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Heterogeneous cellular automata model for straight-through bicycle traffic at signalized intersection

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HIGHLIGHTS

- Cellular automata model is utilized to simulate the straight-through bicycle traffic at signalized intersection.
- The model particularly describes the dispersion phenomenon existing in the straight-through bicycle traffic.
- The influence of dispersion phenomenon on the performance of the heterogeneous bicycle traffic is estimated.
- Bicycles interactions in terms of spilling maneuvers and overtaking maneuvers during the straight-through movements are quantified.

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ABSTRACT

This paper presents a cellular automata (CA) model to elucidate the straight-through movements of the heterogeneous bicycle traffic at signalized intersection. The CA model, via simulation, particularly exposits the dispersion phenomenon existing in the straight-through bicycle traffic. The nonlane-based cycling behavior and diverse bicycle properties are also incorporated in the CA model. A series of simulations are conducted to reveal the travel process, bicycles interaction and influence of the dispersion phenomenon. The simulation results show that the dispersion phenomenon significantly results in more bicycles interactions in terms of spilling maneuvers and overtaking maneuvers during the straight-through movements. Meanwhile, the dispersion phenomenon could contribute to the efficiency of the bicycle traffic, and straight-through bicycles need less time to depart the intersection under the circumstance of dispersion phenomenon. The simulation results are able to provide specific guideline for reasonably utilizing the dispersion phenomenon to improve the operational efficiency of straight-through bicycle traffic.

1. Introduction

As a representative instance of non-equilibrium systems, traffic system has received wide attentions to be studied in the field of statistical physics [1–3]. In recent years, a number of studies have been focused on understanding the characteristics of the heterogeneous traffic flow at intersections in the urban area by statistical physicists [4–7]. In many developing countries, traffic flow usually presents a chaotic scene because of heterogeneous transport modes traveling in the same road. This chaos is especially obvious at signalized intersection, where competition exists between vehicles to use the available space. In order to quickly depart the intersection, heterogeneous transport modes may occupy other modes' traveling district due to the limited space. For instance, bicycles use the adjacent vehicle lane to pass through the intersection. Different

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models of statistical physics have been proposed to investigate the heterogeneous traffic flow at intersection, including hydrodynamic models, car following model, intelligent agents, fuzzy logic, and cellular automaton [8]. It is commonly agreed that a further improvement model requires to represent the peculiar scenarios in the heterogeneous traffic flow, where there is no strict lane discipline for some smaller vehicles, and they move side by side along the cross section of the road [9]. Among these proposed models, cellular automata (CA) have the advantage of its flexibility of accommodating various movements and high computational efficiency, and gradually becomes a prevalent instrument to accurately simulate the heterogeneous traffic flow [10,11].

Numerous CA models have been proposed to explore the macroscopic traffic performance under heterogeneous conditions at signalized intersection. For instance, Radhakrishnan et al. [12] developed a hybrid stochastic CA model to predict the saturation flows and delays of the heterogeneous traffic at signalized intersections. In their model, the multicell concept and the lateral movement rules considering the diversity in vehicle characteristics were proposed to achieve a near to reality representation of nonlane-based heterogeneous traffic. The simulation results shows that the model performed reasonably well in predicting the heterogeneous traffic properties. Krishnamurthy et al. [13] further improved the vehicle movement logics of the CA model and then quantified the traffic volumes in passenger car unit under heterogeneous traffic conditions. With the aim of estimation the operation of heterogeneous traffic at signalized intersections with shared lanes, Chai et al. [14] combined artificial neural network and cellular automata to establish a neural cellular automata model. Their model extended the multicell concept and introduced a decision making module based on artificial neural network to accommodate different vehicle types. In addition, a few CA models, from the microscopic viewpoint, investigated the effects of some specific driving behavior or traffic phenomenon on the interactions between different vehicle types in heterogeneous traffic. For example, Lan et al. [15] proposed a CA model to elucidate the erratic motorcycle behaviors in heterogeneous car and motorcycle flow. The simulation results present that the erratic motorcycle behaviors increase interactions among different vehicles and hence impair the flow efficiency. Hu et al. [16] investigated the formation mechanism of the non-motorized vehicle illegal lane-changing behavior in heterogeneous motorized and non-motorized vehicle flow. In the framework of Kerner's three-phase theory [17], a CA model was introduced by them to reveal the microscopic traffic characteristics such as traffic breakdown, moving synchronized flow pattern and moving jam. Luo et al. [18] developed a CA model to simulate the bicycles spill behavior in the heterogeneous car and bicycle flow. The feature of the model is that the occupancy rule considering the variable lateral distance of mixed vehicular was adopted to capture the complex interactions between cars and bicycles. In these related studies, the most prevalent and intuitive method is to divide road section into small size cells and reflect different vehicle sizes and movements by multiple cell occupancy.

A recent entrant in such research is modeling the mixed electric bicycle and conventional bicycle traffic prevailing on China roads. Jiang et al. [19] conducted a CA simulation considering the honk effect, performance variance and erratic riding behavior of the mixed bicycle so as to more realistically reflect the genuine movements of the mixed bicycles. As inspired by Li et al. [20], they put the concept of speed effect of a bicycle on the successive bicycle into the definition of the forward movement rules. Based upon their findings, the bicycle interaction in terms of slow down-to-wait and overtaking maneuvers were successfully reproduced; besides, the fundamental diagram and space–time trajectories for bicycles were simulated to demonstrate the start-to-stop waves and different traffic flow states which were consistent with the real-world mixed bicycle traffic [21].

In the last decade, electric bicycle has experienced a rapid development in most cities of China. Electric bicycle (e-bicycle) has much larger operational speed than conventional bicycle (c-bicycle) [17,22]. E-bicycles and c-bicycles usually travel in the same bicycle lane, which is a typical case of heterogeneous traffic. The heterogeneous bicycle traffic comprised by e-bicycles and c-bicycles usually presents a stimulating feature when passing straight-through the intersection as shown in Fig. 1 [23]. Fig. 1 presents one of the common geometric designs of intersections in China. To accommodate the large right-turn vehicle volume, protected right-turn signal control and exclusive right-turn lanes are designed for the right-turn vehicles.

At signalized intersections, bicycles arrive and then wait behind the stop line. When the straight-through traffic light turns green, straight-through bicycles go straight across the intersection with straight-through vehicles. During this departure period, right-turn vehicles must wait behind the stop line and the exclusive right-turn lane in the intersection-box area can be provided for straight-through bicycles. In the straight-through traveling, faster cyclists such as e-bicycles would like to overtake slower cyclists from the edges of bicycle stream. As a result, the width of crossing bicycle streams could turn large and occupy more space of the intersection-box area, as shown in Fig. 1. This stimulating feature is termed as the ***dispersion phenomenon*** in the heterogeneous straight-through bicycle traffic at signalized intersections.

Though the dispersion phenomenon of straight-through bicycle traffic commonly exists at signalized intersections, to the best of our knowledge, only one study has particularly studied the characteristics of this phenomenon. Chen et al. [24] developed a traditional generalized regression model to investigate the dispersion phenomenon in the left-turn mixed bicycles. They find that the dispersion phenomenon affects the traffic operation obviously during the peak hour, and the spilling and overtaking maneuvers of bicycles, especially e-bicycles, are the major cause for the dispersion phenomenon. The spilling maneuver refers to bicycles traveling outside the bicycle lane, and the overtaking maneuver denotes that faster bicycles overtake the front slower bicycles. However, the behaviors of cyclists in the heterogeneous bicycle traffic cannot be accurately represented by the traditional mathematical model. The specific influence of the dispersion phenomenon on the heterogeneous bicycle traffic is still ambiguous, and the internal interactions in the heterogeneous bicycle traffic have not been evaluated in a way of statistical physics. From the aforementioned literatures, CA simulation technique is available to