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# Control Strategy of Regenerative/Electro-Mechanical Hybrid Braking System for Hybrid Electric Vehicle Based on Urban Driving Cycle

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**Abstract:** This paper aims to investigate the braking control strategy for an Electro-Mechanical Hybrid Braking system, and compare different control strategies for improving the braking performance and regenerative braking efficiency for Hybrid Electric Vehicles (HEVs) in urban driving conditions. In this paper, the urban driving cycle was analyzed from the point of view of braking process. Different braking control strategies for the hybrid braking system, which was composed of the regenerative braking system and Electric-mechanical Braking system (EMB), were compared and a control strategy that based on a typical urban driving cycle, was proposed. Comparative simulations were carried out to validate the performance of the proposed hybrid braking system. The simulation results indicate that by adopting the proposed control strategy, both the braking performance and regeneration efficiency of the hybrid braking system can be significantly improved, in comparison with the conventional control strategy.

**Keywords:** Driving cycle, Braking control, Electro-mechanical brake, Regenerative braking

## 1 Introduction

A driving cycle is a series of data points representing the speed of a vehicle versus time, it is widely used to determine the fuel consumption, pollution emissions and development of new automotive technologies [1,2]. Research has shown that, in urban driving conditions, nearly one half of the total vehicle traction energy is wasted during braking [3-5]. In contrast to cars with conventional internal combustion engines, A Hybrid Electric Vehicle (HEV) can achieve a better fuel efficiency in busy urban road conditions. The regenerative braking system is seen as the core technology of hybrid electric vehicles, which is an energy recovery mechanism to slow a vehicle down by converting kinetic energy into another energy form, such as electrical energy. The performance of energy recovery mechanism is strongly influenced by the local driving condition Therefore, in order to maximize the regenerative braking energy, the driving cycle should be considered in developing the regenerative braking control strategy.

Due to the restriction of maximum power of regenerative braking system, a mechanical braking system is still required to ensure the safety of vehicle. Therefore, the hybrid braking system of HEV should be well coordinated to achieve a good braking performance and a high regenerative braking efficiency [3,5]. The Electro-Mechanical Braking system (EMB), which eliminates the use of a conventional hydraulic mechanism, is powered by the electric power from a battery and controlled by the electric signals from the Brake Control Unit (BCU). The vacuum booster and hydraulic pipelines in conventional hydraulic systems are replaced by torque motor and EMB actuator. Compared to the conventional hydraulic braking system, EMB system has several advantages such as lighter weight, more compact in size, rapid signal transmission and fast actuation response, high transmission efficiency, powerful electronic control functions and eco-friendly. All of these advantages make the system very suitable for electrified vehicles (HEV/EV/FCEV) [6,7]. The EMB system is considered to be the future direction of braking system as a representative of Brake-By-Wire technology (BBW). Automobile component manufacturers have developed different types of EMB systems, especially Germany, BOSCH, CONTINENTAL TEVES, and SIEMENS, who have their own patents for EMB systems [8]. Researchers worldwide also have carried out studies in this area. However, present research in EMB systems is mainly focused on the control algorithm and control strategy [9-12].

It is noted that for diverse driving conditions, each regenerative braking system will have varying performances, especially for the hybrid braking systems. Thus, in order to further improve the regenerative braking efficiency and braking performance, the investigation into the driving cycle is introduced in this work.

## 2 Driving Cycle Analysis

Driving cycles are produced by different countries and organizations to assess the performance of vehicles in various ways, among them ECE driving cycle (Europe), FTP75 (US), 10.15 (Japan) are the three most widely used ones [4,5]. In this paper work, the ECE driving cycle is introduced as an example, with the cycle is shown in Figure 1. The actual result can be optimized if the used driving cycle that been used is as close to the real driving as possible.

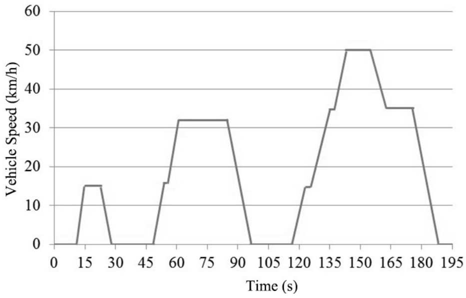



**Figure 1. The ECE Driving Cycle**

When driving on a flat road, the vehicle driving power can be expressed as [4]:

$$P = \frac{V}{1000}\left(Mgf_r + \frac{1}{2}\rho_a C_D A V^2 + M\delta\frac{dV}{dt}\right) \qquad (1)$$

Where $M$ is the vehicle weight; $g$ is the gravitational acceleration; is the rolling resistance coefficient; is the air density; $C_D$ is the air resistance coefficient; $A$ is the vehicle windward area; $V$ is the vehicle speed; and $\delta$ is the rotational inertia factor.

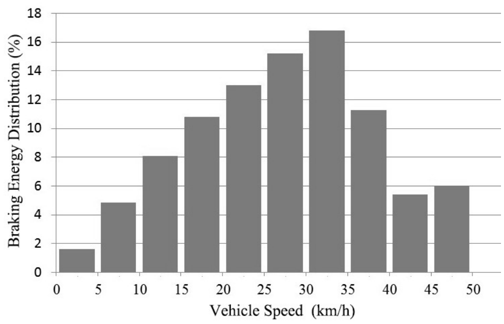



**Figure 2. Braking Energy Distribution of ECE Driving Cycle**

Under the given ECE driving cycle, integrating equation (1) over the driving time can give both the traction energy and braking energy, the vehicle braking energy distribution for the varying in the whole speed range is shown in Figure 2, and Figure 3 illustrates the percentage of braking energy under certain speed. The vehicle parameters are shown in Table 1.

**Table 1. Vehicle Parameters**

| Item | Symbol | Value |
|---|---|---|
| vehicle weight (kg) | M | 1600 |
| rolling resistance coefficient | $f_r$ | 0.015 |
| air resistance coefficient | $C_D$ | 0.25 |
| vehicle windward area ( $m^2$ ) | A | 2.4 |
| wheelbase (m) | L | 2.7 |
| distance between gravity center and front wheels (m) | La | 1.1 |
| height gravity center (m) | hg | 0.6 |
| tires | - | 195/60R15 |

Figure 2 indicates that in the urban driving conditions the vehicle braking energy is mostly consumed in the middle vehicle speed range (20~40km/h), and Figure 3 further indicates that in the low vehicle speed range (0~15km/h), 20% of the total braking energy is dissipated and under 10km/h the percentage is only 10%. Furthermore, electric motor/generator suffers from low efficiency at low speed, and the regenerative braking system cannot provide enough braking torque at low speed. Therefore, the regenerative braking should be applied beyond a threshold speed, and when the vehicle is within the threshold speed, all the braking force is provided by the mechanical braking system. In the design for braking strategy off HEV/EV, the threshold of low vehicle speed needs to be set, which is closely related to the local driving conditions. For the ECE cycle, the speed is recommended to be between 10km/h to 15km/h.

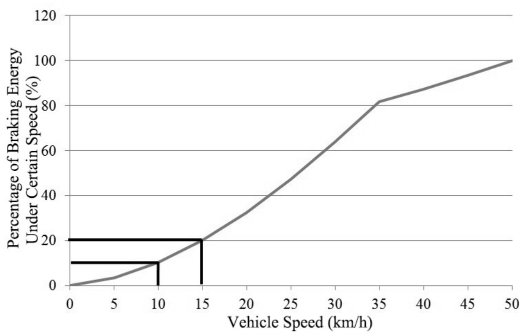



**Figure 3. Percentage of Braking Energy under Certain Speed**

For HEVs, electric motors are only used during low speed driving and regenerative braking. The electric motors adopted in HEVs are not as powerful as that for pure electric vehicles (EVs). Therefore, from the point view of braking, selecting a suitable motor power capacity can help to improve the fuel efficiency and performance of HEV without oversized design, thus reducing the overall cost.

The simulation results of braking energy based on the ECE cycle is shown in Figure 4, with the vehicle parameters are listed in Table 1. The simulation results indicates that most of the braking energy is consumed in mid-power braking, while a small amount of power is dissipated in the power range beyond 17kw. Therefore, theoretically a 17kw electric motor is able to recover over 90% of braking energy.

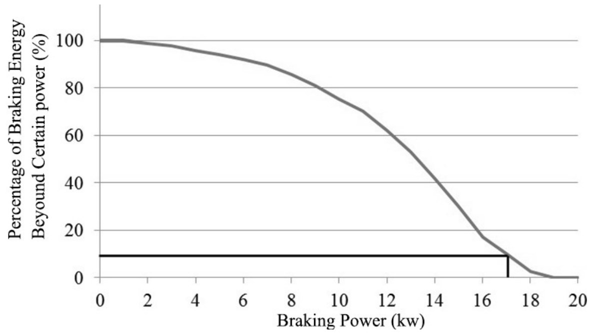



**Figure 4. Percentage of Braking Energy beyond Certain Power**

In HEV, the electric motor is linked with the front wheels with a fixed gear ratio, and the motor power is proportional to the motor speed before reaching the base speed. Therefore, the motor power is also related to the vehicle speed. The bar chart in Figure 5 shows the braking power distribution of the ECE cycle vehicle speed range. It can be seen that the maximum braking power profile naturally matches the motor power–speed characteristics, as shown in Figure 5. It is observed that a 17kw electric motor can cover most area of vehicle braking power-speed range of the ECE cycle.

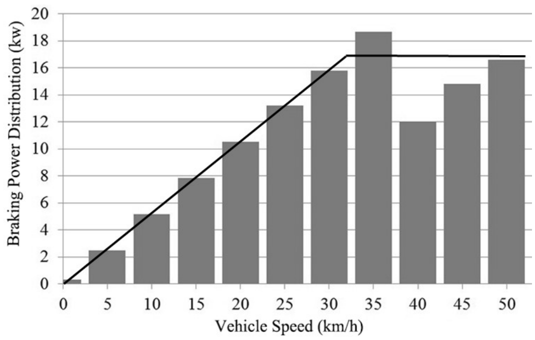
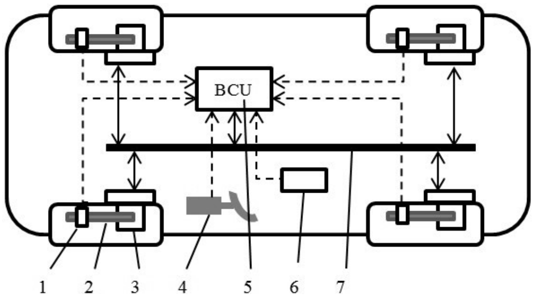



**Figure 5. Braking Power Distribution of Vehicle Speed Range**

## 3 Electro-mechanical Braking System

The EMB system is mainly comprised of an electronic brake pedal, a brake control unit, and EMB actuators, as shown in Figure 6. In contrast to the hydraulic braking system, the brake signals are transferred through wire in the EMB system to realize the idea of Brake-By-Wire. With the benefits from the high performance of electric motor and rapid signal transmission speed, the EMB braking system can greatly improve the vehicle brake performance.

Based on the signal obtained from the electronic brake pedal, BCU controls the angular direction and speed of the EMB motor. The EMB actuator has a gear reduction mechanism, which increases the output torque. Moreover, the EMB actuator transforms the rotating motion from the motor into the linear motion for generating the necessary clamping force on the brake. In order to achieve the brake force close to the target value, the feedback information of the motor current, torque and wheel speed are sent back to BCU to continuously adjust the brake signal output.




1.Wheel speed sensor 2.Brake disc 3.EMB actuator 4.Electronic brake pedal 5.Brake control unit 6.Vehicle sensors 7.Communication network

**Figure 6. EMB System Structure**

## 4 Braking Force Control Strategy

The ideal braking force distribution curve (I curve), as shown in Figure 7, is an ideal braking strategy for both front and rear wheels to obtain the maximum brake force while achieving the best brake performance. However, since it is a nonlinear hyperbolic curve, a precise control system is needed to track the ideal curve, which is very hard to achieve for conventional braking systems. In conventional vehicles, the hydraulic brake pedal is mechanically connected to the hydraulic brake circuits, and the brake force distribution on front/rear wheels is set as a fixed value β, which is determined by the design parameters of the braking system as shown by the β line in Figure 7.

Hybrid electric vehicles usually adopt the front-wheel drive configuration, so the electric motor can only recover braking energy from the front wheels. In order to maximize the regenerative braking efficiency, the brake force needs to be distributed on the front wheel as much as possible. However, to ensure a better braking performance, part of the brake force needs to be distributed on rear wheel. The ECE regulation dictates the minimum braking force on rear wheels, as shown by the ECE curve in Figure 7, and the equation can be expressed by [13]

$$z \geq 0.1 + 0.85(\mu - 0.2)$$
$$z = \frac{du}{dt} \cdot \frac{1}{g} \qquad (2)$$

Where $z$ is the brake intensity; $\mu$ is the adhesion coefficient of the road; and $u$ is the vehicle velocity.

At present, hydraulic braking systems are still widely adopted in HEV, the hybrid braking system of HEV can be simply regarded as the combination of a conventional hydraulic braking system and a regenerative braking system. In most cases, all the braking force is produced by regenerative braking system on the front wheels. When the desired deceleration is larger than a certain value; the hydraulic braking system provides the extra brake force to guarantee the braking performance as shown in Figure 7. However, the major disadvantage of the conventional HEV braking strategy is that the braking energy on front wheel is not fully utilized. Since the $\beta_{\mathrm{hy}}$ line is far from the ideal curve in medium brake intensity, the vehicle may suffer from a poor braking performance in some extreme road conditions, such as in gravel road, wet road and dirt road with a low road adhesion.

With benefits from the advancement of electronics and control technologies, EMB system is being developed, and makes it possible to control the braking force on each wheel independently. This configuration can greatly improve the braking performance by completely track the ideal braking curve. However, there is a contradiction between the braking performance and regenerative braking efficiency. It is observed that a large amount of brake energy is consumed on the rear wheels if the ideal braking curve is to be followed, especially in the small deceleration range.

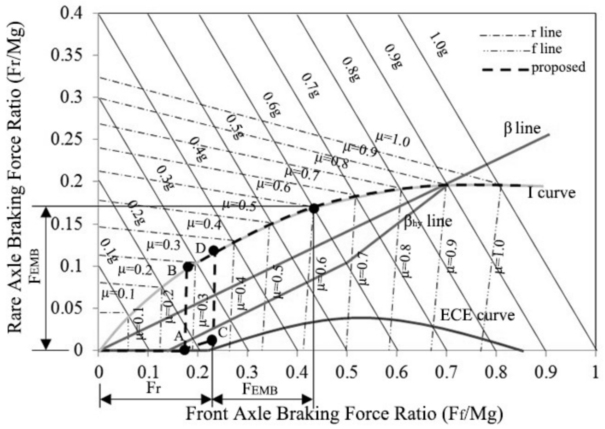


**Figure 7. Brake Force Distribution**

In order to improve the regeneration efficiency of the fully controllable hybrid brake system, a modified braking force distribution (BFD) strategy for regenerative/electro-mechanical hybrid braking system is proposed in this work, as shown in Figure 7. The details of proposed braking strategy are described as follows:

As mentioned in the previous Section, the regenerative braking system suffers from a poor efficiency in the low speed range. Therefore, the braking force is produced completely by the EMB system under the low vehicle speed.

Under the low brake intensity, the regenerative braking system is able to produce enough braking force, so only the regenerative braking system is used to slow down the vehicle, and all the braking force is distributed on the front wheels (Point A). For some HEVs that adopt high powered motors, the BFD curve needs meet the requirement of the ECE regulation, the extra brake force on rear wheel is provided by the EMB system before reaching the limitation of ECE regulation (Point A to point C).

When the required front wheel brake power is beyond the power capacity of the motor (Point B), the designed BFD directly gets close to the ideal curve (Point A to point B or point C to point D);

From point B, the vehicle is under medium to high intensity braking, as the brake performance is the key consideration. The BFD follows the ideal curve; the brake force distributed on each wheel is regulated by the EMB system to ensure the accuracy of brake force control. In addition, when under high brake intensity, the regenerative braking force needs to be reduced to zero, for the mechanical braking to be more reliable.

The designed BFD combines the advantages of the existing BFD strategies, achieving high regenerative braking efficiency under normal deceleration, and optimal brake performance in emergency braking situations.

## 5 Simulations and Results Analysis

Figure 9 illustrates the configuration of Simulink /AMESim Co-Simulation system for hybrid braking system simulation. The entire system is comprised of Simulink control model, AMESim to Simulink Interface and AMESim HEV Model. The control algorithm model and EMB model are established in Simulink environment. A 15 degree-of-freedom vehicle model in the AMESim is used, which includes the regenerative braking system model, data collection module, vehicle aerodynamic model and other models of vehicle components such as suspension, tire and electric motor. To validate the braking performance of the proposed braking control strategy, the conventional braking strategies are also simulated for comparison.

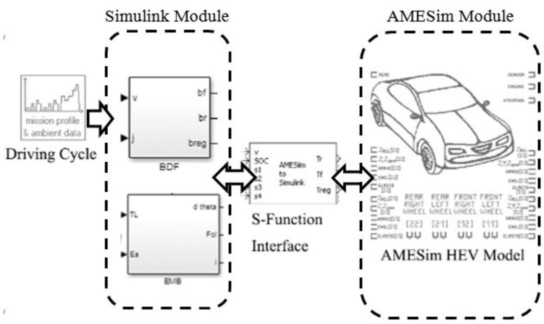



**Figure 9. Simulink/AMESim Co-Simulation**

In the simulation of braking distance, the HEV braking strategy and the proposed braking strategy are simulated in three types of road surface conditions with different road adhesion coefficient [14]. The initial braking speed is set at 50km/h, while the ABS function is introduced in the braking system to ensure the wheel slip rate within the safe range. The simulation results as shown in Table 2, indicate that the proposed braking control strategy can significantly decrease the braking distance compared with the conventional HEV. Thus, the proposed braking strategy improves the braking performance of the vehicle, especially in difficult road conditions with a low adhesion coefficient.

**Table 2. Braking Distance Simulation**

| Road | Road Adhesion Coefficient $\mu$ | Conventional HEV | Proposed | Improvement |
|---|---|---|---|---|
| Wet Concrete | 0.8 | 27.63m | 24.90m | 9.88% |
| Gravel | 0.6 | 41.86m | 34.53m | 17.51% |
| Dirt | 0.68 | 34.82m | 30.47m | 12.49% |

The simulations of the regeneration efficiency are carried out based on the ECE driving cycle. Basic vehicle parameters are shown in Table 1. A 17kw electric motor is adopted in the regenerative braking system, and the threshold speed is set at 15km/h according to the analysis results of the driving cycle. The road is assumed to have high adhesion coefficient of 0.95. The simulation results are shown in Figures 10 and 11.

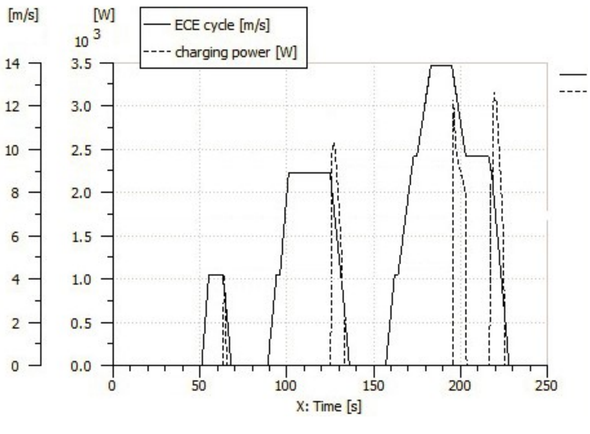



**Figure 10. Simulation of Conventional Strategy**

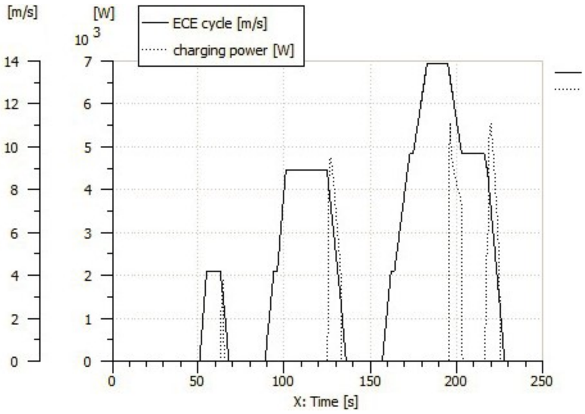



**Figure 11. Simulation of Proposed Strategy**

To evaluate the energy regeneration performance of the proposed braking strategy, the regeneration efficiency $\eta_{\text{reg}}$ is expressed as:

$$\eta_{\text{reg}} = \frac{E_{reg}}{E_b} \times 100\% \quad (3)$$

Where $E_{reg}$ regenerative energy; and $E_b$ is the total braking energy. The simulation results are shown in Table 3.
For the original EMB braking control strategy, since the BFD is on the ideal curve, part of the braking energy is dissipated on the rear wheels, which cannot be recovered by the regenerative braking system. The regeneration efficiency of the original EMB strategy is only 25.73% compared with 44.55% of the proposed strategy. Therefore, the regeneration efficiency improvement is nearly 20% under the ECE driving cycle.

**Table 3. Regeneration Efficiency Simulation**

| Strategy | Total Kinetic Energy | Regenerative Energy | Efficiency | Improvement |
|---|---|---|---|---|
| Original EMB | 23.14kJ | 5.955kJ | 25.73% | - |
| Proposed | 23.14kJ | 10.31kJ | 44.55% | 18.82% |

## 6 Conclusions

In order to design the optimal HEV braking system for urban driving, the urban driving cycle was analyzed in the point view of braking, and a regenerative braking control strategy based on EMB system was proposed. The braking performance and regeneration efficiency of the proposed control strategy were simulated in Simulink/AMESim Co-simulation and compared with other strategies.

The simulation results indicated that by adopting the proposed regenerative braking control strategy, both the braking performance of hybrid braking system and the braking efficiency in urban driving were significantly improved. In future research, more complex urban driving cycles will be introduced, and experiments based on a real EMB system will be carried out to further validate the performance of proposed braking control strategy.

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