An Extended Car-following Model for Urban Merging Section

Kening Sun, Zhongke Shi*

School of Automation, Northwestern Polytechnical University, Xian 710072, Shaanxi, China

Abstract

Traffic flow in the merging section is unstable and often interrupted by the merging vehicles from other lanes. Accidents and congestions may happen in the merging section. Moreover, the merging process lack of the traffic flow research on the microscopic level. In this paper, an extended car-following model considering the lane-changing in the merging section is proposed based on the full velocity difference car-following model. The field data is obtained from the merging section in Xi'an city by the fixed position camera video. To describe the complete merging process, two different directions of lane-changing are discussed in the model. According to the observed data we obtained, parameters in the model are calibrated with the genetic algorithm and verified by the field data. The result shows the relative error of the acceleration is under 20% and indicate that the proposed model can be applied to describe the microscopic traffic flow characteristics of the merging process appropriately.

Keywords: , Merging Section, Car-following Model, Lane-changing,

*Corresponding author
Email address: zkeshi@nwpu.edu.cn (Zhongke Shi)

1. Introduction

To obtain a clear understanding of the ultimate traffic mechanisms, the car-following model is most widely used as a microscopic traffic model now. At the early stage of the research, researchers focus on the primary mathematical model for vehicles. Pipes [1] proposed the early car-following model which pointed out that the velocity difference affects the vehicles motion. Bando et al.[2] introduced the optimal velocity which the following driver strives to maintain. Newell [3] analyzed the effects of time delay in the car-following model and promoted the application of shockwave theory in traffic flow. Helbing [4] calibrated the OVM with empirical data and proved its irrationality. Jiang et al.[5] proposed the FVM which considered both the negative and positive velocity differences to describe the velocity information more reasonable. Applying into different situations, the fundamental car-following model is being improved by considering the external factors of the traffic system. Tang, T. Q., et al.[7] took the drivers forecast effect into account and presented a new car following model. Zhao, J. and P. Li [8] proposed a new car following model with the consideration of speed guidance and analyzed the guiding speed limitation on driver behaviors. For these single-lane car-following model, a variety of methods and stability analysis have been presented [9][10][11][12] [13][14] In the urban transportation system, many accidents happened in the merging section. When the three-lane road merges to the two-lane road, the vehicles on the outside lane will be forced to change the lane to pass the merging section. Uncertainties in the merging section caused different kinds of accidents. Several long queue traffic jams also induced by the uncertain changes in urban merging section. Understanding the dynamic merging mechanism in this situation is significant for the future of urban transportation research. Lane-changing in merging section is a critical factor which affects the stability of traffic flow. To avoid crowdedness or to accelerate the vehicle, drivers often choose to change the lane on a multilane roadway. Under this situation, the passing efficiency of the driver who changes the lane can be improved, but the whole traffic flow in this specific area can be disrupted because of the random lane-changing. The unstable traffic flow causes the capacity reductions [21] and even the traffic accidents. It needs observations and in-depth analysis of the real traffic integrally before the specification of the traffic flow model and requires measured data to calibrate and verify the proposed model. Existing research about the lane-changing pay more attention on drivers choice. Although the behavior of drivers is essential, understanding the characteristics of the dynamic merging process is indispensable for the future construction of the intelligent transportation system. Kesting, et al[22] presented a general lane-changing model with the consideration of the incentive criterion, the MOBIL model, and took the deceleration of drivers into account as a crucial parameter. Moridpour, et al.[23] took the lane-changing maneuver into account and analyzed the different vehicles lane-changing under oppressive conditions. In this paper, the characteristics of urban merging section are investigated. In Section 2, the method of fixed position camera to acquire the field data is introduced, and the data we collected is analyzed. In Section 3, the dynamic mechanism in the merging section is introduced and an extended car-following model to describe the characteristics of the vehicle in the merging section is presented. The extended car-following model considering the langchanging was proposed from the full velocity difference model and divided into three parts which contains the different merging directions. In Section 4, the parameter calibration and model analysis of the proposed model are presented based on the acquired data, and the conclusion is given in Section 5.

2. Data Acquisition and Analysis

The contributory factor of the dynamic mechanism in the merging section should be determined by the observations and the analysis from field data. One of the essential components in the merging process is the lane-changing. To describe the dynamic process of lane changing, we drove a car to pass the merging section and observed the lane-changing by recording the whole merging process appeared. From the observations and camera video, we can figure that the velocities of vehicles and the distance between the vehicles mainly affects the merging process and the different road parameter also influence the real merging situation. Based on the analysis above, we can describe the process as follows, In the merging section, the three-lane road turns to the two-lane road or the two-lane road turn to the single lane road. The driver on the outside lane has to change the lane to pass the merging section. At this time, a group of vehicles is running on the neighbor lane. When the merging vehicle chooses to cut into the lane, the leading vehicle of the group has to slow down and let the merging vehicle enter their lane. The following vehicle keeps observing the velocity changes of the leading vehicle and distance changes between them and adjusts own velocity to keep a safe distance. After the merging process, the merging vehicle becomes the leading vehicle of the group. The dynamic process of the merging section is described in the

Fig. 1.

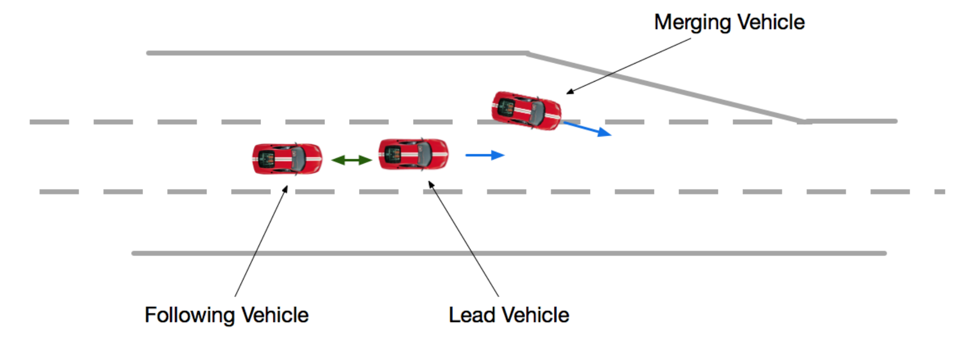

Figure 1: Vehicle's Lane-changing in Merging Section

To analyze the influencing factor of the car-following behavior in urban merging section, we used the fixed position camera to capture the video data from the real traffic. The needed data are collected from traffic videos in the merging section located at the Tangyan South Road of Xian in China. The video camera is installed on the terrace of a building adjacent to the merging section, as shown in Fig. 2. The traffic video obtained is filtered to eliminate the clips with complex traffic composition or without the merging process before data extraction.

3. Model for Urban Merging Section

In general, the model applied to describe the microscopic dynamic transportation usually consider the velocity and distance as vital factors. Taking the effect of Δv into account, the full velocity difference model can be used to describe the most of the situations, given by:

$$\ddot{x_n}\left(t\right) = \kappa\left[V\left(\Delta x_n\left(t\right)\right) - v_n\left(t\right)\right] + \lambda\Delta v_n\left(t\right) \tag{1}$$

Figure 2: The field data collection site

The optimal velocity function is adopted as below:

$$V\left(\Delta x_n\left(t\right)\right) = v_1 + v_2 \tanh\left(C_1 \Delta x_n\left(t\right) - C_2\right) \tag{2}$$

where x_n is the position of car n; Δx_n is the headway between car n and n + 1; v_1, v_2, C_1, C_2 are parameters.

(1) When the merging vehicle is merged from the right lane, the following vehicle could perceive the horizontal distance changes between the merging vehicle and the leading vehicle. The changes which the following vehicle perceived is based on the average lateral distance on this road. The average lateral distance is defined as the safe horizontal distance that two vehicles usually keep on this road. The relative velocity and headway are two critical variables, and they are selected as the input values in modeling vehicular motion. Its motion behavior

can be determined as follows:

$$\ddot{x_n}(t) = \kappa \left[V\left(\Delta x_n(t)\right) - v_n(t)\right] + \lambda \Delta v_n(t) + \beta \left[L_d - D_1 \Delta x_{n+1}(t) + D_2 \Delta v_{n+1}(t)\right] \tag{3}$$

where β, D_1 and D_2 is the sensitivity parameter, L_d is the normal lateral distance, Δx_{n+1} is the headway difference between the leading vehicle and the merging vehicle, Δv_{n+1} is the relative velocity between the leading vehicle and the merging vehicle.

(2) When the merging vehicle is merged from the right lane, the model is not the same as the model that the merging vehicle on the left lane. People drive their cars on the right side of the road in China, and the right rear is often the blind area. Thus, different from the situation on merging from the left lane, drivers have a response delay in recognizing the merging vehicle on the right lane. The equation can be formulated as follows:

$$\ddot{x_n}(t) = \kappa \left[V\left(\Delta x_n(t + t_\beta)\right) - v_n(t + t_\beta)\right] + \lambda \Delta v_n(t + t_\beta) + \beta \left[L_d - D_1 \Delta x_{n+1}(t) + D_2 \Delta v_{n+1}(t)\right] \tag{4}$$

where t_β is the response delay for the leading vehicle, β, D_1, $D_2$is the sensitivity parameter, L_d is the average lateral distance.

(3)When the merging vehicle has finished the merging process, it becomes the new leading vehicles. Then the origin leading vehicle becomes the following vehicle, and the model turns out to be the common car-following behaviors. So the full velocity difference model can be used to describe the mechanism after merging process, given by:

$$\ddot{x_{n+1}}(t) = \kappa \left[V\left(\Delta x_{n+1}(t)\right) - v_{n+1}(t)\right] + \lambda \Delta v_{n+1}(t) \tag{5}$$

where $v_{n+1}$is the velocity of the vehicle at time t; $V(.)$ is the optimal velocity function;$\Delta x_{n+1} = x_{n+2}(t) - x_{n+1}(t)$is the space headway between the leading vehicle n+1 and the following vehicle n+2 at time t; $\Delta v_{n+1} = v_{n+2} - v_{n+1}$ is the velocity difference between the leading vehicle n+1 and the merging vehicle n+2 at time t; κ and λ are sensitivity parameters.

In summary, we obtained an extended car-following model for urban merging section which is named as urban merging(UM) model that can be written as follows:

$$\begin{cases} \ddot{x_n}(t) = \kappa\left[V\left(\Delta x_n(t)\right) - v_n(t)\right] + \lambda\Delta v_n(t) + \beta\left[L_d - D_1\Delta x_{n+1}(t) + D_2\Delta v_{n+1}(t)\right] \\ \ddot{x_n}(t) = \kappa\left[V\left(\Delta x_n(t+t_\beta)\right) - v_n(t+t_\beta)\right] + \lambda\Delta v_n(t+t_\beta) + \beta\left[L_d - D_1\Delta x_{n+1}(t) + D_2\Delta v_{n+1}(t)\right] \\ \ddot{x_{n+1}}(t) = \kappa\left[V\left(\Delta x_{n+1}(t)\right) - v_{n+1}(t)\right] + \lambda\Delta v_{n+1}(t), \left(L_d = D_2\Delta v_{n+1}(t) - D_1\Delta x_{n+1}(t)\right) \end{cases} \tag{6}$$

4. Model Calibration and Verification

In this section, we apply the observed data we obtained to calibrate the related parameters. The data is divided into two parts, one is used to calibrate the model parameters, and the other is used to verify the calibrated model. Before the parameter calibration and model verification, the data is smoothed by moving average method to remove the abnormal point in the data as much as possible. Since the average lateral distance of vehicles on different road sections is different, there are different values for L_d in different study areas. In this paper, the value of L_d is taken as 1.02m based on observations of the selected study area. Genetic algorithm is a stochastic optimization search method derived from the survival of the fittest in the biological world and the genetic mechanism of the survival of the fittest. It is suitable for dealing with complex nonlinear problems. We apply genetic algorithm to calibrate the parameters. For the car-following process affected by vehicles merged from the left lane, we selected six sets of complete follow-up processes with more than 200 pieces of data for parameter calibration. The total number of groups in genetic algorithm is 20, the mutation rate is 0.01, and the crossover rate is 0.65. The response delay is set as 0.5. The result of parameter calibration is shown in Table 1.

Direction	β	D_1	D_2	**Correlation Coefficient**
Left	0.24	1.13	5.63	0.76
Right	0.18	1.76	6.05	0.82

Table 1: Result of Calibration in the Studied Area

The model error stems from the complexity and uncertainty of actual driving behavior. Driving behavior varies from person to person. The model established by the commonality of many individualities is used to simulate the difference between specific behaviors and actual ones.

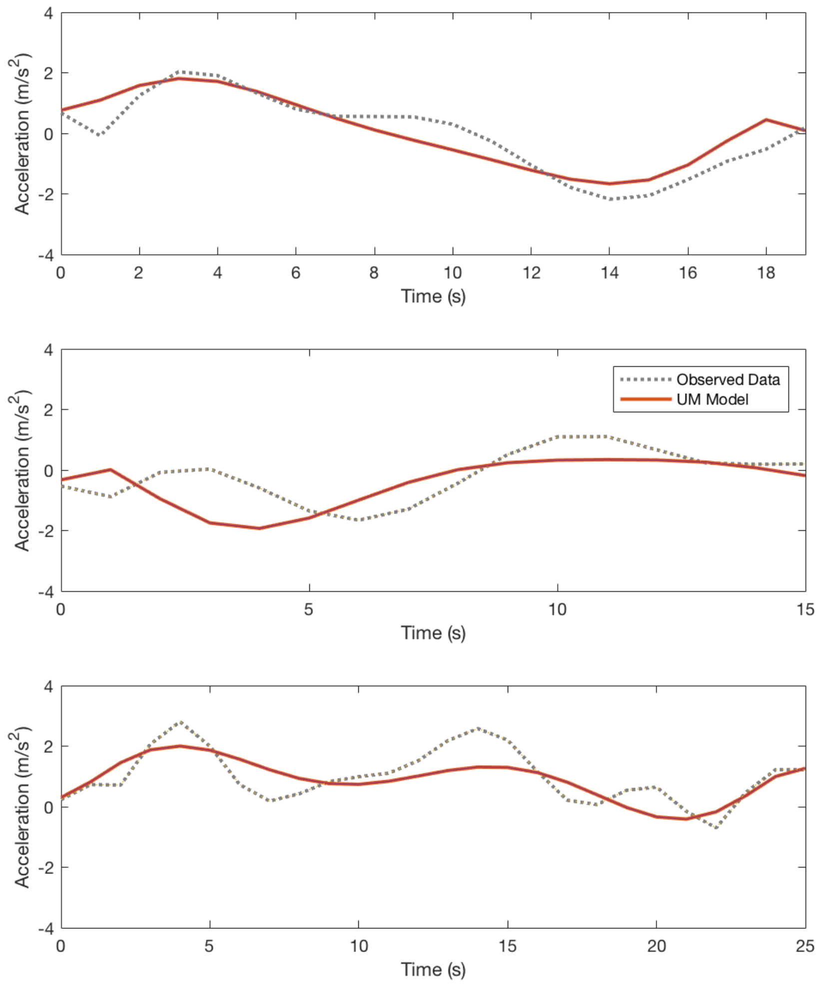

Figure 3: Examples of Simulated Acceleration and Observed data

From Fig. 3, it can be obviously seen that, through the calculation of the UM model, the target vehicle acceleration is consistent with the original data in the change trend, and the error is small. The mean square error is 0.71. And the relative error of acceleration is 13.2%. Therefore, the proposed model can describe the microscopic traffic flow characteristics of the merging section appropriately and simulate the merging process successfully.

5. Conclusions

In this paper, we present an extended car-following model which called the UM model to study the influences of the lane-changing on the merging process at urban merging section. Due to the different mechanism in the merging process, we divide the whole merging process into three parts: Merging from left-lane, Merging from right-lane and After merging. Based on the observed data, we calibrate the sensitive parameters of the UM model and verify its effectiveness. The result shows that the velocity difference and position difference between merging vehicle and leading vehicle can affect their lateral distance and thus cause the velocity fluctuation of the leading vehicle, which influence the car-following process. The observed data has its limitations and there may be errors in the process of distance conversion. The merging section may not occurs in every urban area but the merging process in the section should be valued, which will affect the driving decisions of the future autonomous vehicles.

Acknowledgment

References

[1] L.A. Pipes, An operational analysis of traffic dynamic, J. Appl. Phys. 24 (1953) 274281.

[2] M. Bando, K. Hasebe, A. Nakayama, A. Shibata, Y. Sugiyama, Dynamical model of traffic congestion and numerical simulation, Phys. Rev. E 51 (1995) 10351042.

[3] G.F. Newell, Nonlinear effects in the dynamics of car following, Oper. Res. 9 (1961) 209229.

[4] D. Helbing, B. Tilch, Generalized force model of traffic dynamics, Phys. Rev. E 58 (1998) 133138.

[5] R. Jiang, Q.S. Wu, Z.J. Zhu, Full velocity difference model for a car-following theory, Phys. Rev. E 64 (2001) 14.

[6] Tang, Tieqiao, Haijun Huang, S. C. Wong, and Rui Jiang. ”Lane Changing Analysis for Two-Lane Traffic Flow.” Acta Mechanica Sinica 23, no. 1 (2007): 49-54.

[7] Tang, T. Q., C. Y. Li, and H. J. Huang. ”A New Car-Following Model with the Consideration of the Driver’s Forecast Effect.” Physics Letters A 374, no. 38 (2010): 3951-56.

[8] Zhao, Jing, and Peng Li. ”An Extended Car-Following Model with Consideration of Speed Guidance at Intersections.” Physica A Statistical Mechanics Its Applications 461 (2016): 1-8.

[9] Liu, Da Wei, Zhong Ke Shi, and Wen Huan Ai. ”Enhanced Stability of Car-Following Model Upon Incorporation of Short-Term Driving Memory.”

Communications in Nonlinear Science Numerical Simulation 47 (2017): 139-50.

[10] Zhao, Xiaomei, and Ziyou Gao. ”A Control Method for Congested Traffic Induced by Bottlenecks in the Coupled Map Car-Following Model.” Physica A Statistical Mechanics Its Applications 366, no. 1 (2006): 513-22.

[11] Jin, Yanfei, and Meng Xu. ”Stability Analysis in a Car-Following Model with Reaction-Time Delay and Delayed Feedback Control.” Physica A Statistical Mechanics Its Applications 459 (2016): 107-16.

[12] Yu, Shaowei, and Zhongke Shi. ”An Extended Car-Following Model at Signalized Intersections.” Physica A Statistical Mechanics Its Applications 407, no. 407 (2014): 152-59.

[13] Zhu, Wen Xing, Jun Du, and Li Dong Zhang. ”A Compound Compensation Method for Car-Following Model.” Communications in Nonlinear Science Numerical Simulation 39 (2016): 427-41.

[14] Zhu, Wen Xing, and Li Dong Zhang. ”Analysis of Car-Following Model with Cascade Compensation Strategy.” Physica A Statistical Mechanics Its Applications 449 (2016): 265-74.

[15] Nagel, Kai, Dietrich E. Wolf, Peter Wagner, and Patrice Simon. ”Two-Lane Traffic Rules for Cellular Automata: A Systematic Approach.” Physical Review E Statistical Physics Plasmas Fluids Related Interdisciplinary Topics 58, no. 2 (1997): 1425-37.

[16] Chowdhury, Debashish, Dietrich E. Wolf, and Michael Schreckenberg. ”Particle Hopping Models for Two-Lane Traffic with Two Kinds of Vehicles: Effects of Lane-Changing Rules.” Physica A Statistical Mechanics Its Applications 235, no. 34 (1997): 417-39.

[17] J.C, Deutsch, Santhosh-Kumar C.R, Rickert M, Nagel K, Schreckenberg M, and Latour A. ”Two Lane Traffic Simulations Using Cellular Automata.” Physica A-Statistical Mechanics and Its Applications 231, no. 4 (1995): 534-50.

[18] Gunay, Banihan. ”Car Following Theory with Lateral Discomfort.” Transportation Research Part B Methodological 41, no. 7 (2007): 722-35.

[19] Tang, T Q, Haijun Huang, and Ziyou Gao. ”Stability of the Car-Following Model on Two Lanes.” Physical Review E 72, no. 6 (2005): 066124-24.

[20] Ge, Hong Xia, et al. ”Feedback control for car following model based on two-lane traffic flow.” Physica A 408.32(2014):28-39.

[21] Jin, Wenlong. ”Macroscopic Characteristics of Lane-Changing Traffic.” Transportation Research Record 2188, no. 2188 (2010): 55-63.

[22] Kesting, Arne, Martin Treiber, and Dirk Helbing. ”General Lane-Changing Model Mobil for Car-Following Models.” Transportation Research Record 1999, no. 1999 (2007): 86-94.

[23] Moridpour, Sara, Majid Sarvi, and Geoff Rose. ”Modeling the Lane-

Changing Execution of Multiclass Vehicles under Heavy Traffic Conditions." Transportation Research Record 2161, no. 2161 (2010): 11-19.

[24] Yu, Shaowei and Zhongke Shi. "The Effects of Vehicular Gap Changes with Memory on Traffic Flow in Cooperative Adaptive Cruise Control Strategy." Physica A Statistical Mechanics Its Applications 428 (2015): 206-23.

[25] Yu, Shaowei and Zhongke Shi. "Fuel Consumptions and Exhaust Emissions Induced by Cooperative Adaptive Cruise Control Strategies." International Journal of Modern Physics B 29, no. 14 (2015): 1550084-.

[26] Jinliang Cao, Zhongke Shi, and Jie Zhou. "An extended optimal velocity difference model in a cooperative driving system." International Journal of Modern Physics C 26.05(2015):1550054-.

[27] Tang, Tie Qiao, et al. "A Multilane Traffic Flow Model Accounting for Lane Width, Lane-Changing and the Number of Lanes." Networks Spatial Economics 14.3-4(2014):465-483.

[28] Tang, Tie Qiao, et al. "An extended car-following model with consideration of the reliability of inter-vehicle communication." Measurement 58.11(2014):286-293.

[29] Tang, Tie Qiao, et al. "Effects of on-ramp on the fuel consumption of the vehicles on the main road under car-following model." Physica A Statistical Mechanics Its Applications 419.44(2015):293-300.