Development of the Electrically-Controlled Regenerative Braking System for Electrified Passenger Vehicle

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Junzhi Zhang, Chen Lv, Xiaowei Yue and Mingzhe Qiu
Dept. of Automotive Eng, Tsinghua Univ

Jinfang Gou and Chengkun He
Chinese Academy of Sciences

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ABSTRACT

As one of the key technologies of electrified vehicles, regenerative braking offers the capability of fuel saving by converting the kinetic energy of the moving vehicle into electric energy during deceleration. To coordinate the regenerative brake and friction brake, improving regeneration efficiency and guaranteeing brake performance and brake safety, development of special brake systems for electrified vehicles is needed.

This paper presents a new type of electrically-controlled regenerative braking system (EABS) that has been developed for electrified passenger vehicles, which has the potential to be brought into production in China. By utilizing as much as possible mature components, integrating cooperative regeneration with ABS/TCS functions, EABS can achieve high regeneration efficiency and brake safety while providing system reliability, low development cost and development risk. This article describes the layout of the newly developed regenerative braking system. The operation modes and control methods of the system are introduced. Road test data from a commercialized electric vehicle prove the good performance of this system. The energy consumption of vehicle reduced by EABS developed is over 25% under ECE driving cycle.

INTRODUCTION

As social needs for the global environment conservation and energy-saving growing rapidly, various types of environment friendly vehicles such as hybrid and plug-in hybrid vehicles, fuel-cell vehicles and electric vehicles have become the research focus. As one of the key technologies of electrified vehicles, regenerative braking can improve fuel economy by converting the kinetic energy of the moving vehicle into electric energy during deceleration.

To extend driving range, improving energy efficiency effectively, most of the electrified vehicles now are equipped with regenerative braking systems. However, as the capability of regenerative braking is limited by the states of the motor and the battery, it is not enough to meet all the braking demand under various operating conditions. Therefore an additional friction braking mechanism is needed, i.e. the regenerative brake cooperates with the friction brake to meet the total braking demand of electrified vehicle.

The regenerative braking systems can be generally classified into two types, namely the parallel type and serial type. In parallel systems, the brake pressure is coupled to the brake pedal, and the regenerative braking is added directly to the friction brake operated by brake pedal, which results in a low regeneration efficiency and poor brake comfort. With serial type a blending between friction brake and regenerative brake can be obtained, leading to the vehicle deceleration corresponding to the driver's braking demand. This type offers a high regeneration efficiency and good braking feel, but requests several modifications in the hydraulic brake line to mechanically decouple the connection between the brake pedal and the brake pressure.

Since the serial type regenerative braking systems are much more advantageous over the parallel ones respecting to the regeneration efficiency and the braking feel, automotive makers and component suppliers worldwide have proposed serial-type solutions respectively for electrified vehicles. Toyota, TRW and Honda have developed EHB (Electro Hydraulic Brake) systems [2,3,4], which have been brought into series production and implemented successfully in commercialized HEVs, such as Toyota Prius, Ford Escape, and Honda Insight. EHB systems, decoupling the brake pedal with brake pressure by using stroke simulators and adjusting the brake pressure provided by an additionally set pressure-supply unit via valves control, can achieve the by-wire brake function. The regenerative braking system adopted by Continental Teves, using a pedal feel simulator and its cut-off device, and modulating the brake pressure by controlling a active booster, can realize the pedal-decoupled concept [5]. The Electrically-Driven intelligent Brake (EDiB) system developed by Hitachi has been employed successfully in the Leaf electric vehicle. In the EDiB system, which based on a newly developed master cylinder without using the conventional vacuum booster, the brake pressure is adjusted by an electrically driven motor through a ball screw, and the pedal feel is also adjustable by using a pressure-generating mechanism and a pedal-force compensator [6].

However, the configurations of those regenerative braking systems introduced above are complicated with several newly developed components added, and many modifications of hydraulic brake line are also required, which results in an increase of system price, mounting difficult and development risk.

The present authors have been dedicated to the research and development of regenerative braking for a long period and made some progress [7,8,9,10,11]. In order to further improve the regeneration performance while reducing the system cost and development risk, a new type of electrically-controlled regenerative braking system EABS, which is based on the proven ABS technique, has been developed and will be soon brought into series production in China. Adding two pedal stroke simulators and high-speed solenoid valves on the layout of conventional 4-channel hydraulic ABS modulator, this new solution can realize a high efficiency cooperative control of regenerative and hydraulic brakes with good pedal feel.

The EABS composition, control method, braking performance and regeneration effect from test results of an electric vehicle equipped with the EABS developed are discussed in this paper.

EABS SYSTEM CONFIGURATION

System Outline

The overall structure of the regenerative braking system is shown in figure 1. The main component of this newly developed regenerative braking system is the EABS control unit, which is mounted easily in the brake line between master cylinder and wheel cylinders, replacing the position of ABS control unit in the ordinary hydraulic braking system. The brake pedal force is still assisted by the vacuum booster to build up the brake pressure, without a pressure-supply unit set additionally, unlike the EHB. An electric control unit in the EABS communicates with VCU (Vehicle Control Unit) via CAN bus and adjusts the brake pressure rapidly and accurately as demand. The modulated wheel cylinder pressure cooperates with the regenerative braking torque of electric motor, realizing the cooperative regeneration.

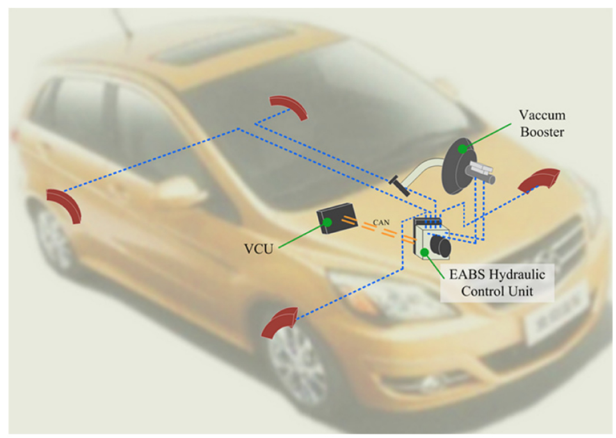


Figure 1. Overall structure of the regenerative braking system

EABS Control Unit

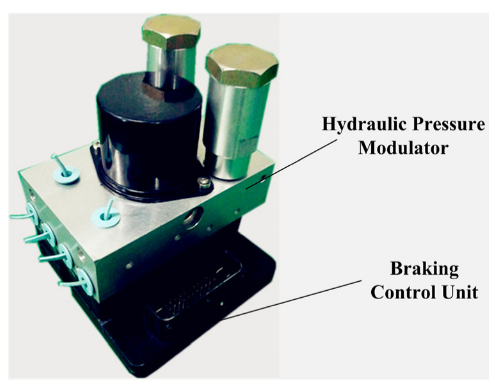


Figure 2. EABS control unit

As the key component of the newly developed regenerative braking system, the EABS control unit is comprised of two parts: the electric braking control unit (BCU) and the hydraulic pressure modulator, as figure 2 shows.

The EABS hydraulic pressure modulator is set as X-split type, as shown in the dotted box in figure 3. Taking the front-wheel-drive vehicle as example, since the brake blending can only be carried out in the front axle, the two rear wheel brake lines, namely LR (Left Rear) and RR (Right Rear), are connected directly to the master cylinder, i.e. the rear wheel pressure keep the same value with master cylinder all the time.

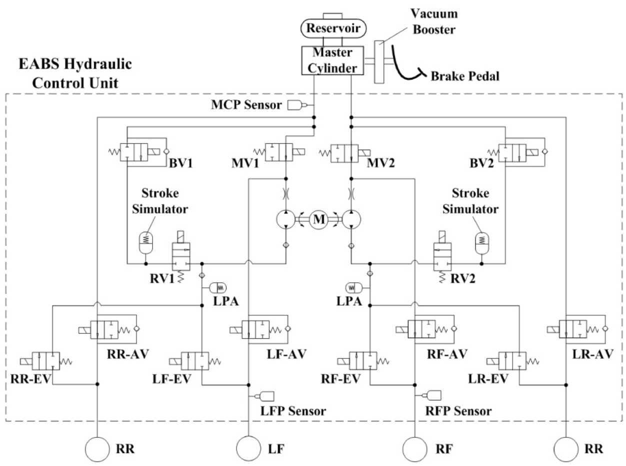


Figure 3. Layout of EABS hydraulic pressure modulator

Without using a high-pressure accumulator, which is the hydraulic pressure supply unit in EHB, the brake pressure in EABS is still generated in master cylinder via brake pedal depressing.

The EABS hydraulic pressure modulator is comprised of high-speed valves, hydraulic pump, hydraulic pressure sensors and pedal stroke simulators. Among the fourteen valves in total, four NO (Normally Open) valves and four NC (Normally Closed) valves in the downstream of the brake line are used for ABS/TCS control, which is the same layout with that of the conventional ABS/TCS. Above the eight valves in downstream, another six valves, namely two NO valves in the main routes (MV1,MV2), two NC valves in the bypass routes (BV1,BV2) and two NC valves for regeneration control (RV1,RV2), are added for the cooperative regen brake control in the front wheel brake lines. The two main routes valves (MV1,MV2) and the two bypass valves (BV1,BV2) are on-off controlled, while the eight ABS/TCS valves and the two valves for regeneration control are pulse width modulated (PWM).

Two pedal stroke simulators with structure of piston-spring, are set in the LF and RF brake lines respectively, providing the feedback force to guarantee driver's good pedal feel during brake blending. One hydraulic pressure sensor for driver's braking request detecting is mounted at the inlet port of the hydraulic modulator, while another two sensors monitoring the front wheel cylinder pressures are set at the outlet port of LF and RF brake lines of the hydraulic modulator. The electric control unit BCU is integrated with the hydraulic pressure modulator. This enables the brake line pressure to be controlled as demanded.

The development of EABS utilizes the existing available resources, adding few proven components to the layout of conventional ABS, reducing the development cost and development risk significantly mounting ease equal to that of conventional brake systems.

OPERATION MODES OF EABS

EABS can realize various brake functions of hydraulic brake, cooperative regenerative brake and ABS/TCS, and also offers the fail-safe mode.

Hydraulic Brake

Under the normal hydraulic state, all of the components of EABS hydraulic pressure modulator are not energized. The brake lines connections are the same with the conventional hydraulic brake system. The hydraulic fluid from master cylinder, passing through the EABS modulator, directly enters the wheel cylinders to build up the wheel pressures without adjusted.

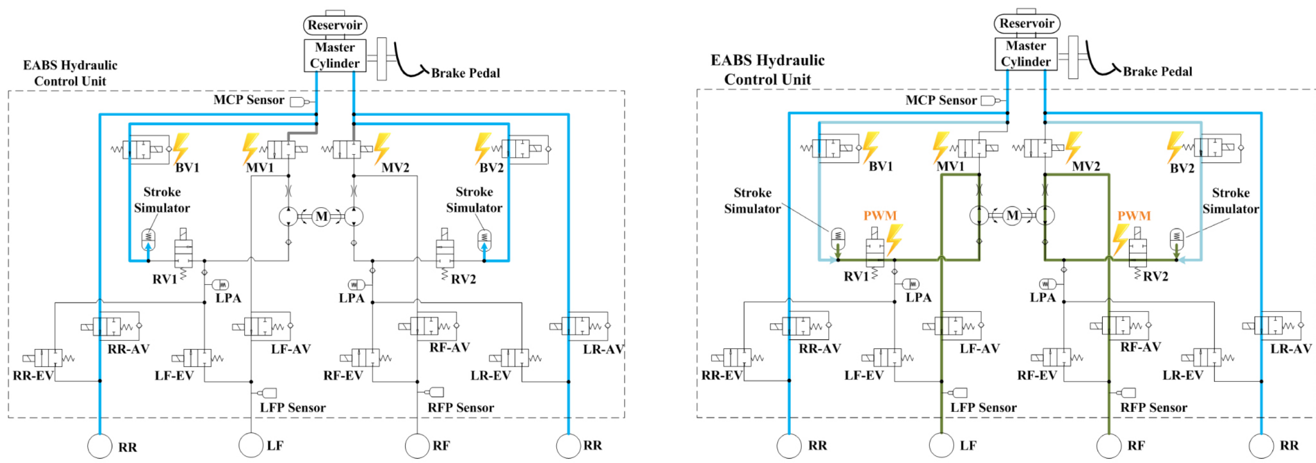
Cooperative Regenerative Brake

The total braking demand of vehicle is provided by regenerative braking force and friction braking force under cooperative regeneration mode. With the two main route valves and the two bypass valves energized, the connections between master cylinder and the two front wheel cylinders are cut off, and the fluid in the two front wheel brake lines are led into the corresponding pedal stroke simulators respectively, which enables the mechanism decoupling of brake pedal and front wheel cylinders, as figure 4 (a) shows. Meanwhile, the regenerative braking torque is applied on the front axle, recovering the kinetic energy of the vehicle.

As the regenerative capability of electric motor has limitation, when the motor's regenerative brake torque cannot meet the brake request of front wheels, the hydraulic brake force is need to be exerted. As shown in figure 4 (b), the main route valves and the bypass valves keep being energized, while the two regeneration control valves (RV1,RV2) are PWM controlled, leading the fluid stored in the pedal stroke simulators and master cylinder entering the front wheel cylinders to supplement the rest part of the braking demand. At this situation, compared with EHB systems, whose brake pedal is always decoupled with brake pressure, the brake pedal and the front wheel cylinders in EABS are non-decoupled again via bypass brake lines.

ABS / TCS Control

When BCU detecting the wheel speed a locked tendency during deceleration procedure, the ABS control mode would



(a) (b)

Figure 4. Regenerative braking mode of EABS

be activated. At that moment, the six valves in the upstream are not energized. According to the motion state of each wheel, BCU controls the four inlet valves and four outlet valves in downstream to realize the pressure increase, decrease and hold control of each wheel cylinder individually.

When driver depresses the accelerator pedal fiercely on a low-adhesion road, the drive wheels may slip, which would make the TCS function activated. Taking the front-wheel-drive vehicle as example, once the TCS control enabled, the regenerative braking torque of electric motor will be removed. The BCU controls the six valves in the upstream of the hydraulic pressure modulator to be energized, cutting off the main route and connecting the bypass route. With the same logic of the conventional TCS control, the fluid of the master cylinder is pumped into the front wheel cylinders by pump motor via bypass route. And by controlling the on-off state of the inlet and outlet valves of the slip wheel, the slip ratio could be controlled decreasing to the target level.

Fail Safe Mode

To guarantee the brake safety of vehicle in the maximum extent, EABS offers two levels of the fail-safe mode based on system control and structure.

On the system control level, once a malfunction of the electric driving system occurring during regenerative braking, the BCU would remove the regenerative brake torque of the electric motor and cut off power supply of all the components in the EABS modulator instantly, recovering the hydraulic brake.

On the structure level, as the two rear brake lines are not decoupled to the brake pedal, the rear wheel hydraulic brake always exists when the driver operates the brake pedal. This means that the rear braking will remain consistent with the driver's pedal input regard less of the amount of regenerative braking being carried out on the front axle. Therefore, when driver depresses the brake pedal, even if the front wheel brake fails, the rear wheel brake can still provide a deceleration of approximately 0.2g, covering the normal deceleration demand.

COOPERATIVE REGENERATIVE BRAKING CONTROL STRATEGY AND ALGORITHM

Braking Force Distribution Strategy

As shown in figure 5, during deceleration process, brake forces of the vehicle are divided into two parts: the brake force imitating the engine brake of the conventional vehicle and the brake force generated by operating the brake pedal.

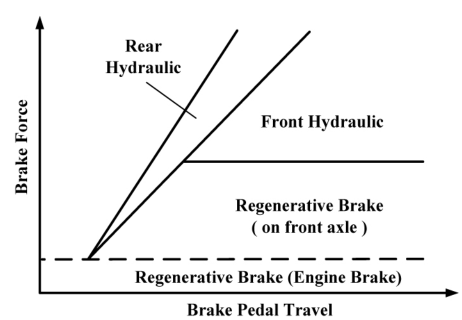


Figure 5. Distribution between regenerative brake and hydraulic brake

The brake force imitating the engine brake is provided by the regenerative brake torque of electric motor. And its amount is determined by the vehicle speed and accelerator pedal operation. The application of this part of brake force is to provide driver of the electrified vehicle a good driving feel similar with the conventional one and also to further exploit the regeneration potential. The brake force generated by operating brake pedal is supplied by regenerative and friction brakes during cooperative regeneration, equaling to the brake amount required by the driver.

Front and Rear Braking Force Allocation

Usually in an ordinary vehicle, the front-rear brake force distribution (BFD) is a fixed value, which is determined by parameters of the installed brake devices. However, for an electrified vehicle, as the regenerative brake is introduced, the front-rear brake force distribution needs to be reconsidered to guarantee the brake safety and regeneration efficiency.

Since no additional power-supply unit used in EHB is set in the EABS and pedal stroke simulators are only set in front wheel brake lines and rear brakes are not decoupled with brake pedal, the adjustment of the front-rear brake force distribution would lead to the fluctuation of the brake pedal. In order to ensure the good pedal feel, a fixed front-rear brake force distribution is adopted in EABS. The brake blending of regenerative and hydraulic brakes is carried out only on front axle, and hydraulic brake is always applied on rear axle which can guarantee the brake stability and avoid issues of steering-loss. Finally the fixed front-rear brake force distribution is implemented, as figure 6 shows.

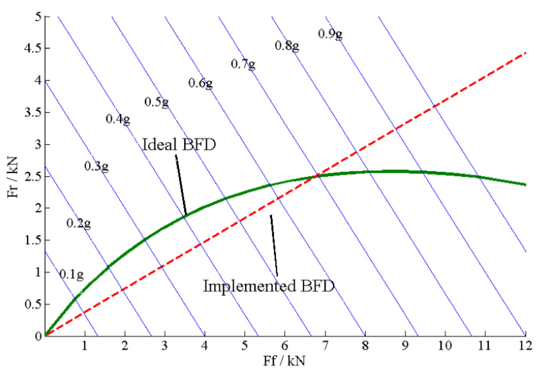


Figure 6. Front and Rear braking force allocation

Regenerative and Hydraulic Brakes Distribution

To improve the regeneration efficiency as much as possible, the maximum regeneration principle is applied for brake blending on front wheels. As shown in figure 5, only regenerative brake is exerted on front axle at first, and the front wheel hydraulic brake is supplemented once the regenerative brake cannot meet the braking demand of front axle while rear wheel hydraulic brake is always applied during deceleration process. The total brake force of the regenerative and hydraulic brakes keeps consistent with the driver's braking intention.

Cooperative Regenerative Braking Algorithm

Figure 7 illustrates the control block diagram of the EABS. Driver operating the brake pedal, the driver's total brake demand (T_{total}) is detected via pressure sensor at the master cylinder. Then the command value of regenerative brake torque (T_{regen_cmd}) calculated by BCU with regard to the vehicle's information based on the regenerative braking control strategy is sent to the MCU (motor control unit) and implemented by the drive motor. Meanwhile, according to the actual motor torque, the target wheel cylinder pressure (p_{w_tgt}) is calculated. A PID controller takes control of the difference (e) between the target wheel pressure (p_{w_tgt}) and the actual value (p_{w_act}) detected by the wheel pressure sensor, calculating the actuation commands of the valves ($Valve\_cmd$) in the EABS modulator, realizing the closed-loop control of the wheel cylinder pressures. Thus, the regenerative brake and hydraulic brake are applied together to meet the total deceleration requirement of the vehicle.

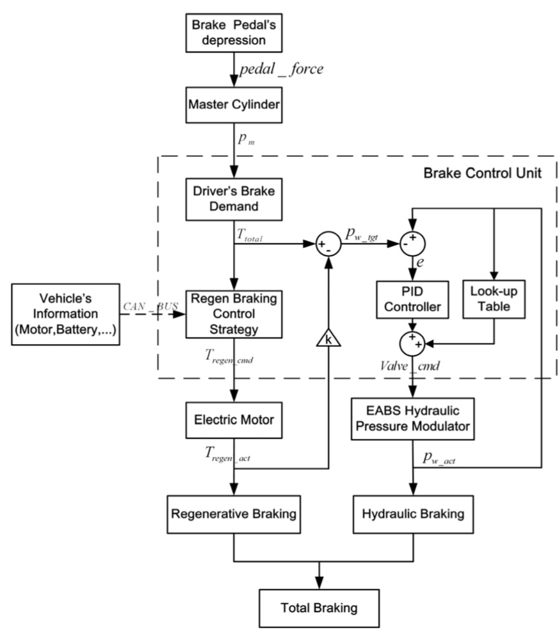


Figure 7. Cooperative regenerative braking algorithm

VEHICLE TEST

Normal Deceleration Process Test

Performance of cooperative control of regenerative and hydraulic brakes is tested on an electric vehicle under normal braking process, as figure 8 shows. With the driver's foot off the accelerator at 0s, the master cylinder pressure remains about 0Mpa until 0.8s, indicating that no brake operation is taken. Meanwhile, a slight regenerative brake torque is applied to imitate the engine brake of a conventional ICE vehicle during coasting. From 0.8s-1.0s, the master cylinder keeps at a relatively low level, corresponding to a small braking demand of driver. During this period, with no hydraulic brake applied, the regenerative brake employed alone can fully meet the brake request of the front wheels. Later, the braking demand increases with the growth of the master cylinder pressure. As the capability of regeneration is limited by the relatively high motor speed, the hydraulic brake is exerted in the front wheel cylinders to supplement the rest part of the braking demand, leading to the rise of deceleration consistent with the driver's brake intention. As the motor's regeneration capability grows up with vehicle slowing down, regenerative brake torque increases gradually with the wheel hydraulic pressure decreasing correspondingly, and the deceleration remains stable. When vehicle speed decreases to a relatively low level after 4.5s, the capability of regeneration drops rapidly, and the hydraulic braking pressure builds up quickly, taking over all the braking demand.

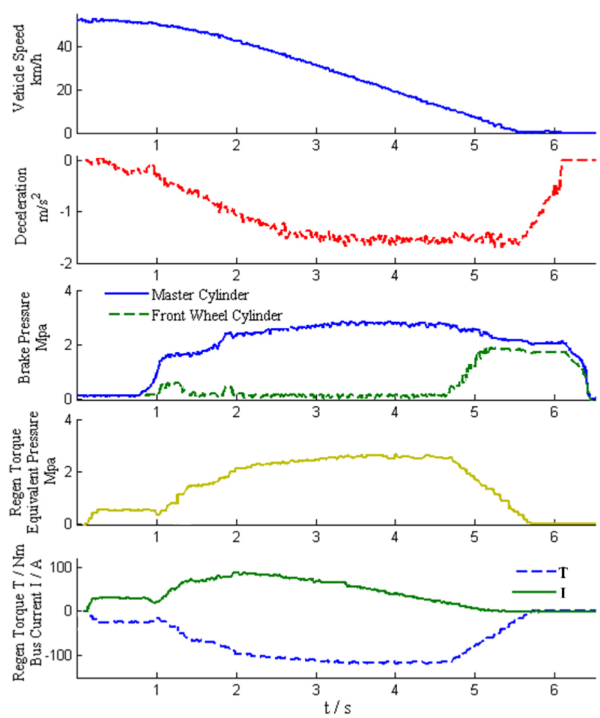


Figure 8. Test results of normal braking process

Normal deceleration vehicle test results show that:

1. EABS, with simple configuration, distinguished from the mainstream brake-by-wire system EHB, can achieve the cooperative control of regenerative and hydraulic brakes with a good brake pedal feel, demonstrating the feasibility of the system layout.

2. Hydraulic braking force adjusted rapidly and accurately by EABS modulator, cooperates with the regenerative braking torque, providing a total brake force corresponding to driver's brake demand, leading to the good brake performance obtained, which validates the control strategy and algorithm developed.

3. The regeneration capability offered by electric motor is utilized completely, converting the kinetic energy of vehicle into electric energy effectively, achieving the high efficiency of regenerative braking, improving the vehicle energy efficiency remarkably.

ECE Driving Cycle Test

Indicating the operating conditions in urban areas of a vehicle, the ECE driving cycle is adopted to carry out the road test for studying the fuel economy improvement of an electric vehicle equipped with EABS, which is of practical significance. During test, four continuous ECE driving cycles, taken as operating target, are carried out. Figure 9 shows the situations of the road test.

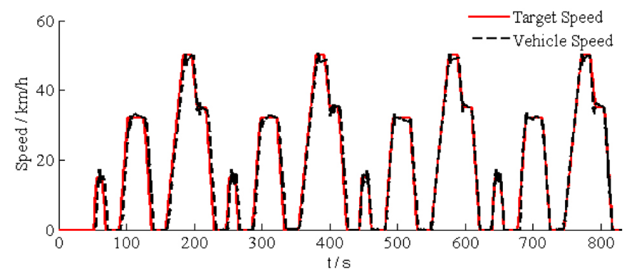


Figure 9. Road test under the ECE driving cycle

To evaluate the improvement in fuel economy of the electric vehicle enhanced by EABS, the contribution rate δ is adopted as an evaluation parameter [11], which can be expressed as

$$\delta = \frac{E_{reg} \cdot \eta_{charge} \cdot \eta_{discharge}}{E_{drive}} \times 100\% \quad (1)$$

where E_{reg} is the regenerated energy at the DC bus of the whole driving cycle, E_{drive} is the consumed energy at the DC bus of the whole driving cycle, η_{charge} is the charge efficiency of the battery, taken to be 0.95 and $\eta_{discharge}$ is the discharge efficiency of the battery, taken to be 0.95.

Table 1. Test results of the ECE driving cycle

Test Process	Consumed Energy(*KWh*)	Regenerated Energy(*KWh*)	Contribution Rate (%)
ECE-1	0.1524	0.0415	24.58
ECE-2	0.1522	0.0427	25.31
ECE-3	0.1492	0.0409	24.74
ECE-4	0.1510	0.0430	25.70
Average	0.1512	0.0420	25.08

The road test results under ECE driving cycle are shown in Table 1. According to equation (1), with cooperative regenerative braking by EABS, during the four ECE driving cycles, the maximum value of the fuel economy contribution rates is 25.70%, the minimum value is 24.57%, and the average value is 25.08%, i.e. the ability of vehicle's range extending offered by EABS is above 25% under ECE driving cycle.

SUMMARY/CONCLUSIONS

Based on the conventional hydraulic ABS techniques, by utilizing as much as possible known and proven components, a new type of electrically-controlled regenerative braking system EABS, distinguished from the layout of the mainstream EHB system, has been developed and will be soon brought into production in China. Integrating cooperative regenerative braking with ABS/TCS functions, this brake system achieves a high regeneration efficiency and brake safety while providing system reliability, low development cost and vehicle mounting ease equal to that of conventional brake systems.

Cooperative regenerative braking control strategy and algorithm have been developed. The hydraulic braking force, which is closed-loop controlled, cooperates with the regenerative braking torque, realizing the brake blending consistent with driver's brake demand, which results in the good brake performance and high regeneration efficiency achieved.

Road tests under normal braking process and the ECE driving cycle were carried out in an electric vehicle equipped with the developed EABS. The normal deceleration test results show the good cooperative regenerative braking control effect offered by EABS, validating the control strategy and algorithm developed. And the test results of the ECE driving cycle also demonstrates that the fuel economy of the electric vehicle improved by EABS is above 25%.

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CONTACT INFORMATION

Prof. Zhang Junzhi
State Key Laboratory of Automotive Safety and Energy
Tsinghua University
Beijing
China
jzhzhang@mail.tsinghua.edu.cn

Dr. Lv Chen
State Key Laboratory of Automotive Safety and Energy
Tsinghua University
Beijing
China
henrylvchen@163.com

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