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Four-independent wheel driven Electric Vehicle Braking System Based on Modeling and Co-simulation

Kun Fan [1,2], Lin Zheng [1,2], Yue-gang Luo [1,2], Zi-yang Zhou [1,2],

[1]*School of Electromechanical Engineering, Dalian Minzu University, Dalian Liaoning, 116600, China*
[2]*Key Laboratory of Intelligent Detection and Diagnostic Technology, Dalian Minzu University, Dalian Liaoning, 116600, China*

Abstract: In this paper, a Carsim/Simulink co-simulation model of a four-wheel independently driven electric vehicle braking system is established to simulate the process of vehicle linear braking. The traditional Carsim car model was modified into a four-wheel independently driven electric car model, and then the torque control model, braking distance calculation model, driver signal judgment model, and braking force calculation model were built in Simulink to realize the establishment of the closed-loop system. The correctness and stability of the model are verified by the co-simulation experiment. This model lays a good foundation for the research of the control algorithm in the future.

Keywords: Electric vehicle; braking system; model; co-simulation

INTRODUCTION

Four-independent wheel driven electric vehicle is an important development direction of electric vehicles in the future, and its main structural feature is that each wheel is driven by an independent drive motor. As the torque of each wheel can be distributed in an arbitrary proportion within the range of motor capacity, and the torque and speed are easy to be measured, it has greater control advantages over traditional internal combustion engine vehicles in terms of power performance, stability and active safety control [Li, *et. al.*, 2014] [K, *et. al.*, 2012].

The reliability and stability of the braking system determine the driving experience and safety of the driver. Through the establishment of a simulation model, we can save research funds and reduce the time of technology research and development. In reference [Sun, *et. al.*, 2014], the dynamic model of the electric vehicle is established by using ADAMS/Car software, but the simulation speed of ADAMS software is slow, which is not conducive to the rapid analysis of simulation experiments. In reference [Yang, et. al., 2010] use Simulink to establish a four-wheel independent drive electric vehicle simulation model, but the model does not consider the vertical movement of the vehicle. In reference [Jin, *et. al.*, 2005], a dynamic simulation model of 18-degree-of-freedom four-wheel independent drive electric vehicle, including steering angle, is established by using Simulink. The simulation accuracy is high and can reflect the response performance of the vehicle under various working conditions.

For the electric vehicle model established by MATLAB/Simulink alone, the simulation condition setting is complex, and the influence of the driver control model can't be fully considered. However, as mature commercial vehicle simulation software, Carsim has the advantages of high expansibility, high simulation accuracy, and fast operation speed. Besides, it also has a complete and high-precision driver model and vehicle model, users can customize the operating conditions to complete different open / closed-loop simulation experiments. In reference [Xiong, *et. al.*, 2014], the whole vehicle model of distributed drive electric vehicle is developed based on Carsim/Simulink and the accuracy of the model is verified by the step input experiment and serpentine experiment. In reference [Ge, *et. al.*, 2017], the hub motor model, speed control model, and vehicle model are established by Carsim/Simulink, and the torque distribution strategy is designed. finally, the correctness of the model and the effectiveness of the allocation strategy are verified by double line-shifting conditions. In reference [Meng, *et. al.*, 2019], taking the electric vehicle driven by four-wheel hub motor as the research object, a torque distribution control strategy based on a fast search algorithm is designed, and a Carsim/Simulink joint simulation platform is built. The experimental results verify the speed and accuracy of the algorithm. In this paper, a simulation model of braking system of four-wheel independent drive electric vehicle is established based on Carsim/Simulink, which simulates the linear braking process of the vehicle in the state of emergency. The accuracy and reliability of the model are verified by joint simulation experiments.

CONSTRUCTION OF VEHICLE SIMULATION MODEL

Carsim simulation platform

Carsim is designed for vehicle dynamics simulation analysis software, it can be convenient and flexible window by the software of the environment and the process is to set parameters, and in the form of graph and the three dimensional animation presents the simulation results, mainly be used to predict and simulate automobile vehicle steering stability and brake, comfort and economy [Guo, *et. al.*, 2011] [Wang, *et. al.*, 2007].

The main interface of Carsim software is shown in figure 1. In the first module (Simulated Test Specifications), researchers can set the working condition of the vehicle model parameters and simulation. The second module (Run Control: build-In solvers) is a mathematical solution module. It can use Carsim internal solver or a custom model solver embedded in C language or extended by Simulink interface according to actual needs. In this paper, co-simulation is conducted by model solver based on Simulink. The third module (Analysis results (Post Processing)) is a running result and post-processing module that presents simulation results in the form of graphical curves and 3D animations. In this paper, the vehicle model, driver model, and simulation condition are set by Carsim and real-time data are called with Simulink to establish a four-wheel independently driven EV braking system model. The idea of model construction is shown in Figure 2.

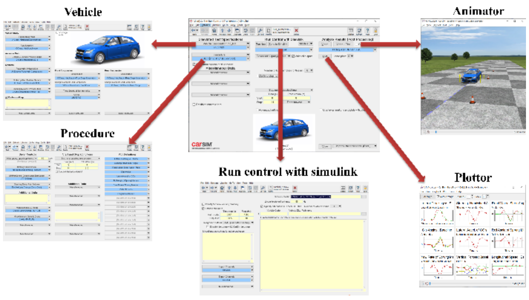

Figure 1. Carsim control interface

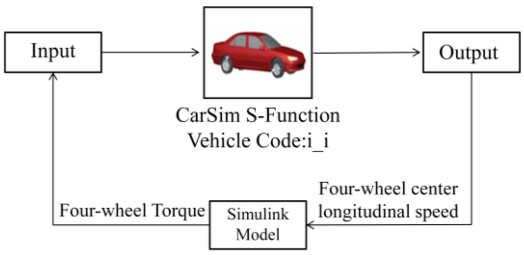

Figure 2. Co-simulation model block diagram

Vehicle model

Carsim includes three types of body models for passenger cars, trailers, and minivans for users to choose from. Carsim software has not developed a four-wheel independent drive electric vehicle model. According to the research goal of this paper, a four-wheel-drive SUV passenger vehicle model is selected as the control vehicle. The car body model mainly includes parameters such as car height, car width, wheelbase, mass and center of gravity, and yaw moment of inertia. The Four-wheel drive electric vehicle model parameters are shown in Table 1 [Farzad, *et. al.*, 2004] [Farzad, *et. al.*, 2003] [Wang, *et. al.*, 2009], and the Four-wheel drive electric vehicle model is shown in Figure 3.

Table 1. Vehicle model key Parameters

Name	Symbol	Value
EV weight	m	1480Kg
Distance of c.g. from the front axle	a	1.220m
Distance of c.g. from the rear axle	b	1.657m
Centroid height(m)	h_g	0.28m
Wheel radius	r	1.780m
Vehicle moment of inertia about yaw axis	I_{zz}	347 Kg m^2
Vehicle moment of inertia about pitch axis	I_{yy}	1808 Kg m^2
Vehicle moment of inertia about roll axis	I_{xx}	1808 Kg m^2
Wheel moment of inertia	J	1.85 Kg m^2
Frontal area	S	2.00 m^2
Dimensionless coefficient	C	0.32
Rolling coefficient	f	0.49m

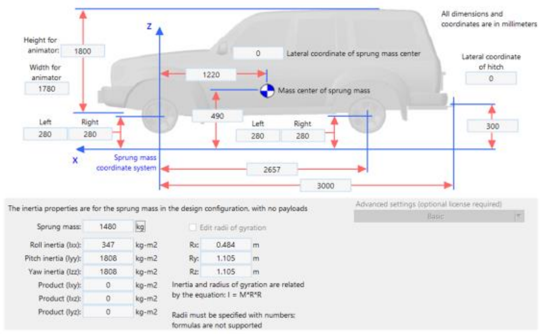

Figure 3. Schematic diagram of body parameters

Powertrain system

The Carsim traditional transmission system consists of a transmission, a hydraulic torque converter, a central differential, a front and rear axle differential and a half shaft [Z, *et. al.*, 2014]. The traditional transmission mode of the fuel vehicle is that the engine transmits the power to the power wheel through the transmission system, while the electric vehicle directly drives the hub movement by the motor and does not need the transmission system. Based on the traditional vehicle, the power transmission interruption between the vehicle transmission system and wheels in Carsim is changed into external input form, and the calculated four-wheel torque is input into the Carsim, power direct drive tire by Simulink to fit the characteristics of four-wheel independent drive electric vehicle. Its setting method in Carsim is shown in Figure 4.

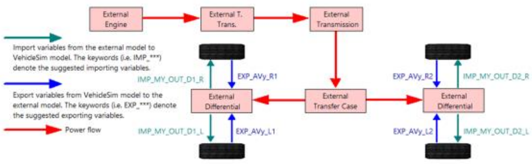

Figure 4. Diagram of power system of Carsim electric vehicle model

Input and output interface setting

After the vehicle simulation model is built, in the mathematical solution module of the Carsim main interface, the simulation mode is set to Simulink simulation, and then the input and output interface is set. The torque control model, braking distance calculation model, driver signal judgment model, and braking force calculation model are built in Simulink. The torque control model outputs the motor torque to Carsim, while Carsim feeds back the wheel speed signals of four wheels to the braking distance model and signal judgment model in Simulink, which forms a complete simulation model of four-wheel independent drive electric vehicle with driver closed-loop control. Its interface settings are shown in Table 2.

Table 2. The interface of Carsim/Simulink co-simulation

Import/Export	Variable Names	Meaning Definition
Import	IMP_MYUSM_L1	Front left wheel torque
	IMP_MYUSM_R1	Front right wheel torque
	IMP_MYUSM_L2	Rear left wheel torque
	IMP_MYUSM_R2	Rear right wheel torque
Export	Vx_Wc_L1	Front left wheel center longitudinal speed
	Vx_Wc_R1	Front right wheel center longitudinal speed
	Vx_Wc_L2	Rear left t wheel center longitudinal speed
	Vx_Wc_R2	Rear right wheel center longitudinal speed

MATLAB/SIMULINK MODEL

In MATLAB, Simulink provides users with a variety of simulation modules, which can easily model and simulate the dynamic multi-dimensional system. Simulink also has model libraries for different areas, and users can build their own model libraries. Simulink can also carry out joint simulation and testing with other software and hardware, such as Carsim vehicle simulation software.

Establishment of braking condition

According to Chinese GB7258-2017 (Technical conditions for Safe Operation of Motor vehicles), some requirements for vehicle road test braking performance [Zhang, *et. al.*, 2017]: the adhesion coefficient between the wheel and the road surface is $\varphi \geq 0.7$, the initial speed of braking is$v_t = 50Km/h$, the braking distance of full load test is $S \leq 20m$, and the average deceleration is $a_x \geq 5.9m/s^2$.

According to the above requirements, this article sets the simulation braking condition as: start on a dry concrete road with adhesion coefficient $\varphi = 0.75$ and accelerate slowly [Zhao, *et. al.*, 2012]. When the vehicle speed $v = v_t$, the vehicle starts to brake until the vehicle stops. Check the correctness of the model by calculating the braking distance. The braking requirements are shown in Table 3.

Table 3. Braking performance requirements for passenger vehicles

Road adhesion coefficient	$\varphi = 0.75$
Initial speed of braking	$v_t = 50Km/h$
Brake deceleration	$a_x = 6.9m/s^2$

Torque control model

The torque control model is composed of a motor torque control model and a braking torque control model. The motor torque is input by means of a timer query experience table to accelerate the vehicle. There is no positive torque when the vehicle is braking, so the driver signal input module is added to the motor torque output port to control the input and stop of the torque. When the vehicle is braking, the driver's reaction time is taken into consideration, and a delay module is added to delay the braking signal by 0.3s. The driver signal and the motor torque control the output of the forward torque through the multiplier.

The braking torque is controlled by the braking force, and the braking force is converted into the braking torque equation as shown in (1).

$$T = Fr \qquad (1)$$

Where T is torque, F is braking force, r is tire radius.

The torque control model shown in Figure 5.

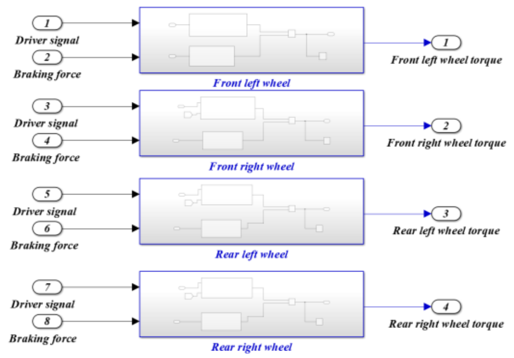

Figure 5. Torque control model

Braking distance calculation model

When the velocity is input to the Simulink, the unit conversion of the velocity is carried out at first, and then the acceleration is obtained by differentiating the velocity. When the car starts braking, the acceleration direction is opposite to the vehicle speed direction (the numerical value is negative). At this time, the speed is integrated until the speed is zero, and the integral result is the braking distance. The braking distance calculation model is described using the following formula (2). The braking distance calculation model is shown in figure 6.

$$\begin{cases} v = \dfrac{1000}{3600} v_1 \\ a_x = \dfrac{dv}{dt} \\ S = \int_{t_2}^{t_1} v_t \end{cases} \tag{2}$$

Where: v_1 is the current vehicle speed, (*Km/h*); v is the vehicle speed after unit conversion, (*m/s*); a_x is the vehicle acceleration, (*m/s*^{2}); t_1 is the time to start braking, t_2 is the system the time when the movement ends, (*s*); *S* is the braking distance, (*m*).

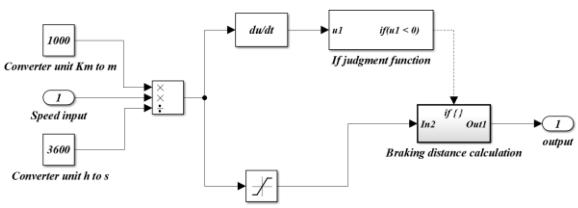

Figure 6. Braking distance calculation model

Driver signal judgment model

The driver signal judgment module is composed of an if judgment function, which controls the forward torque and braking force by judging the vehicle speed and outputting a 0 or 1 signal. When the if function judges that the vehicle speed $v < v_t$, input signal 1 to the motor torque control model, and input signal 0 to the braking torque control module, and the vehicle model accelerates. When the vehicle speed $v \geq v_t$, the two signals are reversed, the vehicle model speed is reduced, and the braking starts. The driver signal judgment process is shown in Figure 7, and the driver signal judgment model is shown in Figure 8.

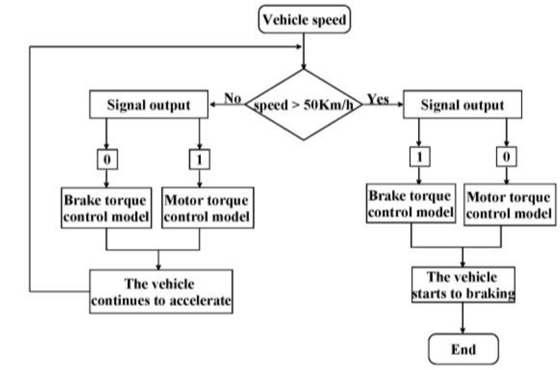

Figure 7. Driver signal judgment structure

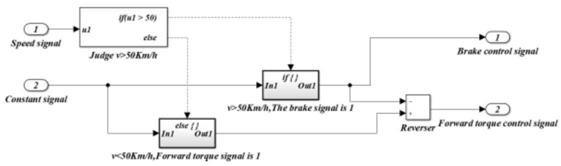

Figure 8. Driver signal judgment structure

Braking force calculation model

1) Force Analysis of Tire during vehicle braking

As shown in figure 9, in the braking process, the car is affected by the external force provided by the air and the ground, but the air resistance is small and can be ignored. The action of external force is mainly provided by the ground, which is called the ground braking force.

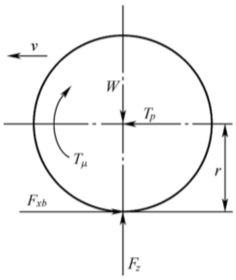

Figure 9. Wheel force diagram during automobile braking

It can be expressed in (3). When the car is braking, it is also affected by the brake force needed by the wheel tire to overcome the friction torque of the brake, which can be expressed as (4).

$$F_{Xb} = \frac{T_\mu}{r} = T_p \tag{3}$$

$$F_\mu = \frac{T_\mu}{r} \tag{4}$$

Where F_{xb} is ground braking force, (*N*); T_μ is brake friction torque, (*N•m*); *r* is Wheel radius, (*m*);T_p is the thrust of the axle to the wheel, (*N•m*).

2) Calculation of normal reaction force of front and rear wheels

The force acting on the vehicle when braking on a horizontal road with an adhesion coefficient of φ, as shown in figure 10. Where, F_{z1} is normal reaction force of front wheel; F_{z2} is normal reaction force of rear wheel; G is automobile gravity; F_{Xb1} is front wheel ground braking force; F_{Xb2} is rear wheel ground braking force; F_j is inertia force; a is the distance from the center of mass of the car to the front axle; b is the distance from the center of mass of the car to the rear axle; L is the wheelbase of the car; h_g is the height of the center of mass of the car.

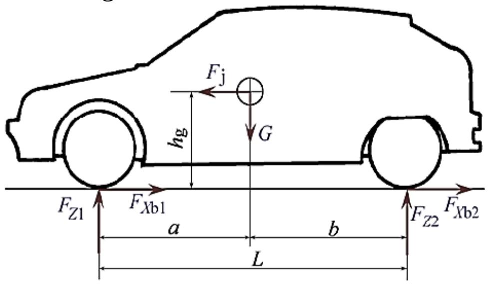

Figure 10. Braking force diagram of automobile on horizontal road

By taking the torque of the front and rear wheel connection points respectively, the results can be obtained (5).

$$\begin{cases} F_{z1}L = Gb + m\dfrac{dv}{dt}h_g \\ F_{z2}L = Ga - m\dfrac{dv}{dt}h_g \end{cases} \tag{5}$$

Set the brake strength to Z. which can be expressed as (6).

$$Z = \frac{dv}{dt}\cdot\frac{1}{g} \tag{6}$$

Bring (5) into (4), and the normal reaction force of the front and rear wheels is (7).

$$\begin{cases} F_{z1} = \dfrac{G\left(b + Zh_g\right)}{L} \\ F_{z2} = \dfrac{G\left(a - Zh_g\right)}{L} \end{cases} \tag{7}$$

When the vehicle is braking, the front and rear wheels are locked, should satisfy the following equations:

$$\begin{cases} F_{xb} = F_{\varphi} = G\varphi = m\dfrac{dv}{dt} \\ \dfrac{dv}{dt} = \varphi g \\ Z = \varphi \end{cases} \tag{8}$$

At this time, the normal reaction force of the front and rear wheels is (9).

$$\begin{cases} F_{z1} = \dfrac{G\left(b + \varphi h_g\right)}{L} \\ F_{z2} = \dfrac{G\left(a - \varphi h_g\right)}{L} \end{cases} \tag{9}$$

When a Vehicle is braking, the braking force of the current rear wheel brake is equal to their respective adhesion force, and when the sum of the braking force of the front and rear wheel brake is equal to the adhesion force, the front and rear wheels are locked at the same time, which can be expressed as a formula (10).

$$\begin{cases} F_{\mu1} + F_{\mu2} = G\varphi \\ F_{\mu1} = F_{z1}\varphi \\ F_{\mu2} = F_{z2}\varphi \end{cases} \tag{10}$$

Here, $F_{\mu1}$ and $F_{\mu2}$ represent the brake force, respectively, in the vehicle front and rear wheels.

According to the above formula and braking conditions, the Simulink simulation model is established, and the output signal of the driver signal judgment module is multiplied at the output to control the output of the braking force. The braking force calculation model is shown in figure 11.

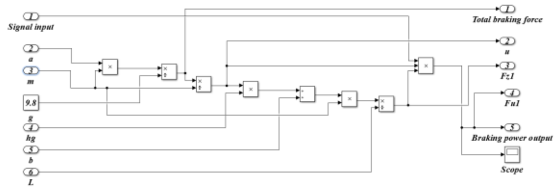

Figure 11. Braking force calculation model

ANALYSIS OF SIMULATION RESULTS

The longitudinal speed of the center of the four wheels of the vehicle is shown in Figure 12. It can be seen from the figure that the vehicle speed status meets the predetermined requirements. When the vehicle speed $v = v_t$, it does not decelerate immediately. This is because the reaction time of the driver when braking is taken into account, and the braking signal lags by 0.3*s*. The vehicle brakes, the speed gradually decreases to 0, and the vehicle stops.

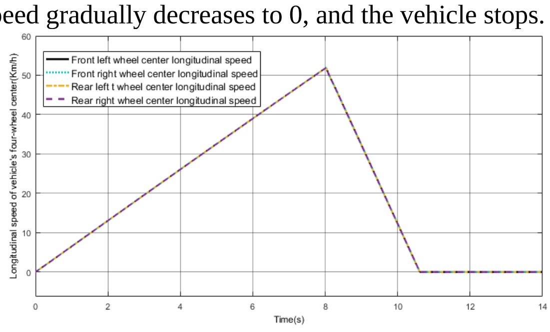

Figure 12. Vehicle Four-wheel center longitudinal speed

Since it is specified as a constant deceleration deceleration, the data of the deceleration module should also be close to the set data. The closer it is, the more stable the system is. The vehicle acceleration is shown in Figure 4.2. From the data in the figure, it can be seen that from 0 to 8.3*s*, the value of a_x is positive, and the vehicle accelerates; at 8.3*s*, the value of a_x changes from positive to negative, and the vehicle starts to brake at this time; 8.3*s* to 10.5*s* is The braking process of the vehicle; the vehicle stops at 11*s*, $v = 0$, $a_x = 0$.

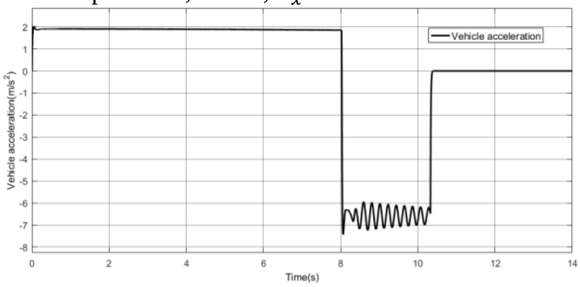

Figure 13. Vehicle acceleration

When it is judged that the vehicle is braking, the vehicle speed is integrated and accumulated with the change of time, and the value obtained is the total braking distance at the current moment. It can be seen from figure 14 that the vehicle accelerates before 8.3*s*, and the braking distance from 8.3*s* seconds to 10.5*s* in the braking process of the vehicle, and the braking curve changes; when the vehicle speed is equal to 0, the braking distance data remains unchanged. The final results show that the braking distance is $S = 17m$, and the braking system model meets the requirement that the braking distance is less than 20*m* in the GB7258-2017 standard.

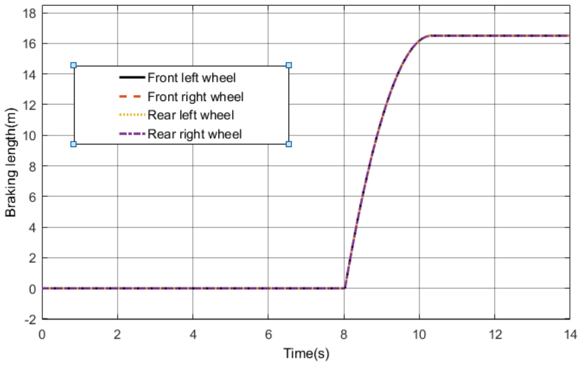

Figure 14. Vehicle braking distance

CONCLUSION

In this paper, the whole vehicle model of four-wheel independent drive electric vehicle is built by using Carsim software, and the torque control model, driver signal judgment model and braking force calculation model are built by MATLAB/Simulink, the output of braking distance figure is designed, and the distribution of braking force between front and rear axles is completed. The joint simulation results show that when the vehicle speed reaches 50*Km/h*, the vehicle can carry out emergency braking, and the braking distance meets the requirement of GB7258-2017 that the braking distance is less than 20*m*, and the vehicle running speed and braking deceleration can run well according to the working conditions, indicating that the braking system model of four-wheel independent drive electric vehicle established in this paper is correct and feasible, which provides a basis for follow-up research.

ACKNOWLEDGMENTS

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REFERENCES

Farzad Tahami, Reza Kazemi, Shahrokh Farhangi. A novel driver assist stability system forall-wheel-drive electric vehicles[J]. IEEE Transactions on Vehicular Technology, 2003,52(3):683-692.

Farzad Tahami, Shahrokh Farhangi and Reza Kazemi. A fuzzy logic direct yaw-moment control system for all-wheel-drive electric vehicle[J]. Vehicle System Dynamics, 2004, 41(3):203-221.

GE Ping-shu, ZHANG Tao, ZHAO Xiu-chun, CUI Yan-qiu. Modeling and Co-simulation for Four-in-wheel-motor-driven Electric Vehicle. Journal of Dalian Nationalities University, 2017, 19(5): 451-455.

Guo Kong-hui. “Principles of car control dynamics,” Jiangsu: Phoenix Science Press, 2011.

JIN Li-qiang, WANG Qing-nian, YUE Wei-qiang, et al. “Dynamic Model for Simulation of EV with 4 Independently-driving Wheels,” Journal of System Simulation, 2005, 17(12):3053-3055.

Li Gang, Zong Chang-fu. “Review on Electric Vehicle with Four-wheel Independent Drive In-wheel Motors,” Journal of Liaoning University of Technology (Natural Science Edition), 2014,34(01):47-52.

Meng Bin, “Research on Torque Optimal Distribution of Four-Wheel Motor Driven Electric Vehicle,” Chang’an University, 2019.

Nam K, FUJIMOTO H, HORI Y. Lateral Stability Control of In-Wheel - Motor - Driven Electric Vehicles Based on Sideslip Angle Estimation Using Lateral Tire Force Se-nsors [J]. IEEE Transactions on Vehicular Technology, 2012, 61(5):1972-1985.

Shuai Z, Zhang H, Wang J, et al. Combined AFS and DYC Control of Four-Wheel-Independent-Drive Electric Vehicles over CAN Network with Time-Varying Delays[J]. IEEE Transactions on Vehicular Technology, 2014, 63(2):591-602

Sun Yan, Wang Chang-ming. “Establishment of Mini Electric Car Dynamic Model Based on ADAMS/Car,” Auto Engineer, 2014(12):23-25.

Wang Jun-nian. “Study on Differential Drive Assist Steering Technology for Electric Vehicle with Independent-Motorized-Wheel-Drive,” Jilin:Jilin University, 2009.

Wang Ling-long. “Control strategy modeling and Simulation of hub-type electric vehicle drive System,” Hubei: Hubei Polytechnic University, 2007.

Xiong Lu, Chen Chen, Feng Yuan. “Modeling of Distributed Drive Electric Vehicle Based on Co-simulation of Carsim/Simulink,” Journal of System Simulation, 2014, 12(5):1143-1148.

Yang Fu-guang. “Research on Anti-skid and Yaw Stability Control of 4WID/4WIS Electrical Vehicle,” Shandong University, 2010.

Zhang Hong-guang. The revised content and influence of GB7258-2017 in braking[J]. Auto Time, 2017(24):18-20.

Zhao Chen. “Simulation and Analysis of Road Traffic Accident based on Crashview,” ShaanXi:Chang’an University ,2012.