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Modeling mechanical restriction differences between car and heavy truck in two-lane cellular automata traffic flow model

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HIGHLIGHTS

- The limited deceleration capability differences between the car and the heavy truck are considered.
- The active deceleration behavior of the heavy truck is depicted.
- The well-known plug is effectively eliminated.
- The synchronized flow is reproduced under mixed traffic condition.

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ABSTRACT

Real traffic is heterogeneous with car and truck. Due to mechanical restrictions, the car and the truck have different limited deceleration capabilities, which are important factors in safety driving. This paper extends the single lane safety driving (SD) model with limited deceleration capability to two-lane SD model, in which car–truck heterogeneous traffic is considered. A car has a larger limited deceleration capability while a heavy truck has a smaller limited deceleration capability as a result of loaded goods. Then the safety driving conditions are different as the types of the following and the leading vehicles vary. In order to eliminate the well-known plug in heterogeneous two-lane traffic, it is assumed that heavy truck has active deceleration behavior when the heavy truck perceives the forming plug. The lane-changing decisions are also determined by the safety driving conditions. The fundamental diagram, spatiotemporal diagram, and lane-changing frequency were investigated to show the effect of mechanical restriction on heterogeneous traffic flow. It was shown that there would be still three traffic phases in heterogeneous traffic condition; the active deceleration of the heavy truck could well eliminate the plug; the lane-changing frequency was low in synchronized flow; the flow and velocity would decrease as the proportion of heavy truck grows or the limited deceleration capability of heavy truck drops; and the flow could be improved with lane control measures.

1. Introduction

It is definitely true that the traffic flow is heterogeneous. The vehicle driving on freeway can be simply classified into car and truck. Although the number of trucks on freeway is smaller than the number of cars, the truck has a significant influence on traffic flow characteristics. Most of the existing traffic flow models, especially the works done in the earlier period, mainly focus on analyzing the homogeneous traffic flow [1–7]. Recently, many works have been done to investigate the properties of heterogeneous traffic flow.

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Based on the empirical vehicle trajectory data, Yang et al. [8] explored the characteristics of the four types of car–truck following combinations, car–car, car–truck, truck–car and truck–truck, and their impact on traffic flow stability. Aghabayk et al. [9] and Sarvi and Kuwahara [10] studied the driving behavior in heterogeneous traffic flow. Kim et al. [11] investigated the behavioral parameters of car-following models. Furthermore, Ward [12] analyzed the instability in heterogeneous traffic flow and concluded that slower vehicles tend to stabilize the system. Deng and Zhou [13] investigated the macroscopic and microscopic traffic states by using multiple data sources. And Kerner et al. [14,15] studied spatial–temporal patterns and the effect of speed limit control at freeway bottlenecks with measured data, respectively.

Besides, all kinds of theoretical traffic flow models, including continuum model, car-following model and cellular automata (CA) model, have been adopted to study the properties of heterogeneous traffic flow.

As to continuum model, Laval and Daganzo [16] extended LWR model [1,2] to explore the effects of abottleneck on multilane traffic flow. Gupta et al. [17] proposed a multi-class continuum model for traffic flow. Jin [18] developed a simple kinematic wave model of lane-changing traffic. Moridpour et al. [19] investigated and compared the traffic flow characteristics with different lane changing behaviors of the heavy vehicle and the passenger car drivers on freeways under heavy traffic conditions. Tang et al. [20–25] proposed a series of continuum models with consideration of the traffic interruption probability, the relationship between the micro and macro variables, the driver's forecast effect, road width, (multi) static bottleneck, and so on respectively. And other works in the framework of continuum model focusing on heterogeneous traffic flow can be found in Refs. [26–28].

As to microscopic car-following models, Mason et al. [29] proposed a single-lane model that considers the interactions between cars and trucks. Aghabayk et al. [30–32] and Ye et al. [33] investigated different car-following behaviors of drivers in heterogeneous traffic. Peeta et al. [34] considered the interaction between passenger cars and heavy vehicles by introducing a discomfort level for passenger car drivers in the vicinity of heavy vehicles. Li et al. [35] built and validated a car-following model with speed-dependent control gains. And other human drivers' characteristics have also been considered in the framework of car-following model [36–40].

CA model has become an excellent tool for modeling traffic flow since the NaSch model was proposed in 1992 [5]. The rule based CA model could be easily modified to describe heterogeneous two-lane traffic flow by introducing lane-changing rules. Nagatani et al. [41] first presented a definitive two-lane CA model. Rickert et al. [42] and Chowdhury et al. [43] proposed two-lane CA models based on the NaSch model. In heterogeneous two-lane traffic model, there will be plug which is formed by two nearly parallel moving heavy truck. It heavily depresses the traffic flux. In order to eliminate the plug, Jia et al. [44] introduced honk effect into two-lane CA model. Li et al. [45] proposed aggressive lane-changing behavior of fast vehicles. More microscopic driving behaviors under heterogeneous traffic condition have also been investigated by two-lane CA traffic flow models [46–49]. For instance, Yang et al. [49] proposed a cellular automata model to describe different vehicle following behaviors among the four car–truck following combinations.

In CA traffic flow models, the rule that vehicle decelerates according to gap makes the collision-free mechanism effective. But the main drawback of the rule is that the vehicle has no limitation on deceleration capability. This will result in the unpractical deceleration behavior, of which the vehicle would abruptly drop from the maximum velocity to 0. Krauss and Wagner [50] perhaps made the first effort to introduce limited deceleration capability into CA traffic flow model, although the value of deceleration capability is exaggerated. Later, Lee et al. [51] proposed a model taking into account the limited acceleration and deceleration capability. But the model is not intrinsically collision-free, large deceleration is also needed to avoid the rare collision [52]. Larraga and Alvarez-Icaza [53,54] introduced a safety driving (SD) model with limited deceleration capability. In SD model, the crash was completely avoided by the velocity updating rule based on the inclusion of three safe distances required by the following vehicle to accelerate, slow down or maintain its velocity. Furthermore, the model could well reproduce synchronized flow and other complex spatiotemporal traffic patterns under Kerner's three-phase traffic theory [55–59].

Recently, Guzman et al. extended the single lane SD model to asymmetric two-lane traffic flow model, and investigated the car–truck mixed traffic [60]. But car and heavy truck are only different in vehicle length and maximum velocity. As we know that the main property of SD model is the inclusion of limited deceleration capability. In this paper, the limited deceleration capability difference between car and heavy truck is considered and the symmetric lane-changing rule based on safety distance is proposed. In the four different vehicle following scenarios, car–truck scenario should be specially paid attention when calculating the safety distances. In addition, the active deceleration behavior of heavy truck is introduced to eliminate the plug.

The rest of the paper is organized as follows. In Section 2, a detailed description and analysis of the SD model is presented. In Section 3, the expansion model with the limited deceleration capability difference and the symmetric lane change rule are introduced in detail. In Section 4, simulation results under periodic boundary condition are given and discussed. Finally, Section 5 includes the concluding remarks and a summary of findings.

2. Single lane SD model

SD model is a single-lane CA model, which integrates space gap, relative velocity of adjacent vehicle and limited deceleration capacity. In multi-lane CA models, the road is divided into $N \times L$ cells. N is the number of lanes on the road, and L is the length of road with the unit of cell. The vehicle has a length of l, that is to say a vehicle occupies l cells. The velocities of vehicle are integer values that vary from 0 to $v_{\max}$. Here $v_{\max}$ denotes the maximum velocity of a vehicle. The