Theory and Practice of Science and Technology
2025, VOL. 6, NO. 10, 48-52
DOI: 10.47297/taposatWSP2633-456910.20250610

# Review of Combined Braking Systems for Electric Vehicles

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**ABSTRACT**

The combined braking system for electric vehicles is a cooperative braking solution that integrates mechanical braking and electric braking. Its core lies in balancing braking safety and the need to extend driving range by accurately matching energy recovery and mechanical braking.The system takes electric braking as the priority execution unit. When the vehicle brakes, it first activates the motor to reverse so as to realize kinetic energy recovery—converting mechanical energy into electrical energy and storing it in the battery. When the braking intensity exceeds the capacity of electric braking or under special working conditions, mechanical braking will intervene as needed to ensure braking efficiency.Its key technologies include brake torque distribution algorithm, system cooperative control and fail-safe strategy. These technologies can effectively reduce the wear of mechanical braking and improve the efficiency of energy recovery. Besides, reasonable gear shifting during braking can further enhance energy recovery efficiency. At the same time, compensation control is used to solve problems like power interruption and torque impact during gear shifting, ensuring the smoothness of the shifting and braking process. This system has become a core component to improve the overall performance of electric vehicles, and it is the mainstream development direction of current new energy vehicle braking technology.

**KEYWORDS**

Automotive engineering; Electric vehicles; Review; Combined braking; Cooperative control; Brake torque control; Energy recovery; Braking strategy

## 1 Introduction

Developing electric vehicles is an important way to deal with global energy shortages and environmental crises. Driven by domestic and foreign policies and energy structure adjustments, the technological level and production-sales scale of electric vehicles keep improving [1]. However, the market penetration rate of electric vehicles, especially pure electric vehicles, is still at a low level. From a technical perspective, the problem of driving range is the main reason that limits their market acceptance.

Using high-energy-density batteries to increase a vehicle's driving range is the most direct and effective method. But lithium-ion batteries, as the most widely used energy storage devices at present, still need further development to meet more users' needs.

Regenerative braking, also known as brake energy recovery, partially recovers the kinetic and potential energy when an electric vehicle slows down or brakes. This energy is turned into electrical energy by the motor and stored in the energy storage device, which is then used for the vehicle's re-acceleration or start-up. In typical urban driving conditions, the energy used for braking accounts for about half of the total driving energy. Even on highways—where the frequency of acceleration and deceleration is relatively low—the energy consumed by braking is still considerable, making up 15%. Recovering this braking energy can effectively improve the vehicle's energy efficiency to increase its driving range. At the same time, combining the motor's advantages of fast response and accurate control can further enhance the overall braking performance of the vehicle.

In view of this, this paper summarizes and organizes the research on key technologies of combined braking control in recent years. It conducts a review from three aspects: brake energy recovery efficiency and optimization, dynamic coordinated control, and combined braking control based on braking control strategies. In addition, it looks into the future research directions of this field by considering current research hotspots and shortcomings.

## 2 Principles and Structure of the Combined Braking System

There are two ways to achieve combined braking currently. One is adding a regenerative braking system to the traditional mechanical-hydraulic friction braking. The other is a combined braking system that combines electro-hydraulic braking (EHB) with mechanical-hydraulic friction braking. At present, the second one has broad market prospects and application value [2].

In the combined braking system of electric vehicles, the core advantage of EHB is that it breaks away from the rigid transmission logic of traditional mechanical braking. It uses electronic signals to achieve precise control of braking force and integration with energy efficiency. When the driver steps on the brake pedal, the pedal travel sensor sends the action signal to the brake controller in real time [3]. Then the controller integrates multi-dimensional data such as vehicle speed, remaining battery power, and road adhesion, and issues two commands at the same time.

On one hand, it sends a signal to the motor controller to activate the electric braking function. This makes the drive motor switch to generator mode, which generates braking torque through reversal to slow down the wheel speed. At the same time, it converts the recovered kinetic energy into electrical energy and recharges it into the battery. On the other hand, it uses the electro-hydraulic unit to precisely adjust the brake fluid pressure, driving the brake calipers to apply hydraulic braking force to the wheels.

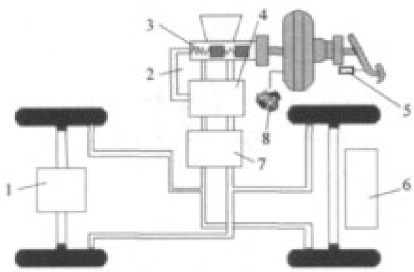


Figure 1 Schematic Diagram of the Electro-Hydraulic Composite Braking System Structure[4]

This "electric + hydraulic" cooperative braking method has a faster response speed. It can not only dynamically adjust the braking force distribution ratio according to different working conditions, but also maximize energy recovery efficiency to effectively extend the vehicle's driving range. Chen Jing's paper mentions that simulation experiments were conducted by modeling components such as accumulators, vacuum boosters, hydraulic pumps, master brake cylinders, wheel brake cylinders, and high-speed valves, and their dynamic response characteristics were recorded [4].

Traditional friction braking serves as a safety guarantee in the combined braking system, and it is an important guarantee for braking performance under extreme working conditions. In scenarios like bad weather—when the combined force of EHB and electric braking cannot meet the demand for safe braking—traditional friction braking will intervene quickly. The master brake cylinder delivers high-pressure brake fluid to the brake calipers of each wheel through hydraulic pipelines. It pushes the brake shoes or pads to clamp the brake discs, generating strong braking force through mechanical friction to quickly reduce the vehicle speed and shorten the braking distance [5].

At the same time, the ABS or ESP equipped in the system monitors the wheel speed in real time. By adjusting the brake fluid pressure at high frequency, it prevents skidding or loss of control caused by wheel lock-up, ensuring the stability of the braking process. In addition, in fault scenarios where the electric braking system fails, traditional friction braking can also act as an independent braking unit. It ensures the vehicle's basic braking function and provides double protection for driving safety.

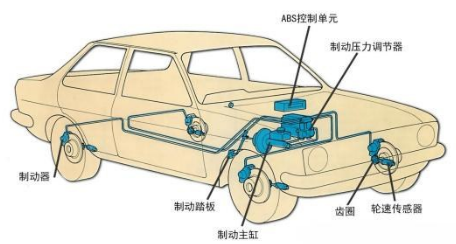


Figure 2 Schematic Diagram of the Traditional Friction Braking System Structure

## 3 Brake Energy Recovery and Optimization

Brake energy recovery for electric vehicles is one of the core technologies to improve driving range. Its essence is to use energy conversion devices to turn the kinetic energy that would otherwise be lost through friction when the vehicle brakes or coasts into storable electrical energy, realizing the reuse of kinetic energy.

The core execution units of this technology are the drive motor and motor controller [6]. When the driver releases the accelerator pedal or gently presses the brake pedal, the VCU immediately triggers a mode switch command, changing the drive motor from drive mode to power generation mode. The wheels drag the motor rotor to rotate in reverse to generate electrical energy. During this process, the motor also produces a reverse braking torque to help the vehicle slow down, forming a dual effect where braking and power generation happen simultaneously [7]. The generated alternating current (AC) is converted into direct current (DC) that meets the charging requirements of the power battery after rectification and voltage stabilization by the motor controller. Finally, it is stored in the battery, completing the energy recovery loop.

The efficient operation of brake energy recovery is inseparable from in-depth coordination with the braking system.

The system dynamically adjusts the recovery strategy according to braking intensity:

• When following other vehicles on urban roads under light braking or coasting conditions, it prioritizes relying on motor recovery to provide braking force. At this time, mechanical braking does not intervene temporarily to minimize energy loss. Meanwhile, it avoids the vehicle's jerking sensation by smoothly adjusting the recovery torque.

• When braking intensity increases during emergency braking or high-speed deceleration, and the braking force from motor recovery cannot meet the safety braking requirements, the VCU sends signals to the brake controller in real time to trigger the intervention of mechanical braking. It supplements braking force through friction between brake calipers and brake discs, ensuring braking distance and driving safety.

Besides, the system also optimizes the recovery strategy based on the vehicle's real-time status. When the remaining battery power is too high, it reduces the recovery intensity appropriately to avoid overcharging damage to the battery. During low-speed driving, the recovery function gradually weakens or turns off to prevent driving smoothness from being affected by braking force fluctuations. When descending long slopes and in similar scenarios, it increases the recovery intensity – this not only supplements power through continuous power generation, but also helps control the vehicle speed through the motor's braking force, reducing the wear of mechanical braking. This multi-dimensional dynamic adjustment enables brake energy recovery to improve energy efficiency while taking into account driving experience and system safety.

However, literature [8] mentions that regenerative braking is restricted by many factors such as the vehicle, road and motor. It is not as safe and reliable as mechanical braking under extreme working conditions, and has poorer braking safety[8]. Therefore, based on the above two control strategies, a hybrid brake energy recovery control strategy based on working condition recognition has been established, which uses the optimal control strategy under different conditions.

## 4 Dynamic Coordinated Control (Global Overall Control System)

Dynamic coordinated control of electric vehicles is a key technology that takes VCU as the core to conduct overall scheduling of multiple systems such as driving, braking, energy management and chassis stability. Its final goal is to realize the unity of driving safety, energy efficiency optimization and riding comfort.

Studies by Wuhan University of Science and Technology and Wuhan University of Technology point out that the key to dynamic coordinated control lies in controlling the fluctuation range of total required torque (i.e., the sum of engine and motor torque) during the control switching process [9]. The main control method is based on the real-time torque feedback of the engine, and uses the fast response characteristic of the motor for torque compensation. This can prevent large fluctuations in the total required torque, thus improving comfort.

A study by Jiangsu University proposes a torque estimation algorithm based on BP neural network, and combines genetic algorithm to optimize the initial weights and thresholds of the network [10]. The optimized BP neural network has further improved convergence speed and prediction ability. Then, the engine's speed regulation and speed compensation are carried out to make the torque respond to the target torque.

In the normal driving phase, the VCU collects real-time data such as accelerator pedal opening, current vehicle speed, battery power and motor working status. It dynamically calculates and distributes the output torque of the drive motor [11] to avoid motor overload or insufficient power. At the same time, it cooperates with the battery management system to adjust the rhythm of electric energy output according to battery temperature and health. This not only ensures timely power response, but also prevents over-charging and over-discharging of the battery.

When the vehicle is in complex working conditions such as steering, ramps or slippery roads, the VCU quickly links with ESP and the steering control system. By fine-tuning the braking force or motor torque of one-side wheels, it suppresses the vehicle's unstable trends such as roll and skid, and maintains a stable driving posture [12].

The role of dynamic coordinated control is more prominent in braking scenarios. The VCU communicates with the brake controller in real time, and accurately distributes the torque ratio between electric braking and mechanical braking based on parameters such as brake pedal opening and road adhesion coefficient. When the brake is applied lightly, electric braking is activated first to recover kinetic energy, and the braking force is adjusted smoothly to avoid jerking. During emergency braking, the intervention intensity of mechanical braking is increased rapidly, and ABS is coordinated to prevent wheel lock-up [13].

In addition, the system can also adaptively adjust the energy recovery intensity according to driving conditions. On the premise of not affecting the driving experience, it maximizes the electric energy recovery efficiency and further extends the driving range.

## 5 Brake Control Strategy (Local Special Strategy)

The core of the brake control strategy for electric vehicles lies in the deep integration of regenerative braking and hydraulic friction braking, aiming to balance the maximization of energy recovery and the priority of safety guarantee.

Literature [14] points out that if the vehicle speed is not zero, the vehicle enters the braking mode; if the accelerator pedal opening is greater than 0, the vehicle enters the driving mode; if the brake pedal opening is 0, the vehicle enters the electric creep mode [14]. This strategy identifies the vehicle's status (such as vehicle speed, brake pedal opening and master cylinder pressure) and the driver's input intention. It then determines the electronic braking force and hydraulic braking force required by the vehicle, and intelligently distributes them to the regenerative braking system and the traditional hydraulic system.

Second, the distribution logic follows a multi-level principle. The top priority is the current state of the power battery, including its state of charge (SOC), temperature and allowable charging power. If the battery is nearly fully charged or its temperature is too high to absorb energy efficiently, the strategy will restrict or even turn off regenerative braking, and assign most of the braking force to the hydraulic system to ensure safety.

Second, the strategy considers factors such as vehicle speed and motor characteristics (i.e. the maximum regenerative braking force the motor can provide at different speeds). It strives to expand the contribution ratio of regenerative braking as much as possible within legal regulations and without affecting driving experience, thus significantly improving the vehicle's driving range [15]. This process is completed through real-time collaboration via high-speed network communication between the vehicle control unit, battery management system and motor controller, achieving efficiency and smoothness in brake energy recovery.

At a more detailed level, it is also necessary to integrate the anti-lock braking function to form an integrated electro-hydraulic combined braking system. When the system detects the risk of lock-up for any wheel, it first intervenes by quickly and accurately adjusting the motor's regenerative braking force, as the response speed of motor torque is much faster than that of the hydraulic system.

Literature [16] proposes a model predictive control algorithm: the upper controller calculates the slip ratio, while the lower controller distributes the regenerative braking force and hydraulic braking force, and optimizes the desired braking torque for the front and rear wheels [16]. If regenerative braking alone is not enough to prevent slipping, the system will seamlessly switch to hydraulic braking for auxiliary adjustment to ensure braking stability.

In addition, the strategy must also consider various complex working conditions. For example, when driving on low-adhesion roads or braking while turning, it will appropriately reduce the regenerative braking force to avoid unnecessary interference with the vehicle's posture. When the brake pedal is lightly pressed, to achieve the highest energy recovery efficiency, it will even use motor resistance to achieve the deceleration effect of the one-pedal mode. The hydraulic system only intervenes when greater deceleration is needed.

Finally, the entire control strategy is a dynamic and adaptive complex algorithm. Its ultimate goal is to provide the driver with a stable, reliable and efficient braking experience in any scenario, while converting every piece of recoverable kinetic energy into electrical energy.

## 6 Conclusions and Prospects

This paper focuses on the combined braking control of electric vehicles and summarizes relevant studies over the past decade from three aspects. At present, the research objects of combined braking control are mainly passenger cars and distributed drive electric vehicles. Compared with the research on static brake torque distribution control and dynamic coordinated control, the research on brake shift control and combined braking control in electro-hydraulic combined braking started relatively late and needs further exploration.

Currently, most mass-produced electric vehicles adopt rule-based torque distribution strategies, which have the advantages of good real-time performance and high reliability. However, the performance of regenerative braking is limited under complex driving conditions, so we can consider using optimization results to improve the torque distribution rules.

Optimization-based torque distribution strategies can achieve goal optimization based on the current vehicle state, but they require appropriate simplification of optimization problems or the use of offline optimization and online lookup tables to ensure control real-time performance. For dynamic coordinated control, we should give play to the advantages of the motor's fast response and precise controllability, as well as the mechanical brake's large torque working range and high reliability/stability. This can improve braking efficiency and stability, enhance safety, and further promote the vehicle's safety and economy. At the same time, accelerating the industrialization of electric vehicles plays an important driving role in the rapid development of the new energy vehicle industry.

Based on the limitations of the above research and the inspiration from the latest studies in related fields, future research on combined braking control can be carried out from the following aspects:

(1) Intelligent Information Collection and Processing: To promote the development of intelligence and automation, a predictive energy recovery strategy based on navigation and traffic information can be adopted [6]. This strategy intelligently predicts deceleration needs and gently applies regenerative braking force in advance by integrating information such as high-precision maps, real-time traffic conditions and ahead traffic lights. This converts more inertial energy into electrical energy, significantly extending the driving range while achieving more stable and precise system control.

(2) Analysis Combining Models and Possibilities: This algorithm predicts future states through a built-in vehicle model. Following the principle of multi-objective collaborative optimization (including braking safety, maximum energy recovery and comfort), it performs real-time rolling calculation of the optimal distribution ratio between regenerative braking force and hydraulic braking force. Thus, it achieves more accurate and smoother dynamic coordinated control under complex working conditions.

(3) Improved Decoupled Braking System: This system decouples the brake pedal from the actuator. The pedal signal only serves as a demand command – the control system prioritizes the distribution of the maximum regenerative braking force, and the hydraulic system then precisely compensates for the insufficient part. This fundamentally optimizes the force distribution efficiency in terms of structure, maximizes the recovery potential, and provides a better control foundation for advanced driver assistance functions [17].

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