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Ship interaction in narrow water channels: A two-lane cellular automata approach

Zhuo Sun [a], Zhonglong Chen [a], Hongtao Hu [b], Jianfeng Zheng [a,*]

[a] Transportation Management College, Dalian Maritime University, Dalian 116026, China

[b] Logistics Engineering College, Shanghai Maritime University, Shanghai 201306, China

HIGHLIGHTS

- A two-lane cellular automata model is proposed to investigate ship movement.
- Ship interactions are considered when overtaking occurs.
- Ship interactions lead to "lump" formation.

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ABSTRACT

In narrow waterways, closed ships might interact due to hydrodynamic forces. To avoid clashes, different lane-changing rules are required. In this paper, a two-lane cellular automata model is proposed to investigate the traffic flow patterns in narrow water channels. Numerical experiments show that ship interaction can form "lumps" in traffic flow which will significantly depress the flux. We suggest that the lane-changing frequency of fast ships should be limited.

1. Introduction

Maritime transportation plays an important role in freight transportation, especially for international trade [1–3]. Recently, marine traffic has been greatly increased, which makes narrow waterways (such as channels and straits) congested. As a result, ship collision often occurs in narrow waterways [2]. Hence, it is very important to investigate the feature of ship movement in narrow waterways, which is helpful for ship navigation. This motivates the present paper.

There have been many studies on the feature of vehicle movement for road traffic. Here, we simply introduce two kinds of prevailing models. One is the car-following model, which is used to determine how vehicle follows one another. Early studies focused on single-lane traffic flow [4–6]. Recently, some car-following models for two-lane traffic flow had been developed [7,8]. Later, Tang et al. [9,10] proposed a couple of models to study the lane-changing behavior. These models faced difficulties on overtaking phenomena. This study chooses the other kind of model, i.e., the cellular automata (CA) model [11], which has been widely used in road traffic due to its high-efficiencies in describing the complex driver behavior and simulating corresponding traffic patterns. The well-known Nagel–Schreckenberg (NaSch) model proposed by Nagel and Schreckenberg [12] in 1992 firstly represented the realistic road traffic patterns in a single lane. This model is also known as the stochastic traffic cellular automata (STCA) in which a stochastic noise term is introduced in its speed update rule. After that, many single-lane models are developed, such as STCA-CC model [13], SFI-TCA model [14], slow-to-start model [15],

* Corresponding author.
E-mail address: jfzheng@dlmu.edu.cn (J.F. Zheng).

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T^2-TCA model [16], BJH-TCA model [17] and VDR-TCA model [18]. To simulate the overtaking processes in heterogeneous traffic, Rickert et al. [19] proposed a symmetric two-lane CA model in which a set of lane-changing rules are introduced to extend the single-lane CA models. The symmetric lane-changing effect was further studied by Chowdhury et al. [20]. Asymmetric lane-changing rules were investigated afterwards [21,22]. Knospe et al. [23,24] considered anticipation effects in a two-lane CA model. Jia et al. [25,26] added honk behavior to a fast vehicle when it is hindered by a preceding slow vehicle. Li et al. [27] considered aggressive lane-changing behavior of fast vehicles.

As compared with road traffic, marine traffic in narrow waterways has similar features based on the data retrieved from the Vessel Traffic Service (VTS) and the Automatic Identification System (AIS) [1]. First, ships in narrow waterways are closed to each other; in other words, ship congestion and collision are common [1,2]. Second, for the sake of easy management and safety, the region in narrow waterways is divided into several lanes. Ships sail in lanes, and they should change lane for overtaking or calling at the port. Third, ship queuing can be formed in narrow waterways because of ship congestion, similar to the phenomenon reproduced by car-following or CA models for road traffic. Then, ship speed varies based on its preceding ships.

Furthermore, marine traffic in narrow waterways has some unique characteristics. First, ships are much larger than cars. It is necessary to keep enough safety space around them when ships perform ship-following and lane-changing behavior. Second, water resistance can delay the steering actions; then it takes a relatively long time for ships to accelerate, decelerate and change lane. Third, ships in water are more susceptible than cars in road. Although sailing in different lanes, a reduced distance between two ships leads to hydrodynamic interactions when meeting and overtaking maneuvers are unavoidable [28]. As a result, these two ships will be probably pulled to each other and collide. This phenomenon is called as ship interaction, which can be regarded as the key difference between marine traffic and road traffic.

To study the marine traffic in narrow waterways, we set up a two-lane CA model. The sizes of the discretized space and time unit are enlarged to adapt the first two differences mentioned above between marine traffic and road traffic. In order to compare the effect of ship interaction with the traditional CA model, when one ship is going to overtake another ship ahead, the overtaken ship has to slow down to let the ship interaction time as short as possible. This paper aims to investigate the feature of ship movement by introducing the above ship interaction into the traditional lane-changing rule.

The rest of this paper is organized as follows: In Section 2, the new model is introduced. Numerical experiments are provided in Section 3. Finally, a summary and conclusions are given in Section 4.

2. Model

Before introducing our model, we review the single-lane STCA model, in which the road is discretized into X cells and the time span is discretized into T ticks. A vehicle occupies one cell x at a specific time t. The velocity of a vehicle is denoted as $v = 0, 1, \ldots, v_{\max}$. The vehicles are numbered $1, 2, 3, \ldots, N$. Following NaSch model [2], the parallel updating rules for the single lane STCA model are as follows:

Rule 1: acceleration, $v_n = \min(v_{\max}, v_n + 1)$; (1)

Rule 2: deceleration, $v_n = \min(v_n, d_n)$; (2)

Rule 3: randomization, $v_n = \max(v_n - 1, v_{\min})$ with probability p; (3)

Rule 4: position update, $x_n = x_n + v_n$. (4)

Here v_n and x_n denote the velocity and position of the vehicle n; $v_{\max}$ is the maximum velocity; $v_{\min}$ is the minimum velocity; $d_n = x_{n+1} - x_n - 1$ denotes the space gap between vehicle n and vehicle $n+1$; p is the randomization probability.

For two-lane STCA model, each lane can be considered as a single-lane STCA model. However, when a vehicle is hindered by the preceding vehicle it may change to the other lane to get faster speed. The symmetric lane-changing rules in two-lane STCA are proposed by Chowdhury et al. [20] where vehicles change its lane with the lane-changing probability $p_{n,\text{change}}$ in the following conditions:

$$d_n < \min(v_{\max}, v_n + 1) \quad \text{AND} \quad d_{n,\text{other}} > d_n \quad \text{AND} \quad d_{n,\text{back}} > d_{\text{safe}}. \tag{5}$$

Here $d_{n,\text{other}}$ and $d_{n,\text{back}}$ denote the space gap between the vehicle n and its two neighbor vehicles on the other lane. d_{safe} is the safety space required in the other lane. The lane-changing rules depicts that a vehicle can change its lane to improve its speed if there is no safety issues in the other lane.

To take the ship interaction into account, we need to extend the two-lane STCA model. The new model is called as ship interaction STCA (SI-STCA). In the SI-STCA model we set l as the length of a ship, so one ship occupies numbers of consecutive cells. The notation x_n stands for the head position of the ship n. The space gap between two adjacent ships can be recalculated as $d_n = x_{n+1} - x_n - l$. We consider the ship interaction effect while one ship is overtaking another. The ship deceleration rule (2) is rewritten as:

$$v_n = \begin{cases} \max(\min(v_n - 1, d_n), v_{\min}), & \text{if } v_n < v_{n,\text{overtaking}}; \\ \min(v_n, d_n), & \text{otherwise.} \end{cases} \tag{6}$$

Here $v_{n,\text{overtaking}}$ denotes the velocity of the overtaking ship paralleled to the ship n in the other lane. This rule depicts that to avoid ship interaction, the ship overtaken by another ship in the other lane decelerates to the minimum velocity. The overtaking time will be shortened.