Braking-Style-Based Optimization for Regenerative Braking System of an Electric Commercial Vehicle

Da-wei Pi (pidawei@mail.njust.edu.cn)
Nanjing University of Science and Technology https://orcid.org/0000-0001-9135-2623
Peng-yu Xue
Nanjing University of Science and Technology https://orcid.org/0000-0002-3194-1992
Qing Cheng
Nanjing University of Science and Technology
Wen-bo Chu
China intelligent and connected vehicles (Beijing) research institution
Jing-jing Fan
North China University of Technology
Bo-yuan Xie
Nanjing University of Science and Technology

Original Article

Keywords: Connected Autonomous Electrified Vehicles, Regenerative braking, Model predictive control, Braking style, Experimental test

Posted Date: October 7th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-84020/v1

Title page

Braking-Style-Based Optimization for Regenerative Braking System of an Electric Commercial Vehicle

Da-wei Pi, born in 1983, is currently an associate professor at *Nanjing University of Science and Technology*. He received the B.S. degree in vehicle engineering from *Southeast University, Nanjing, China*, in 2005, and the Ph.D degree in vehicle engineering from *Southeast University, Nanjing, China*, in 2010. He was a visiting scholar with *Ohio State University* in 2016.
His current research interests include vehicle system dynamic, intelligent control for electric vehicle and intelligent fault tolerant control of electro-mechanical system.
E-mail: pidawei@mail.njust.edu.cn

Peng-yu Xue, born in 1994, is currently pursuing the M.S. degree in *School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, China*. He received the B.S. degree from the School of *Transportation Science and Engineering, Beihang University, Beijing, China*, in 2017.
E-mail: 13131013@buaa.edu.cn

Qing Cheng, born in 1995, is currently pursuing the M.S. degree in *School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, China*. He received the B.S. degree in *vehicle engineering from Hunan University, Changsha, China*, in 2017.
E-mail: 237685462@qq.com

Wen-bo Chu, born in 1986, is currently a Research Fellow with *China Intelligent and Connected Vehicles (Beijing) Research Institute Co., Ltd*， which is also the *National Innovation Center of Intelligent and Connected Vehicles*. He received his B.S. degrees in *Automotive Engineering from Tsinghua University, China*, in 2008, and his M.S. degrees in *Automotive Engineering from RWTH-Aachen, German* and Ph. D. degrees in *Mechanical Engineering from Tsinghua University, China*, in 2014. His current research interests include intelligent connected vehicles, new energy vehicles and vehicle dynamics and control.
E-mail: chuwenbo@china-icv.cn

Jing-jing Fan, born in 1982, is currently an associate professor of *School of Electrical and Control Engineering, North China University of Technology, Beijing, China*. He received his B.S. degrees in automotive Engineering from *Tsinghua University, China*, in 2004, and his M.S. degrees in vehicle engineering from *China North Automotive Research Institute, China*, in 2007, and Ph. D. degrees in vehicle engineering from *Automotive Engineering from Tsinghua University, China*, in 2011. His current research interests include hybrid electric vehicle control technology, military hybrid power technology and intelligent network vehicle control technology.
E-mail: 13466391008@163.com

Bo-yuan Xie, born in 1979, is currently an engineer at *Nanjing University of Science and Technology*. He received the B.S. degree in *vehicle engineering from Jiangsu University, Zhenjiang, China*, in 2002, the M.S. degree in vehicle engineering from *Tongji University, Shanghai, China* in 2009, and Ph.D degree from *Tsinghua University, Beijing, China* in 2014. His current research interests include vehicle networking, automatic driving and so on.
E-mail: wsxby02@aliyun.com

Corresponding author: Da-Wei Pi E-mail: pidawei@mail.njust.edu.cn

Braking-Style-Based Optimization for Regenerative Braking System of an Electric Commercial Vehicle

Da-wei Pi[1] • Peng-yu Xue[1] • Qing Cheng[1] • Wen-bo Chu[2] • Jing-jing Fan[3] • Bo-yuan Xie[1]

1. School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, China
2. China Intelligent and Connected Vehicles (Beijing) Research Institute Co., Ltd, Beijing, China
3. School of Electrical and Control Engineering, North China University of Technology, Beijing, China

✉ Da-Wei Pi pidawei@mail.njust.edu.cn

Abstract

With the development of intelligent transportation system, intelligent network technology has been studied on a large scale in vehicle field. Electrification of vehicles and drive-by-wire chassis provide possibilities for the application of connected autonomous electrified vehicles. Regenerative braking control is an important field among drive-by-wire chassis control technologies. Regenerative braking control is a multi-objective optimization problem, which has the aim of improving regenerative energy efficiency, brake performance, and brake comfort. Therefore, a model predictive control (MPC) is proposed to solve the problem with consideration of different brake styles, such as aggressive, moderate and conservative. Then, the models of the main components associated with the regenerative braking system are designed and built up in a typical deceleration process for simulation and analysis. The simulation results show that the aggressive style mode is the best brake performance, which cause issues on brake comfort as well. The conservative style mode makes full use of motor braking and has advantage of the brake comfort and regenerative energy efficiency. But, it is not good at rapid braking performance of low brake intensity. The moderate style mode is suitable for most drivers, which is balanced of the above characteristics. Finally, experimental tests under ECE driving cycle are also carried out to further verify the characteristics of proposed three brake modes.
Keywords: Connected Autonomous Electrified Vehicles, Regenerative braking, Model predictive control, Braking style, Experimental test.

1 Introduction

In recent years, the rise of intelligent transportation system (ITS) and electrification of vehicles brings new opportunities and challenges for accelerating the development of environment-friendly transportation system. The Connected Autonomous Electrified Vehicles industry continues and expands the interdisciplinary characteristics of the traditional automobile industry, and specifically integrates key technologies such as environmental perception system, automatic driving decision system, vertical and horizontal control system, network communication system, battery energy management system, etc., with a broad space for development. The growing concern about the environmental friendliness and energy-saving requires vehicles to be more efficient and cleaner considerably [1-2]. With the rapid development of advanced electric vehicle technology to deal with non-renewable fossil fuels consumption and serious environment pollution, regenerative braking system (RBS) has been actively studied and applied to improve energy efficiency in various types vehicles, including battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs) [3]. In the braking process of energy management, braking style also plays a vital role in the energy recovery efficiency and braking safety in addition to the braking distribution strategy [4-5]. For instance, high-intensity-deceleration events have particularly negative influences of RBS, because excessive energy regenerated may affect braking performance and safety and greatly damage the battery. However, low-intensity-deceleration events can greatly enhance energy recovery efficiency while ensuring braking performance in the meantime [6]. Therefore, small change of braking styles can result in unnecessary energy waste and decreasing vehicle mobility performance. In order to address above challenges, a human-vehicle integrated optimization scheme of braking force distribution is proposed to realize a better overall performance of RBS [7-8].

In regenerative braking control, many scholars from all over the world have conducted comprehensive and in-depth researches on braking control strategies of various types of electric vehicles from all aspects. A lot of literatures focused on RBS coordinated with anti-lock braking system (ABS) of safety–critical driving maneuvers [9-11]. Similarly, various researches had concentrated on electric powertrain system [12-15]. For normal braking process, present studies shared the aims of improving the regeneration efficiency and the coordinated control effect between the regenerative brake and the frictional brake. Zhang et al. designed a coordinated braking strategy of RBS for a fuel cell hybrid electric bus and proposed a modified control strategy of regenerative braking control for rear-driven electrified minivans, which improved the regeneration efficiency by 15% compared with the baseline control strategy [16-17]. Lv et al. proposed a novel pressure-difference-limiting control method for hydraulic pressure modulation, which polished up the cooperative regenerative braking performance of electrified vehicles [18-19]. And a cyber-physical system based framework for co-design optimization of an automated EV with different driving styles was proposed to significantly improve overall performances of the vehicle [20]. Li et al. proposed an efficient energy recovery control strategy based on the modified nonlinear model predictive control method for regenerative braking system of hybrid electric bus, which balanced the vehicle safety and braking energy recovery efficiency [21]. Kumar et al. studied study the impact of regenerative braking on vehicle lateral stability and energy regeneration while braking in a turn and a suitable solution is proposed to improves lateral stability [22-23] .Wu et al. put forward a novel hierarchical control strategy with the battery aging consideration and controller-in-loop tests is designed to verify the real-time calculation performance of the proposed method [24]. Ruan et al. proposed three blended braking strategies, which not only achieved comfortable and safe braking during all driving conditions, but also significantly reduced cost in both the short and long term [25]. Bravo et al. designed and analyzed a parallel hydraulic-pneumatic regenerative braking system for heavy-duty hybrid vehicles and the research results indicated an opportunity for significantly improving the overall energy efficiency of delivery trucks and buses [26]. Nevertheless, the braking style/mode effectively cooperated with the regenerative braking has rarely been seen in the existing research on regenerative braking control.

The primary objective of this paper is to develop a forward-looking optimal control framework from the point of view of co-design optimization to maximize energy recovery efficiency for an electric truck equipped with RBS under the premise of meeting the requirements of braking safety.

Following original vital contributions are made to further advance CPS methods as well as their applications, which clearly distinguish our efforts from the above-mentioned literature:

1) Three brake force distribution (BFD) schemes with three different optimization objectives are adopted in the electric light truck equipped with regenerative braking system for deceleration.

2) The model predictive control (MPC) algorithm based on prior knowledge of braking style is utilized for BFD. After system modeling, a multi-objective optimal energy management strategy considering energy recovery efficiency, braking dynamic performance and the battery life can be formulated.

3) Three different scenarios are tested to verify the performance of the EV equipped with different BFD strategies.

The rest of this paper proceeds as follows. In Section 2, the structure of case-study EV are developed and illustrated and the system modeling is elaborated. The MPC optimal controller synthesis for three braking styles with different BFD strategies is formulated in Section 3. Then, the results and analysis of simulation and experimental tests are presented in Section 4. Finally, conclusions are ultimately summarized in Section 5.

2 System modeling

The overall configuration of the electric vehicle with regenerative braking system in this case study is shown in Figure 1. The regenerative braking system is realized on the basis of this electronic-pneumatic braking system of the adopted truck, in which the brake pedal is decoupled from the braking actuator and the wheel cylinders is all controlled by wire. The motor and transmission are set at the rear axle and the car is a rear-drive light truck. On each axle of the vehicle, an axle valve, which integrates two on-off valves (normally closed), is set between the wheel cylinder and the braking controller to modulate braking pressure. When the brake pedal is pushed down and the vehicle is on the deceleration process, the regenerative braking controller controls front and rear axle valves respectively according to braking force distribution rules and communicates with the motor controller through the controller area network (CAN) bus to complete the whole braking process collaboratively. Therefore, in this way, the regenerative braking is realized on the basis of combining pneumatic braking torque and motor regenerative braking torque so as to maintain the high efficiency of normal braking.

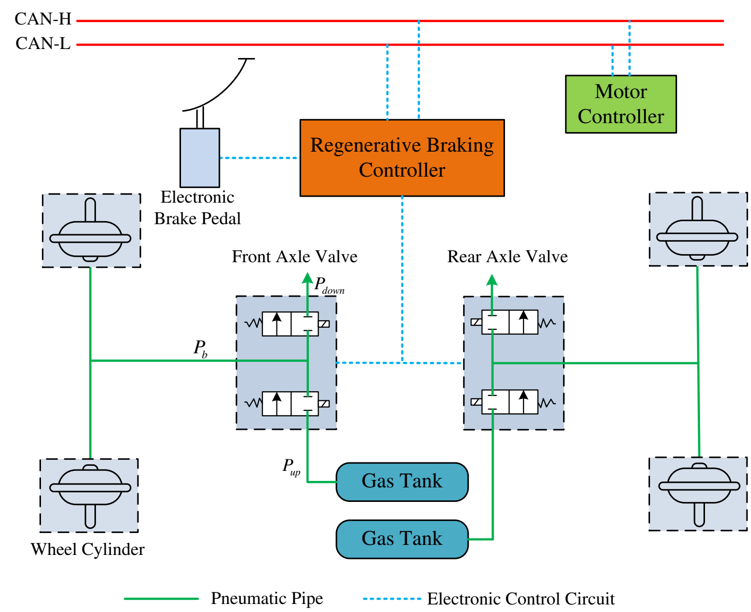

Figure 1　Configuration of the electric truck with regenerative braking system.

2.1 Vehicle dynamic model

A seven degree of freedom (DOF) vehicle model is adopted to illustrate the vehicle dynamics, including the longitudinal motion and four front/rear wheels' rotations, as shown in Fig. 2.
The equations of the motions are as follows.
The longitudinal motion of the vehicle is expressed as:

$$m(\dot{v}_x-\gamma v_y)=(F_{x1}+F_{x2})\cos\delta-(F_{y1}+F_{y2})\sin\delta+F_{x3}+F_{x4}-\frac{C_d A}{21.15}(3.6u)^2 \tag{1}$$

The transverse motion of the vehicle is expressed as:

$$m(\dot{v}_x+\gamma v_x)=(F_{x1}+F_{x2})\sin\delta+(F_{y1}+F_{y2})\cos\delta+F_{y3}+F_{y4} \tag{2}$$

The yaw of the vehicle is expressed as:

$$\begin{aligned}I_z\dot{\gamma}=&\frac{c_1}{2}[(F_{x1}-F_{x2})\cos\delta+(F_{y1}-F_{y2})\sin\delta]+a[(F_{x1}+F_{x2})\sin\delta+(F_{y1}+F_{y2})\cos\delta]\\&+\frac{c_2}{2}(F_{x3}-F_{x4})-b(F_{y3}+F_{y4})\end{aligned} \tag{3}$$

The motion of the tires of a drive wheel can be expressed as:

$$I_w\dot{w}_i=T_{di}-F_{xi}r-T_{bi}\qquad i=fl,fr,rl,rr \tag{4}$$

In the equations above, m is the overall mass of the vehicle, v_x is the velocity along OX and v_y is the velocity along OY. F_{x1}, F_{x2}, F_{x3} and F_{x4} are the longitudinal tire force of the front left wheel, front right wheel, rear left wheel and rear right wheel respectively. a is the longitudinal distance from the center of gravity of the vehicle to the front axle, b is the longitudinal distance from the center of gravity of the vehicle to the rear axle and L is the wheelbase. c_1 and c_2 are the widths of the front track and the rear track respectively. I_w is the rotational inertia of wheel. w_i is the rotational speed of the wheel. r is the nominal radius of the tire and T_{di} and T_{bi} are the driving and braking torques respectively exerted on the wheel.

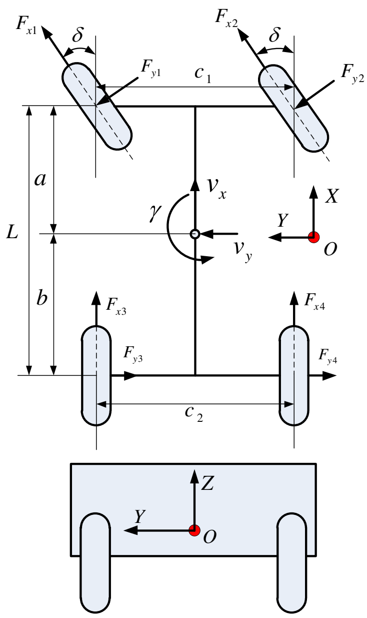

Figure 2 Diagram of vehicle dynamic model in OXYZ coordinate system.

2.2 Tire model

In research on vehicle braking, the tire model is of great significance to simulate the real adhesion and sliding of tires. There are different theories developed for estimating tire-road force and this paper adopts the Dugoff tire model.

For a single wheel, the longitudinal and lateral forces of the tire can be expressed by the following equations in the tire coordinate system.

$$\begin{cases} \dot{s}_i(t) = v_i(t) \\ \dfrac{\eta_i T_i(t)}{R_i} = \dfrac{C_{A,i} v_i^2(t)}{m_i} + \mu g + \dot{v}_i(t), \quad i \in ¥ \\ \tau \dot{T}_i(t) + T_i(t) = u_i(t) \end{cases} \tag{5}$$

$$\lambda_i = \frac{\mu F_{zi}\left(1+\sigma_{xi}\right)\left(1-\varepsilon_v v_x\left(\sigma_{xi}^2+\left(\tan\left(\alpha_i\right)\right)^2\right)^{1/2}\right)}{2\left[\left(C_\sigma \sigma_{xi}\right)^2+\left(C_\alpha \tan\alpha_i\right)^2\right]^{1/2}} \tag{6}$$

$$f_i(\lambda_i) = \begin{cases} (2-\lambda_i)\lambda_i & (\lambda_i < 1) \\ 1 & (\lambda_i \geq 1) \end{cases} \tag{2}$$

$$\begin{cases} F_{xi} = C_s \dfrac{\sigma_{xi}}{1+\sigma_{xi}} f_i(\lambda_i) \\ F_{yi} = C_\alpha \dfrac{\tan\alpha_i}{1+\sigma_{xi}} f_i(\lambda_i) \end{cases} \quad (i = fl, fr, rl, rr) \tag{7}$$

This tire model requires fewer identification parameters. μ is the adhesion coefficient of tire pavement. C_s and C_a represent the longitudinal and lateral stiffness of the tire respectively. ε_v is the velocity impact factor. l_i is the tire nonlinear factor.

2.3 Motor model

The motor model is built up according to the measured motor parameters of the case-study vehicle. In regenerative braking mode, the motor has almost the same rotational speed in the driving mode, which has symmetry characteristics. And the transfer function of electric motor can be written in the form of a first order transfer function:

$$G(s) = \frac{1}{0.05s+1} \tag{8}$$

As is shown in Fig. 3, different lines represent the different efficiency of electric motor in a certain working zone. When the speed and torque are given, the efficiency of the electric motor can be obtained from this map.

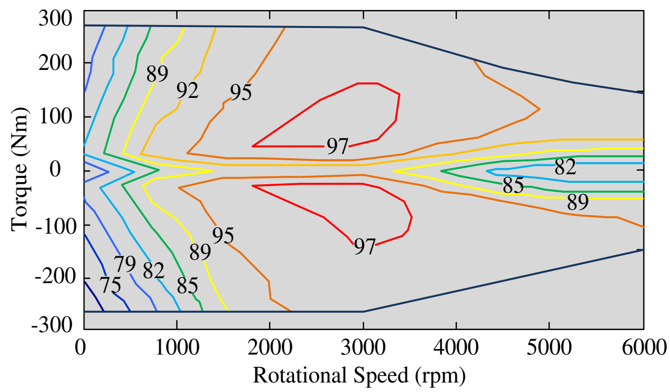

Figure 3 The efficiency map of the electric motor.

2.4 Pneumatic Braking System Model

The pneumatic braking system model established in this paper is a theoretical model based on the braking principle of the test vehicle, which has been introduced in section 2. The input of the model is the brake air chamber pressure, and the output is the brake torque of the wheels. The equation is expressed as follows:

$$T_{bi} = K_{efi}(P_i - P_0)r \qquad i = fl, fr, rl, rr \tag{9}$$

where K_{efi} is the braking efficiency factor, P_i is the braking pressure of wheel cylinder, P_0 is the atmospheric pressure and r is the radius of the vehicle wheel.

2.5 Battery Model

The lithium battery is used to provide electric power for the whole vehicle. The battery model is simplified as the PNGV equivalent circuit model and the SOC estimation module adopts the Ampere-Hour integration method. The model's input is the power required by the electric motor. Its output includes the SOC, the voltage at the output port of battery and the current of the battery.

3 Controller design

3.1 Control framework of the system

This novel regenerative braking control system is aimed to output a suitable deceleration, satisfying different braking styles and finishing the goals of energy recovery, great brake comfort and safety. As is shown in Fig. 4, in this study, the whole control algorithm is developed based on different braking styles.

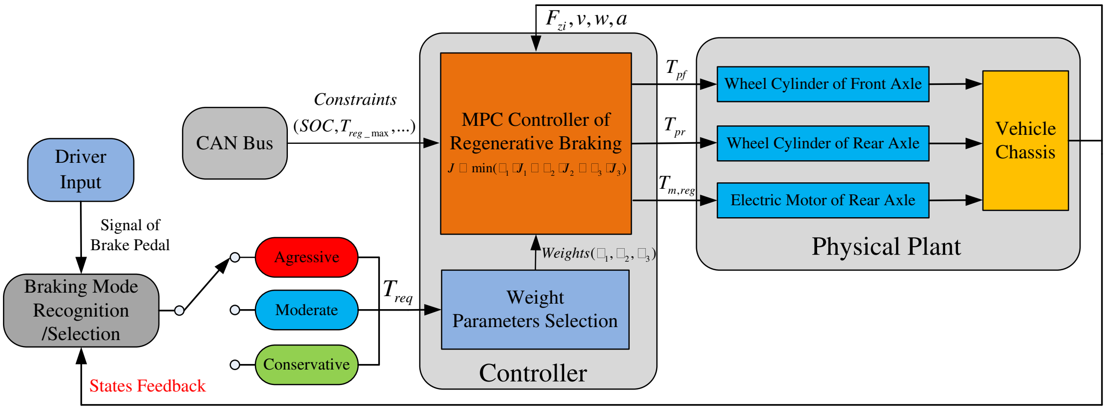

Figure 4 Hierarchical control schematic graph for different driving styles.

3.2 Braking Mode Selection

This novel regenerative braking controller is synthesized by considering different braking styles. So the requested output braking torque distribution is not only determined by the driver's operation, but also distinguished by the braking modes. In the actual implementation stage, the regenerative braking mode of electric vehicles can be selected through the human-machine interface (HMI) or use machine learning to perceive a driver's intentions or preferences through smart sensors, which is prepared for highly automated vehicles within a few years. In this paper, the switching of braking style selection is assumed to be realized via HMI of braking modes.

Oriented by the braking-mode-aware regenerative braking control described above, three braking modes are considered in this work and defined as follows.

(1) Aggressive: The aggressive braking mode exhibits sharp and abrupt deceleration, aiming at vehicle dynamic performance. This mode results in more pneumatic braking torque and less electric braking torque because of braking distance is short and regenerated current is overshoot.

(2) Conservative: The braking mode of conservative driver often exhibit mild operational braking behaviors and they pay more attention to the energy efficiency and ride comfort, in which electric braking torque can intervene to recover more energy to avoid abrupt variations of vehicle state.

(3) Moderate: The moderate braking mode is in between of above two. This kind driver may value the balance of vehicle performance, energy efficiency and ride comfort.

Through a large number of literatures and practical road test of a light truck with different drivers, the human-like deceleration behavior profiles are developed for each braking mode, as illustrated in Fig. 5.

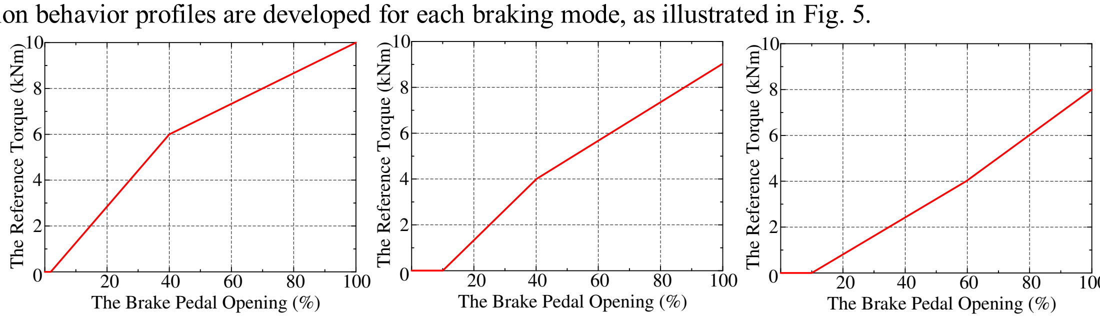

Figure 5 The profiles of relationship of brake pedal opening and reference torque

3.3 MPC controller

The regenerative braking is a multi-objective and multi-constraints nonlinear control problem, which should ensure recover more energy, high-effective braking performance and better braking comfort. As we know, the most important characteristic of MPC is that it can integrate multiple control objectives of a complex system into one equation for coordination, and the control parameters are easy to be adjusted. In this paper, the MPC is finally introduced to solve the control problem in the regenerative braking system of electric vehicles.

3.3.1 Predictive model

The rotational direction of a single wheel is modeled dynamically and the model is discretized and the equation of state of the system is expressed as:

$$\begin{cases} w_{fi}(k+1) = \dfrac{T_s}{2I_w}\left[2\cdot r\cdot F_{xfi}(k) - T_{pf}(k)\right] + w_{fi}(k) \\ w_{ri}(k+1) = \dfrac{T_s}{2I_w}\left[2\cdot r\cdot F_{xri}(k) - T_{pr}(k) - T_{m,reg}(k)\right] + w_{ri}(k) \end{cases} \tag{10}$$

where k represents the time step, T_s is the sampling time, T_{pf} and T_{pr} are pneumatic braking torque of front and rear axle respectively and $T_{m,reg}$ is the motor regenerative braking torque. Hence, we select angular velocity of the front and rear wheels as the state variable and front and rear axle pneumatic brake torque and motor torque as the control variable. Definitions are as follows:

$$\begin{cases} x(k) = [w_f(k), w_r(k)]^T \\ u(k) = [T_m(k), T_{pf}(k), T_{pr}(k)]^T \\ d(k) = [F_{x1}(k), F_{x2}(k)]^T \\ y(k) = x(k) \end{cases} \tag{11}$$

The state-space model equations of MPC can be written as:

$$\begin{cases} x(k+1) = A_x x(k) + B_u u(k) + D_d d(k) \\ y(k) = C_y x(k) \end{cases} \tag{12}$$

The coefficients matrixes are given as follows:

$$A_x = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, B_u = \begin{bmatrix} 0 & -\dfrac{T_s}{I_w} & 0 \\ \dfrac{T_s}{I_w} & 0 & -\dfrac{T_s}{I_w} \end{bmatrix}, D_d = \begin{bmatrix} \dfrac{T_s}{I_w} & 0 & 0 \\ 0 & \dfrac{T_s}{I_w} & 0 \end{bmatrix} \tag{13}$$

$$C_y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{14}$$

3.3.2 Dynamic constraints

Through setting the dynamic constraints of MPC, the motor and battery can be effectively protected and the deceleration performance can be more stable during the regenerative braking process. The constraints include maximum motor torque, maximum battery charging current, limited SOC and maximum change rate of pneumatic braking torque.

$$\begin{cases} (T_m)_{\max} \le T_{m,reg} \le 0 \\ (I_c)_{\max} \le I_{reg} \\ (SOC)_{reg} \le (SOC)_{reg} \\ T_p(k+1) - T_p(k) \le (\Delta T_p)_{\max} \\ 0 \le T_p \le (T_p)_{\max} \end{cases} \tag{15}$$

The first constraint is the maximum of electric motor torque, which is relevant to the motor angular speed ω_m and can be obtained from the motor map of Fig. 3. The second one is the charge current of battery. Too much current will burn the battery and it is should be limited by the experimental test data of 280A in this work. The third one is SOC. When the SOC of the charged state of the battery is higher than the upper limit value of 90%, the battery is not able to continue charging. The last two constraints are about of pneumatic pressure. Considering actual pneumatic braking system has the large hysteresis and maximum pressure limitation, the maximum change rate of pneumatic torque is 10000 N/m/s and the maximum pressure is set at the 3000N/m by measured data.

3.3.3 Cost function of MPC

Energy recovery, vehicle braking stability and braking comfort are the main concerns in regenerative braking controller design. These three objective functions J_1, J_2 and J_3 are designed according to the characteristics of the whole control system.

First of all, in order to meet the braking demand, the optimized braking torque should be able to track the total braking deceleration well. This target is realized through the target function J_1 and the specific expression is as follows:

$$J_1 = \sum_{i=1}^{h_p} [T_{pf}(k+i|k) + T_{pr}(k+i|k) + T_{m,reg}(k+i|k) - T_{ref}(k+i|k)]^2 \tag{16}$$

where T_{ref} the reference vehicle deceleration.

Secondly, the braking energy recovery efficiency is an important index to evaluate the quality of the designed control system. Under the premise of braking demand, objective function J_2 is added to ensure energy recovery efficiency, which is expressed as:

$$J_2 = \sum_{i=1}^{h_c-1} [E_{reg}(k+i|k)]^2 \tag{17}$$

$$E_{reg} = \eta_{gen} \int T_{m,reg} \omega_m dt \tag{18}$$

where E_{reg} is the regenerated braking energy, η_{reg} is the braking efficiency of the motor at the current moment, which both can be checked from the motor efficiency map .

If the control operation of the vehicle changes a lot, it will have a great impact on the comfort. The comfort level of a vehicle, also known as drivability, can be assessed by vehicle's jerk j . So the objective function J_3 is added to ensure the driving comfort of the electric vehicle, which is expressed as:

$$J_3 = \sum_{i=1}^{h_c-1} [j(k+i|k)]^2 \tag{19}$$

$$j = \ddot{v} \tag{20}$$

While aggressive drivers may enjoy intense vehicle's jerk, the ride comfort are important features for those who prefer conservative or moderate driving style. In this article, the jerk is used to capture the comfort level of the vehicle.

The model predictive control algorithm can integrate all the control objectives in one equation, and the control parameters are easy to adjust. The overall objective function of the system designed in this paper is expressed as follows

$$J = \min(w_T \times J_1 - w_h \times J_2 + w_j \times J_3) \tag{21}$$

where w_T, w_h and w_j are the weight coefficients of each control objective, which can be adjusted to a satisfactory control effect according to the different braking styles or HMI operation.

As described before, the braking modes are differentiated as three kinds, which are aggressive mode, moderate mode and conservative mode, and in different modes, the cost function has different weights. When making weight selection, a much great weight is given for every featured cost function and a much lower weight on the other unrelated functions is set to 1 under different driving styles. The detailed setting of weights for three braking modes is presented in Table 1.

Table 1 Weight selection for different styles

Braking Mode	Weight		
	w_T	w_h	w_j
Aggressive	10	1	1
Moderate	1	1	1
Conservative	1	10	10

3.3.4 MPC implementation

The online computing speed of MPC is a key problem, which has been blocking the application further. In order to improve computational efficiency, a simplified optimization method is implemented to solve the problem. In the meantime, the predictive time horizon is set at 8 and control time horizon is set at 4.

In view of the total requested braking torque is given by driver operation and obtained by the lookup tables of different braking styles, as long as two variables are given in the control variable $u(k)$ the third one will be confirmed. Hence, if we give a rule of front and rear wheel torque distribution, the computing burden of MPC will be greatly reduced.

In order to prevent the dangerous sideslip of rear axle, it is required that the actual BFD curve (b curve) of the vehicle braking system should be more and more close to the ideal braking curve (I curve) to improve the adhesion efficiency of the wheels. Integrated the ECE regulations and regenerative energy requirements, the implemented BFD of front and rear wheels can be shown in Fig. 6.

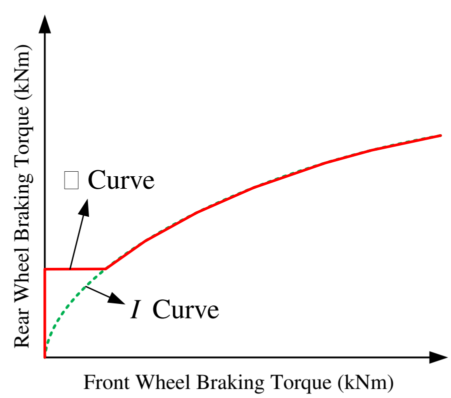

Figure 6 Diagram of braking torque distribution.

3.4 Pneumatic pressure controller

In order to realize the cooperative control of motor and pneumatic brake system, wheel cylinders should be controlled to track the desired pressure. Thus, a proportional-integral-differential (PID) controller with Pulse Width Modulation (PWM) is designed to implement the process, which has fast calculation and satisfied dynamic performance. Take front axle valve system for example, the control logic diagram is shown in Fig. 7.

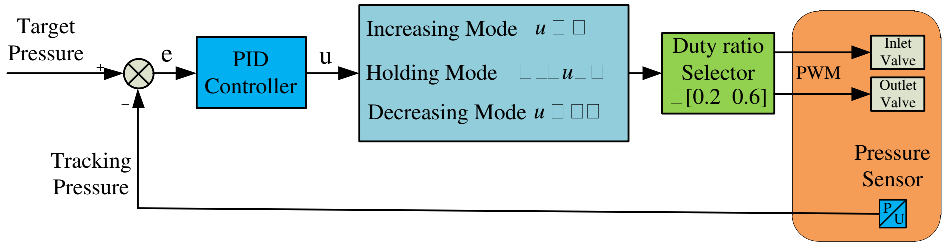

Figure 7 Pneumatic pressure control logic.

4 Simulation Results and Analysis

Based on the data of a real truck shown in Fig. 8, a similar electric model and controller is built up in MATLAB/Simulink and some parameters of simulation are given in Table 2.

Figure 8 Electric light truck for simulation.

In this simulation, to simplify the problem within a reasonable complexity, the following assumptions are made.
(1) The vehicle is assumed to run in normal braking conditions, excluding the emergency braking condition.
(2) The slope of the road is assumed to be zero and only longitudinal motion control of vehicle is considered.
(3) It is also assumed that parameters of electric powertrain system are fixed and current vehicle states can be measured by actual sensors and obtained by simple calculation.
On the basis of above developed control method, three braking style modes are simulated to compare with each other and the performance exploration is carried out. The detailed results with different driving styles are shown as follows and the parameters of vehicle adopted in the numerical simulation are shown in Table 2.

Table 2. Parameters of simulation.

Parameters	Value
Total vehicle mass m	4550 kg
Wheelbase L	3.3 mm
Height of center of gravity h_g of the vehicle	0.8 m
Transmission ratio i_g	1.5
Final drive ratio i_0	6.2
Nominal radius R of the wheel	0.3831 m
Moment of inertia of a wheel I_w	20 $kg \times m^2$
Distance from the front axis to the center of mass a	1.52 m
Distance from the rear axis to the center of mass b	1.78 m

4.1 Simulation of three braking modes

By simulating the driver braking process, some curves of different regenerative braking process are obtained.
From the simulation results of the aggressive mode shown in Fig. 9, the vehicle is braking within 5s by the driver's normal braking command, causing wild fluctuations of jerk values, which seriously affect the brake comfort. Meanwhile, because of giving priority to braking performance, less regenerative torque participate in the braking and the less energy is regenerated as well. In addition the front axle pneumatic torque is excessively changed, which is disadvantage for the life of braking valves.
The simulation results of the moderate mode are shown in Fig. 10, the vehicle is stopped within 6s and the jerk is kept relatively stable. The motor regenerative torque increases to its maximum extent gradually in following 3s of the deceleration. In the meantime, the pneumatic torques of rear axles compensate for the remaining request braking torque. Once the request torque reaches a high value at 1.5s, the pneumatic torque of front axle starts to be exerted to ensure the brake safety. After the regenerative braking torque stabilizes at its maximum, the front torque is maintained at a low value of 2kNm. When the regenerative torque decreases in about 5.2s, which is restricted by controller restrictions and its working characteristics, the pneumatic torque of rear axle is supplemented to keep vehicle stable.
The simulation results of the conservative are shown in Fig. 11, at the beginning of the braking procedure of 2s, the regenerative torque takes responsible for most of the braking request, which is relatively small enough to be exerted by electric motor. Then, after reaching a certain threshold, the pneumatic torque also starts to coordinate with the regenerative torque to provide the lacking overall torque in the following 2s. Afterwards, when the vehicle speed decrease to a low value in 6.3s, the regenerative torque begins to evacuate and the pneumatic torque of front and rear axle remain a relative low level to make vehicle stopped. Therefore, because the requirement of brake intensity in the most time is guaranteed in low stage and the brake torque changes steadily, the small jerk and high regeneration efficiency are both obtained naturally.

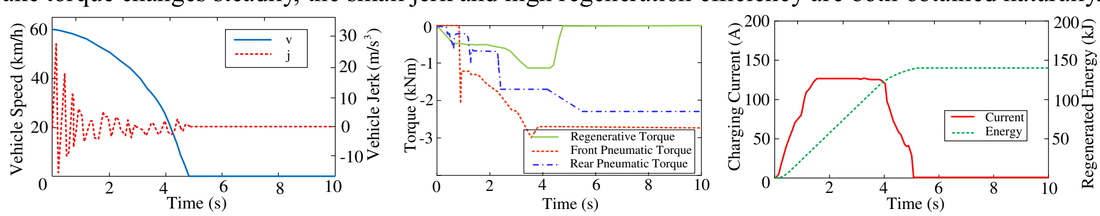

Figure 9 Simulation of the aggressive mode.

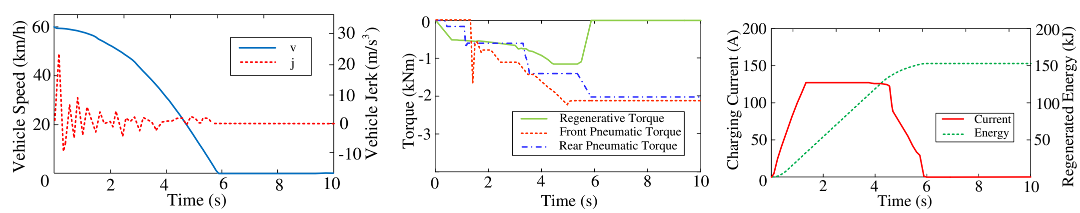

Figure 10 Simulation of the moderate mode.

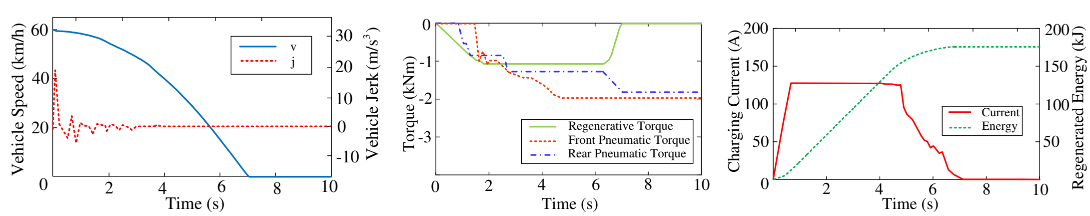

Figure 11 Simulation of the conservative mode.

4.2 Comparisons of the three brake modes in simulation

Comparisons of above results are given in Table 3.The aggressive style, which is in favor of vehicle dynamic performance, achieves the best performance of brake time in the same brake intensity of less than 5s.The conservative style, which prefers to the ride jerk and regenerated energy efficiency, dominates in vibration reduction and regenerated energy. The maximum jerk of this style is under $20\,m/s^3$ and regenerated energy is top of all. Last of all, the moderate style, which is in the middle of three styles, has a balanced performance in all aspects of dynamic performance, ride comfort, and regenerated energy efficiency.

Table 3 Results comparison of three brake mode.

Brake style	Performance		
	Brake time (s)	Maximum jerk (m/s^3)	Regenerated energy (kJ)
Aggressive	4.8	28	142.8
Moderate	5.9	21	151.2
Conservative	7.1	17	172.5

4.3 Experimental Tests

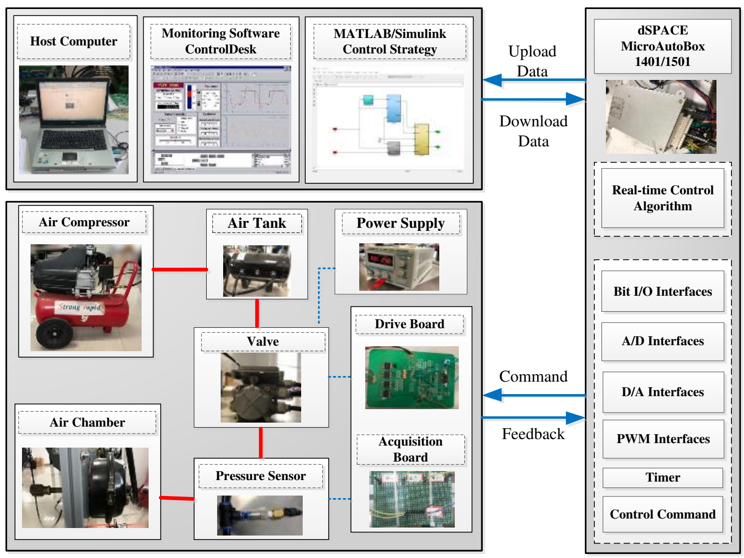

Figure 12 Overall configuration of the experimental test platform.

To further the study of influence on vehicle's energy efficiency enhancement by the regenerative braking, tests based on MircoAutoBox 1401/1501 from dSPACE are carried out. As is shown in Fig. 12, the entire control platform setup for the regenerative braking system, which consists of four parts: host computer and software, real-time workshop, drive and feedback units and physical actuators. The proposed MPC controller and vehicle model in MATLAB are downloaded in MircoAutoBox by Real-Time Interface (RTI) to run the actuators.

Thanks to the average speed of ECE driving cycle is close to the urban driving condition of China, the ECE driving cycle is extracted to compare the energy efficiency of the vehicle improved by a regenerative braking system under three different styles respectively, which has the practical significance. Fig. 13 depicts the test results of ECE driving cycle.

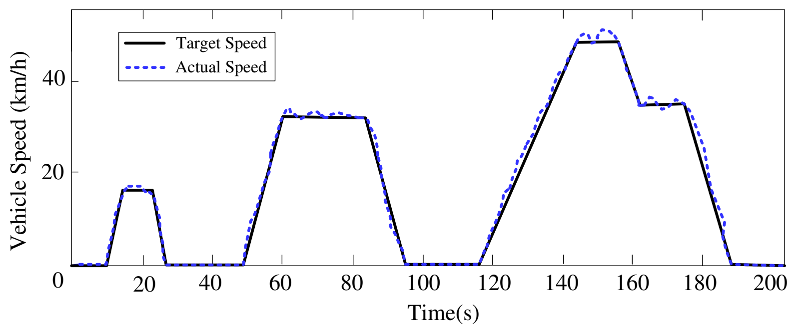

Figure 13 Test result of the ECE driving cycle.

In order to quantitatively measure and evaluate energy efficiency of vehicle with regenerative braking system, the contribution rate η_{reg} is proposed as an evaluation parameter, which can be expressed as follows:

$$\eta_{reg} = \frac{E_{reg}}{E_{drive}} \times 100\% = \frac{\int_{P_{reg}<0} U_{battery} I_{reg} \eta_{charge} dt}{\int_{P_{drive}>0} P_{drive} dt}$$

where E_{reg} is the regenerated energy of the whole driving cycle, E_{drive} is the whole consumed energy of the driving cycle, P_{reg} is the charging power, $U_{battery}$ is the battery voltage, I_{reg} is the charging current, η_{charge} is the charge efficiency of the battery and P_{drive} is the consumed power of the vehicle.

The comparison of the ECE driving cycle results are shown in Table 4. Based on equation (x), the fuel economy contribution rate of the aggressive style mode is below 22%. However, the fuel economy contribution rate of the moderate style mode is nearly 24%. Particularly, for the conservative style mode, the contribution rate is above 26%, which is at a relatively high level.

Table 4 Comparison of for the ECE driving cycle test results.

Braking style	Consumed energy (kJ)	Regenerated energy (kJ)	Contribution rate (%)
Aggressive	2273.1	481.9	21.2%
Moderate	2091.2	497.7	23.8%
Conservative	1932.5	512.1	26.5%

5 Conclusions

In this paper, a novel MPC controller of regenerative braking system considering the braking styles is proposed to optimize different targets. A new regenerative braking system is designed and simulation model is built based on experimental data. The results of simulation and experimental tests strongly demonstrate that the proposed controller coordinated with different braking styles ensures the request characteristics with respect to brake performance, brake comfort and regenerative energy efficiency.

In future research, studies will be carried out in some areas such as the following: road tests of the real case-study vehicle in different driving cycles; the influence of the motor overheating and battery aging on the regenerative braking control; life and stability tests of the regenerative braking system.

6 Declaration

Acknowledgements

Not applicable

Funding

This work was supported by Beijing Nova Program of Science and Technology (No. Z191100001119087) and Beijing Municipal Science & Technology Commission（No.Z181100004618005 ）

Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author' contributions are as follows: DP was in charge of the whole trial; PX designed the MPC algorithm and wrote the manuscript; QC designed the braking torque distribution strategy; WC drafted the work; JF assisted with sampling and laboratory analyses; BX substantively revised the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

Reference

[1] Katrasnik, T. . (2011). Energy conversion phenomena in plug-in hybrid-electric vehicles. *Energy Conversion & Management, 52*(7), 2637-2650.

[2] Hoehne, Christopher G., Chester, & Mikhail V. (2016). Optimizing plug-in electric vehicle and vehicle-to-grid charge scheduling to minimize carbon emissions. *Energy*. 115:646-57.

[3] Zhang, J. , Lv, C. , Yue, X. , Qiu, M. , & He, C. . (2013). Development of the Electrically-Controlled Regenerative Braking System for Electrified Passenger Vehicle. *SAE 2013 World Congress & Exhibition*.

[4] Ruan, J. , Walker, P. , & Zhang, N. . (2016). A comparative study energy consumption and costs of battery electric vehicle transmissions. *Applied Energy, 165*, 119-134.

[5] Li, L. , Wang, X. , Xiong, R. , He, K. , & Li, X. . (2016). AMT downshifting strategy design of HEV during regenerative braking process for energy conservation. *Applied Energy, 183*, 914-925.

[6] Zhang, J. , Lv, C. , Gou, J. , & Kong, D. . (2012). Cooperative control of regenerative braking and hydraulic braking of an electrified passenger car. *Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering, 226*(10), 1289-1302.

[7] Chen, L. , Hong, W. , Bolin, Z. , Dongpu, C. , Wang, H. , & Junzhi, Z. , et al. (2017). Cyber-physical system based optimization framework for intelligent powertrain control. *Sae International Journal of Commercial Vehicles, 10*(1), 2017-01-0426-.

[8] Lv, C. , Xing, Y. , Lu, C. , Liu, Y. , & Cao, D. . (2018). Hybrid-learning-based classification and quantitative inference of driver braking intensity of an electrified vehicle. *IEEE Transactions on Vehicular Technology, PP*(99), 1-1.

[9] Zhang, J. , Kong, D. , Chen, L. , & Chen, X. . (2012). Optimization of control strategy for regenerative braking of an electrified bus equipped with an anti-lock braking system. *Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering, 226*(4), 494-506.

[10] Qiu, C. , Wang, G. , Meng, M. , & Shen, Y. . (2018). A novel control strategy of regenerative braking system for electric vehicles under safety critical driving situations. *Energy*, 329-340.

[11] Lv, C. , Zhang, J. , Li, Y. , & Yuan, Y. . (2015). Novel control algorithm of braking energy regeneration system for an electric vehicle during safety–critical driving maneuvers. *Energy Conversion & Management, 106*, 520-529.

[12] Lv, C. , Zhang, J. , & Li, Y. . (2014). Extended-kalman-filter-based regenerative and friction blended braking control for electric vehicle equipped with axle motor considering damping and elastic properties of electric powertrain.

Vehicle System Dynamics, 52(11), 1372-1388.

[13] Li, L. , Li, X. , Wang, X. , Song, J. , He, K. , & Li, C. . (2016). Analysis of downshift's improvement to energy efficiency of an electric vehicle during regenerative braking. *Applied Energy, 176*, 125-137.

[14] Lv, C. , & Zhang, J. . (2011). Research of parameter design and matching of powertrain system in plug-in hybrid electric vehicle. *International Conference on Electric Information & Control Engineering*. IEEE.

[15] Nian, X. , Peng, F. , & Zhang, H. . (2014). Regenerative braking system of electric vehicle driven by brushless dc motor. *IEEE Transactions on Industrial Electronics, 61*(10), 5798-5808.

[16] Junzhi, Z. , Yutong, L. , Chen, L. , & Ye, Y. . (2014). New regenerative braking control strategy for rear-driven electrified minivans. *Energy Conversion & Management, 82*(jun.), 135-145.

[17] Zhang, J. , Lv, C. , Qiu, M. , Li, Y. , & Sun, D. . (2013). Braking energy regeneration control of a fuel cell hybrid electric bus. *Energy Conversion & Management, 76*(dec.), 1117-1124.

[18] Lv, C. , Zhang, J. , Li, Y. , & Yuan, Y. . (2015). Mechanism analysis and evaluation methodology of regenerative braking contribution to energy efficiency improvement of electrified vehicles. *Energy Conversion and Management, 92*, 469-482.

[19] Lv, C. , Zhang, J. , Li, Y. , Sun, D. , & Yuan, Y. . (2014). Hardware-in-the-loop simulation of pressure-difference-limiting modulation of the hydraulic brake for regenerative braking control of electric vehicles. *Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering, 228*(6), 649-662.

[20] Chen, L. , Xiaosong, H. , Alberto, S. V. , Clara, M. , Yutong, L. , & Dongpu, C. . (2018). Driving-style-based codesign optimization of an automated electric vehicle: a cyber-physical system approach. *IEEE Transactions on Industrial Electronics, 66*, 2965-2975.

[21] Li L, Zhang Y, Yang C, Yan B, Marina Martinez C. (2016). Model predictive control-based efficient energy recovery control strategy for regenerative braking system of hybrid electric bus. *Energy Conversion & Management, 111*, 299-314.

[22] Kumar, C. N. , & Subramanian, S. C. . (2016). Cooperative control of regenerative braking and friction braking for a hybrid electric vehicle. *Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering, 230*(1), 103-116.

[23] Nanda Kumar, C. , & Subramanian, S. C. . (2017). Brake force sharing to improve lateral stability while regenerative braking in a turn. *Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering*, 095440701774737.

[24] Wu, J. , Wang, X. , Li, L. , Qin, C. , & Du, Y. . (2018). Hierarchical control strategy with battery aging consideration for hybrid electric vehicle regenerative braking control. *Energy, 145*(FEB.15), 301-312.

[25] Ruan, J. , Walker, P. D. , Watterson, P. A. , & Zhang, N. . (2016). The dynamic performance and economic benefit of a blended braking system in a multi-speed battery electric vehicle. *Applied Energy, 183*, 1240-1258.

[26] Silva Bravo, R. R. , De Negri, V. J. , & Martins Oliveira, A. A. . (2018). Design and analysis of a parallel hydraulic – pneumatic regenerative braking system for heavy-duty hybrid vehicles. *Applied Energy, 225*(SEP.1), 60-77.

[27] Xun, Z. , Liang, L. , Xiangyu, W. , Mingming, M. , Congzhi, L. , & Jian, S. . (2018). Braking force decoupling control without pressure sensor for a novel series regenerative brake system. *Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering*, 095440701878574.

[28] Li, L. , Li, X. , Wang, X. , Liu, Y. , Song, J. , & Ran, X. . (2016). Transient switching control strategy from regenerative braking to anti-lock braking with a semi-brake-by-wire system. *Vehicle System Dynamics, 54(*2), 231-257.

[29] Qiu, C. , & Wang, G. . (2016). New evaluation methodology of regenerative braking contribution to energy efficiency improvement of electric vehicles. *Energy Conversion & Management, 119*(Jul.), 389-398.

[30] Lv, C. , Zhang, J. , Li, Y. , & Yuan, Y. . (2016). Directional-stability-aware brake blending control synthesis for over-actuated electric vehicles during straight-line deceleration. *Mechatronics*, 121-131.

[31] Li, L. , Wang, X. , Hu, X. , Chen, Z. , Song, J. , & Muhammad, F. . (2016). A modified predictive functional control with sliding mode observer for automated dry clutch control of vehicle. *Journal of Dynamic Systems Measurement and Control.*

[32] Bjornsson, L. H. , & Karlsson, S. . (2016). The potential for brake energy regeneration under swedish conditions. *Applied Energy, 168*, 75-84.

Biographical notes

Da-wei Pi, born in 1983, is currently an associate professor at *Nanjing University of Science and Technology*. He received the B.S. degree in vehicle engineering from *Southeast University, Nanjing, China*, in 2005, and the Ph.D degree in vehicle engineering from *Southeast University, Nanjing, China*, in 2010. He was a visiting scholar with *Ohio State University* in 2014.

His current research interests include vehicle system dynamic, intelligent control for electric vehicle and intelligent fault tolerant control of electro-mechanical system.

Peng-yu Xue, born in 1994, is currently pursuing the M.S. degree in *automobile electronic control with Nanjing University of Science and Technology, Nanjing, China*. He received the B.S. degree from the School of *Transportation Science and Engineering, Beihang University, Beijing, China*, in 2017.

His current research interests include vehicle dynamic simulation, intelligent control for electric vehicle and automatic driving control.

Qing Cheng, born in 1995, is currently pursuing the M.S. degree in *automobile electronic control with Nanjing University of Science and Technology, Nanjing, China*. He received the B.S. degree in *vehicle engineering from Hunan University, Changsha, China*, in 2017.

His current research interests include vehicle dynamic simulation, intelligent control for electric vehicle, and automatic driving control.

Wen-bo Chu, born in 1986, is currently a Research Fellow with *China Intelligent and Connected Vehicles (Beijing) Research Institute Co., Ltd*， which is also the *National Innovation Center of Intelligent and Connected Vehicles*. He received his B.S. degrees in *Automotive Engineering from Tsinghua University, China*, in 2008, and his M.S. degrees in *Automotive Engineering from RWTH-Aachen, German* and Ph. D. degrees in *Mechanical Engineering from Tsinghua University, China*, in 2014.

His current research interests include intelligent connected vehicles, new energy vehicles and vehicle dynamics and control.

Jing-jing Fan, born in 1982, is currently an associate professor of *North China University of Technology*. He received his B.S. degrees in automotive Engineering from *Tsinghua University, China*, in 2004, and his M.S. degrees in vehicle engineering from *China North Automotive Research Institute, China*, in 2007, and Ph. D. degrees in vehicle engineering from *Automotive Engineering from Tsinghua University, China*, in 2011.

His current research interests include hybrid electric vehicle control technology, military hybrid power technology and intelligent network vehicle control technology.

Bo-yuan Xie, born in 1979, is currently a senior engineer at *Nanjing University of Science and Technology*. He received the B.S. degree in *vehicle engineering from Jiangsu University, Zhenjiang, China*, in 2002, the M.E. degree in vehicle engineering from *Tongji University, Shanghai, China* in 2009, and Ph.D degree from *Tsinghua University, Beijing, China* in 2014.

His current research interests include vehicle networking, automatic driving and so on.

Figures

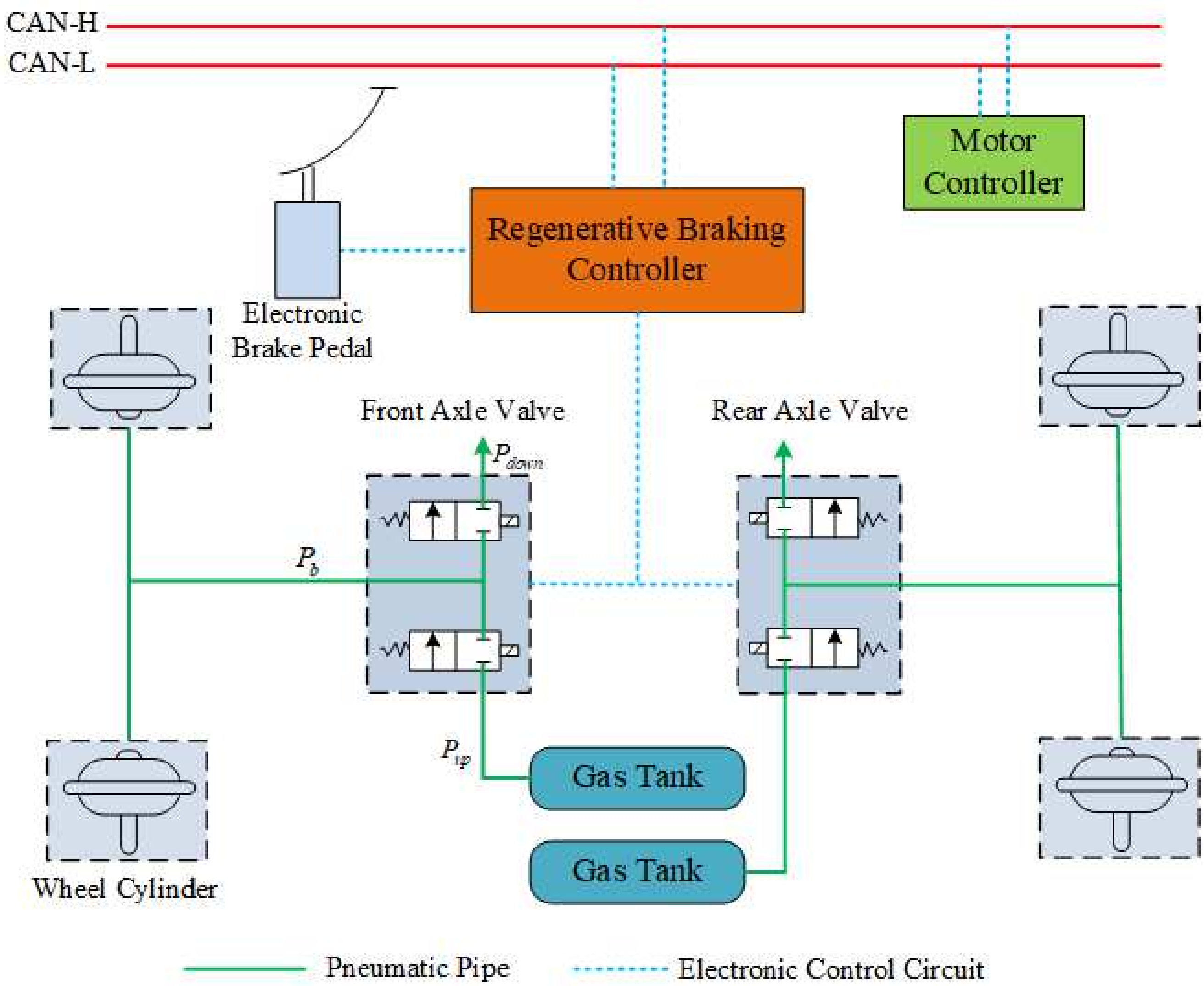

Figure 1

Configuration of the electric truck with regenerative braking system.

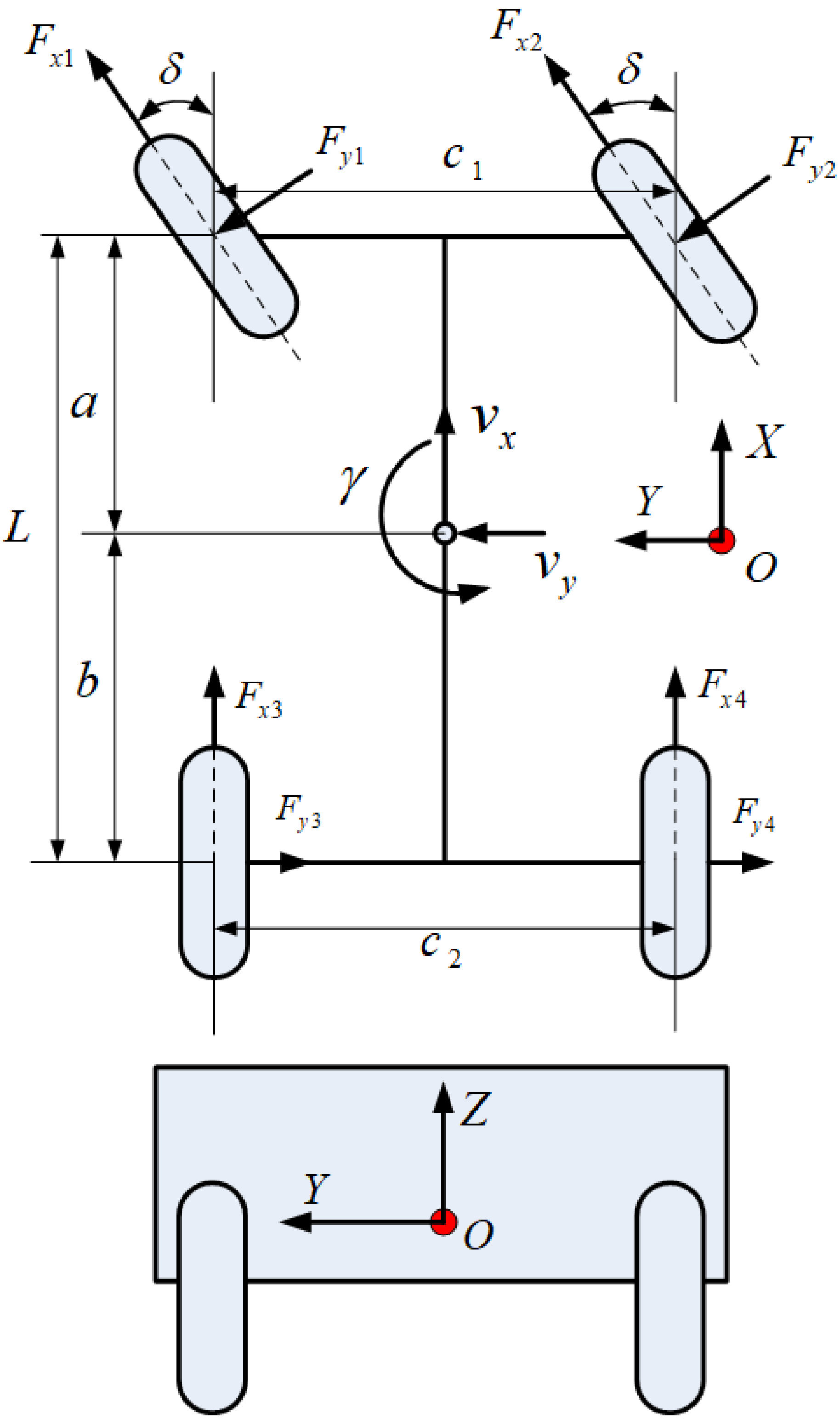

Figure 2

Diagram of vehicle dynamic model in OXYZ coordinate system.

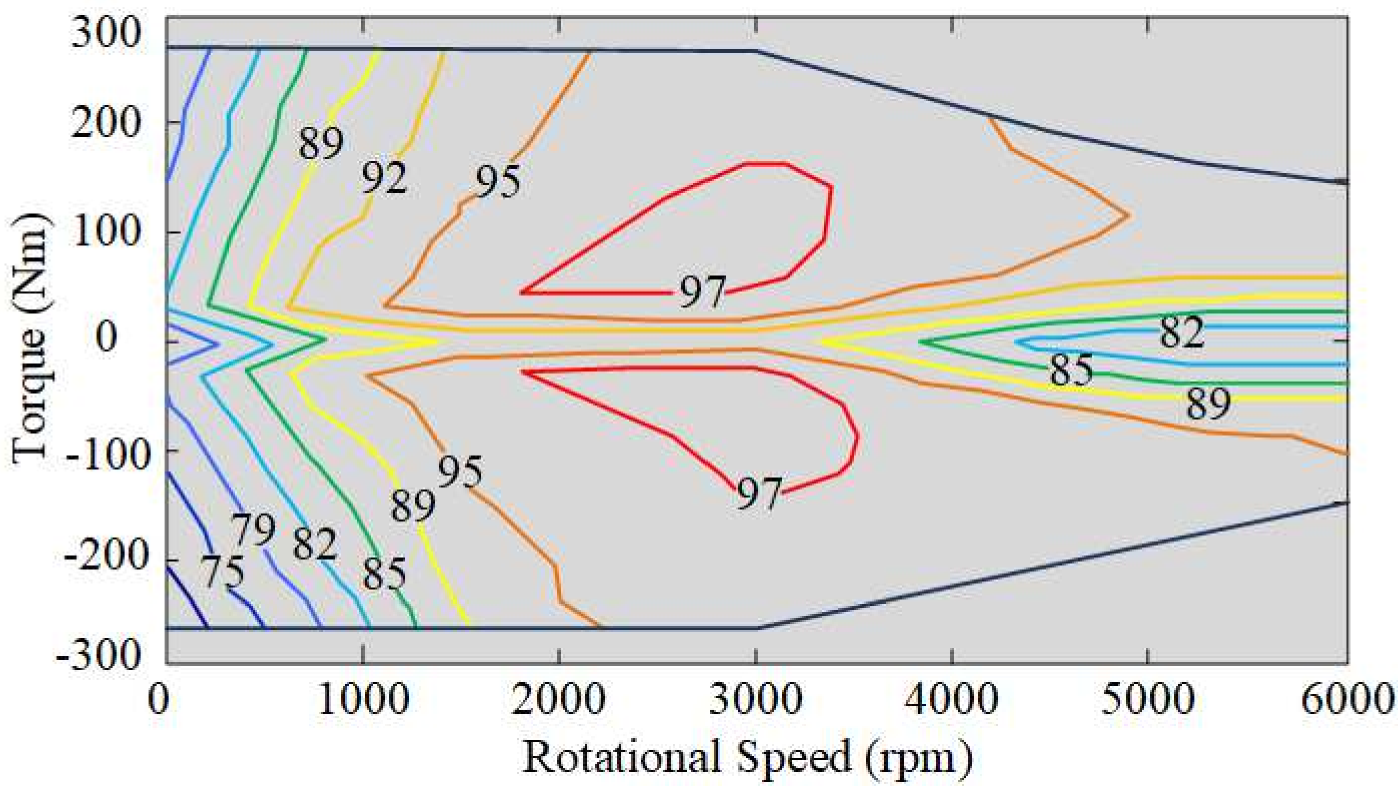

Figure 3

The efficiency map of the electric motor.

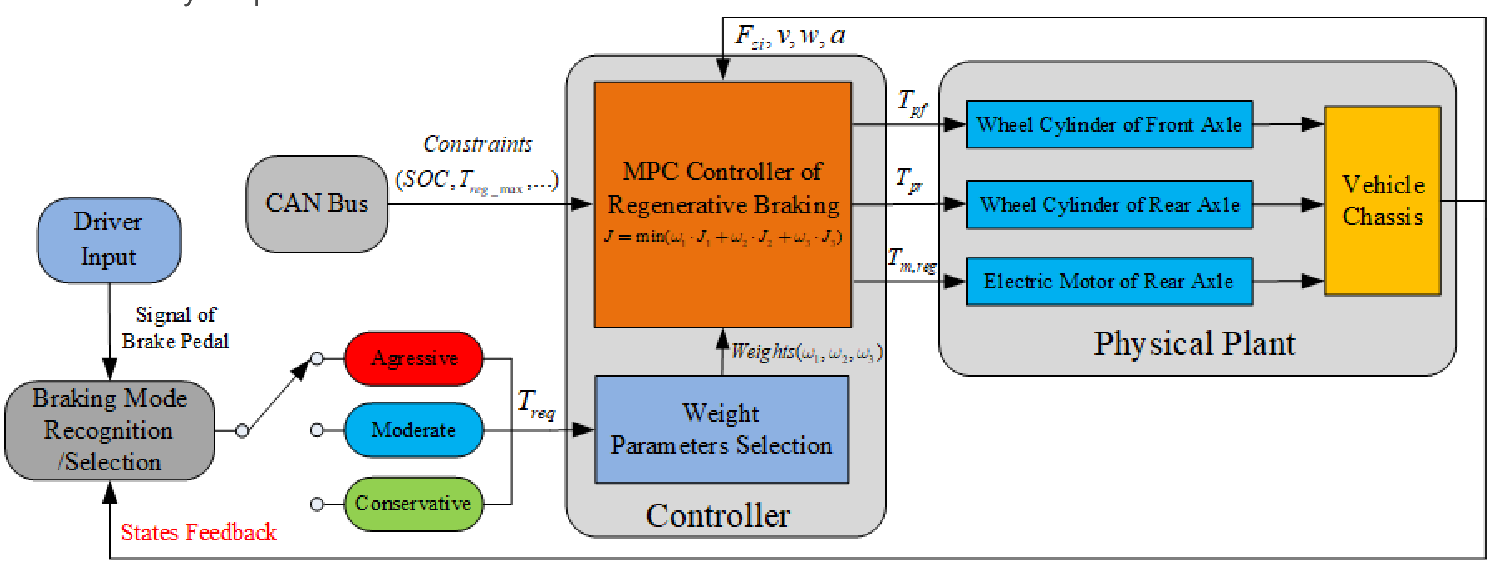

Figure 4

Hierarchical control schematic graph for different driving styles.

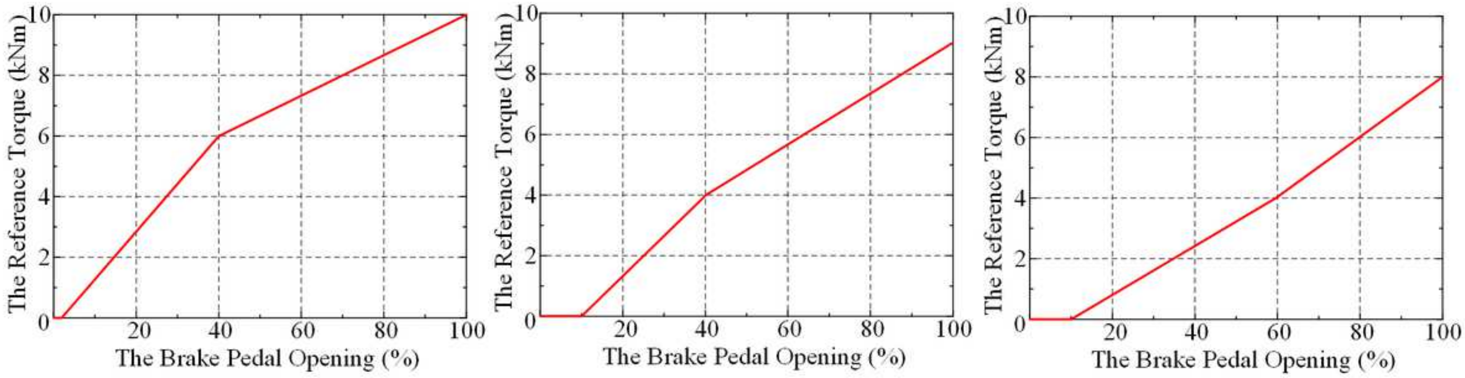

Figure 5

The profiles of relationship of brake pedal opening and reference torque

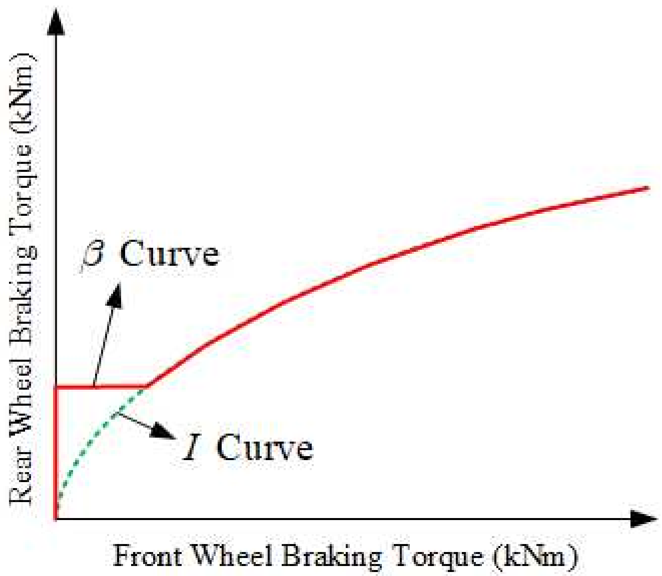

Figure 6

Diagram of braking torque distribution.

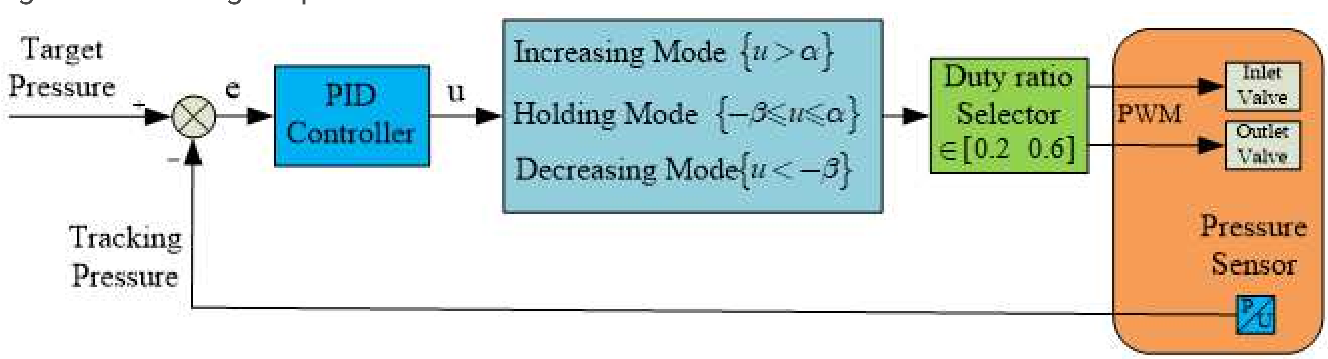

Figure 7

Pneumatic pressure control logic.

Figure 8

Electric light truck for simulation.

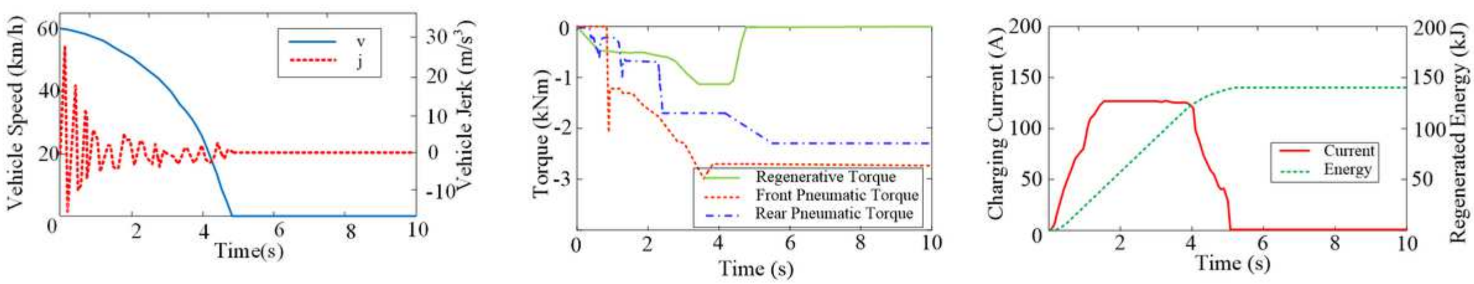

Figure 9

Simulation of the aggressive mode.

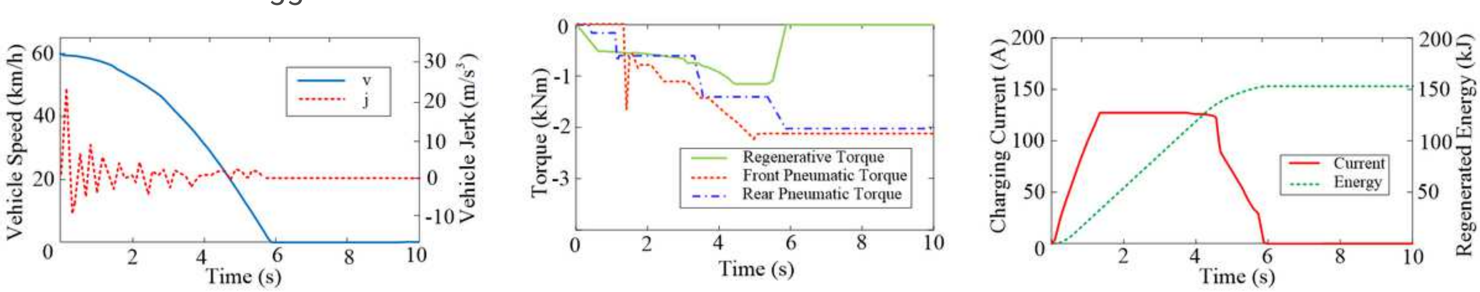

Figure 10

Simulation of the moderate mode.

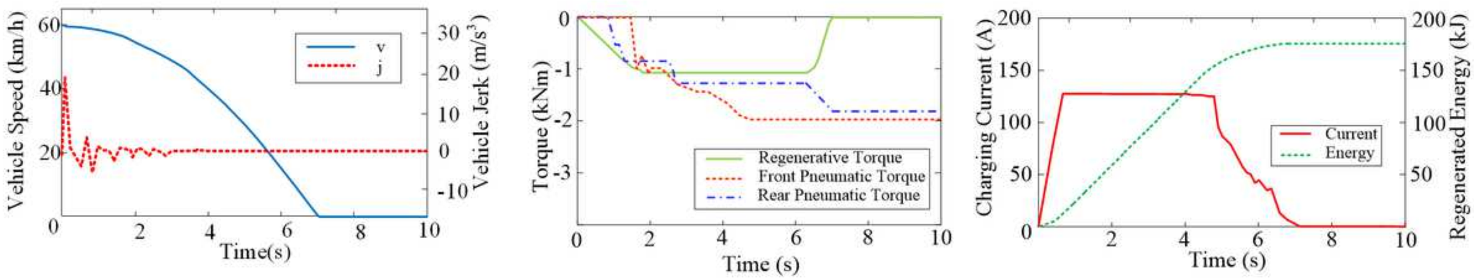

Figure 11

Simulation of the conservative mode.

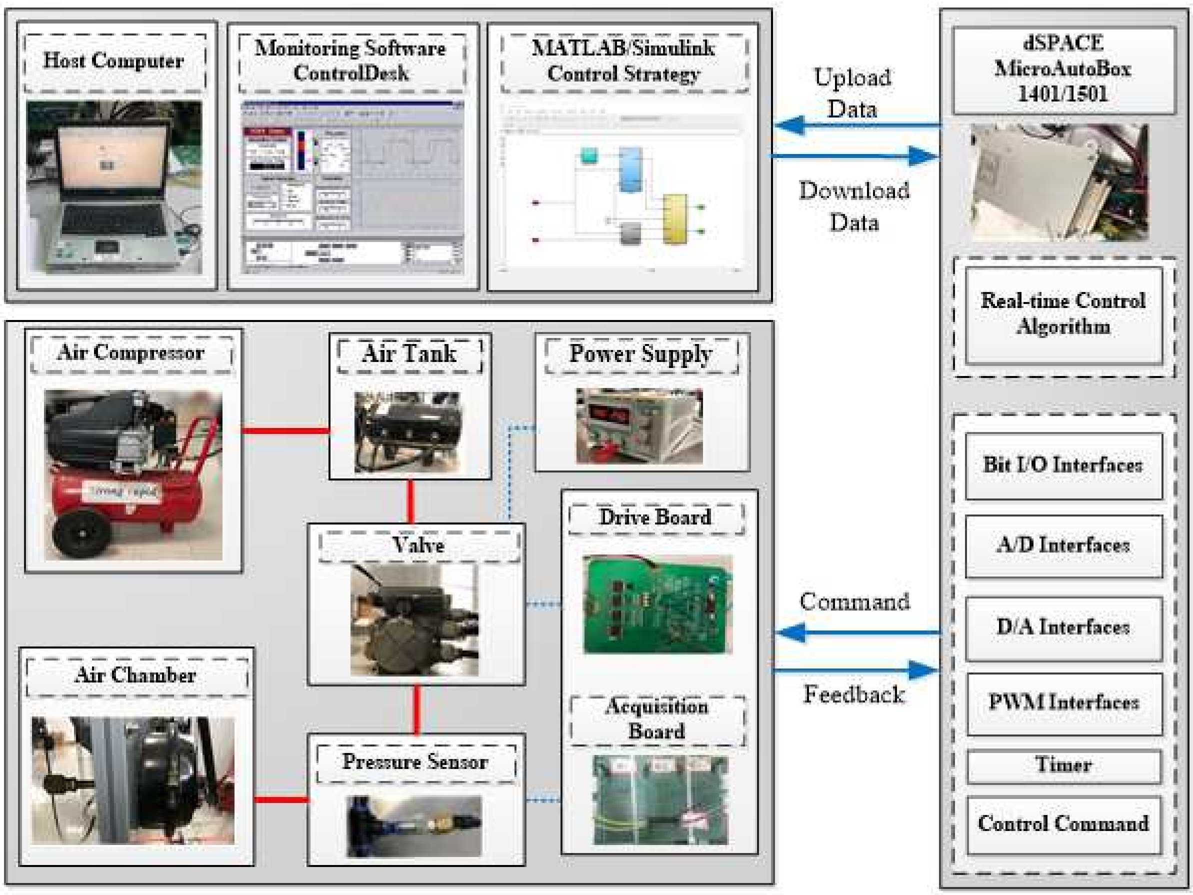

Figure 12

Overall configuration of the experimental test platform.

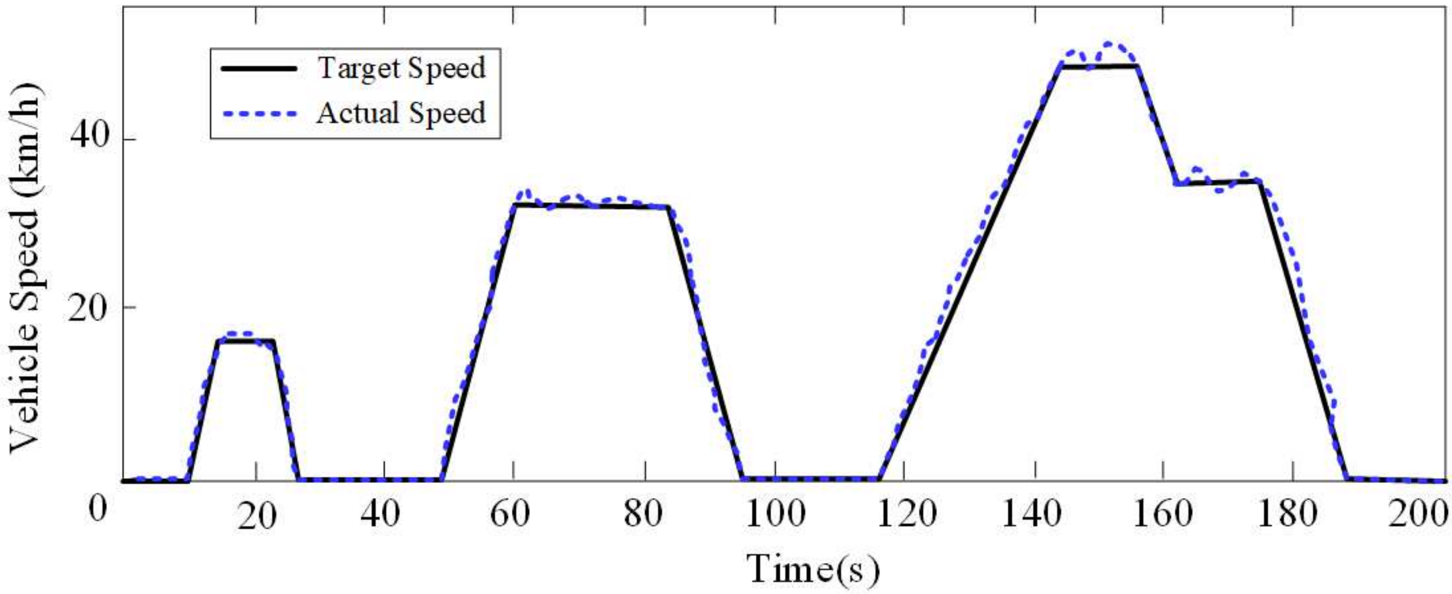

Figure 13

Test result of the ECE driving cycle.