A Modified Mixed Car-following Model Considering that the Connected and Intelligent Vehicle and Non-connected Vehicle

Junjie Zhang\textsuperscript{1,2}\textsuperscript{*}, Miaomiao Liu\textsuperscript{3,4} and Zhentian Sun\textsuperscript{5}

\textsuperscript{1} School of Electronic and Information Engineering, Beihang University, Beijing, China
\textsuperscript{2} Hefei Innovation Research Institute, Beihang University, Hefei, China
\textsuperscript{3} Key Laboratory of Road Safety Technologies, Ministry of Transport, Beijing, China
\textsuperscript{4} Key Laboratory for Cooperative Vehicle Infrastructure Systems and Safety Control, School of Transportation Science and Engineering, Beihang University, Beijing, China
\textsuperscript{5} Research Institute of Highway Ministry of Transport, Beijing, China

Email: zhangjunjie55@163.com

Abstract. With the development of networking and intelligence, a mixture of multi-type vehicles will become normal in the road transportation system, which lead to more complex for vehicle motion in microscopic traffic system. Therefore, non-connected vehicle car-following model is established considering the subjective perception errors of preceding vehicles based on the desired safety margin model. Moreover, the effective range of vehicle-to-vehicle communication is considered, and the connected and intelligent vehicle car-following model considering the multi-vehicles information perception effect is constructed. We investigated the influence of penetration rate of the connected and intelligent vehicle on the stability of mixed traffic. Numerical simulations results show that the connected and intelligent vehicle can improve the mixed traffic flow stability to a certain extent. And setting reasonable feedback gain coefficients for connected and intelligent vehicle car-following model can stabilize mixed traffic flow.

Keywords. Mixed traffic flow, String stability, Connected and intelligent vehicle, Driver’s perception error.

1. Introduction

In recent years, intelligent transportation technology has developed from solving traffic control to vehicle-to-infrastructure cooperation. Considering the research status and development trends at home and abroad, vehicle-to-infrastructure cooperation system is gradually moving from the laboratory to the practical application. Then the mixed traffic will become the normal operation mode of future transport system. Therefore, revealing the evolution of traffic flow chaos in the mixed traffic becomes a difficult problem in the future intelligent traffic control research.

To explore the evolution of mixed traffic flow, many scholars have done extensive research on this subject. Yuan et al. investigated traffic flow characteristics in the traffic scenes of adaptive cruise control vehicles and human-driving vehicles [1]. Zhu and Zhang used a car-following model to investigate the evolution of mixed traffic flow consisting of human-driving cars and automatic-driving cars [2]. Nakayama et al proposed a new two-dimensional optimal velocity car-following model to investigate the evolution of mixed traffic flow with automatic-driving cars and non-motorized cars in
the car-following process [3]. Xie et al. further analyzed the features of mixed traffic flow consisting of automatic-driving cars and non-motorized cars at an unsignalized intersection [4]. Li et al. used some numerical experiments to analyze the rear-end collision risk in different proportions of cooperative adaptive cruise control (CACC) vehicles [5]. Yu et al. built a CACC model considering the change of headway with a memory delay [6]. Jia et al. proposed CACC control strategies based inter-vehicle communication and vehicle-to-infrastructure communication to analyze the stability of CACC control model, but they did not discuss the mixed traffic flow stability consisting of the CACC vehicle and human-driving vehicle [7-8]. Ge et al. proposed an intelligent and connected vehicle model considering the preceding vehicle’s acceleration feedback control term to investigate the string stability in the platoon [9]. Although the existing research results have studied the evolution of traffic flow using different car-following models in the mixed traffic, few scholars have constructed coupled relation car-following model between intelligent and connected vehicle and non-connected vehicle considering the driver’s risk perception, the perception error, and the feedback control of multi-preceding and multi-following vehicles. Therefore, we propose a modified mixed car-following model considering that the connected and intelligent vehicle and non-connected vehicle on the basis of the desired safety margin (DSM) model in this paper [10].

The remainder of this paper is arranged as follows: in section 2, a modified mixed car-following model is introduced, including non-connected vehicle car-following model and connected and intelligent vehicle car-following model. In section 3, the influence of connected and intelligent vehicle on the evolution of mixed traffic flow is investigated using numerical simulations. In section 4, conclusions are drawn.

2. Modified Mixed Car-following Model

2.1. Non-connected Vehicle Car-following Model

Non-connected vehicle cannot obtain multi-vehicles information in the platoon, it only can perceive the preceding vehicle information. That is to say, the driver makes a decision in car-following process according to the perceived acceleration and its perception error, the acceleration of the non-connected vehicle is given as:

\[ \hat{a}_n(t+\tau) = a_n(t+\tau) + \epsilon|_{\hat{a}_n(t)} \]  

(1)

where \( \hat{a}_n(t) \) and \( a_n(t) \) are the decision and actual acceleration of the \( n \)th vehicle, respectively; \( \epsilon \) denotes the perception error for the acceleration of the \( n \)th vehicle.

In this paper, we give two assumption conditions for the driver as follows:

Assumption 1: Perception error of unit acceleration for the driver follows the normal distribution as \( N\left(\mu, \sigma^2\right) \).

Assumption 2: Driving behaviors of all non-connected vehicles are homogeneity and have the same subjective perception characteristics.

Therefore, the conditional probability distribution of perception error is obtained in the given acceleration \( \xi^0 \) according to Assumption 1 as follows:

\[ \epsilon|_{\xi^0} \sim N\left(\mu\xi^0, \sigma^2\xi^0\right) \]  

(2)

and conditional moment generating function

\[ M_{\Phi_\epsilon, \xi^0}(s) = e^{(\mu\xi^0s + \sigma^2\xi^0s^2)} \]  

(3)

where \( s \) is real number.

Through calculating, the expected acceleration of the \( n \)th vehicle can be obtained as follows:
\[ E(\ddot{a}_n) = \frac{\ddot{c}M_D[s(1 + \mu + \dddot{s}^2)]}{\ddot{c}s} = (1 + \mu)E(a_n) \] (4)

With the simplified DSM model as the basis of modeling, non-connected vehicle car-following model can be:

\[ \ddot{a}_{n \text{non-connected}}(t+\tau) = \alpha(1 + \mu)(SM_n(t) - SM_D) \] (5)

and

\[ SM_n(t) = 1 - \left( \frac{0.15V_n(t)}{D_n(t)} + \frac{(V_n(t) - V_{n-1}(t))(V_n(t) + V_{n+1}(t))}{1.5g \cdot D_n(t)} \right) \] (6)

where \( SM_D \) is desired safety margin of the driver, \( D_n(t) \) is the vehicle spacing in the platoon, \( V_n(t) \) is speed of the \( n \)th vehicle; \( V_{n+1}(t) \) is speed of the \( n+1 \)th vehicle; \( g \) denotes the acceleration of gravity.

2.2. Connected and Intelligent Vehicle Car-following Model

Connected and intelligent vehicle can accept the feedback information of multi-preceding and multi-following vehicles in the platoon, including velocities and accelerations of the connected and intelligent vehicles and non-connected vehicles. In this paper, connected and intelligent vehicle car-following model considers the feedback acceleration information of multi-preceding and multi-following vehicles on the basis of the simplified DSM model, then the connected and intelligent vehicle car-following model is given as:

\[ \ddot{a}_{n \text{connected}}(t+\tau) = \alpha(1)(SM_n(t) - SM_D) + \sum_{i=1, j=n+1}^{m_1} \left( \gamma_i \ddot{a}_{n-i \text{non-connected}}(t) + \gamma_j \ddot{a}_{n-j \text{connected}}(t) \right) \]

\[ + \sum_{i=1, j=n+1}^{m_2} \left( \beta_i \ddot{a}_{n+i \text{non-connected}}(t) + \beta_j \ddot{a}_{n+j \text{connected}}(t) \right) \] (7)

where \( m_1 \) and \( m_2 \) denote the number of non-connected vehicles and connected and intelligent vehicles at the front and rear of the \( n \)th in the platoon, respectively, \( \beta_i \) and \( \gamma_i \) indicate the feedback gain coefficients.

In the car-following process, we assume that connected and intelligent vehicle only can receive communication distance with radius of 2 vehicles, as shown in figure 1.

![Figure 1](image-url) A mixture of connected and intelligent vehicles (CIV) and non-connected vehicles (NCV) in the car-following process.

3. CIV Effect on the Mixed Traffic Flow

We will analyze the influence of CIV on the evolution of mixed traffic flow using numerical simulations in this subsection.
We assume that the initial velocities and positions of all vehicles are shown in Equation (8), a small disturbance of velocity for the leading vehicle is produced after time \( \hat{t} \), and other vehicles are followed in turn.

\[
\begin{align*}
X_i(0) &= SM_i, V_i(0) = 20, \dot{V}_i(0) = 0, \\
V_i(t) &= \eta(\hat{t}), t \geq \hat{t}, \\
X_n(0) &= S \cdot (M - n + 1), V_{n-1}(0) = 20, \dot{V}_{n-1}(0) = 0, n = 2, \cdots, M - 1,
\end{align*}
\]

where the number of vehicles \( M = 50 \), the initial headway \( S = 35m \), \( X_i(0) \), \( V_i(0) \), and \( \dot{V}_i(0) \) denote the position, velocity, and acceleration of the \( n \)th vehicle at time \( t = 0 \), respectively. \( \eta(\hat{t}) \) represents a small disturbance of acceleration of leading vehicle, which follows uniform distribution in the range of \([-5 \times 10^{-2}, 5 \times 10^{-2}]\).

Fifty vehicles of the platoon are composed of the corresponding proportions of CIV and NCV. We will investigate ten proportions of CIV as 10%, 30%, 50%, 70%, 90%, and 100% effect on the fluctuations of mixed traffic flow. Here the parameters of CIV and NCV car-following models are set as \( \alpha = 15 \text{ m/s}^2 \), \( \mu = 0.2 \), \( \tau = 0.5 \), \( SM_{D} = 0.9 \), \( \beta_i = 0.2 \), and \( \gamma_i = 0.3 \).

In the mixed traffic, the fluctuations of velocities increase with the number of vehicles as shown in figures 2a-2j. Compared with 0 of the proportion of CIV as shown in figure 3a, the velocities of vehicles fluctuate small when the proportion of CIV is about 30%~40% in the platoon. It shows that the feedback information of multi-preceding and multi-following vehicles is conducive to improve string stability. Results imply that CIV can improve the mixed traffic flow stability to a certain extent.

Furthermore, we adjust the feedback gain coefficients of \( \beta_i \) and \( \gamma_i \) from 0.2 and 0.3 to 0.1 and 0.2. The fluctuations of velocities decrease obviously in the mixed traffic compared with figures 3b and 2c. Therefore, setting reasonable feedback gain coefficients for CIV car-following model can stabilize mixed traffic flow.
Figure 2. Velocity boxplots of vehicles for a mixture of CIV and NCV in the car-following process.

(a) Proportion of NCV: 100%.
(b) Proportion of CIV: 30%, $\beta = 0.1$, $\gamma = 0.2$.
(c) Proportion of CIV: 50%.
(d) Proportion of CIV: 70%.
(e) Proportion of CIV: 90%.
(f) Proportion of CIV: 100%.

Figure 3. Velocity boxplots of vehicles for a mixture of CIV and NCV after the change of feedback gain coefficients.

(a) Proportion of NCV: 100%.
(b) Proportion of CIV: 30%, $\beta = 0.1$, $\gamma = 0.2$.
4. Conclusions
It is presented a new mixed car-following model considering that the CIV and NCV in this paper. NCV car-following model is established considering the subjective perception errors of preceding vehicles based on the simplified DSM model. CIV car-following model is constructed considering the effective range of vehicle-to-vehicle communication and multi-vehicles information perception effect. The effect of penetration rate of the CIV on the mixed traffic flow stability is investigated using numerical simulation experiments. It shows that CIV can enhance the mixed traffic flow stability to a certain extent. And setting reasonable feedback gain coefficients for CIV car-following model can stabilize mixed traffic flow. Therefore, a local string optimal control strategy of the CIV is an effective stabilizing method for the mixed traffic flow.

Acknowledgments
This work was supported by the Opening Project of Key Laboratory of Road Safety Technologies, Ministry of Transport, China (2019RST01), the National Key R&D Program of China (No. 2018YFB1601104, 2018YFC0807500), Chinese Postdoctoral Science Foundation Science (No. 2019M660407), and Technology Project of Beijing Municipal Commission of Science and Technology (No. Z181100003918011).

References
[1] Yuan Y M, Jiang R, Hu M B, Wu Q S and Wang R 2009 Traffic flow characteristics in a mixed traffic system consisting of ACC vehicles and manual vehicles: A hybrid modelling approach Physica A: Statistical Mechanics and its Applications 388 2483-2491
[2] Zhu W X and Zhang H M 2017 Analysis of mixed traffic flow with human-driving and autonomous cars based on car-following model Physica A: Statistical Mechanics and Its Applications 496 274-285
[3] Nakayama A, Hasebe K and Sugiyama Y 2005 Instability of pedestrian flow and phase structure in a two-dimensional optimal velocity model Physical Review E 71 (3) 036121
[4] Xie D F, Gao Z Y, Zhao X M and Li K P 2009 Characteristics of mixed traffic flow with non-motorized vehicles and motorized vehicles at an unsignalized intersection Physica A: Statistical Mechanics & its Applications 388 2041-2050
[5] Li Y, Wang H, Wang W, Xing L, Liu S W and Wei X Y 2017 Evaluation of the impacts of cooperative adaptive cruise control on reducing rear-end collision risks on freeways Accident Analysis & Prevention 98 87-95
[6] Yu S and Shi Z 2015 The effects of vehicular gap changes with memory on traffic flow in cooperative adaptive cruise control strategy Physica A: Statistical Mechanics and Its Applications 428 206-223
[7] Jia D and Ngoduy D 2016 Platoon based cooperative driving model with consideration of realistic inter-vehicle communication Transportation Research Part C: Emerging Technologies 68 245-264
[8] Jia D and Ngoduy D 2016 Enhanced cooperative car-following traffic model with the combination of v2v and v2i communication Transportation Research 90 172-191
[9] Ge J I and Orosz G 2014 Dynamics of connected vehicle systems with delayed acceleration feedback Transportation Research 46 46-64
[10] Wang Y P, Zhang J J and Lu G Q 2019 Influence of driving behaviors on the stability in car following IEEE Transactions on Intelligent Transportation Systems 20 1081-1098