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An improved multi-value cellular automata model for heterogeneous bicycle traffic flow

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ABSTRACT

This letter develops an improved multi-value cellular automata model for heterogeneous bicycle traffic flow taking the higher maximum speed of electric bicycles into consideration. The update rules of both regular and electric bicycles are improved, with maximum speeds of two and three cells per second respectively. Numerical simulation results for deterministic and stochastic cases are obtained. The fundamental diagrams and multiple states effects under different model parameters are analyzed and discussed. Field observations were made to calibrate the slowdown probabilities. The results imply that the improved extended Burgers cellular automata (IEBCA) model is more consistent with the field observations than previous models and greatly enhances the realism of the bicycle traffic model.

1. Introduction

The non-motorized traffic trip (e.g. on a regular bicycle (RB) or electric bicycle (EB)) is one of the main trip modes in developing countries, especially in Southeast Asian countries such as China, India, and Vietnam. In recent years, due to their low cost, convenience, and energy efficiency, EBs have quickly become one of the dominant non-motorized travel modes in China [1]. Heterogeneous bicycle traffic flow containing a mixture of EBs and slower-moving RBs is and will continue to be a very common feature of bicycle paths. With the increase in bicycle traffic, the need to realistically model the movement and interactions of heterogeneous bicycle traffic is rapidly gaining importance in the planning, design, management, and operations of bicycle facilities. In response to this need, several approaches to modeling bicycle movements and interactions have been developed [2].

Many traffic flow models (such as the car-following model, lane-changing model, cellular automata (CA) model, and gas dynamics model) have been proposed for motorized vehicles [3–6]. However, the behavior of bicycle traffic is non-lane-based and more complicated, making it more difficult to model. Based on the previous studies, almost all of the bicycle flow microscopic models are based on the concept of CA, and the related studies are very limited. We have summarized the modeling approaches that depict the state of the art in bicycle traffic modeling and have found that overall microscopic models of bicycle traffic can be divided into the modeling of bicycle operations and the modeling of interactions between bicycles and other motorized vehicles [7].

In respect of modeling bicycle traffic, the Nagel–Schreckenberg (NS) model [8], the best-known CA model, is widely used in modeling bicycle flow. The NS model, and the many improvements on it, reproduce some basic and complicated phenomena such as stop and go, metastable states, capacity drop, and synchronized flow in real traffic conditions. Gould and Karner [9] proposed a two-lane inhomogeneous CA simulation model, an improved version of the NS model combined with a lane-changing rule. Field data under uncongested conditions, from Davis, California, were used for calibration. Zhang et al. [10] also used a three-lane NS model and an improved lane-changing rule for analyzing the speed–density characteristics of mixed bicycle flow. Zhao et al. [11] used the CA method to model the characteristics of bicycle passing events in mixed bicycle traffic on separated bicycle paths. An improved three-lane NS model and lane-changing rule were proposed. The dynamic floor field and CA model were introduced to investigate the characteristics of bicycle flow by Yang et al. [12], and a new concept called the lane-changing cost was proposed to study the

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effect of driving styles. Jiang et al. [13] proposed a new three-lane NS model to simulate the flow characteristics, overtaking maneuver patterns and segregation effect in heterogeneous traffic composed of RBs and EBs. Due to its advantage of not considering lane-changing rules, the extended Burgers CA (EBCA) model [14] is very well-suited to modeling bicycle traffic flow. Jiang et al. [15] were the first to introduce two different multi-value CA models (MCA) considering stochastic randomization for modeling bicycle flow. Jia et al. [16] considered the fact that bicycles do not all have the same maximum speed due to differences in the characteristics of cyclists. Therefore, they included two types of bicycles (fast and slow) with different maximum speeds (1 cell/s and 2 cells/s) in the EBCA model. Li et al. [17] presented a MCA model for mixed non-motorized traffic flow composed of bicycles and tricycles. A bicycle was assumed to occupy one unit of cell space and a tricycle two units of cell space.

In respect of modeling interactions between bicycles and other motorized vehicles, conflict rules between them have been modeled and simulated. Vasic and Ruskin [18] addressed this with a novel technique, based on one-dimensional CA components, for modeling a network infrastructure and its occupancy by vehicles. Using this modeling approach, the simulation combined car and bicycle traffic for two elemental scenarios. The characteristics of mixed traffic flow at the intersection were more complicated than on roadways. Based on motorized-vehicle-bicycle interference characteristics, and the coupling between the vehicle CA model and the bicycle CA model, Zhang et al. [19] presented a different kind of CA model (NS-BCA) to analyze the mixed traffic flow at intersections. Luo et al. [20] proposed a new CA model to simulate car and bicycle heterogeneous traffic on an urban road. The proposed model captured the complex interactions between the two types of vehicles. Ding et al. [21] proposed an improved CA model to simulate mixed traffic flow composed of motor vehicles and bicycles near bus stops. The typical NS CA model for motorized traffic flow and the BCA model for bicycle flow were combined to simulate the mixed traffic flow.

Table 1 provides a summary of bicycle traffic flow modeling using CA models. It shows the simulation scenarios, vehicle types, model types, cell size, and maximum speeds of the reported models. From the table, it can be clearly seen that the NS and EBCA models have been widely used in the modeling of heterogeneous bicycle flow. For the NS model, the cell length and the maximum speeds of different bicycles were selected based on real bicycle data (speeds were RBs 4 m/s and EBs 6 m/s), while all of the proposed EBCA models for bicycle simulation used 1 and 2 cells/s as the maximum speeds of RBs and EBs, which are significantly different from real bicycle speed data. However, based on different numbers of bicycle lanes and simulation scenarios, the lane-changing rules of the NS models are significantly different from each other. With an increase in the number of bicycle lanes, these rules become more complex, making them impossible to calibrate, validate, and evaluate.

As can be seen from the above, the EBCA models are more suitable for modeling bicycle traffic flow and investigating the characteristics of heterogeneous bicycle flow than the NS models. However, the assumption that RBs have a maximum speed of 1 cell/s and EBs a maximum of 2 cells/s is not realistic. Therefore, this paper expands the maximum speed and update rules for bicycle traffic and proposes an improved EBCA (IEBCA) model for modeling heterogeneous bicycle traffic. Both simulation analysis and field data calibration are presented so as to compare the models.

The remaining parts of the paper are organized as follows. Section 2 introduces the IEBCA model. Section 3 presents the simulation results of the proposed model. Section 4 uses field bicycle data for the calibration and validation of the proposed model. Finally, the conclusions and possibilities for future study are addressed.

2. The IEBCA model

2.1. Definition of bicycles' maximum speeds

The size and speed differences between RBs and EBs will inevitably lead to more complicated characteristics and a higher risk of traffic collisions. Accurately describing the size and speed of heterogeneous bicycles is the foundation of modeling bicycle traffic. Based on field surveys [2,22], the typical lengths of RBs and EBs in China are not significantly different from one another, at around 1.7–1.9 m. Adding in a safe distance between two successive bicycles, the length of a bicycle cell is set to 2 m, which has also been widely used in most of the previous bicycle CA models [9–12]. Based on the criteria in the US and China, it is recommended that the standard width of a bicycle lane should be 1–1.2 m [2,10]. Therefore, we use 2×1 m as the cell size of a bicycle in this paper.

The maximum speeds of different bicycles are the other important parameters that will affect the free flow speed and capacity of heterogeneous bicycle traffic flow. According to the results of field investigations in China [2,22] and reported studies [9,10,12,13], the average speeds of RBs and EBs in free flow are round 14–16 km/h and 20–22 km/h, respectively. Accordingly, in this paper, 2 cells/s (4 m/s or 14.4 km/h) and 3 cells/s (6 m/s or 21.6 km/h) were chosen as the maximum speeds for RBs and EBs, respectively (assuming that the update time step corresponds to 1 second).

2.2. IEBCA model

Due to its easy-to-follow concept, simple rules, and speed for numerical investigations, the CA model is an efficient tool for simulating traffic flow [23]. Nishinari and Takahashi [14] were the first to propose a multi-value CA model. The initial multi-value CA model comes from the ultradiscretization of the Burgers equation, and is therefore called the Burgers cellular automata (BCA) model. Its evolution equation is

$$U_j(t+1) = U_j(t) + \min\big(U_{j-1}(t), L - U_j(t)\big) - \min\big(U_j(t), L - U_{j+1}(t)\big) \tag{1}$$

where $U_j(t)$ represents the number of vehicles in cell j at time t.

Then, Nishinari and Takahashi extended the maximum speed of BCA to 2, and presented the extended BCA (EBCA) models [24,25]. As mentioned earlier, the EBs' maximum speed is considered to be 3 cells/s in this paper. Therefore, the updating rules are more complex than in the EBCA and are extended as follows:

(1) Assume that the numbers of RBs, EBs, and all bicycles at location j at time t are $U_j^r(t)$, $U_j^e(t)$, and $U_j(t)$, respectively.
(2) All bicycles at location j move to the next location $j+1$ if the next location is not fully occupied, and the EBs have priority over the RBs.
(3) All bicycles that have moved based on procedure (2) can move to location $j+2$ if location $j+2$ is not fully occupied after procedure (2), and the EBs have priority over the RBs.
(4) Only the EBs that have moved in procedure (3) can move to location $j+3$ if location $j+3$ is not fully occupied after procedure (3).

Because of the higher speed, stability, and flexibility of EBs, we assume that the EBs have priority to pass the RBs in the proposed model. We assume that the numbers of RBs and EBs that move one cell from location j at time t in procedure (2) are $b_j^r(t)$ and $b_j^e(t)$, respectively; the numbers of RBs and EBs that move two cells from location j at time t are $c_j^r(t)$ and $c_j^e(t)$, respectively; the total number of bicycles that move one and two cells from location