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A cellular automaton model for ship traffic flow in waterways

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HIGHLIGHTS

- A novel cellular automaton-based ship traffic flow model is proposed.
- A spatial–logical mapping rule is made to solve the ship pseudo lane-change issue.
- Dynamic ship domain is considered in the update rules.
- The ship traffic flow under the influence of waterway bottleneck is studied.
- Relationship between traffic capacity of waterways and ships' lengths is explored.

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ABSTRACT

With the development of marine traffic, waterways become congested and more complicated traffic phenomena in ship traffic flow are observed. It is important and necessary to build a ship traffic flow model based on cellular automata (CAs) to study the phenomena and improve marine transportation efficiency and safety. Spatial discretization rules for waterways and update rules for ship movement are two important issues that are very different from vehicle traffic. To solve these issues, a CA model for ship traffic flow, called a spatial–logical mapping (SLM) model, is presented. In this model, the spatial discretization rules are improved by adding a mapping rule. And the dynamic ship domain model is considered in the update rules to describe ships' interaction more exactly. Take the ship traffic flow in the Singapore Strait for example, some simulations were carried out and compared. The simulations show that the SLM model could avoid ship pseudo lane-change efficiently, which is caused by traditional spatial discretization rules. The ship velocity change in the SLM model is consistent with the measured data. At finally, from the fundamental diagram, the relationship between traffic ability and the lengths of ships is explored. The number of ships in the waterway declines when the proportion of large ships increases.

1. Introduction

As one of the three main transportation forms, maritime transportation plays an important role in freight transportation, especially for international trade [1]. Recently, with the development of maritime transportation, ships are becoming larger and waterways are becoming narrower for ships. Some important waterways in the world are becoming very busy [2,3], and complicated phenomena are observed in those waterways. Such phenomena always have some relationship to traffic safety and efficiency, but this cannot be precisely explained by the macroscopic traffic flow model. Therefore, in order to improve traffic conditions, it is necessary to build a microcosmic traffic flow model to study these complicated phenomena.

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One of the best choices is the cellular automaton (CA) model, which is widely used in the study of vehicle traffic flow. A CA model can simulate complex phenomena in the real world using a set of simple rules [4–7]. CA micro simulations can be easily implemented using computers and have been successfully applied to the modeling of traffic flows [8–11]. In CA simulations, very simple models are capable of capturing the essential features of systems of extraordinary complexity [12–14]. Some heterogeneous CA models have been proposed recently [15–19], which can support the study of ship traffic, because different ships have different maximum velocities, types, sizes, etc. However, two important issues should be solved first. One is that in most cases there are no lanes for ships in waterways and the width of waterways always change, which makes it hard to achieve spatial discretization. The other is that the interactions among ships are different from those of vehicles due to the differences of traffic rules and movement characteristics between vehicles and ships.

To study ship traffic flow, some models have been proposed based on the CA model. In these models, issues like ship interactions in narrow water channels, and ship movements in narrow and busy shipping channels, etc. have been solved successfully. According to spatial discretization rules and update rules, ship CA models can be divided into two main types. In the first type, a waterway is imagined to be composed of one or two lanes without any bottleneck [1,20]. Each lane is integrated and has no part missing. In this model, which is similar to the classic vehicle traffic flow models, the research results of vehicle traffic flow can be used directly. Then by considering the motion features of the ship, some complex phenomena in ship traffic flow can be simulated. This performs very well in studying ship traffic flow where there is no bottleneck in the waterway. In the second type, a waterway is imagined to be constituted of one or two lanes too. But there is bottleneck, and part of lane is reduced [21]. This model can simulate ship traffic perfectly, when there is an obstacle in the waterway and ships have to steer clear of it. The influence of the bottleneck on ship traffic flow can be studied and predicted, which is very helpful for ship traffic management.

However, it is known that the widths of waterways are always changing and sometimes this leads to a traffic bottleneck. First, because the bottleneck is not considered in the first model above, it cannot simulate the ship traffic flow in this situation. Second, when ships sail through the bottleneck, the direction of ships may not change much. And the ships tend to veer at a small angle, in order to avoid speed reduction. But in the second model, some ships have to steer and change lane because part of lane is reduced at the bottleneck. The ships slow down in this process. Therefore, the second model is not suitable to simulate the ship traffic flow in this situation either.

In addition, another novel model was presented recently [22]. In that model, the waterway was discretized to two-dimensional spatial cells. The velocity of ships was also divided into two directions. No lane was defined and the rules for lane-changes are not applicable anymore. Instead, the relative position between ships can be achieved and the movement of ships follows collision avoidance regulations. The shape of the waterway can be irregular and the course of ship can be any direction. The spatial discretization in this model is similar to the two-dimensional cellular automaton for pedestrian traffic simulation [23]. Traffic conflicts can be studied very well using this model. And the time a ship takes to sail through a complex traffic net can be calculated successfully. So it is more suitable to simulate ship traffic flow at intersections, in harbors, etc., where the ships' movements are more complex in two-dimensional planes than the one-directional traffic flows in waterways. As it is a two-dimensional cellular automaton, much of the research results on vehicle traffic models based on one-dimensional cellular automaton cannot be referenced. This model is more complex than the two models above and consumes more computing resources.

As mentioned above, the widths of waterways always change, and the models are not very applicable to simulate ship traffic flow under these conditions. Based on the advantages of the above research results and according to the motion features of ships, a novel cellular automaton model for ship traffic flow in waterway was proposed, called the spatial–logical mapping (SLM) model. This model contained a mapping rule with which the lanes for ships were redefined. Ship lane-changes were consistent with the actual situation at the bottleneck. In addition, the dynamic ship domain was considered in building update rules to define the safe gap between ships, which helped to describe ships' interactions more exactly.

The remainder of this paper is organized as follows: Section 2 describes the methodology of the SLM model. Section 3 presents simulation results and discusses the performance of the model. Section 4 summarizes the conclusions as well as the prospect of future research.

2. Methodology

In the CA model, the interactions among the particles, like vehicles, pedestrians, trains, ships, etc., are based on understandable behavioral rules rather than functions [12]. For the CA-based traffic flow model, the discrete space and time should be identified. First, time discretization can be determined empirically, balancing accuracy and computational resource consumption. Second, because a waterway is different from a road, in the SLM model, novel spatial discretization rules are proposed, which contain a mapping rule to solve the problems caused by changes in waterway width. Based on the discretized space and time, improved update rules are built. Next, the spatial discretization rules and update rules are introduced.

2.1. Spatial discretization rules

In ship traffic, variation in the waterway width is very common. If there is a bottleneck because part of a road lane is reduced, a vehicle needs to steer and change lanes to get through, as shown in Fig. 1(a). However, there may be no