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Modeling and simulation of the car-truck heterogeneous traffic flow based on a nonlinear car-following model

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ABSTRACT

The traffic flow heterogeneity caused by vehicle type difference has drawn increasing attention recently. This paper uses real data to explore the characteristics of the traffic flow consisting of the four types of car-truck car-following combinations, car-following-car (CC), car-following-truck (CT), truck-following-car (TC) and truck-following-truck (TT). To overwhelm the shortcoming that the existing car-following model, Optimal Velocity Model, cannot reflect the complexity of real heterogeneous traffic flow, a new model is proposed based on a nonlinear ordinary differential car-following model, Intelligent Driver Model (IDM). Next Generation Simulation (NGSIM) vehicle trajectory data is applied to calibrate and evaluate the proposed model. Based on the calibrated model, the traffic regime, linear stability, fundamental diagrams, and shock wave characteristics of the car-truck heterogeneous traffic flow are investigated. The results reveal some new findings of the car-truck heterogeneous traffic flow. The mixture of congested and free flow regime occurs when the trucks reach their maximum speeds. Cars and trucks can both stabilize and destabilize the traffic flow, depending on the combination type and the equilibrium velocity. Moreover, the fundamental diagrams of different car-truck combinations converge to several clusters with the same proportion difference between the CC and TT combinations. The speeding-up effect of trucks on shock wave propagation in the car-truck heterogeneous traffic flow is observed in the simulation.

1. Introduction

Heterogeneity is a crucial characteristic of real-world traffic flow. Although traffic flow theories and models are usually developed first for the homogeneous traffic flow, most of them can be easily converted into their heterogeneous forms. The difficulty in studying the heterogeneous traffic flow is the lack of fine data to calibrate the heterogeneous traffic flow models. With the development of the new data collection technology in recent years, such as the video-based method and the GPS-based method, traffic information, especially individual vehicle dynamics, can be obtained in detail. Many researchers use new data sources to investigate the characteristics of car-truck heterogeneous traffic flow in the past years. Early researchers focused on investigating the driving behavior differences between cars and trucks. Huddart and Lafont [1], McDonald et al. [2] and Sayer et al. [3] compared the headway differences between the two cases, car-following-car and car-following-truck. However, their studies did not reach conclusive results that which case had the larger headway. Peeta et al. [4,5] analyzed interactions of cars and trucks in multiple lanes. Highway Capacity Manual [6] presented that trucks occupied more space, had poorer operating capabilities

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and could create larger gaps than cars. However, these studies [1–5] did not mention that the car-following behavior in car-truck flow also depended on the type of the following vehicle. Ye's study [7] first explored the impact of the following vehicle type (car or truck) on traffic flow. He concluded that the four types of car-truck combination should be taken into account in the study of the car-truck heterogeneous traffic flow, that is, car-following-car (CC), car-following-truck (CT), truck-following-car (TC) and truck-following-truck (TT). Sarvi [8] also studied the driving behavior of the three car-following combinations, car-following-car, truck-following-car, and car-following-truck. Aghabayk et al. [9] further empirically studied variations of the distance headway, time headway, reaction time and car-following threshold among the four types of combination. One major limitation of the early studies on car-truck traffic flow is their lack of modeling of the dynamic car-truck traffic flow. Mason and Woods [10] extented the homogeneous Optimal Velocity (OV) car-following model to a heterogeneous form to describe the interaction between cars and trucks. The derived OV heterogeneous car-following model is as follows,

$$\frac{d^2x_n(t)}{dt^2} = \lambda_n(U_n(x_{n-1} - x_n) - v_n) \tag{1}$$

where $x_n(t)$ and $v_n(t)$ respectively denote the location and velocity of the vehicle n at time t, $x_{n-1}(t)$ denotes the location of the vehicle $n-1$ (the preceding vehicle of n) at time t, λ_n denotes the sensitivity parameter of the vehicle n, and $U_n(x_{n+1} - x_n)$ denotes the optimal velocity function the vehicle n wishes to take and it is the function of the headway of vehicle n.

However, the Optimal Velocity Model is a simple model, which cannot reflect the real characteristics of heterogeneous car-truck traffic flow. Therefore, in this study, based on a more realistic nonlinear ordinary differential car-following model, Intelligent Driver Model (IDM), we develop a new model for the heterogeneous traffic flow. The model has a sub-model for each car-truck following combination. The model parameters for each car-truck car-following combination are calibrated separately using the real car-following data extracted from NGSIM (Next Generation Simulation) data. Based on the calibrated model, we study the four characteristics of the car-truck heterogeneous traffic flow, traffic regime, linear stability, fundamental diagram, and shock wave.

2. Methodology

2.1. An IDM-based nonlinear car-following model for the car-truck heterogeneous traffic flow

Treiber et al. [11] proposed Intelligent Driver Model in 2000 for the homogeneous traffic flow. This model is a widely explored car-following model [12–14], and its formulation is as follows,

$$\begin{cases} \dfrac{d^2x_n(t)}{dt^2} = a\left[1 - \left(\dfrac{v_n(t)}{V}\right)^{\delta} - \left(\dfrac{S(v_n(t), \Delta v_n(t))}{\Delta x_n(t) - l}\right)^2\right] \\ S(v_n(t), \Delta v_n(t)) = s^0 + s^1\sqrt{\dfrac{v_n(t)}{V}} + \tau v_n(t) - \dfrac{v_n(t)\cdot\Delta v_n(t)}{2\sqrt{ab}} \end{cases} \tag{2}$$

where a denotes the maximum acceleration, V denotes the desired velocity, δ denotes the acceleration exponent, $S(\cdot)$ denotes the desired minimum gap, s^0 and s^1 denote the jam distances, τ denotes the safe time headway, b denotes the desired deceleration, l denotes the leading vehicle length, and $\Delta v_n(t) = v_{n-1}(t) - v_n(t)$ denotes the velocity difference between the vehicle n and its preceding vehicle $n-1$.

We develop the homogeneous IDM to its heterogeneous form by giving subscripts to the model parameters. This procedure of introducing heterogeneity into car-following models was also described by Treiber and Kesting [15]. The proposed heterogeneous IDM formulates the four different car-truck car-following combinations as follows,

$$\begin{cases} \dfrac{d^2x_n(t)}{dt^2} = a_n\left[1 - \left(\dfrac{v_n(t)}{V_n}\right)^{\delta_n} - \left(\dfrac{S_n(v_n(t), \Delta v_n(t))}{\Delta x_n(t) - l_n}\right)^2\right] \\ S_n(v_n(t), \Delta v_n(t)) = s_n^0 + s_n^1\sqrt{\dfrac{v_n(t)}{V_n}} + \tau_n v_n(t) - \dfrac{v_n(t)\cdot\Delta v_n(t)}{2\sqrt{a_n b_n}} \end{cases} \tag{3}$$

where all the parameters a_n, δ_n, V_n, s_n^0, s_n^1, τ_n and b_n have four alternatives. Taking a_n as an example, a_n can be a_{cc}, a_{ct}, a_{tc} and a_{tt}. The leading vehicle length l has two alternatives, l_c and l_t.

In the homogeneous traffic flow, all vehicles at equilibrium states have zero acceleration, the same distance headway, and the same velocity. However, for the heterogeneous traffic flow, the equilibrium state is quite different, in which all vehicles have zero acceleration and the same velocity, but their distance headways vary for different types of vehicle. The equilibrium state can be described using the following equations,

$$v_n = v^*, \ \dot{v}_n = 0, \text{ and } h_n = h_n^* \tag{4}$$