Design of Hardware-in-the-loop Model for Electric Vehicles

Thiết kế mô hình mô phỏng hardware-in-the-loop cho xe ô tô điện

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Abstract

Recently, researches on electric vehicle are focused on motion control and autonomous control. These works require a model that represent a real vehicle as close as possible. We propose in this paper a hardware-in-the-loop model of electric vehicles that includes driving system and vehicle model using dSPACE-DS1103 control card as the hardware interface. The model is validated in Matlab/Simulink environment by implementing various test cases. Result of this paper can be a useful tool for electric vehicle researches.

Keywords: Magic Formula, Pacejka’s tire model, Drivetrain model, Dynamic model, Kinematic model, Hardware-in-the-loop model, Electric Vehicle.

Tóm tắt

Hiện nay, các nghiên cứu về ô tô điện được tập trung vào lĩnh vực điều khiển chuyển động và điều khiển vận hành tự động xe ô tô. Thông thường, các nghiên cứu này trước hết cần một mô hình mô tả chân thực các đặc tính của xe. Trong bài báo này, chúng tôi đề xuất một mô hình mô phỏng hardware-in-the-loop cho xe ô tô điện bao gồm cả mô hình xe và hệ thống lái, trong đó, card điều khiển dSPACE-DC1103 được sử dụng như một giao tiếp phần cứng. Mô hình được chạy thử nghiệm trên môi trường Matlab/Simulink thông qua nhiều thí nghiệm khác nhau. Kết quả của bài báo này sẽ là một công cụ tốt cho các nghiên cứu về ô tô điện.

Từ khóa: Magic Formula, Mô hình bánh xe Pacejka, Mô hình truyền lực, Mô hình động học, Mô hình động lực học, Mô hình Hardware-in-the-loop, Xe ô tô điện.

1. Introduction

In order to improve safety, efficiency and sustainability of a vehicle, driver support systems and fully automated intelligent transport systems are focused in various researches. Extensive development and testing process are necessary to ensure that these systems are safe and reliable. Until now, real road test on a real vehicle have been expensive, time-consuming and sometimes dangerous. So, developing control algorithm on a simulation model [2], [7] is a reasonable substitution. However, not only describing exactly characteristic of the vehicle, the model has to simulate driver’s behavior which is a very complicated work. Driver’s manipulation simulation needs a combination of several actions at the same time and normally it depends on experience of the driver. In such demands, testing platform based on hardware-in-the-loop model is a significant solution. Hardware-in-the-loop simulation is a technique that replaces physical parts of an electric vehicle by their mathematical representation. Many platforms are found not only for electric vehicle [1], [3] but also for hybrid vehicles [4], [6] and general automotive application [5]. Nonetheless, these models has a common disadvantage that is still expensive since they require various hardware systems of both power electronics and control boards.

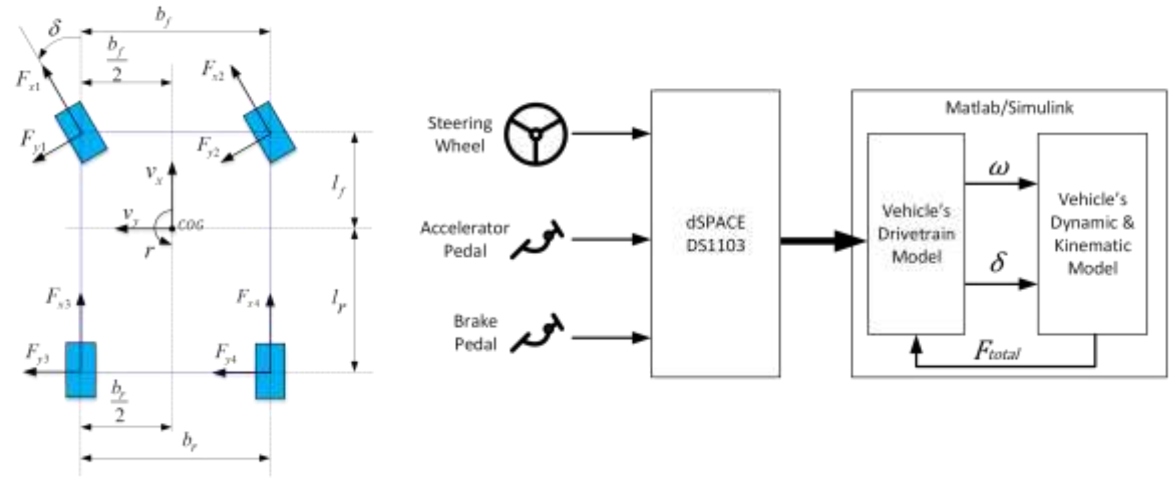
Inheriting research work in [7], in this paper, we propose a hardware-in-the-loop model of an electric vehicle that combines hardware of driving system and simulation model. This model has some prominent features as (1) applicable for all kind of 4-wheel-controlled vehicles, (2) cost effective, (3) drivable by human through hardware system. Section 2 shows the configuration of proposed system. Section 3 models the dynamic and kinematic relationship in a vehicle. In Section 4, model of drivetrain is obtained. Section 5 describes the design of the whole hardware in the loop system. Section 6 illustrates the validation results. Finally, some conclusions are given in Section 7.

2. System Configuration

A vehicle moving in three dimension space can be seen as a rigid body with 6 degree of freedom (DOF). However, to reduce complexity of the model as well as to increase computational performance, the following assumptions are made:

- The vehicle moves on the balance flat surface.
- Effect of roll and pitch motion are neglected.

The model is now simplified to 3 DOF including longitudinal, lateral and yaw motion as shown in Fig. 1(a). System configuration is illustrated in Fig. 1(b). There are two main parts in this configuration, hardware and software. The hardware of the system



(a) (b)

Fig. 1. (a) Vehicle model with applied forces and motion features. (b) System Configuration

includes dSPACE-DS1103 for hardware interface and driving system with accelerator pedal, brake pedal and steering wheel. The software is the model of the electric vehicle that simulates drivetrain, vehicle dynamic and kinematic. These models are implemented in Matlab/Simulink environment to obtain vehicle's states, such as longitudinal velocity, lateral velocity, yaw rate, etc.

3. Vehicle Dynamic and Kinematic Modelling

3.1. Vehicle Kinematic

Fig. 1(a) shows the vehicle model with fix-body frame at the Center of Gravity (COG) which is used as the reference coordinate frame. As in [8], the kinematic relationships among velocities, yaw rate and accelerations of the vehicle are written as follows.

$$\begin{aligned}\dot{v}_x &= a_x + r v_y \\ \dot{v}_y &= a_y - r v_x\end{aligned} \tag{1}$$

where a_x and a_y are the longitudinal and lateral acceleration of vehicle COG, v_x, v_y and r are longitudinal velocity, lateral velocity and yaw rate of the vehicle respectively.

3.2. Force model

The forces applied to the moving vehicle can be listed as:

- Tire-road contact forces include longitudinal forces F_{xi} and lateral forces F_{yi}, $i = 1..4$ with respect to front-left, front-right, rear-left, rear-right wheels
- Air resistance force F_{air}

Assume that rolling resistance is small and can be neglected. The force balance in longitudinal, lateral direction and the torque balance around the vertical axis are given by

$$\begin{aligned} ma_x &= (F_{x1}+F_{x2})\cos\delta - \left(F_{y1}+F_{y2}\right)\sin\delta \\ &\quad + F_{x3} + F_{x4} - F_{air} \\ ma_y &= (F_{x1}+F_{x2})\sin\delta + \left(F_{y1}+F_{y2}\right)\cos\delta \\ &\quad + F_{y3} + F_{y4} \\ J_z\dot{r} &= l_f(F_{x1}+F_{x2})\sin\delta + l_f\left(F_{y1}+F_{y2}\right)\cos\delta \\ &\quad - l_r\left(F_{y3}+F_{y4}\right) - \frac{b_f}{2}(F_{x1}-F_{x2})\cos\delta \\ &\quad + \frac{b_f}{2}\left(F_{y1}-F_{y2}\right)\sin\delta - \frac{b_r}{2}(F_{x3}-F_{x4}) \end{aligned} \tag{2}$$

$$F_{air} = sign(v_x) c_W A \frac{\rho}{2} v_x^2 \tag{3}$$

where c_W is the aerodynamic drag coefficient, A is the frontal area of the vehicle, ρ is the air density, b_f and b_r are the front and rear track width, l_f and l_r are the distance from front and rear axles to the COG of the vehicle, δ is the steering angle of driven wheels.

3.3. Tire model

Solving equations (2) to obtain acceleration in 3 DOF requires tire-road forces must be determined. However, these forces are nonlinear and depends on many parameters, e.g. road condition, tire quality, slip ratio, side slip angle…. In [9], [10], Pacejka has proposed tire formula (called Magic Formula) based on semi-empirical tire model to calculate longitudinal forces as follow.

$$\begin{aligned} F_{xi} = D\sin\bigl(C\arctan(B(1-E)(\lambda_i + Sh) + \\ E\arctan\left(B(\lambda_i + Sh_i)\right))\bigr) + Sv_i \end{aligned} \tag{4}$$

in which λ_i is the slip ratio of the ith wheel, B, C, D, E are the variables that are a function of coefficients $b_n, n = 0..10$ as

$$C = b_0$$

$$D = F_{zi}(b_1 F_{zi} + b_2)$$

$$B = \frac{\left((b_3 F_{zi}^2 + b_4 F_{zi})\exp(-b_5 F_{zi})\right)}{CD}$$

$$E = b_6 F_{zi}^2 + b_7 F_{zi} + b_8$$

$$Sh_i = b_9 F_{zi} + b_{10}$$
$$Sv_i = 0$$

where F_{zi} are the normal force of the ith wheel.

The lateral forces is also written as follows.

$$\begin{aligned} F_{yi} = D \sin\Big(C \arctan\big(B(1-E)(\alpha_i + Sh_i) + \\ E \arctan\big(B(\alpha_i + Sh_i)\big)\big)\Big) + Sv_i \end{aligned} \tag{5}$$
$$C = a_0$$
$$D = F_{zi}(a_1 F_{zi} + a_2)$$
$$E = a_6 F_{zi} + a_7$$
$$B = \frac{a_3 \sin\left(2 \arctan\left(\frac{F_{zi}}{a_4}\right)\right)}{CD}(1 - a_5|\gamma|)$$
$$Sh_i = a_8\gamma + a_9 F_{zi} + a_{10}$$
$$Sv_i = (a_{11}F_{zi}^2 + a_{12}F_{zi})\gamma + a_{13}F_{zi} + a_{14}$$

where α_i is the sideslip angle of the ith wheel, γ is the camber angle. The coefficients b_n in (4) and $a_n, n = 0..14$ in (5) have fixed values depend on the tire and the road conditions. If the vehicle is parked on level pavement, the normal forces depend only on gravitational acceleration, total mass and geometric features of the vehicle. When speeded up with an acceleration, the normal forces under front and rear wheels are written as [8]:

$$\begin{aligned} F_{z1} &= \left(k_{rx} - k_x \frac{a_x}{g}\right)\left(1 - k_{fy}\frac{a_y}{g}\right) = F_{z1,x}.F_{z1,y} \\ F_{z2} &= \left(k_{rx} - k_x \frac{a_x}{g}\right)\left(1 + k_{fy}\frac{a_y}{g}\right) = F_{z2,x}.F_{z2,y} \\ F_{z3} &= \left(k_{fx} + k_x \frac{a_x}{g}\right)\left(1 - k_{ry}\frac{a_y}{g}\right) = F_{z3,x}.F_{z3,y} \\ F_{z4} &= \left(k_{fx} + k_x \frac{a_x}{g}\right)\left(1 + k_{ry}\frac{a_y}{g}\right) = F_{z4,x}.F_{z4,y} \end{aligned} \tag{6}$$

where:

$$\begin{gathered} k_{rx} = \frac{1}{2}mg\frac{l_r}{l};\ k_{fx} = \frac{1}{2}mg\frac{l_f}{l};\ k_x = \frac{1}{2}mg\frac{h}{l} \\ k_{ry} = \frac{2h}{b_r};\ k_{fy} = \frac{2h}{b_f} \end{gathered} \tag{7}$$

in which, m is the vehicle's total mass, g is the gravitational constant, h denotes the height of COG of the vehicle with respect to the ground. The coefficients k_{rx}, k_{fx}, k_x, k_{ry}, k_{fy} in (7) are constants and can be calculated once at the beginning of the program to improve computational performance.

3.4. Sideslip angle and Slip ratio

Sideslip angle and slip ratio play important roles in controlling vehicles. They must be determined to complete Pacejka's tire model. The slip ratio is the difference between wheel velocities $R_{eff}\omega_i$ and longitudinal velocity v_x when the vehicle is moving.

$$\lambda_i = \frac{R_{eff}\omega_i - v_x}{\max\left(R_{eff}\omega_i, v_x\right)} \tag{8}$$

where R_{eff} is the effective radius of tire. It is can be assumed that slip ratio of all wheels are the same when the vehicle moving straight since angular velocities of all wheels are equal. However, when cornering, the lateral motion takes into account and this makes the difference in velocity between wheels. In such a case, the cornering radius must be obtained to determine the slip ratio. As in [11], when the vehicle moves in corner with steering angle δ, its COG will draw a circle with radius that can be written as

$$R = \sqrt{l_r^2 + \left(l_f + l_r\right)^2 \cot^2\delta} \tag{9}$$

Therefore, the angular velocity of individual wheels can be calculated as follow

$$\begin{aligned} \omega_1 &= \left(1 - \frac{b_f}{2R}\right)\omega \\ \omega_2 &= \left(1 + \frac{b_f}{2R}\right)\omega \\ \omega_3 &= \left(1 - \frac{b_r}{2}\right)\omega \\ \omega_4 &= \left(1 + \frac{b_r}{2}\right)\omega \end{aligned} \tag{10}$$

From (8)-(10), the slip ratio of all wheel of the vehicle can be obtained.

The sideslip angle of tires are given by:

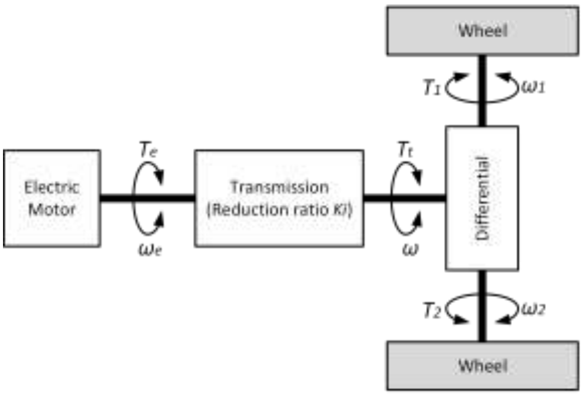


Fig. 2. Electric vehicle drivetrain configuration

$$
\begin{aligned}
\alpha_1 &= \delta - \arctan\left(\frac{v_y + l_f r}{v_x - \frac{b_f}{2} r}\right)\\
\alpha_2 &= \delta - \arctan\left(\frac{v_y + l_f r}{v_x + \frac{b_f}{2} r}\right)\\
\alpha_3 &= -\arctan\left(\frac{v_y - l_r r}{v_x - \frac{b_r}{2} r}\right)\\
\alpha_4 &= -\arctan\left(\frac{v_y - l_r r}{v_x + \frac{b_r}{2} r}\right)
\end{aligned}
\tag{11}
$$

4. Drivetrain Modelling

Drivetrain of a vehicle is series of component that dispatches power to driving wheels. In internal combustion engine vehicles (ICEV), the main parts of drivetrain may include traction engine, clutch, transmission with gear, shafts and wheels. On the other hand, electric vehicle is simplified with electric motor(s), transmission with fixed ratio (also called Overall Reduction Ratio) and wheels [14], [15]. Fig. 2 shows the typical configuration of electric vehicle.

As illustrated in Fig. 2, the Electric Motor rotates and generates torque on its shaft to deliver power to wheels through transmission and differential. In general, differential mechanism basically allows each

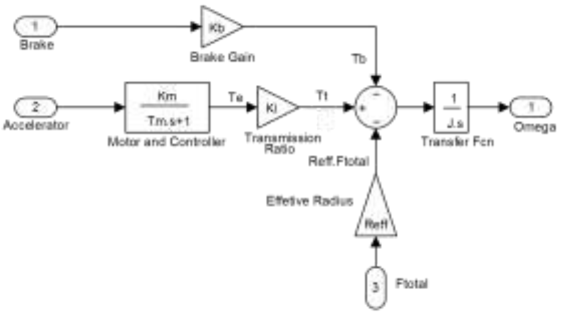


Fig. 3. Model of Drivetrain

Fig. 4. Hardware description

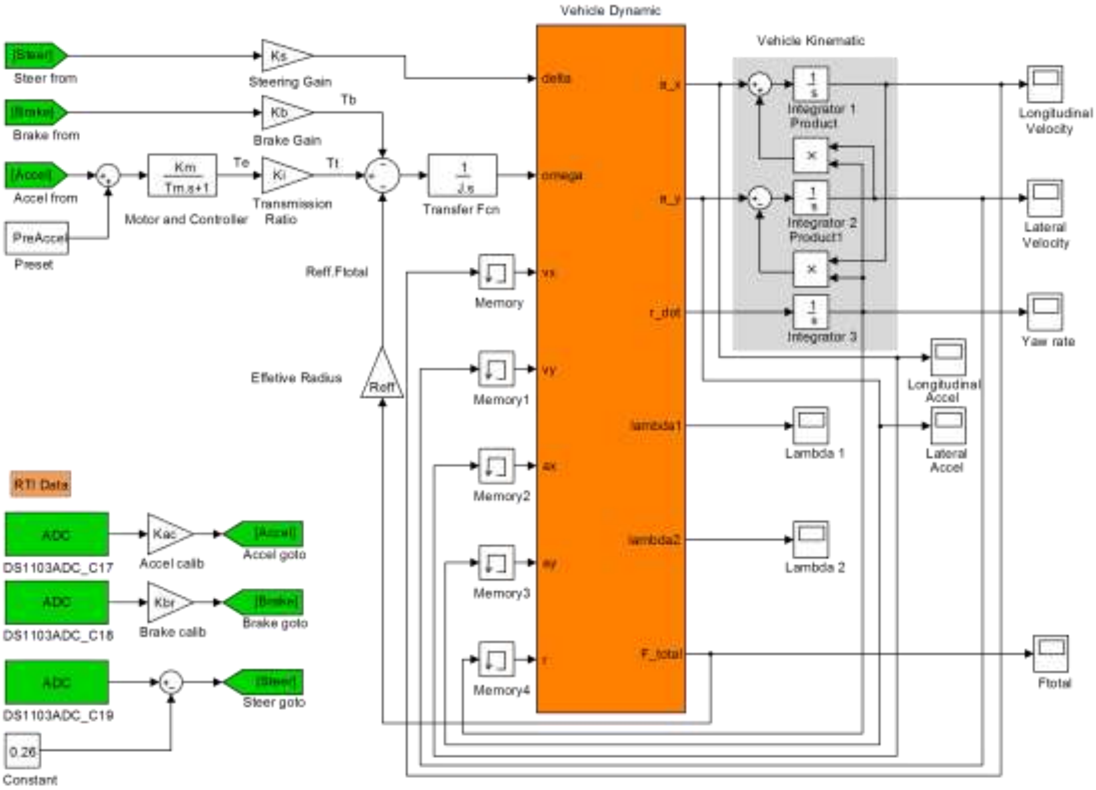


Fig. 5 Complete Model of Electric Vehicle

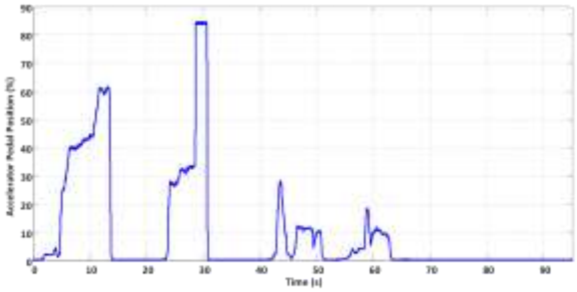
wheel to spin freely of the other while providing to both. Differential plays an important role in case of front wheel drive or rear wheel drive vehicles but it is absent in 4 wheel motor drive electric vehicle since the rotation of wheels of such kind of vehicle can be controlled independently. The model of differential can be described by (10).

Transmission of an electric vehicle is responsible for transferring torque from motor shaft to differential with fixed ratio K_i. Torque outputs from transmission can be written as below

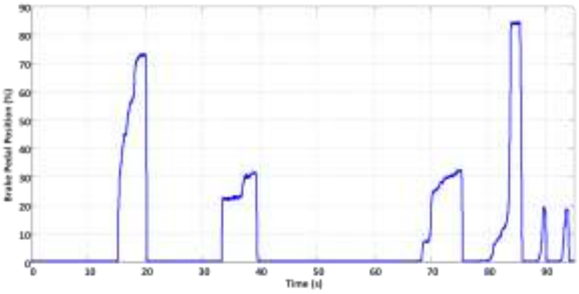
$$T_t = K_i T_e$$

where T_e is the torque that is generated by motor. The torque balance around the transmission shaft is [12], [13]

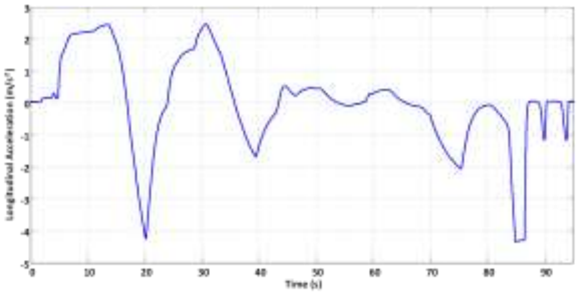
$$\begin{aligned} J_x \frac{d\omega}{dt} &= T_t - R_{eff} F_{total} - T_b \\ &= K_i T_e - R_{eff} F_{total} - T_b \end{aligned} \tag{12}$$



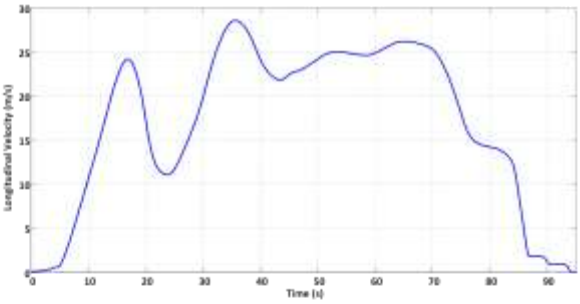
(a) Accelerator pedal



(b) Brake pedal



(c) Longitudinal acceleration



(d) Longitudinal velocity

Fig. 6. Longitudinal run test

where $F_{total} = \sum_{i=1}^{4} F_{xi}$ is the longitudinal force on all wheels of the vehicle that is converted back to shaft of transmission, J_x is the moment of inertia of the vehicle and T_b is the brake torque that is proportional to brake command of the driver.

5. Hardware and system design

Simulating driving action can be done by simulation software, e.g. Matlab/Simulink. However, imitating behavior of driver is not as easy as putting some unit steps or signal builders since it requires combination of many complex actions. In this paper, a racing wheel Betop 3181 is utilized as the driving system which has steering wheel, accelerator and brake pedals. Basically, racing wheels are connected to computer by USB protocol with manufacture's driver and it is impossible to decrypt data transfer through USB port of this device. Therefore, a hardware modification is made to extract signal from potentiometers that are attached to each part of the racing wheel. These signals are analogous and then assigned to the inputs of dSPACE – DS1103 control board. On the computer side, the dSPACE – DS1103 control board is selected as the interface between hardware – the racing wheel and the software – the vehicle model. The inputs from the racing wheel are defined in the Matlab/Simulink and connected to appropriate inputs of the vehicle model. Fig. 4 shows the description of whole hardware system and Fig. 5 illustrate the complete model in Matlab/Simulink. The model in Fig. 5 contains the Vehicle Dynamic block which is written in S-function block, Vehicle Kinematic block, Drivetrain and the dSPACE – DS1103 Input/Output Interface.

6. Experimental Results

6.1. Validation scenarios

In order to validate the Hardware-in-the-loop model, two test cases are implemented. In the first test, the vehicle model is controlled to run straight with random speed. This can evaluate the performance of accelerator and brake pedal as well as the simulation model in the longitudinal direction. The second test is to evaluate responses of the system when the car is driven in periodic cornering. According to this test, the vehicle at first is accelerated to a given speed, then the steering wheel is turned in clockwise and anti-clockwise periodically. As the result, the car should turn right and left, respectively.

The system parameters used in the model are based on the Electric Vehicle i-MiEV by Mitsubishi and listed in Table 1.

6.2. Results

Fig. 6 shows the first test results when the vehicle runs straight. Normally, accelerator and brake pedal are not allowed to be pushed at the same time. This is illustrated in Fig. 6(a) for accelerator pedal position and Fig. 6(b) for brake pedal position. When the accelerator is pushed, longitudinal velocity increases and so as acceleration. The deeper position of accelerator pedal, the higher velocity and acceleration. When brake pedal is pushed, the acceleration changes to negative and velocity decrease as described in Fig. 6(c) and Fig. 6(d).

The second test's results are illustrated in Fig. 7. As shown in Fig. 7(a), the steering wheel is turned from zero to negative and positive values periodically. This results in the change of yaw rate of the vehicle accordingly in Fig. 7(c). Also, the longitudinal velocity varies with this change. When the steering wheel turns back to zero, yaw rate and longitudinal are returned to their steady states.

7. Conclusion

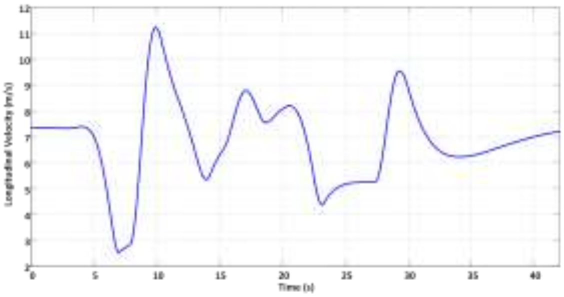
This paper has proposed the design of hardware-in-the-loop system for electric vehicle. In this system, the hardware is a racing wheel with all functions of a real driving system, the model of electric vehicle including drivetrain, dynamic and kinematic model is built based on Magic Formula of tire-road contact relationship. The performance of system is validated by various testing scenarios in Matlab/Simulink environment. The result of the paper can be used for further studies in motion control, autonomous control and vehicle state estimation of electric vehicles.

Acknowledgement

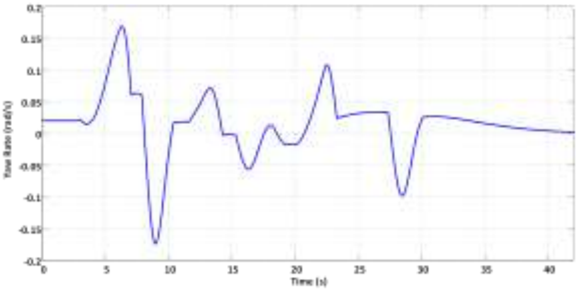
Table 1. Simulation model parameters

Pacejka's Tire model coefficients			
Coefficients	Value	Coefficients	Value
a_0	1.3	b_0	1.57
a_1	-49.0	b_1	-48.0
a_2	1216.0	b_2	1338.0
a_3	1632.0	b_3	5.8
a_4	11.0	b_4	444.0
a_5	0.006	b_5	0.0
a_6	-0.04	b_6	0.0034
a_7	-0.4	b_7	-0.008
a_8	0.003	b_8	0.66
a_9	-0.002	b_9	0.0
a_{10}	0.0	b_{10}	0.0
a_{11}	-11.0		
a_{12}	0.045		
a_{13}	0.0		
a_{14}	0.0		
Drivetrain coefficients			
Ks	0.15	Km	7.84
Kb	500	Tm	0.5
Ki	6.07	J_x	100
Vehicle's Parameters			
Parameters		Value	Unit
l_f		1.275	m
l_r		1.275	m
b_f		1.475	m
b_r		1.475	m
m		1080	kg
h		0.47	m
R_{eff}		0.3	m
J_z		900	kg.m^2

(a) Steering angle



(b) Longitudinal velocity



(c) Yaw rate

Fig. 7. Cornering test

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