Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 6, No. 1, January, 2020

Car-following Behavior Analysis of Left-turn Vehicles at Signalized Intersections

Wei Fulu [a*], Chen Long [a], Guo Yongqing [a], Chen Mingtao [b], Ma Jiaxiang [a]

[a] *Department of Traffic Engineering, Shandong University of Technology, Zibo 255000, China.*

[b] *Hualan Design and Consulting Group, Nanning 530022, China.*

Received 05 October 2019; Accepted 26 December 2019

Abstract

In order to enrich the car-following theory of urban signalized intersections, and reveal the car-following characteristics of left turn at signalized intersections, the car-following behavior of left turn at signalized intersections is studied. The car-following data acquisition test which was based on high precision GPS was designed. And the car-following characteristics of left-turning vehicles at signalized intersections with different turning radii were analyzed. Based on which, the influence of radius on the car-following behavior was explained, and the New Full Velocity Difference (NFVD) model was developed. The genetic algorithm was used to calibrate the parameters of the NFVD model. The stability and accuracy of the calibrated model was further analyzed by using field data. The results showed that the average speed of the following car increases with the turning radius of the signalized intersection; the car-following speed which the highest frequency occurs under different turning radii tends to increase with the enlargement of turning radius; the larger the average headway distance between the car-following vehicles, the more intense of the driver's response to the deceleration of the front vehicle. These findings could be used in traffic simulation and to make engineering decisions.

Keywords: Car-following Theory; Driver Behavior; Left-turning Vehicles; FVD Model; Signalized Intersections.

1. Introduction

Car-following behavior is one of the most common and typical driving behaviours. It is also a key component of traffic flow theory, which directly relates to traffic efficiency and driving safety. A deep understanding and modeling of the details of left-turning vehicle's car-following behavior at signalized intersections is of great significance in alleviating traffic congestion at intersections, ensuring traffic safety, and enriching the theoretical connotation of urban traffic flow [1].

Domestic and foreign scholars have been carrying out multi-dimensional and deep-seated systematic research on car-following behavior and modeling:

In the research of car-following behavior at signalized intersections: Yu et al. [2] considered the influence of signal lights on the following behavior. Based on the generalized force model (GF) and the optimal velocity model (OV), the parking-following model was constructed through experimental analysis at the signalized intersection. Tan et al. [3] considered the effect of the geometric design parameters of the signalized intersection on the following behavior, and improved the intelligent driver model (IDM) by using the two-degree-of-freedom vehicle dynamics model. The new car-following model showed that the improved car-following model performed well on curved and super-high roads;

* Corresponding author: fulu1011@163.com

http://dx.doi.org/10.28991/cej-2020-03091463

Wang et al. [4] considered the influence of the lane-changing behavior of the vehicle in front. Based on the measured data of Next Generation Simulation (NGSIM), the car-following model under different lane-changing scenarios was established based on the full velocity difference model (FVD). Keiji Konishi et al. [5] proposed a car-following model according to the coupled map. The following model described the dynamic behavior of a group of vehicles traveling on a single lane without overtaking. Carolina Osorio et al. [6] calibrated the car-following model by the simulation optimization method, providing a traffic flow model corresponding to the Gipps model. In addition, some scholars have studied the car-following behavior under the influence of bad weather [7-8]; some scholars also considered the influence of the front car, the rear car or the side car on the car-following, and established the car-following model under the influence of multi-car. [9-11].

Most of the research objects of car-following models are through vehicles, and the understanding of the car-following behavior of turning vehicles at the signalized intersection is not deep enough. The pre-research on the left turn car-following behavior has shown that there is new characteristics of the following behavior under the influence of the turning radius [12].

In this paper, based on high-accuracy Global Positioning System (GPS), a real-time dynamic vehicle tracking data acquisition method was designed to collect the left turn car-following data at the urban signalized intersections [1]. Through data analysis, the data, the car-following characteristics and the key influencing factors of left turn vehicles at signalized intersections were clarified. And then, the New Full Velocity Difference (NFVD) model of the left-turning vehicle was established to describe the car-following behavior of left-turning vehicles at the signalized intersection.

2. Data Acquisition Experiment Design

The car-following experiment of turning vehicle was designed, as shown in Figure 1. Two ordinary cars were used as experimental vehicles in the experiment. Two high-precision GPS instruments and cameras were installed on the experimental vehicles to record the speed, position, environment and other data of the vehicle during the car-following experiment and the emergencies on the following behavior. The experiment was carried out at the signalized intersection of several sections at the area of Zhangdian District, Zibo City, Shandong Province from April 23 to April 24, 2019. The selected survey sections of the experiment contain signalized intersections with different turning radii, which provide diversified data support for the research of the thesis.

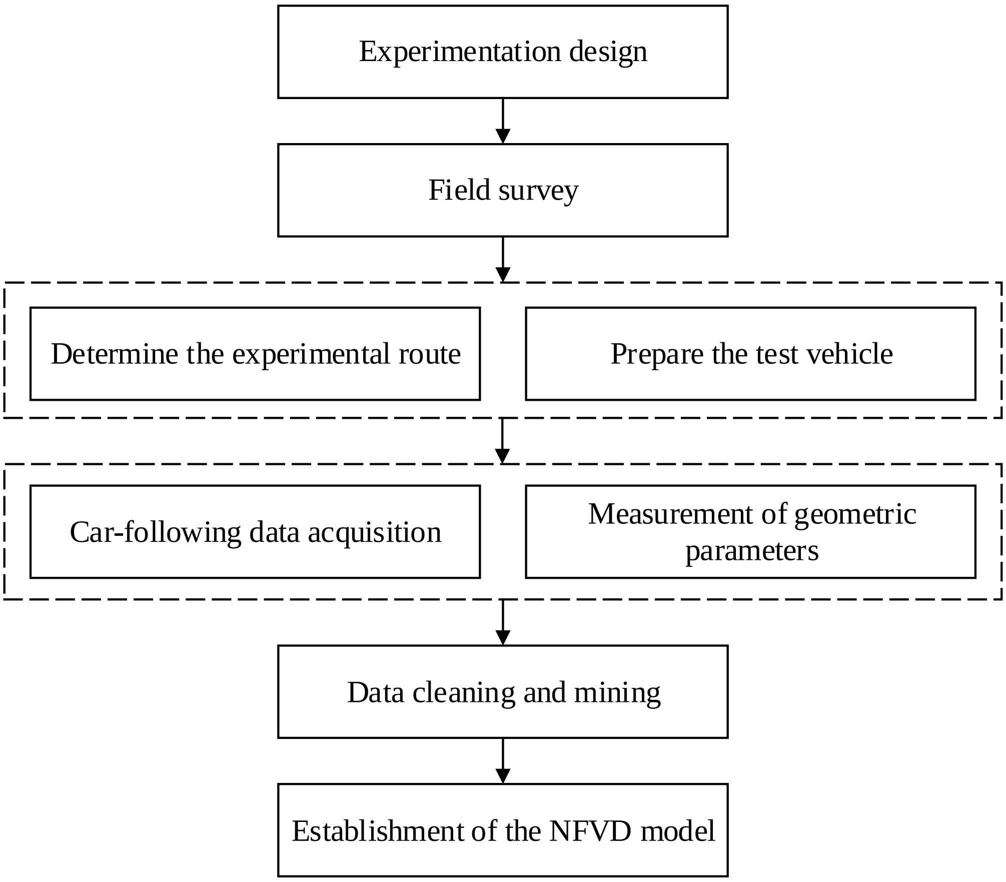

Figure 1. The car-following experiment of turning vehicle

2.1. Car-following Data Collection

The data collection of the actual car-following experiment is to record the speed trajectory of the preceding and following vehicles in the selected experimental route by using the vehicle-mounted high-precision GPS instrument, and obtain the real-time position of the vehicle, speed, direction and other information. The high-precision GPS instrument selected for the experiment is small in size, easy to carry, and can be installed at any position of the vehicle according to the experimental needs. In this data acquisition experiment, the high precision GPS instrument is installed under the front windshield of the leading car and the rear car in the following experiment, so as to eliminate the difference of the position of the collection due to the different locations, and avoid the influence of other equipment and experimental environment on driver's driving behavior. Obtaining the data that can reflect the following characteristics of the left-turning vehicle in the actual traffic flow at the signalized intersection, to analyze the operating law of the left-turning following vehicle at the signalized intersection, to verify the stability of the model and to provide a solid basis for parameter calibration.

The high-precision GPS real-time dynamic vehicle following data acquisition method is used to record the car-following behavior of the left-turning vehicle at different intersections. The whole process uses video recording, video and data are combined to further ensure the accuracy of the data, and at the same time obtain data that can reflect the following characteristics of the left-turning vehicle in the actual traffic flow at the signalized intersection, to analyze the operating law of the left-turning following vehicle at the signalized intersection, to verify the stability of the model and to provide a solid basis for parameter calibration.

The selection of the survey location is related to the diversity and accuracy of data collection. It is a crucial part of the experimental scheme and must be taken seriously. Grasp the following principles in the choice of survey location:

1) When selecting the experimental route, try our best to include several intersections with different grades of road, so that we can get the following data of left-turn vehicles at intersections with different grades of road and different turning radius;

2) Select the appropriate left-turn lane as the investigation lane at the intersection where the experimental route passes, and avoid the influence of the interlaced vehicle on the left-turning vehicle following behavior at the signalized intersection.

2.2. Data Preprocessing

Before the data acquisition, set the Mobile GIS software acquisition in the high-precision GPS instrument to the line acquisition-distance mode in advance, and record a collection point every one meter. The high-precision GPS instrument will automatically obtain the time, position and direction of this point, speed, acceleration and other information, and then import the data into the computer, GIS Office software will display the specific follow-up route; Mobile GIS software in high-precision GPS instrument can also automatically record and save the driving track in real time, and display it directly according to the location information, which can judge the accuracy of the data. According to the real-time trajectory, the collection point in the turning process can be judged, and the method is used to initially obtain the data of the following experiment. The experimental routes in map and actual view of intersections is shown as Figure 2. And the GIS Office data acquisition route is shown in Figures 3 and 4.

Figure 2. The experimental routes in map and actual view of intersections

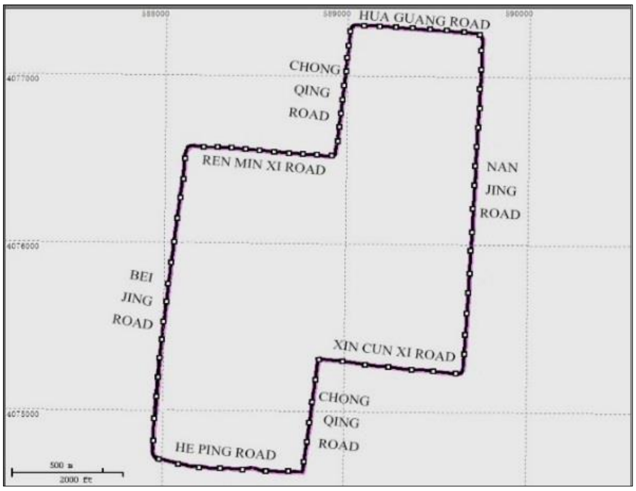

Figure 3. GIS Office data acquisition route 1

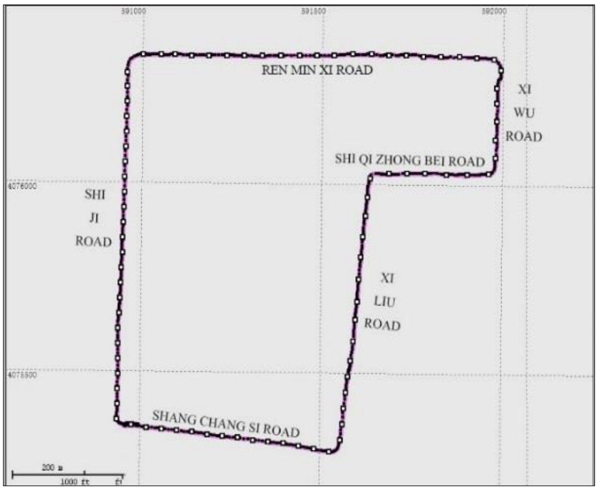

Figure 4. GIS Office data acquisition route 2

After the completion of the data acquisition experiment, the computer exports the collection point information in the GIS office software, including the latitude and longitude coordinates of the collection point, the acquisition time, the altitude, the precision PDOP value, the vehicle speed and direction according to the Mobile GIS software. Recording the real-time trajectory map and the full-process video taken during the follow-up data acquisition experiment to find the collection point of the GPS record at the left turn of the signal intersection, and select the collection point at the left turn of the signalized intersection according to the index information. After converting the coordinate system into the projected coordinate system in the GIS office software, the data is preprocessed by mathematical statistics and analysis and data mining techniques to obtain the data of the following data under different turning radii.

3. Car-following Speed Characteristics of Left Turn

3.1. Speed Characteristics under Different Turning Radii

The driver's speed is an important factor affecting the behavior of the heel, and it is also the main parameter of the vehicle following model. According to the data collected by the vehicle following test, the vehicle speed of the left-turning vehicle at different turning radii of the urban signal intersection is obtained, as shown in Figure 5.

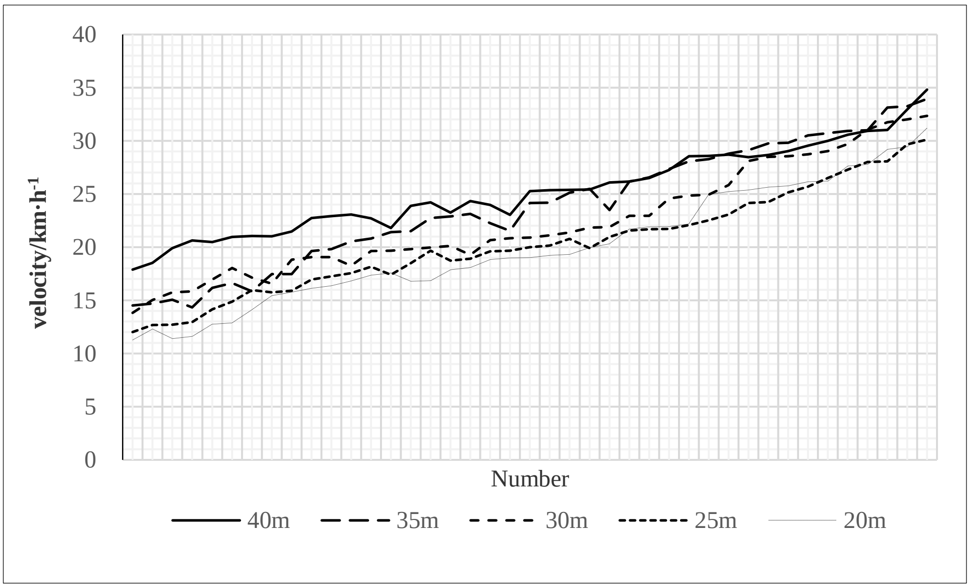

Figure 5. Tracking speed chart under different turning radius

From the statistics of vehicle following speeds at different turning radii above, it can be seen that the speed of the left-turning vehicle at the urban signalized intersection is different under different turning radii conditions, and generally shows the same trend; the speed of car following increases gradually in the course of turning.

3.2. Velocity Distribution Characteristics

According to the follow-up data acquisition experiment, the maximum frequency of frequency is obtained under different turning radii, as shown in Figure 6.

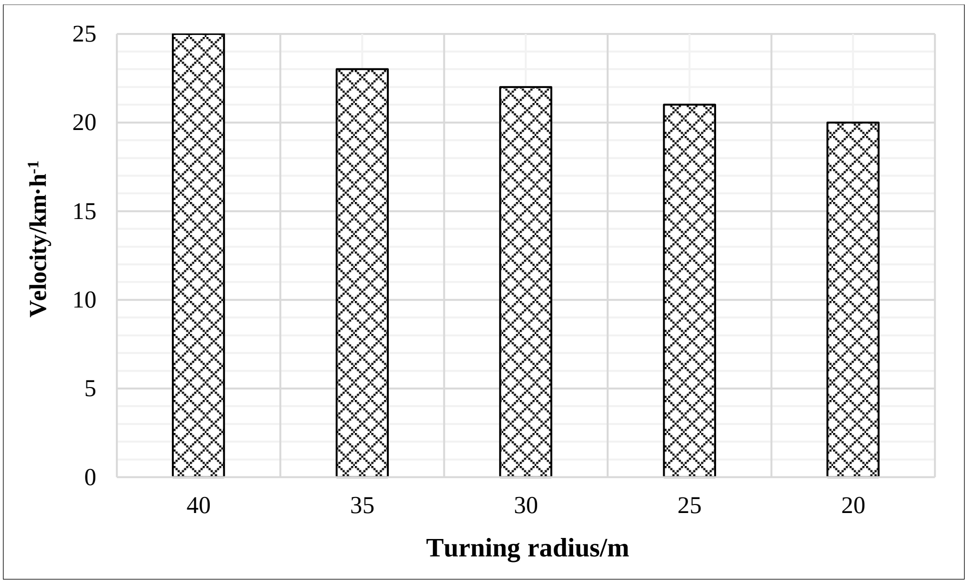

Figure 6. Maximum speed map of frequencies under different turning radius

The results of the changes in the average speed of left-turning and following vehicles at different turning radii at the intersection of Zhangdian District, Zibo City, as shown in Table 1.

Table 1. Average speed statistics of Car-following vehicles with different turning radius

Turning radius (m)	R=40m	R=35m	R=30m	R=25m	R=20m
Average speed / (km/h)	24.68	23.59	22.85	20.99	19.53

As can be seen from Table 1, the average speed of the left-turning and following vehicles will change in different degrees under different turning radii at the signalized intersections in Zhangdian District of Zibo City. As the turning radius increases, the average speed of the following vehicle will gradually increase.

4. The NFVD Model for the Left-turn Car-following Model

Based on the comparative analysis of the existing car-following model at home and abroad, it is found that the FVD model is more practical in describing traffic flow phenomenon such as stop-and-go wave and partial blockage at the intersection of urban signals. From the physical point of view, the description of traffic flow by FVD is more in line with the actual operation situation [13, 14].

However, the sensitivity of the Mercedes-Benz to the acceleration and deceleration of the front vehicle is not considered to be different in the traditional FVD model. When modeling the following behavior of the left-turn vehicle, it is necessary to consider the asymmetry of the driver's response to the acceleration and deceleration of the front vehicle. Thus, the traditional FVD model was improved, and the New Full Velocity Difference (NFVD) model was developed, which was shown as follows in Equation 1:

$$a_{n(t)} = k_{\pm}\left[V\left(\Delta x_n(t)\right) - v_n(t)\right] + \lambda_{\pm}\Delta v_n(t) \tag{1}$$

Where, k_+, $\lambda_+$are the sensitivity coefficients of the model when the front car accelerates; k_-, λ_- are the sensitivity coefficients of the model when the front car decelerates; $v_n(t)$ is the speed of the nth car at t; $x_n(t)$ is the position of the nth car at t; $\Delta v_n(t)$is the speed difference between the front car and the following car, which is the following car's speed minus the front one's speed at t; $\Delta x_n(t)$ is the headway distance between the front and following vehicles, and $\Delta x_n(t) = x_{n+1}(t) - x_n(t)$; $\mathrm{V}\left(\Delta x_n(\mathrm{t})\right)$ represents the optimized speed function, as shown in Equations 2 and 3.

$$\mathrm{V}\left(\Delta x_n(\mathrm{t})\right) = \frac{v_{max}}{2}\left[\tanh(\Delta x_n(t) - h_\varepsilon) + \tanh(h_\varepsilon)\right] \tag{2}$$

$$h_\varepsilon = \frac{v_n^2(t) - v_{n+1}^2(t)}{2a} + \tau \cdot v_n(t) + L \tag{3}$$

Where, h_ε represents the safety headway spacing; v_{max} represents the maximum driving speed; $v_n(t)$ and $v_{n+1}(t)$ are the speeds of the following vehicle and the front car at t; τ is the driver's reaction time, take τ=1s; L is the length of the front car; a is the acceleration of the following car at t.

5. Results and Discussions

5.1. Model Parameters Calibration

After the objective function and the model parameters to be calibrated are determined, the car-following data are brought into the NFVD model to prepare the next parameter calibration of the car-following model [13].

In this paper, the genetic algorithm is used to deal with the parameters' calibration. In order to ensure the accuracy of the running results, several operations and repeated comparisons have been made. Finally, values of the parameters in the FVD model and the NFVD model are obtained at different turning radii of the signalized intersection, as shown in Table 2.

Table 2. Regression coefficient of the NFVD model

Acceleration				Deceleration			
Turning radius (m)	**k+**	**λ+**	**Fobjective**	**Turning radius (m)**	**k-**	**λ-**	**Fobjective**
40	0.018	0.647	0.492	40	0.019	0.665	0.434
35	0.022	0.692	0.465	35	0.024	0.715	0.479
30	0.026	0.709	0.517	30	0.029	0.722	0.469
25	0.028	0.731	0.421	25	0.031	0.739	0.514
20	0.033	0.741	0.482	20	0.037	0.752	0.419

As can be seen from the Table 2, the sensitivity coefficient increases with the decease turning radius. It indicates that the driver's reaction intensity increases with the decrease of the turning radius. In addition, when the front car decelerates, the sensitivity coefficient of the following car is greater than that when the front car accelerates. This indicates that the driver's car-following behavior is more sensitive and intense to the response of the leading car, when the leading car decelerates during the left turn at the signalized intersection.

5.2. Model Evaluation

The NFVD model was evaluated with statistical knowledge. The evaluation indexes adopted in the paper include: mean absolute error (MAE) and mean absolute relative error (MARE) [15]. MAE is the average of absolute deviation between all single observation values and arithmetic average values. It can avoid the problem of mutual cancellation of errors and accurately reflect the actual prediction error. MARE is the average of relative error. There must be a difference between the simulation results and the real values. In error analysis, it is usually necessary to do parallel analysis several times, and then take the average of these results as the final result.

Firstly, the parameters selected according to the principle of data processing will be input into the improved model. And then, the calculated values of the FVD model and the NFVD model are output by using Matlab programming, which is the simulation value of the model. The error of acceleration is used as the test standard for the effect of car-following model. Comparing the simulation value of the model with the actual data collected (after eliminating invalid data), the evaluation results of the relevant models are obtained, as shown in Tables 4 and 5.

Table 4. Evaluation results of the FVD model

Turning radius (m)	MAE	MARE
40	2.587	0.279
35	2.614	0.265
30	2.541	0.282
25	2.516	0.265
20	2.489	0.285

Table 5. Evaluation results of the NFVD model

Acceleration			Deceleration		
Turning radius (m)	MAE	MARE	Turning radius (m)	MAE	MARE
40	2.316	0.167	40	2.412	0.149
35	2.322	0.154	35	2.354	0.167
30	2.308	0.149	30	2.344	0.195
25	2.337	0.178	25	2.179	0.139
20	2.294	0.153	20	2.419	0.151

According to the comparison results of Tables 4 and 5, the NFVD model has lower MAE value and MARE value than the FVD model. That is to say, the NFVD model can more accurately describe the car-following behavior in the left-turning process of signalized intersection.

6. Conclusions

Through the study of the left-turn car following behavior at the signalized intersection, the following conclusions are obtained:

- Based on the statistics of left turn car following speed at urban signalized intersections with different turning radii, it is found that the greater the turning radius of the intersection, the greater the average speed of the following car.
- Through the analysis of the frequency of car-following speed under different turning radii, we can see that the larger the turning radius is, the larger the velocity corresponding to the maximum frequency is. On the contrary, the smaller the turning radius is, the smaller the velocity corresponding to the maximum frequency is.
- In the process of left turn following car at signalized intersection, the response sensitivity of the following car to the deceleration behavior of the front car is higher than that of the acceleration behavior. That is to say, the behavior of the following car is more easily affected by the deceleration behavior of the front car.
- Based on the traditional FVD model, considering the difference of the response intensity of the following car to the acceleration and deceleration of the front car, the NFVD model is improved. And the parameters of the model under acceleration and deceleration are calibrated, respectively. Through error evaluation, it is found that the NFVD model can more accurately describe the car-following behavior in the actual scene.

7. Funding

Work described in this paper was supported by Jiangsu Planned Projects for Postdoctoral Research Funds (Grant No. 2018K118C), National Natural Science Foundation of China (Grant No. 71901134).

8. Conflicts of Interest

The authors declare no conflict of interest.

9. References

[1] Jing Ming, Wang Hao and Wang Wenjing. “Heterogeneous car-following model based on chimer data collection and analysis.” Journal of Jilin University (Engineering and Technology Edition) 178 (3) (2015): 761-768. doi:10.13229/j.cnki.jdxbgxb201503012.

[2] Yu Shaowei and Shi Zhongke. “Model of car-following vehicle aggregation at signalized intersections.” China Journal of Highway and Transport 27(11) (2014): 93-100. doi:10.19721/j.cnki.1001-7372.2014.11.013.

[3] Tan Pinpin, Pei Shikang, Yang Chunlan, et al. “Influence of road geometry design on the following behavior of IDM model.” Journal of Transportation Systems Engineering and Information Technology 17(6) (2017): 77-84. doi:10.16097/j.cnki.1009-6744.2017.06.012.

[4] Wang Xuanjin. “Consider the car-following model of the preceding car change process.” Chongqing: Chongqing University, 2017.

[5] Konishi, Keiji, Hideki Kokame, and Kentaro Hirata. “Coupled Map Car-Following Model and Its Delayed-Feedback Control.” Physical Review E 60, no. 4 (October 1, 1999): 4000–4007. doi:10.1103/physreve.60.4000.

[6] Ling Daijian and Xiao Peng. “Analysis of stability and bifurcation of a class of car-following models.” Journal of Transportation Engineering and Information 7(4) (2009): 6-11. doi:10.3969/j.issn.1672-4747.2009.04.002.

[7] Tan Jinhua. "Traffic flow following model and simulation in dust environment." Journal of Transportation Systems Engineering and Information Technology 18(3) (2018): 67-71. doi:10.16097/j.cnki.1009-6744.2018.03.010.

[8] Zhao Xiaohua, Ren Guichao, Chen Chen, et al. "Research on the comprehensive influence of bad weather on driver's heel behavior based on driving simulation technology." Journal of Chongqing Jiaotong University (Natural Science) 38(6) (2019): 90-95. doi:10.3969/j.issn.1674-0696.2019.06.16.

[9] Qu Dayi, Chen Wenjiao, Guo Tao, et al. "Research on cross-following model considering lateral interference." Journal of Highway and Transportation Research and Development 32(1) (2015): 122-127. doi:10.3969/j.issn.1002-0268.2015.01.020.

[10] Peng Yong, Liu Shijie and Dennis Z Yu. "The car-following model and stability analysis of the influence of front and rear vehicles." Journal of Transportation Systems Engineering and Information Technology, 2018, 18(6): 42-48. doi:10.16097/j.cnki.1009-6744.2018.06.007.

[11] Qin Yanyan, Wang Wei and Ran Bin. "Intelligent networked vehicle following model considering multiple front vehicle feedback." Journal of Transportation Systems Engineering and Information Technology, 2018, 18(3): 49-54. doi:10.16097/j.cnki.1009-6744.2018.03.008.

[12] Wei Fulu and Liu Yang. "Review of the development of classic car-following models." Journal of Jilin Jianzhu University 35(4) (2018): 19-23.

[13] Wang Xuesong, Zhu Meixin. Calibration and verification of Chinese driver's urban expressway car-following model based on natural driving data [J]. China Journal of Highway and Transport, 2018, 31(9): 133-141.

[14] Zhang Shiyue. "Research on the car-following model of urban expressway on ice and snow pavement." Science Technology and Engineering 14(19) (2014): 128-141.

[15] Yang Da, Pu Yun, Zhu Yuling, et al. "Improved vehicle-following model based on safety distance." Journal of Beijing Polytechnic University 39(9) (2013): 1335-1342.