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Simulating synchronized traffic flow and wide moving jam based on the brake light rule

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HIGHLIGHTS

- A new brake-light based CA model is proposed to describe the behaviors of drivers.
- The model can reproduce the three traffic phases of three-phase traffic flow theory.
- Our new model can well describe the complexity of traffic evolution.

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ABSTRACT

A new cellular automaton (CA) model based on brake light rules is proposed, which considers the influence of deterministic deceleration on randomization probability and deceleration extent. To describe the synchronized flow phase of Kerner's three-phase theory in accordance with empirical data, we have changed some rules of vehicle motion with the aim to improve speed and acceleration vehicle behavior in synchronized flow simulated with earlier cellular automaton models with brake lights. The fundamental diagrams and spatial–temporal diagrams are analyzed, as well as the complexity of the traffic evolution, the emergence process of wide moving jam. Simulation results show that our new model can reproduce the three traffic phases: free flow, synchronized flow and wide moving jam. In addition, our new model can well describe the complexity of traffic evolution: (1) with initial homogeneous distribution and large densities, the traffic will evolve into multiple steady states, in which the numbers of wide moving jams are not invariable. (2) With initial homogeneous distribution and the middle range of density, the wide moving jam will emerge stochastically. (3) With initial mega-jam distribution and the density close to a point with the low value, the initial mega-jam will disappear stochastically. (4) For the cases with multiple wide moving jams, the process is analyzed involving the generation of narrow moving jam due to "pinch effect", which leads to wide moving jam emergence.

1. Introduction

Traffic flow consists of four parts: route, vehicle, driver and environment. The four parts interact and make the traffic flow system a complex system. The complex behaviors of traffic flow are explored based on real measured traffic data [1–3]. Based on the spatiotemporal analysis for empirical traffic data on German highways, Kerner et al. proposed the three-phase traffic theory [1,2,4–6], in which the congestion traffic is divided into two traffic phases, synchronized flow and wide moving jam,

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and the phase transitions between the free flow, synchronized flow and moving jam are analyzed. In addition, the common traffic congestion features of the empirical data observed in the UK, the USA and Germany can be well described by Kerner's three-phase theory [7].

To describe the mechanism of traffic flow characteristics, many traffic flow models are proposed from different perspectives [4,8–23]. Among these models, cellular automaton (CA) models can be used to implement the dynamic evolution process of the complex system. Because of the flexible evolution rules and the discrete character, CA models are applicable to traffic simulation. Nagel and Schreckenberg proposed the NS model [13] in 1992, which can simulate the basic traffic phenomena, such as stop-and-go wave and phantom jams. And then many CA models are proposed to show the features of real traffic [4,15–23].

In Kerner's three-phase theory, the synchronized flow is the most complex one, whose nature is still controversial. CA models based on the brake light rule can simulate the synchronized flow [20,21,23]. In 2000, Knospe et al. proposed the comfortable driving model based on the NS model, which considers the desire of the drivers for smooth and comfortable driving [20]. Because the effect of brake light is used in the model, the model is also called the brake light (BL) model. The Jiang and Wu (JW) model is proposed to improve the performance of the BL model [21]. However, in the JW model, the brake light will switch off only when the vehicles accelerate, which is not consistent with the real traffic [23]. Tian et al. proposed an improved model (Tian model) based on the JW model. In the Tian model, the difference in accelerating and decelerating performance under different driving conditions is considered [23], which makes that the model can better describe the behaviors of real traffic compared with the JW model. However, we think that there are two points which can be improved in the Tian model.

First, the Tian model proposed that the driver will tend to drive with a higher acceleration if the driving condition is very well. If the time gap is bigger than the safe time gap and the leading vehicle's brake light is off, the scenario is regarded as very well driving condition [23]. However, we think that the definition is insufficient. If the time gap is much larger than the safe time gap, the status of the brake light of the leading vehicle should not influence the driver's behavior. Thus the sub-condition of "the leading vehicle's brake light is off" should not take effect when the time gap is relatively large.

Second, in the above BL models, the randomization probability is computed according to the driving conditions. In these models, the velocity may decrease after the step of deterministic deceleration. However, in the next step, i.e., randomization step, the randomization probability and the deceleration extent are not influenced by the results of the step of deterministic deceleration. That is, the above models do not consider the influence of deterministic deceleration on randomization. We think that if the velocity has already decreased in the step of deterministic deceleration, the randomization probability and the deceleration extent should decrease accordingly.

However, as shown in Ref. [4] the CA models with brake lights exhibit a drawback related to large non-realistic random changes in vehicle speed and acceleration (deceleration) in synchronized flow. This leads to random emergence and dissolution of narrow moving jams in synchronized flow independent of a synchronized flow speed. In this article we change some rules of vehicle motion with the aim to decrease these non-realistic speed and acceleration vehicle behavior in synchronized flow simulated with earlier cellular automaton models with brake lights. Based on the above two considerations, a new CA model is proposed considering the influence of deterministic deceleration on randomization probability and deceleration extent. Simulation results show that the new model can reproduce the three traffic phases: free flow, synchronized flow and wide moving jam. In addition, the new model can well describe the complexity of traffic evolution.

The rest of the paper is organized as follows. In Section 2, the Kerner's three-phase theory and the BL models are introduced, in which the Tian model is depicted in detail. We present our new model in Section 3. The fundamental diagrams and spatial–temporal diagrams are shown and analyzed in Section 4. In Section 5, we analyze the complexity of the traffic evolution. The emergence process of the wide moving jam is analyzed in Section 6. Finally, our work is concluded in Section 7.

2. Related works

2.1. Kerner's three-phase theory

After analyzing the spatiotemporal feature of the empirical data on German highways, Kerner et al. proposed the three-phase traffic theory [1,2,4–6]. In the traffic theory, the three phases are free flow, synchronized flow and wide moving jam.

In free flow [F], the vehicle density is small, which means the interactions between vehicles are negligible and vehicles have chances to move with the maximum speeds. In the flow-density diagram, the relationship between the flow rate and the vehicle density is almost linear [1,2].

Synchronized flow and wide moving jam belong to the congestion traffic phase. The two phases can be defined according to the macroscopic criteria [4].

Wide moving jam [J]: a wide moving jam is a moving jam, whose characteristic is that it maintains the mean velocity of the downstream front of the jam, even when it propagates through any other states of traffic flow or any bottlenecks. Within the downstream jam front, vehicles accelerate from standstill or negligible low speed states to higher speeds. The word *wide* reflects the feature that the width (in the longitudinal direction) is considerably greater than the widths of the jam fronts.

Synchronized flow [S]: unlike the wide moving jam, the characteristic of synchronized flow is that the downstream front of the synchronized flow does not maintain the mean velocity of the downstream front. In addition, the downstream front