studying their effects can help maritime authorities to establish appropriate management strategies. In this study, a two-lane cellular automation model is proposed. Further, the behavior of ship traffic is analyzed by setting different water flow velocities and considering ship interactions. Numerical experiment results show that the ship traffic density-flux relation is significantly different from the results obtained by classical models. Furthermore, due to ship interactions, the ship lane-change rate is influenced by the water flow to a certain degree.

Keywords: Narrow channel, Cellular automata, Simulation, Ship interaction

INTRODUCTION

A narrow channel often refers to navigable water restricted by its lane width, and to some extent, sailing in narrow channel restricts the ship maneuvers [1]. Due to some features of narrow channels, such as the narrow width, changeable water depth, large density of ships etc., ship collisions often occur in narrow channels, which seriously holds back the development of marine transportation [2, 3]. Therefore, it is important to investigate the characteristics of ship traffic in narrow channels.

General vehicle traffic models are based on basic kinetics models, which cannot simulate dynamic traffic features. However, Cellular Automata (CA) can be used to study phenomena where many individuals interact with each other. The CA can reproduce the time and satisfies the dynamic system needs for evolution in a discrete form [4].

In the 1980s, the CA technology entered people' field of vision. The NaSch model and BML model proposed by Nagel and Schreckberg are classical traffic flow models based on the CA [5]. The NaSch model is a classical single-lane model, After improvement, this classical model can reproduce many major features of traffic flows [6]. However, the NaSch model does not allow overtaking, which is a limitation. Accordingly, many single-track multiple lanes models considering overtaking [7-9] and many lane-change rules [10-12] were proposed. Nowadays, the CA is widely used in studying of road traffic flows. Tieqiao Tang et al. [13] develop a macro traffic flow model with consideration of varying road conditions. Xiaobo Qu et al. [14] develop an improved multi-value cellular automata model for heterogeneous bicycle traffic flow taking the higher maximum speed of electric bicycles into consideration, greatly enhances the realism of the bicycle traffic model.

In marine traffic flows, Xiaobo Qu et al. [15] propose a cellular automata model based simulation approach for the Singapore Strait, and a two-lane cellular automata model is proposed by Zhuo Sun et al. [16] to investigate the traffic flow patterns in narrow water channels. There are two main differences between water traffic and road traffic. First, both water flow direction and velocity can accelerate or hold back ships. In ship traffic flows, the actual speed of ships equals the composition of the hydrostatic speed and water velocity. The hydrostatic speed changes frequently in a range. Through superposition, the range of the actual speed of ships also changes, and the lower bound of this range depends on the water velocity. The second important difference is due to ship interactions [17]. When two ships sail in parallel in close lanes, the water accelerates between the two ships, since the water pressure decreases, and the water slows down on the external side of the ship where the water pressure is relatively high. As a result, a difference in pressure is produced between the portside and starboard, so that the two ships are pushed towards each other.

MODEL

A ship interaction cellular automation model (SICA) based on the NaSch model is proposed. The new lane-change update rule for the period from t to $t+1$ is introduced as follows.

Rule1 Acceleration:

$$v_n^t \quad \min(v_n^t + a_n, v_{\max}) \tag{1}$$

where v_n^t and v_n^{t+1} represent the speed of ship n at moment t and $t+1$, respectively, a_n is the acceleration of ship n, and $v_{\max}$ is the maximum speed of the ship. Rule1 describes the feature that the driver wants to maneuver the ship at the maximum speed.

Rule2 Deceleration to avoid ship collisions:

$$v_n^{t+1} = \min(v_n^t, d_n^t) \tag{2}$$

where $d_n^t = x_{n+1}^t - x_n^t - l_{n+1}$, x_n^t and x_{n+1}^t represent the position of ship n and the front ship $n+1$ at moment t, respectively, and l_{n+1} is the length of the front ship $n+1$. Accordingly, d_n^t means the distance between the front ship and the rear ship. Rule2 describes the action of the driver to avoid a collision between the two ships.

Rule3 Deceleration due to a ship interaction:

$$v_n^{t+1} = \max\left(\min\left(v_n^t - a_n, d_n^t\right), v_{\min}\right) \tag{3}$$

Considering a ship interaction, the rule says: if overtaking happens in two lanes, the ship having a lower speed needs to slow down, and, while avoiding the collision with the front ship, it should also keep the speed over the minimum speed $v_{\min}$.

Rule4 Lane changing:

$$L_n^{t+1} = \begin{cases} \text{other lane} & \text{if } d_n^t < \min(v_{\max}, v_n^t + 1) \text{ and } d_{n,oa}^t > d_n^t \text{ and } d_{n,ob}^t > d_{safe} \\ \text{not change} & \text{otherwise} \end{cases} \tag{4}$$

where L_n^{t+1} denotes the lane ship n stays in at moment $t+1$, $d_{n,oa}^t$ and $d_{n,ob}^t$ represent the distance between ship n and the front or rear ship in adjacent lanes, and d_{safe} denotes the safe distance. Taking the example of ship A in the right lane in Fig.1, at moment t, the horizontal distance $d_{n,oa}^t$ is larger than the distance d_n^t. And in the left lane, the horizontal distance $d_{n,ob}^t$ is larger than the safe distance d_{safe}. At moment $t+1$, ship A changes the lane from right to left. However, if one of the above conditions cannot be satisfied, ship A cannot change the lane.

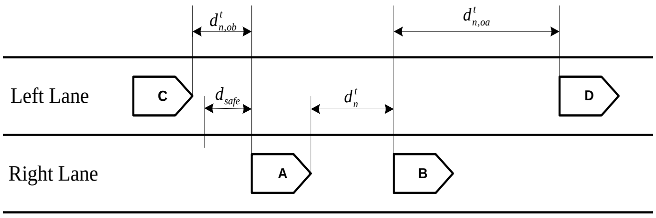

Fig.1. The description of the formula (4) parameter

Rule5 Randomization with possibility ***p*****:**

$$v_n^{t+1} = \max(v_n^t - 1, v_{\min}) \tag{5}$$

Due to many uncertainties, such as poor conditions for sailing, different mentalities of drivers, and so on, ships may slow down.

Rule6 Updated positions:

$$x_n^{t+1} = x_n^t + v_n^t + v_{n,flow}^t \tag{6}$$

where $v_{n,flow}^t$ denotes the water velocity in the lane of ship A at moment t. The sailing distance per unit time is not only related to the speed of the ship but also to the water velocity in the lane.

NUMERICAL EXPERIMENT

The simulation is based on the open source software MicroCity (http://microcity.github.io). A two-dimensional 1000×140 simulation space is built, where the square's length is defined as 30 meters. The value 120 of ordinate is the position of the left lane, and the value 80 of ordinate is the position of the right lane. The important parameters used in the simulation are shown in Table 1.

We assume that the water flows in the two lanes are the same and unchangeable during the simulation. When the water velocity is positive, this means that the water flows are downstream; when the water velocity is negative, this means that the water flows are upstream; when the water velocity is zero, this means that the water is static.

Tab. 1. Important parameters used in the simulation

The name of the simulation parameter	Parameter value
Cell Size	30
Lane Length (cells)	1000
Ship Length (cells)	4
Slow Ship Speed (cells/unit time)	3
Fast Ship Speed (cells/unit time)	5
Ship Minimum Speed (cells/unit time)	0
Slow Ships / All Ships	0.5
Safe Space (cells)	4
Ship Acceleration (cells/unit time)	1
Deceleration Probability	0.3
Left Lane Speed	0
Right Lane Speed	0

FUNDAMENTAL DIAGRAMS

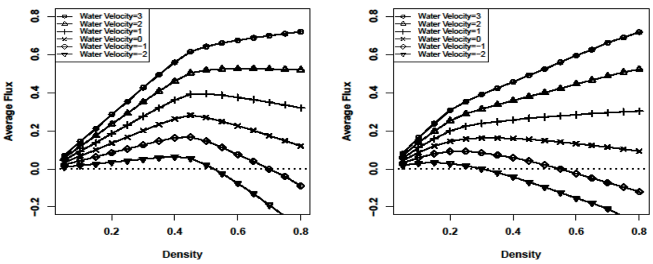

Fig.2.The density-average flux diagram:
(a) the NO-SICA model; (b) the SICA model

Fig. 2(a) shows that without ship interactions, with a small density, the average flux in all lanes shows a linear increase with an increase in the density. When the density increases constantly, the lanes start to be crowded. To avoid collisions, ships have to slow down. Additionally, random slowing down also plays an important role in the increase in the density, so the average speed of ships in all lanes is also lowered. As a result, the slope is changed at 0.45 in Fig.2(a).

By comparing 2(a) and 2(b), with ship interactions and a medium density, the average flux is lower than without ship interactions. The curve of the density-average flux becomes smooth, and the "Peak Phenomenon" is not evident. The reason is that with ship interactions, an overtaken ship needs to slow down to reduce the time of the ship interaction, so that the speeds in all lanes are influenced, resulting in the offset of the average flux brought by the density.

The effect of water flows is further considered. From Fig2(b), a conclusion can be drawn: regardless of whether upstream or downstream, the "Peak Phenomenon" is undermined by an increase in the water velocity, and further, the "Peak Phenomenon" disappears when downstream, with ship interactions, where this situation is even more evident.

Regarding why an increase in the water velocity undermines the "Peak Phenomenon", we consider the downstream case with ship interactions as an example. If the density of the lanes is significantly large, ships slow down to avoid collisions. At the same time, randomization also can also hold back ships significantly with a high density. Without the consideration of the water velocity, the average flux of the lanes should decline sharply. However, it hardly changes, because the water velocity of the downstream is high. So, compared to a high water velocity, the influence of the speed of ships on the average flux of the lanes is small. When the water velocity is close to or larger than the speed of ships, the influence from random slowing down can be ignored, and the average flux of the lanes depends on the water velocity. According to the formula of the average flux, Average flux = (Density × Composite speed of ships considering water velocity) / Average ship length, the density-average flux curve is infinitely close to a linear one with an increase in the water velocity.

This result is meaningful for ships sailing in narrow channels. With ship interactions, the experimental results show that if the upstream velocity is high, the value of the average flux can even be negative even if the density is small, which means that the upstream is so strong that ships go backward instead of going forward. Furthermore, narrow channels have many features, such as the narrow width, changeable water depth and flux, curved vessel lanes, low speed of ships, and so on. Additionally, ships often change directions to overtake other ships, so the load on the propeller changes drastically. Therefore, facing terrible sailing conditions, such as a high upstream velocity or dead wind, all crews have to pay more attention to the changes in various parameters related to the power, and corresponding actions should be taken to avoid ship's reversing.

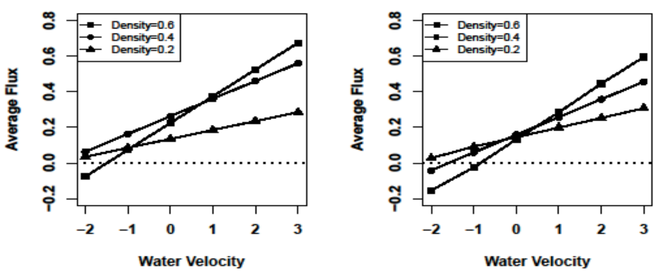

Fig.3. The water velocity diagram:
(a) the NO-SICA model; (b) the SICA model

In Fig.3, regardless of whether with ship interactions or without them, the slope of the water velocity-average flux curve is the same for the same density values. This means that when the water velocity increases by one unit, the average flux increases by the same quantity. The reason is that the water velocity is an external environment. But with different densities, the effect of the water velocity on the average flux is different. The higher the density, the more clear the effect on the average flux. According to the formula of the average flux, Average flux = (Density × Composite speed of ship considering water velocity) / Average ship length, when the water speed and average ship length are unchanged, the density becomes the only changeable parameter. So, the higher the density, the larger the average flux.

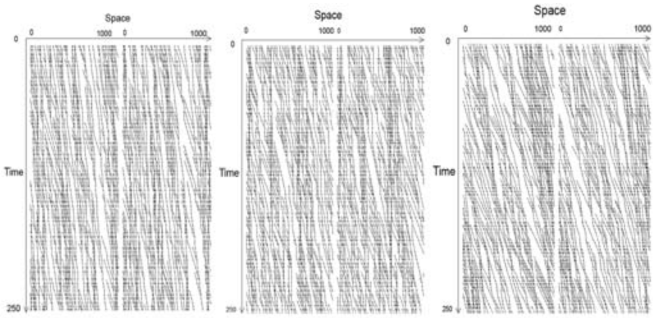

Fig.4. The time-space diagram for the SICA model: (a) water velocity=-1; (b) water velocity=0; (c) water velocity=1

Fig.4 shows the time-space diagram with ship interactions under different water velocity conditions, where the density is equal to 0.6. Lanes are symmetric, so the diagrams for the right lane and left lane have similar features. Comparing the three diagrams for the water velocity equal to -1, 0 and 1, we can notice that the downstream water makes ships faster, and with the water velocity -1, the motion of ships is viscous. Fig.4(a) also shows that the upstream makes lanes more crowded, and it is hard for ships to move under these conditions.

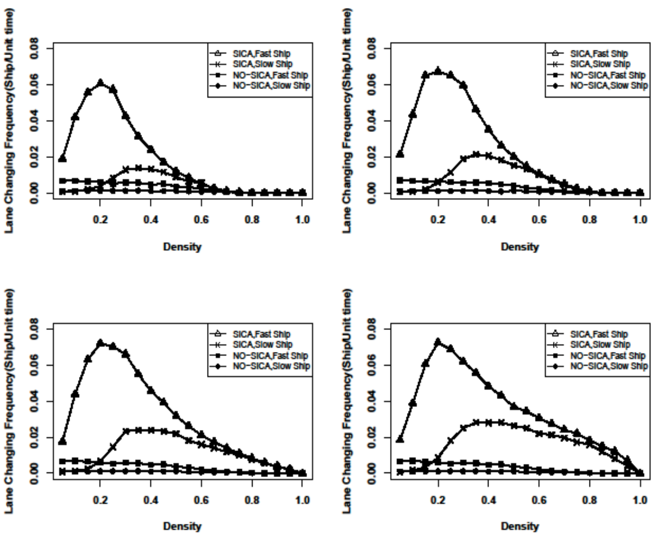

Fig.5. The density-lane-change frequency diagram: (a) water velocity=-1; (b) water velocity=0; (c) water velocity=1; (d) water velocity=2

LANE-CHANGE FREQUENCY

According to Fig.5, without ship interactions, the lane-change frequency of slow ships is almost zero, because slow ships' speed is the lowest in all lanes. Accordingly, overtaking of front ships rarely occurs. On the contrary, fast ships choose to change lanes if the density is small and the distance is safe. However, with a high density, both lanes are crowded, and the distance is not enough for ships to change lanes, so all ships can only sail in the same lane keeping the safe distance. In this situation, the lane-change frequency is close to zero.

With ship interactions, the density-lane-change frequency diagram shows a great difference. For both fast ships and slow ships, their lane-change frequency increases dramatically. The reason is that ship interactions slow down ships frequently, and to avoid collisions, the rear ship has to change lanes frequently to pass the entire channel quickly.

Furthermore, Fig.5 also shows that with ship interactions, an increase in the downstream velocity can hold back the decrease of the lane-change frequency. To clearly observe the influence of different water velocities on the lane-change frequency, Fig.6 shows the relationship between the water speed and lane-change frequency with ship interactions.

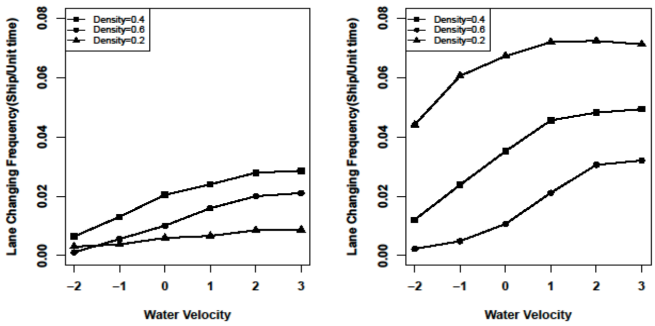

Fig.6. The water velocity-lane-change frequency diagram: (a) slow ships; (b) fast ships

Fig.6 shows that ships are held back when sailing in the upstream case. So, the lane-change frequency is the lowest under this circumstance. When downstream, the rear ship can find many chances to overtake the front ship, so the lane-change frequency is increased. However, with an increase in the water velocity, the lane-change frequency stays at a certain value. The reason is that even with an increase in the water velocity, the relative speeds of ships are unchanged, and the relative distances between ships are also not related to the water velocity. So, an increase in the water velocity does not clearly affect the lane-change frequency.

Furthermore, Fig.6 also shows that the lane-change frequency of a fast ship is influenced more by the water velocity than that of a slow ship, because the slow ship is restricted by its maximum sailing speed. Therefore, rarely can the front ship be overtaken by a slow ship.

CONCLUSIONS

This article studies the effect of water flows on vessel traffic flows in narrow channels. Based on the one-lane NaSch model, and considering the water velocity, a ship interaction cellular automation model is built. Using simulation, ships having different velocities in two lanes are compared. Considering the density, as well as ship interactions, the influence of different water velocities on the average flux and the lane-change frequency is studied. After the analysis of a large amount of experimental data from many simulation experiments, the results show that in both downstream and upstream cases, an increase in the water velocity makes the "Peak Phenomenon" undermined and even disappeared in the density-average flux curve, especially with ship interactions. Furthermore, using independent analysis of fast ships and slow ships, the results show that, for both fast ships and slow ships, an increase in the water velocity can render the lane-change frequency stable and unchangeable gradually. However, the lane-change frequency of fast ships is influenced by the water velocity more clearly than that of slow ships.

Many factors are considered in this article, and each factor is analyzed and compared accompanied by the corresponding explanation. Therefore, meaningful references can be provided to vessel traffic in narrow channels in real applications. However, vessel traffic is much more complicated in real life situations, and further research can be done based on this article to make the model more suitable for real life situations, providing greater contributions to the shipping industry.

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