

Article

Regenerative Braking of Electric Vehicles Based on Fuzzy Control Strategy

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Abstract: Regenerative braking technology is a viable solution for mitigating the energy consumption of electric vehicles. Constructing a distribution strategy for regenerative braking force will directly affect the energy saving efficiency of electric vehicles, which is a technical bottleneck of battery-powered electric vehicles. The distribution strategy of the front- and rear-axle braking forces of electric vehicles that possess integrated front-wheel-drive arrangements is established based on the Economic Commission of Europe (ECE) regulations, which enables the clarification of the total braking force of the front axle. The regenerative braking torque model of the motor is adjusted to optimize the ratio of motor braking force to the whole front-axle braking force. The regenerative braking process of electric vehicles is influenced by many factors, such as driving speed and braking intensity, so regenerative braking presents characteristics of nonlinearity, time variability, delay, and incomplete models. By considering the impact of fuzzy controllers having better robustness, adaptability, and fault tolerance, a fuzzy control strategy is employed in this paper to accomplish the regenerative braking force distribution on the front axle. A regenerative braking model is created on the Simulink platform using the braking force distribution indicated above, and experiments are run under six specific operating conditions: New European Driving Cycle (NEDC), World Light-Duty Vehicle Test Cycle (WLTC), Federal Test Procedure 72 (FTP-72), Federal Test Procedure 75 (FTP-75), China Light-Duty Vehicle Test Cycle-Passenger (CLTC-P), and New York City Cycle (NYCC). The findings demonstrate that in six typical cycling road conditions, the energy saving efficiency of electric vehicles has greatly increased, reaching over 15%. The energy saving efficiency during the WLTC driving condition reaches 25%, and it rises to 30% under the FTP-72, FTP-75, and CLTC-P driving conditions. Furthermore, under the NYCC road conditions, the energy saving efficiency exceeded 40%. Therefore, our results verify the effectiveness of the regenerative braking control strategy proposed in this paper.

Keywords: battery-powered electric vehicles; regenerative braking force distribution; fuzzy control strategy; energy saving efficiency improvement



Citation: Yin, Z.; Ma, X.; Su, R.; Huang, Z.; Zhang, C. Regenerative Braking of Electric Vehicles Based on Fuzzy Control Strategy. *Processes* **2023**, *11*, 2985. <https://doi.org/10.3390/pr11102985>

Academic Editor: Jie Zhang

Received: 22 September 2023

Revised: 5 October 2023

Accepted: 12 October 2023

Published: 15 October 2023



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1. Introduction

Electric vehicles have steadily improved as a viable remedy to address the challenges of energy consumption and ecological pollution. However, the limited vehicle range has become an obstacle to the popularization of pure electric vehicles due to the slow development of battery energy storage in the electric vehicle industry [1,2]. Regenerative braking control in electric vehicles aims to recover more braking energy by reasonably distributing the regenerative braking force while ensuring braking safety. Therefore, the development of regenerative braking technology to efficiently recover electrical power from motor braking possesses a positive effect on improving the energy utilization and range of electric vehicles [3].

The methods for improving the energy recovery of regenerative braking in electric vehicles include many aspects, such as the structure of the power system, the working char-

acteristics of the electric motor and battery, braking regulations, the distribution strategy of the braking force of the front and rear axles, and the distribution strategy of regenerative braking. The structure of regenerative braking systems can be divided into three categories according to the arrangement of driving motors: center-integrated motor type [4], wheel-side motor type [5], and in-wheel motor type [6]. The in-wheel motor adopts an electric connection, effectively reducing mechanical losses and thus producing high energy recovery efficiency. The energy storage devices for automobile regenerative braking can be divided into hydraulic energy storage devices [7], flywheel energy storage devices [8], and electric energy storage devices [9]. In hydraulic energy storage devices, when the vehicle brakes, hydraulic oil is pumped into the energy storage device to store hydraulic energy and provide braking torque. The flywheel regenerative braking system stores some of the braking energy in the high-speed rotating flywheel. The electric energy storage regenerative braking system uses batteries or supercapacitors to store braking energy. The braking torque distribution strategies for typical electric vehicle regenerative braking include parallel, optimal energy recovery rate, and ideal regenerative braking control strategies [10,11]. The parallel regenerative braking control strategy distributes the required total braking force in a fixed proportion, which is a function of vehicle speed or braking intensity. The optimal energy recovery strategy maximizes energy recovery based on sufficient braking torque to meet the braking safety distance and performance of new energy vehicles. The ideal regenerative braking control strategy refers to the distribution of braking force between the front and rear wheels according to the ideal front- and rear-wheel braking force distribution curve (I curve). The allocation strategies for regenerative braking include fuzzy control [12], optimal control [13], hierarchical control [14], sliding mode control [15], and neural network control [16]. Fuzzy control technology is based on fuzzy mathematics theory, which improves the controllability, adaptability, and rationality of control algorithms by simulating human approximate reasoning and comprehensive decision-making processes. The optimal control problem is to find the extreme value of the performance index function with the control function and motion state as variables under the constraints of the motion equation and allowable control range. Hierarchical control is the decomposition of an extensive system into several small systems, where a coordination level is added to optimize the entire extensive system when considering the connections between subsystems. The structure of sliding mode control is not fixed, and it can purposefully change continuously during the dynamic process based on the current state of the system, forcing the system to move according to the predetermined “sliding mode” state trajectory. Neural network control refers to the use of neural networks as a tool in control systems to model complex nonlinear objects that are difficult to describe accurately. Vodovozov et al. [17] reviewed the braking energy management in electric vehicles and provided a detailed description of the fuzzy logic and neural network control in the application of regenerative braking. Verma et al. [18] made a review on various topologies of electric vehicles based on energy sources.

In recent years, research on regenerative braking technology has been heating up. Li et al. [19] designed optimization distribution methods for fixed- and variable-proportion braking forces. A regenerative braking strategy with an optimized allocation algorithm that relies on braking strength was proposed by Jiang et al. [20]. The state of charge (SOC) value of the battery, in addition to the motor speed, were both carefully taken into account by Jiang et al. [21], who then distributed the braking force between the front and rear wheels. A more effective regenerative braking technique was created by Bian et al. [22] using the Global Positioning System (GPS) and inertial sensors. A regenerative braking control strategy was proposed by Liu [23] depending on a novel braking strength definition method and a dynamic allocation algorithm for front- and rear-axle braking forces. Qiu et al. [24] calculated the optimal braking torque for Anti-Lock Braking System (ABS) control of electric vehicles based on phase plane theory. They divided the required optimal braking torque into two parts, which were distributed by friction brakes and regenerative brakes. Zhang et al. [25] aimed to investigate the regenerative braking characteristics of

four-wheel-drive electric vehicles by using the parallel distribution strategy. A dual-layer, multi-parameter regenerative braking control technique was put forward by Geng et al. [26], and it was shown to considerably increase the ability of vehicles to recover energy. A fuzzy control technique was developed by Ning et al. [27] with a 5.4% increase in the effective recovery rate of regenerative braking energy. Fuzzy optimization algorithms were utilized by Zhao et al. [28] to reduce battery usage by 1.22%. Chai et al. [29] used a particle swarm optimization (PSO) algorithm for optimizing multiple vital parameters in the regenerative braking strategy of front-drive pure electric vehicles.

In the classical control field, the accuracy of the dynamic mode of the control system is the most important factor affecting the quality of control. The more detailed the dynamic information of the system, the more precise the control that can be achieved. However, for complex systems, due to the large number of variables, it is often difficult to accurately describe the dynamics of the system. Fuzzy control is the application of fuzzy mathematics methods to control fuzzy problems that cannot be accurately modeled. Fuzzy control is a rule-based control. It directly adopts language-based control rules, starting from the control experience of on-site operators or the knowledge of relevant experts [30,31]. In the fuzzy design, there is no need to establish an accurate mathematical model of the controlled object, making the control mechanism and strategy easy to accept and understand, simple in design, and easy to apply [32,33]. In 1965, Zadeh founded the fuzzy set theory, and in 1973, he provided the definition and related theorems of fuzzy logic control [34]. In 1974, Mamdani first composed a fuzzy controller based on fuzzy control statements and applied it to the control of boilers and steam engines [35]. In recent years, fuzzy control has made significant progress in both theory and technology. Typical applications include washing machines, air conditioners, microwaves, vacuum cleaners, cameras, and camcorders in household electrical equipment [36–38]; water purification treatment, fermentation processes, chemical reaction kettles, and cement kilns in industrial control [39–41]; and subway parking, car driving, elevators, escalators, and machine arms [42–44]. The biggest advantage of fuzzy control is that it is based on a qualitative understanding of industrial processes, and it is relatively easy to establish language control rules [45]. Therefore, fuzzy control is very suitable for objects that it is difficult to obtain mathematical models for, objects that it is difficult to grasp the dynamic characteristics of, or objects that have significant structural changes.

Although pure electric vehicles have enormous advantages in energy conservation and environmental protection, the problem of insufficient driving range seriously restricts their rapid development and application. Regenerative braking energy recovery technology has made up for the problem of insufficient driving range to a certain extent. The braking control system of electric vehicles is very complex and nonlinear. If regenerative braking force and mechanical braking force are distributed according to a fixed value, the goal of highly efficient braking energy recovery may not be achieved. The regenerative braking process of electric vehicles is influenced by many factors, such as driving speed, battery state of charge (SOC), and braking strength. Therefore, when determining the distribution ratio of motor braking force and hydraulic braking force, these factors should also be taken into account. That is to say, it is necessary to maximize the recovery of regenerative braking energy based on the actual braking situation of the vehicle. The use of robust fuzzy control can simplify the control logic of such complex nonlinear systems. This is because fuzzy control has strong adaptability to environmental changes and can automatically correct the controller in random environments, enabling the control system to maintain good performance even in the event of changes or disturbances in the characteristics of the controlled object. The main contribution of this study is to maximize the involvement of the regenerative braking force in the braking process through the use of fuzzy control, thus recovering braking energy with higher efficiency.

This paper demonstrates a well-structured organization, commencing with a “Literature review” surrounding the control strategy for regenerative braking in electric vehicles that underscores its importance in reducing energy wastage and extending driving dis-

tance. In Section 2, we first detail the structure of the electric vehicle braking system and the energy recovery principle. This section provides a comprehensive understanding of energy conversion and six road working conditions. Proceeding further, Section 3 describes the two distribution processes of braking force. The first distribution is the distribution of front- and rear-axle braking force, taking into account the safe braking range of pure electric vehicles and the constraints on feedback braking factors. The second distribution is the redistribution of the braking force on the front axle. The required braking force on the front axle is jointly provided by the regenerative braking force of the motor and the hydraulic braking force. In order to recover as much braking energy as possible, the ratio of regenerative braking force to the braking force on the front axle should be as large as possible. Herein, the fuzzy control method is utilized for distributing the motor and hydraulic braking forces in terms of the front axle regenerative braking. With the objective of maximizing the involvement of the regenerative braking force in the braking process, the degree of membership and fuzzy rules of the fuzzy controller are determined. The energy saving efficiency of the regenerative braking is measured by using the R2022b version of the Simulink/MATLAB simulation software. Subsequently, Section 4 articulates the effectiveness of the regenerative braking control strategy designed in this article. By simulating and analyzing the designed braking force distribution strategy under six different cycle conditions, we verify that the regenerative braking control strategy proposed in this paper can significantly improve the efficiency of braking energy recovery, which has important practical significance and application value. Next, Section 5 reports a comparison of energy recovery efficiency with other scholars, emphasizing the significance of this study. Lastly, the conclusion is shown in Section 6.

2. Models and Problem Formulation

2.1. Design of Motor/Hydraulic Braking System

Figure 1a illustrates the schematic diagram of the motor/hydraulic braking system [46]. The electric vehicle power system layout is an integrated layout of front-wheel driving, which not only reduces the installation size of the power train but also increases transmission efficiency. The braking system includes a hydraulic braking system comprising a hydraulic master cylinder, four hydraulic brakes, etc., as well as a regenerative braking system composed of a drive motor, reducer, power battery, regenerative braking Electronic Control Unit (ECU), etc., at the front axle. The control system of electric vehicles is divided into two layers, as shown in Figure 1b. The assembly brake controller, which distinguishes between the ABS and regenerative control, is the first layer. The allocation of braking torque between hydraulic and motor braking forces is coordinated by a regenerative braking controller, which can be found in the second layer. When the vehicle is coasting or braking, the brake pedal travel sensor and wheel speed sensor transmit the analog signals of vehicle speed and pedal pressure to the assembly brake controller. For the purpose of distributing the required total braking force to the front and rear wheels, the assembly brake controller analyzes the braking intention and calculates the required total braking force. When regenerative braking is needed, the regenerative braking controller assesses the maximum regenerative braking force of the motor and balances the regenerative braking force of the front wheel with the hydraulic braking force. Meanwhile, the electric motor is in power generation mode, converting some of the kinetic energy to electrical energy and subsequently charging this energy back into the power battery. Consequently, the energy recovery of regenerative braking is realized.

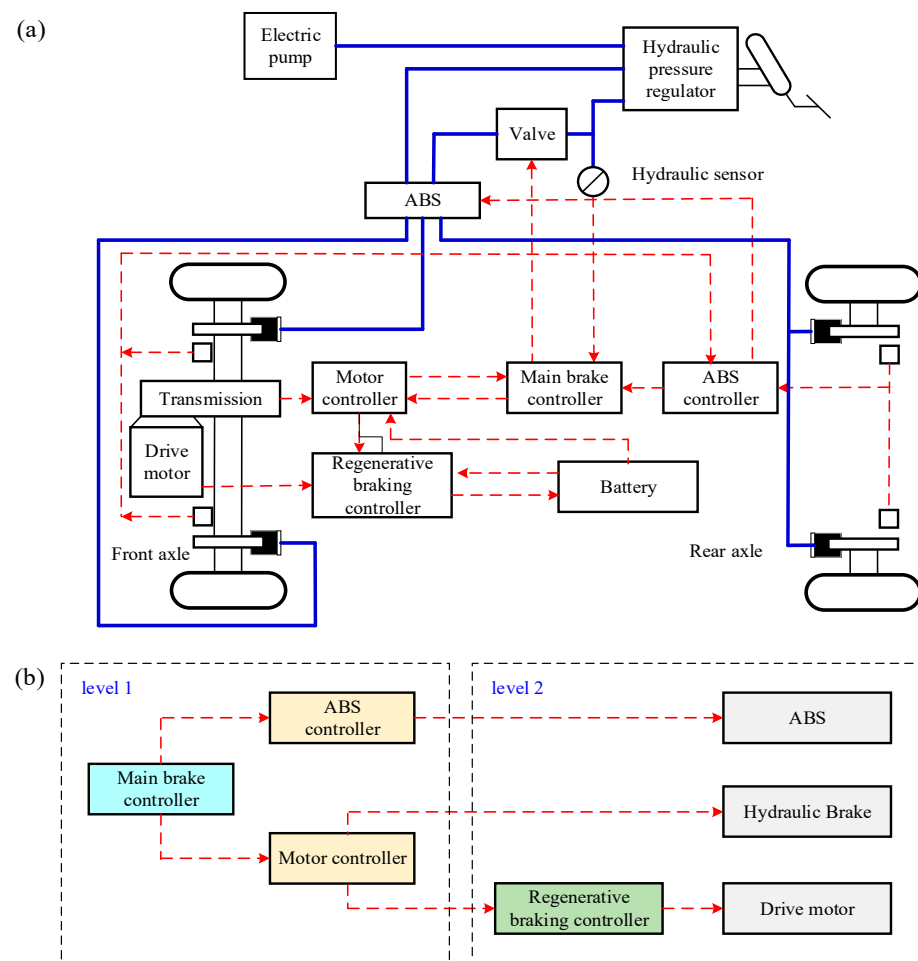


Figure 1. Composition and structure of regenerative braking system: (a) structural schematic diagram of the electric motor/hydraulic braking system and (b) hierarchical structure of the control system of electric vehicles.

2.2. Dynamics Model of Electrical Vehicles

The dynamics of a vehicle are determined by two aspects: the driving force determined by the power unit and the vehicle's adhesion properties determined by the tire–road friction coefficient. When a vehicle travels at equal speed on a horizontal road, it must overcome rolling resistance from the ground and air resistance from the air. When a vehicle is traveling uphill on a ramp, it must also overcome the force of gravity divided along the ramp, called slope resistance. When the vehicle accelerates, it also has to overcome the acceleration resistance. The rolling resistance F_f is due to hysteresis losses in the tires. The air resistance F_w is the component force of the air force in the direction of travel on a car traveling in a straight line. Gradient resistance F_i is the component force of the vehicle's gravity along the ramp. Acceleration resistance F_j is the force of inertia that overcomes the accelerating motion of the mass of the car when it accelerates, including the inertia force of the translational mass and the moment of inertia of the rotating mass. The torque generated by the driving device is transmitted through the transmission system to the driving wheel, generating the driving torque T_{iq} . Under the action of T_{iq} , the driving wheel will exert a circumferential force on the ground, and the reaction force on the ground to the driving wheel is the driving force F_t . Based on driving force and various driving resistances, as shown in Figure 2, the driving equation of a vehicle is as follows [47]:

$$F_t = F_f + F_w + F_i + F_j. \quad (1)$$

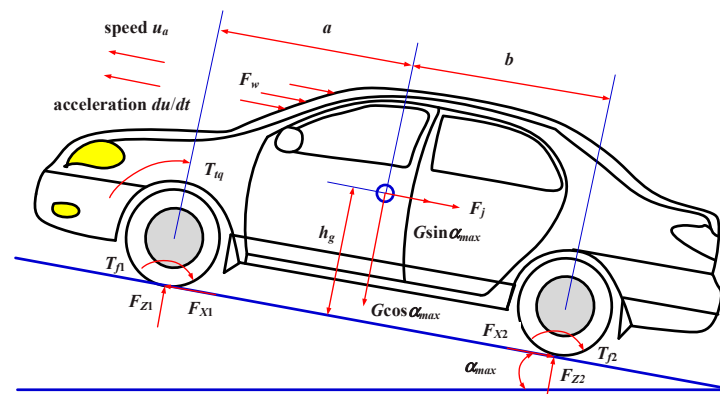


Figure 2. Force diagram of a vehicle accelerating uphill.

Expanding the above equation completely, it can be expressed as [48,49]

$$\frac{T_{tq} i_{min} \eta_T}{r} = G f \cos \alpha + G \sin \alpha + \frac{C_D A u_a^2}{21.15} + \delta m \frac{du}{dt}, \quad (2)$$

where T_{tq} is the output torque of the motor, i_{min} is the transmission ratio, $\eta_T = 0.98$ represents the mechanical efficiency of the driveline, r is the rolling radius of the wheels, G refers to the weight of the vehicle, f is the rolling resistance coefficient, i is the gradient of the road, C_D is the coefficient of air resistance, A is the windward surface area, u_a represents the speed of the car, δ is the conversion factor of the rotating mass of the vehicle, m is the mass of the vehicle, and du/dt is the acceleration. The geometrical parameters and performance indexes of the vehicle are given in Table 1. In addition, the COM denotes the vehicle's center of mass.

Table 1. Parameters and performance indicators of the vehicle.

Parameter	Value	Parameter	Value
Unloaded weight m_u /kg	1650	Air resistance coefficient C_d	0.45
Fully loaded weight m_f /kg	1920	Position of COM h_g	0.58
Wheelbase L /m	2.670	Rolling resistance coefficient f	0.02
Distance from the front axle to COM a /m	1.340	Driving range S /km	400
Distance from the rear axle to COM b /m	1.430	Maximum speed u_{max} /km·h ⁻¹	150
Windward area A /m ²	2.5	Tire rolling radius r /m	0.33

During the driving process of a vehicle, the power P_e emitted by the power device is always equal to the energy lost by the mechanical transmission and the power consumed by all motion resistance [50,51]:

$$P_e = \frac{1}{\eta_T} \left(\frac{G f u_a}{3600} + \frac{C_D A u_a^3}{76140} + \frac{G i u_a}{3600} + \frac{\delta m u_a}{3600} \frac{du}{dt} \right). \quad (3)$$

Among the aforementioned resistances, rolling resistance and air resistance exist under any driving conditions.

2.3. Parameters of the Drive Motor

Regenerative braking refers to switching the motor into a generator in the braking condition and then using the inertia of the vehicle to drive the motor rotor to rotate and generate the reversing torque, which will promote converting a part of the kinetic energy into electric energy. When the backup power of the vehicle motor is too high during normal driving, it will be in an inefficient working area for a long time, with a low energy

utilization rate and shortened vehicle range; the motor power is too low and the starting power of the vehicle is insufficient, making it difficult to meet the driving needs. Therefore, to meet the driving needs, it is necessary to choose the appropriate motor power. The motor output power can be evaluated based on the maximum speed u_{max} , acceleration time t_m , and maximum climbing slope α_{max} [52]:

(1) The motor power P_a calculated from the maximum vehicle speed u_{max} of the vehicle is as follows:

$$P_a = \frac{u_{max}}{3600\eta_T} \left(mgf + \frac{C_D A u_{max}^2}{21.15} \right), \quad (4)$$

(2) The motor power P_b determined by the acceleration time $t_m < 14$ s from 0 to $u_a = 100$ km/h:

$$P_b = \frac{1}{3600\eta_T} \left(\frac{2}{3} mgf u_a + \frac{4}{5} \frac{C_D A u_a^3}{21.15} + \frac{1}{2t_m} \delta m \frac{u_a^2 + u_e^2}{3.6} \right), \quad (5)$$

(3) The maximum climbing slope $\alpha_{max} = 30\%$ determines the motor power P_c as follows:

$$P_c = \frac{u_i}{3600\eta} \left(mgf \cos \alpha_{max} + mg \sin \alpha_{max} + \frac{C_D A u_i^2}{21.15} \right), \quad (6)$$

where $\eta_T = 0.97$ indicates the power coefficient, u_e is the vehicle speed at the lowest motor speed, and u_i is the climbing speed. In summary, the motor peak power P_{mmax} should satisfy the requirements listed below:

$$P_{mmax} = \max(P_a, P_b, P_c). \quad (7)$$

The motor-rated power P_{me} should meet the following conditions:

$$P_{me} = P_{mmax} / \lambda, \quad (8)$$

where the motor load factor λ is 2.5. The maximum speed of the motor n_{mmax} is governed by the maximum vehicle speed u_{max} :

$$n_{mmax} = \frac{u_{max} i_{min}}{0.377r}, \quad (9)$$

where i_{min} means the minimum transmission ratio of the transmission system. Considering transmission loss, the speed corresponding to the highest vehicle speed is 90~95% of the highest motor speed. The motor-rated speed n_{me} is

$$n_{me} = \frac{n_{mmax}}{\xi}, \quad (10)$$

where the constant power zone coefficient is equal to $\xi = 2.5$. Increasing the value of ξ can make the motor obtain a larger torque in the constant torque region and improve the acceleration and climbing performance of the vehicle. However, if the ξ value is too large, it will lead to an increase in the motor operating current and power loss of the inverter [53]. The peak torque of the motor T_{mmax} can be obtained based on the maximum starting power P_{mmax} and rated speed n_{me} of the motor:

$$T_{mmax} = \frac{9550 P_{mmax}}{n_{me}}. \quad (11)$$

The relationship between the rated torque T_{me} , rated power P_{me} , and rated speed n_{me} of the motor is as follows:

$$T_{me} = \frac{9550 P_{me}}{n_{me}}. \quad (12)$$

The motor of a new energy vehicle needs a suitable drive system to provide sufficient torque and power. The reduction gear is the core component of this drive train. It utilizes

reduction gears to slow down the output speed of the motor and transfer power to the wheel drive system. The reduction gear can amplify the torque of the drive motor, while a multi-gear transmission will allow the motor to operate in a more efficient speed range, resulting in a system with a wider speed range and more torque [54]. Currently, most electric vehicles are equipped with a single-speed transmission, where the motor can output high torque at low speeds and constant power at high speeds. Most of the time, vehicles are driven in the highest gear, the gear with the minimum transmission ratio. Therefore, the selection of the minimum transmission ratio is very important. If the minimum transmission ratio of the transmission system is too high, it will lead to poor power performance of the vehicle and insufficient acceleration, but fuel economy will be improved. A smaller minimum transmission ratio in the transmission system will improve the vehicle's power performance and it will accelerate more quickly, but fuel economy will be affected, and fuel consumption will increase [55]. Therefore, when selecting the minimum transmission ratio of the transmission system, it is necessary to consider the operating environment and needs of the vehicle. The upper limit of the minimum transmission speed ratio is determined from the maximum vehicle speed requirement, i.e.,

$$i_{min} \leq 0.377 \frac{n_{mmax} r}{u_{max}}. \quad (13)$$

At the highest speed, the driving force of the motor should not be less than the driving resistance:

$$\frac{9550 P_{me} \eta_T i_{min}}{n_{mmax} r} \geq mgf + \frac{C_d A u_{max}^2}{21.15}. \quad (14)$$

Combining the above discussion, the transmission ratio of the selected speed reducer is $i_{min} = 7.238$. Table 2 shows the list of technical parameters of the motor.

Table 2. Parameters of motor.

Parameter	Value	Parameter	Value
Rated power P_e /kW	36	Peak speed n_{max} /r·min ^{−1}	9000
Peak power P_{max} /kW	95	Rated torque T_e /N·m	96
Rated speed n_e /r·min ^{−1}	3600	Peak torque T_{max} /N·m	255

2.4. SOC Calculation of Power Battery

The distance traveled at a constant speed $u_a = 60$ km/h should not be less than $S = 400$ km, which is used to match the energy E_{bat} and capacity Q_{cap} of the power battery (see Table 3) [56]:

$$E_{bat} \geq \frac{mgf + C_D A u_a^2 / 21.15}{3600 \times \eta_{soc} \times \eta_T \times \eta_{cut}} \times S, \quad (15)$$

$$Q_{cap} = 1000 \frac{E_{bat}}{U_e}, \quad (16)$$

where the power battery discharge depth η_{soc} is 0.8, the discharge current efficiency η_{cut} is 0.9, and U_e is the power battery rated voltage.

Table 3. Parameters of power batteries.

Parameter	Value	Parameter	Value
Rated voltage U_e /V	336	Maximum charging power P_{Bmax} /kW	110
Battery capacity Q_{cap} /Ah	270	Specific energy E /Wh/kg	120

Since the development of battery technology, there have been many methods used to estimate SOC, including the traditional current integration method, battery internal resistance method, discharge test method, open circuit voltage method, load voltage method,

Kalman filtering method, fuzzy logic theory method, and neural network method [57]. In the current integration method, SOC is estimated by accumulating the amount of charge and discharge during the charging and discharging of the battery. During charging, all the charge entering the battery stays in the battery, and during discharging, all the charge leaving the battery results in a decrease in SOC. The power battery SOC is estimated according to the current integration method [58]:

$$SOC = SOC_{init} - \frac{1}{3600Q_{cap}} \int \eta_b I_m dt, \quad (17)$$

in which SOC_{init} denotes the battery's initial SOC, $\eta_b = 0.95$ is the motor power generation efficiency, and I_m is the current during the charging and discharging process. The main circuit current of the battery pack is measured in real time, with negative current during charging and positive current during discharging.

During the operation of a pure electric vehicle, the battery outputs electrical energy to the electric motor. The output power of the electric motor is used to overcome the internal resistance of the mechanical devices of the electric vehicle itself, as well as the power consumed by the external resistance determined by the driving conditions. The analysis of the force condition of the electric vehicle while driving yields the calculation of the current in the main circuit as follows [59]:

$$I_m = \frac{\eta_b T_{tq} n}{9.55 U_{ec}}. \quad (18)$$

Upon utilizing regenerative braking technology, the motor operates in the form of electricity generation, converting the kinetic energy generated by the brakes into chemical energy and ultimately storing this energy in the battery. The current I_m generated during motor braking is expressed as follows:

$$I_m = \frac{-\eta_b T_{tm} n}{9.55 U_{ec}}, \quad (19)$$

where T_{tm} is the motor braking torque, n is the motor rotational speed, and U_{ec} is the power battery terminal voltage; $U_{ec} = U_e - I_m R$, where R is the internal resistance of the battery, and $R = 0.015 \sim 0.060 \, \Omega$. The internal resistance of a battery includes ohmic internal resistance and polarization internal resistance [60]. Polarization internal resistance includes electrochemical polarization internal resistance and concentration polarization internal resistance. The ohmic internal resistance is related to the size, structure, and assembly of the battery, and the polarization internal resistance is the internal resistance caused by the polarization of the positive electrode and the negative electrode of the battery when they have an electrochemical reaction. Batteries with high internal resistance have high internal power consumption and serious heat generation during charging and discharging, which will cause accelerated aging and life decay of lithium-ion batteries as well as limit charging and discharging at large multiplication rates [61].

2.5. Analysis of Energy Conversion

During regenerative braking, the kinetic energy of an electric vehicle is partially converted into braking energy, which is transmitted by the transmission system to the motor. At this time, the motor acts as a generator to generate electricity and store the generated electrical energy in the battery. During the braking process, the vehicle's speed decreases from initial speed v_{int} to terminal speed v_{ter} , and the energy conversion relationship can be obtained as follows [62]:

$$\frac{1}{2} m v_{ter}^2 - \frac{1}{2} m v_{int}^2 = W_f + W_w + W_h + W_m, \quad (20)$$

where W_f , W_w , W_h , and W_m are the work performed by rolling resistance, air resistance, hydraulic braking, and regenerative braking, respectively. Only W_m can be converted to electrical energy. The regenerative braking recovery efficiency ε_r can be expressed as the proportion of the braking energy recovered and stored in the battery E_r to the total energy consumed by the braking system E_{total} throughout the entire cycle, as shown below [63]:

$$\varepsilon_r = \frac{E_r}{E_{total}} = \frac{\eta_b W_m}{\frac{1}{2}mv_{ter}^2 - \frac{1}{2}mv_{int}^2}, \quad (21)$$

where η_b is the motor power generation efficiency. The energy recovered and stored in the battery E_r can also be calculated as

$$E_r = \int_{\text{braking}} U_{ec} I_m dt. \quad (22)$$

When an electric vehicle without regenerative braking experiences braking, the ΔSOC_n between the SOC values at the end SOC_{end} and the initial SOC_{int} is directly related to the total energy E_{total} . The ΔSOC_y contains the energy recovered and stored in the battery E_r for an electric vehicle with regenerative braking. Thus, the regenerative braking recovery efficiency ε can also be calculated as

$$\varepsilon_r = \frac{\Delta SOC_n - \Delta SOC_y}{\Delta SOC_n}. \quad (23)$$

The regenerative braking recovery efficiency ε_r reflects the energy recovery of the vehicle's kinetic energy in a single braking situation. Still, it cannot evaluate the energy recovery throughout the entire driving cycle. Another important parameter is the energy saving efficiency ε . The energy saving efficiency ε is the ratio of the total energy returned to the battery to the recovered energy from the regenerative braking system in the process of the driving cycle. The expression is as follows [64]:

$$\varepsilon = \frac{E_r^{dc}}{E_{total}^{dc}}, \quad (24)$$

where

$$E_r^{dc} = \int_{\text{braking}} U_{ec} I_m dt, \quad (25)$$

$$E_{total}^{dc} = \int_{\text{driving cycle}} P_e dt, \quad (26)$$

in which P_e is the power emitted by the power device. Equation (23) is also suitable for calculating the energy saving efficiency ε .

2.6. Six Driving Cycle Conditions

The vehicle driving cycle is a speed–time curve used to describe the driving characteristics of a certain type of vehicle (such as passenger vehicles, buses, heavy vehicles, etc.) in a specific traffic environment (such as highways and urban roads). The main purpose of establishing a vehicle driving cycle is to determine pollutant emissions and fuel consumption, develop and evaluate new vehicle technologies, and determine traffic control risks.

Figure 3a shows that the NEDC includes two driving cycles: an urban driving cycle of 0–780 s and suburban operating conditions after 780 s. The characteristics of the NEDC conditions are short testing time, low mileage, low speed, and few gear changes. It does not consider the impact of environmental temperature or the continuous starting and stopping of vehicles during urban traffic congestion on energy consumption [65].

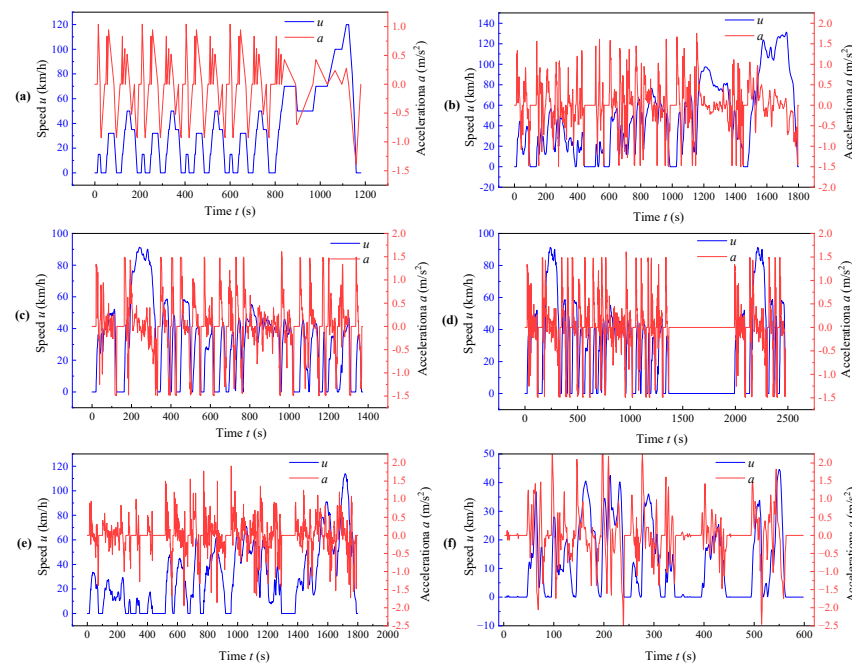


Figure 3. Speed u and acceleration a curves: (a) NEDC; (b) WLTC; (c) FTP-72; (d) FTP-75; (e) CLTC-P; (f) NYCC. (Readers can access this website <https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules>, accessed on 13 October 2023).

As described in Figure 3b, the WLTC mainly consists of low, medium, high, and super-high speeds; the whole cycle time is 1800 s, the total mileage is 23.25 km, and the average speed is 46.5 km/h. The WLTC tests four different operating conditions: urban, circular, rural, and high-speed sections. The durations of low-, medium-, high-, and ultra-high speeds are 589 s, 433 s, 455 s, and 323 s, respectively, and the maximum speed reaches 131 km/h. The proportions of acceleration, deceleration, uniform speed, and idle speed are about 30%, 27%, 28%, and 12% [66].

FTP-72 is also known as the Urban Dynamometer Driving Schedule (UDDS) (as shown in Figure 3c). The FTP-72 cycle simulated 12.07 km of urban road conditions, including frequent parking. The maximum and average speeds are 91.2 and 31.5 km/h, respectively. The FTP-72 cycle consists of two stages. The first stage is 505 s, with a speed of 5.78 km/h and an average speed of 41.2 km/h. The second stage is 864 s [67].

As shown in Figure 3d, FTP-75 adds a 600 s hot-dip and a hot transition condition on the basis of FTP-72. FTP-75 consists of one urban cycle and two supplementary cycles. The two supplemental cycle conditions are the SC03 full-load operation cycle under high-temperature air conditioning and the US06 high-speed and high-acceleration cycle. The urban cycle of FTP-75 is divided into three parts. The first part is the cold-start stage, which takes 505 s. The second part is the transient phase, which takes 864 s. Subsequently, the engine is shut down for 9–11 min, and the third part is a hot-start phase test, which takes 505 s. The total duration is approximately 2474 s [68].

As presented in Figure 3e, the CLTC-P is a standard operating condition based on 41 cities in China, 3832 vehicles, 32.78 million km, and 2 billion GIS (Geographic Information System) traffic low-frequency dynamic big data definitions. It includes 37.4% low-speed, 38.5% medium-speed, and 24.1% high-speed conditions. The working condition lasts for a total of 1800 s, with a cumulative mileage of 14.48 km and maximum and average speeds of 114 km/h and 29 km/h, respectively [68].

As presented in Figure 3f, the NYCC test was developed specifically for low-speed urban road conditions with frequent parking [69]. The driving time of the vehicle is 598 s, with a driving distance of 1.89 km. Its average speed is 11.4 km/h, and the maximum speed is 44.6 km/s.

3. Methodology

3.1. Braking Force Distribution on the Front and Rear Axles

3.1.1. *I* Curve, *f* Curve, and *r* Curve

On the basis of ignoring the rolling resistance moment, air resistance moment, and inertia moment caused by the rotating mass deceleration of the vehicle, the force analysis of the electric vehicle braking on a horizontal road surface is carried out to obtain the ground normal reaction forces F_{Z1} and F_{Z2} as follows [70]:

$$\begin{cases} F_{Z1} = G(b + zh_g) / L \\ F_{Z2} = G(a - zh_g) / L \end{cases} \quad (27)$$

When both the front and rear wheels of a car are locked, the values of the ground braking force and adhesion are equal ($z = \varphi$, where $z = a/g$ is the braking strength and φ is the tire–road friction coefficient), and the ground normal reaction forces F_{Z1} and F_{Z2} are converted into

$$\begin{cases} F_{Z1} = \frac{G}{L}(b + \varphi h_g) \\ F_{Z2} = \frac{G}{L}(a - \varphi h_g) \end{cases} \quad (28)$$

The distribution ratio of the braking force between the front and rear brakes will affect the locking sequence of the front and rear wheels during braking, thereby affecting the directional stability and utilization of adhesion conditions during car braking. (1) The front wheels first lock and drag, and then the rear wheels lock and drag. This is a stable operating condition, but the steering ability is lost, and the adhesion conditions are not fully utilized. (2) The rear wheels first lock and drag, and then the front wheels lock and drag. The rear axle may experience side slip, which is an unstable working condition with low adhesion utilization. (3) Both the front and rear wheels lock and slip at the same time. This can avoid rear-axle side slip and make better use of adhesion conditions. The condition for both the front and rear wheels to lock simultaneously is that the sum of the brake braking forces of the front and rear wheels $F_{\mu1}$ and $F_{\mu2}$ is equal to the adhesion force, and the brake braking forces of the front and rear wheels are equal to their respective adhesion force, expressed as follows [71]:

$$\begin{cases} F_{\mu1} + F_{\mu2} = \varphi G \\ \frac{F_{\mu1}}{F_{\mu2}} = \frac{F_{z1}}{F_{z2}} = \frac{b + \varphi h_g}{a - \varphi h_g} \end{cases} \quad (29)$$

After eliminating the variable φ , it can be concluded that [72]

$$F_{\mu2} = \frac{1}{2} \left[\frac{G}{h_g} \sqrt{b^2 + \frac{4Lh_g}{G} F_{\mu1}} - \left(\frac{Gb}{h_g} + 2F_{\mu1} \right) \right] \quad (30)$$

The above relationship is the relationship curve between the brake braking force of the front and rear wheels when both the front and rear wheels lock simultaneously, which is the *I* curve.

The *f* curve is the relationship curve between the ground braking forces F_{Xb1} and F_{Xb2} of the front and rear wheels when the rear wheels are not locked and the front wheels are locked. When the front wheels lock up, the following relationship exists [73]:

$$F_{Xb1} = \varphi F_{Z1} = \varphi \left(\frac{Gb}{L} + \frac{F_{Xb1} h_g}{L} \right), \quad (31)$$

where $F_{Xb} = mg\varphi$ and $F_{Xb} = F_{Xb1} + F_{Xb2}$. Therefore, the relationship between the front and rear ground braking forces of a vehicle, when only the rear wheels lock up on different road surfaces, is

$$F_{Xb2} = \frac{L - \varphi h_g}{\varphi h_g} F_{Xb1} - \frac{Gb}{h_g}. \quad (32)$$

Substituting different values of φ into the equation yields the set of *f* curves.

The r curve is the relationship curve between F_{Xb1} and F_{Xb2} when the front wheels are not locked and the rear wheels are locked. When the rear wheels lock up, the following relationship holds [74]:

$$F_{Xb2} = \varphi F_{Z2} = \varphi \left(\frac{Ga}{L} - \frac{F_{Xb1}h_g}{L} \right). \quad (33)$$

After organizing the above equation, it is concluded that

$$F_{Xb2} = \frac{-\varphi h_g}{L + \varphi h_g} F_{Xb1} + \frac{\varphi Ga}{L + \varphi h_g}. \quad (34)$$

Substituting different values of φ into the above equation gives the r -curve set.

3.1.2. ECE Regulation Curve

The ECE regulation is a guiding regulation formulated by the United Nations Economic Commission for Europe (ECE). In order to ensure good directional stability and sufficient braking efficiency when braking, for all kinds of vehicles with $\varphi = 0.2 \sim 0.8$, ECE regulations require that the braking strength meet the following conditions [75]:

$$z \geq 0.1 + 0.85(\varphi - 0.2). \quad (35)$$

According to ECE regulations, the brake braking forces of the front and rear wheels must meet the following relationship:

$$\begin{cases} F_{\mu 1} = \frac{z+0.07}{0.85} \frac{G}{L} (b + zh_g) \\ F_{\mu 2} = Gz - F_{\mu 1} \end{cases}. \quad (36)$$

By eliminating the parameter z , we obtain [76]

$$(F_{\mu 1} + F_{\mu 2})^2 + G \left(0.07 + \frac{b}{h_g} \right) (F_{\mu 1} + F_{\mu 2}) - \frac{0.85GL}{h_g} F_{\mu 1} + \frac{0.07G^2b}{h_g} = 0. \quad (37)$$

The above equation indicates that the line for utilizing the adhesion coefficient on the rear axle is below the line for utilizing the adhesion coefficient on the front axle.

3.1.3. Design of Braking Force Distribution for Front and Rear Axles

Depending on the I curve, ECE regulation curve, f curve, and r curve, the allocation rules for front- and rear-axle braking forces are specified with the braking strength z as the independent variable. As depicted in Figure 4, there are four steps regarding the braking force distribution on the front and rear axles of a vehicle:

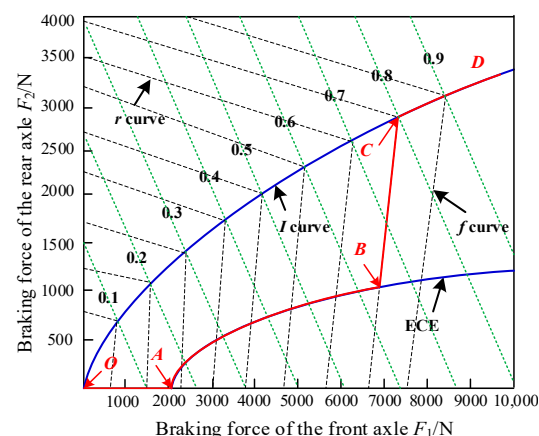


Figure 4. Brake force distribution curve of front and rear axles based on brakes.

(1) During the OA section, where the braking strength $z \leq 0.15$, the required braking demand is comparatively low. It is significant that the ECE regulations do not impose any limitations on the braking strength $z \leq 0.15$. Consequently, the front axle is capable of supporting the total braking force requirement, whereas the rear axle remains uninvolved in the braking process. The following is the principle of braking force distribution:

$$\begin{cases} F_1 = Gz \\ F_2 = Gz - F_1 = 0 \end{cases} \quad (38)$$

where subscripts 1 and 2 represent the braking forces of the front F_1 and rear F_2 axles, respectively.

(2) Once the braking strength meets the requirements of $0.15 < z \leq 0.525$, i.e., the AB section, the braking force demand is borne by both the front and rear axles for ensuring braking safety. The subsequent principle pertains to the braking force distribution, which aims to avert the occurrence of rear wheel lock-up or slip:

$$\begin{cases} F_1 = \frac{z+0.07}{0.85} \frac{G}{L} (b + zh_g) \\ F_2 = Gz - F_1 \end{cases} \quad (39)$$

(3) When the braking strength is $0.525 < z < 0.7$, that is, the BC section, the braking strength at this stage easily leads to the locking of the front wheel and the loss of directional stability. For the purpose of ensuring that the front axis braking force cannot reach the braking force provided by the ground, the braking force distribution principle is as follows:

$$\begin{cases} F_1 = \frac{G\varphi}{L} (b + \varphi h_g) \\ F_2 = Gz - F_1 \end{cases} \quad (40)$$

(4) Once the braking strength $z > 0.7$, i.e., the CD segment, the braking force is distributed relying on the I curve. Both the front and back wheels are simultaneously locked, allowing for safe braking by making the most of the road adhesion. The following is the principle of braking force distribution:

$$\begin{cases} F_1 = G\varphi \frac{b+zh_g}{L} \\ F_2 = G\varphi \frac{a-zh_g}{L} \end{cases} \quad (41)$$

Figure 5 shows the braking process of the front and rear-axle braking forces under 6 cycle conditions. From Figure 5, it can be seen that the WLTC, FTP-72, FTP-75, and the CLTC-P have higher front-axle braking forces, while the NEDC and NYCC have relatively lower braking forces. In these six operating conditions, the rear-axle braking force is almost zero, so the rear wheels will not lock up.

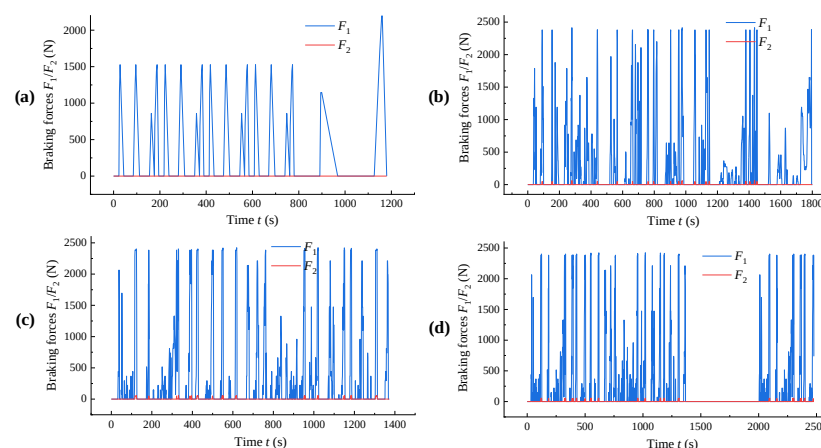


Figure 5. Cont.

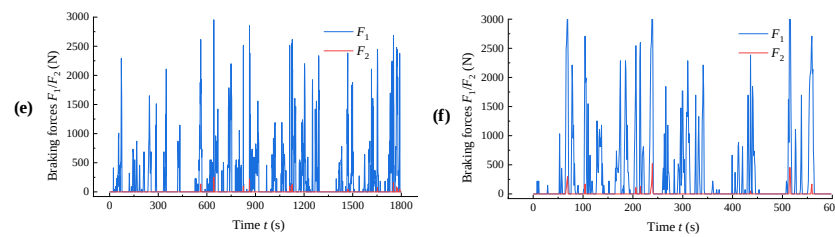


Figure 5. Braking force distribution of front and rear axles: (a) NEDC; (b) WLTC; (c) FTP-72; (d) FTP-75; (e) CLTC-P; and (f) NYCC.

3.2. Fuzzy-Based Controller Design

3.2.1. Restrictions on Regenerative Braking

A vehicle should have high braking efficiency as well as braking stability. Although regenerative braking can participate in braking, traditional hydraulic braking systems should be retained for vehicle braking safety and dependability. A brake system should ensure that the front wheels are not held in advance when the vehicle experiences braking; that is, the vehicle needs to avoid the loss of steering ability and unstable working conditions such as slip. Our research object is the front-drive electric vehicle since the braking power of an electric motor can only be applied to the front axle. Upon pressing the braking pedal, the front axle's braking force is regulated by both hydraulic and regenerative forces, while the rear axle's braking force is only supplied by hydraulic forces. When both the entire demand for braking and the braking strength are low ($z < 0.15$), the motor can accomplish braking only. On a moderate braking strength ($0.15 < z < 0.7$), the braking force of an electric vehicle requires the combination of hydraulic braking force and regenerative braking force for energy recovery. Additionally, only hydraulic braking force is employed for driving safety considerations during emergency braking situations where the braking intensity is large ($z > 0.7$). The key factors affecting motor participation in braking mainly start from two aspects: the maximum braking force limit of the motor and the battery charging power.

First, the aim of the regenerative braking force distribution strategy is to maximize the proportion of motor braking force to the total braking force of the front axle as much as possible. The maximum regenerative braking torque T_{emax} of the motor is influenced by its electrical features and is also constrained by the battery's electrical characteristics. The following describes the calculation model for the maximum braking torque of the electric motor T_{emax} [77]:

$$T_{emax} = \begin{cases} \min \left[\frac{9550P_{mmax}}{n}, \frac{9550P_{Bmax}}{\eta_b n} \right], & n > n_e \\ \min \left[T_{mmax}, \frac{9550P_{Bmax}}{\eta_b n_e} \right], & n_{min} \leq n \leq n_e \\ 0, & n \leq n_{min} \end{cases} \quad (42)$$

where P_{max} means the motor's peak power, P_{Bmax} denotes the battery's maximum charging power, η_b is the battery charging efficiency, T_{max} indicates the motor's peak torque, and $n_{min} = 356 \text{ r} \cdot \text{min}^{-1}$.

Second, in order to prevent overcharging and extend battery life, charging the battery pack is prohibited when the battery pack SOC is too high. We think that the regenerative braking of the motor is prohibited when the SOC of the battery pack exceeds 90%, and only hydraulic braking systems should be employed instead [78].

3.2.2. Fuzzy Control Rules

Fuzzy control is a form of intelligent control of a control strategy and/or behavior of a controlled object using expertise. This expertise is expressed in terms of If–Then rules and linguistic variables. As shown in Figure 6a, the architecture of fuzzy control contains five main components: fuzzy variables, fuzzification, knowledge base, reasoning machine, and defuzzification [79]. Fuzzy variables are the condition variables that determine the state of

the program to be observed and the action to be considered for control. For example, in general control problems, the input variables are the output error and the rate of change of the output error, whereas fuzzy control also uses the control variables as inputs for the next state. Fuzzification converts the input values to the values of the domain in appropriate proportions, using linguistic variables (e.g., large, medium, and small) to describe the process of measuring physical quantities and the relative degree of affiliation of the values according to the appropriate linguistic value, which are called fuzzy sets. The knowledge base consists of two parts, a database and a rule base, where the database provides definitions related to the processing of fuzzy data and the rule base describes the control goals and strategies by a group of linguistic control rules. The inference machine mimics the fuzzy concepts of human judgment and uses fuzzy logic and fuzzy inference to make inferences and obtain fuzzy control signals. Defuzzification converts the fuzzy values obtained from the inference into explicit control signals, which are used as inputs to the system.

The fuzzy controller uses braking strength z , vehicle speed u , and SOC as input variables and the regenerative braking coefficient k as the output variable. A Mamdani-type fuzzy controller is used, as shown in Figure 6b. The braking intensity z generally varies between 0 and 1, so the domain of the braking intensity is $z = [0, 1]$, and the fuzzy set is {L M H SH}, where L, M, and H represent “low”, “medium”, “high”, and “very high” for braking intensity, respectively. The driving speed range of the electric vehicle is $u = 0\text{--}140$ km/h; when the vehicle speed is too slow, the motor speed is low and it is not suitable for braking energy recovery, so the domain of the vehicle speed is $u = [0, 140]$, and the fuzzy set is {L M H SH}. The state of charge range of the battery is often expressed as $\text{SOC} = 1\text{--}100\%$. When the SOC value is too large or too small, braking energy recovery is not appropriate. The domain of SOC is $\text{SOC} = [0, 1]$ and the fuzzy set is {L M H SH}. The output of the fuzzy controller is the regenerative proportionality coefficient k . The k represents the ratio of the regenerative braking force to the total braking force of the front wheels, and the larger the value of k , the larger the regenerative braking force; k is between 0 and 1. Therefore, the domain of the regenerative proportionality coefficient is $k = [0, 1]$, and the fuzzy set is {SL L M H SH}, and SL, L, M, H, and SH represent “very small”, “small”, “medium”, “large”, and “very large” for the regenerative proportionality coefficient k . The membership functions μ of the input and output of the fuzzy controller are both expressed as Gaussian functions:

$$\mu(y, \sigma, c) = e^{-\frac{(y-c)^2}{2\sigma^2}}, \quad (43)$$

where σ and c are the shape and center position of the function curve. Figure 6c shows the membership function diagram of each fuzzy variable.

The designed fuzzy controller has three inputs and one output, and the fuzzy rules are in the form of If–Then rules:

$$\begin{aligned} \text{Rule } R_i: & \text{ IF } z \text{ is } \mathcal{N}_1^i \text{ AND SOC is } \mathcal{N}_2^i \text{ AND } u \text{ is } \mathcal{N}_3^i \\ & \text{ THEN } k \text{ is } \mathcal{W}^i, i = 1, 2, \dots, n, \end{aligned} \quad (44)$$

where $\mathcal{N}_1^i$, $\mathcal{N}_2^i$, $\mathcal{N}_3^i$, and $\mathcal{W}^i$ are the fuzzy set and n is the total number of fuzzy control rules. The design based on fuzzy logic control rules should follow the following principles:

(1) The braking requirements of the driver are related to driving safety, and the value of braking intensity represents the braking distance and time required by the driver. If the braking intensity is high, it indicates that the vehicle should stop for a short distance and time, and the proportion of the regenerative braking force should be reduced at this time. When the braking strength is moderate, the proportion of the regenerative braking force should be increased. In the case of low braking force, a larger regenerative braking force can be applied to the vehicle.

(2) When the state of charge of the battery is less than 10%, the internal resistance of the battery is high, and it is not suitable to charge it. In this case, the proportion of regenerative braking force should be reduced. When the SOC value is within the range of 10% to 90%, the battery can withstand high-current charging, and the proportion of regenerative braking force should be increased. When the SOC value is greater than 90%, to prevent battery deposition, the charging current should be reduced, and regenerative braking should no longer be used.

(3) Vehicle speed is closely related to braking safety, and when conducting regenerative braking, the speed of electric vehicles should be taken into account to a large extent. When the vehicle speed is low, the proportion of regenerative braking force can be increased to the maximum. When the vehicle speed is moderate, in order to ensure braking safety and meet relevant regulations, the proportion of regenerative braking force should gradually decrease. When the vehicle speed is very high, the regenerative braking force can be further reduced. This is because at high speeds, the safety and stability of the vehicle must be ensured first.

(4) The value of the regenerative proportionality coefficient indicates the proportion of energy output by the motor. When the regenerative proportionality coefficient is small, it indicates that the motor participates less in the braking process, and at this time, the energy recovery is also less. As the regenerative proportionality coefficient increases, it indicates that the participation of the motor in the braking process is also increasing, leading to a gradual increase in the recovery of braking energy.

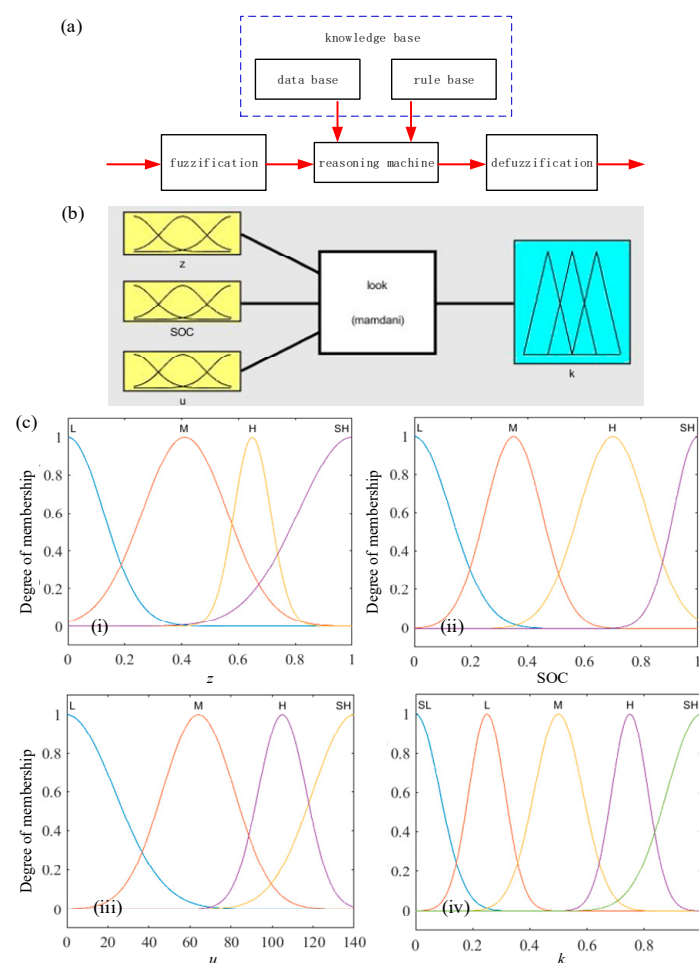


Figure 6. Fuzzy control rules: (a) architecture of fuzzy control; (b) Mamdani-type fuzzy controller; (c) degree of membership; (i) z ; (ii) SOC; (iii) u ; and (iv) k .

Fuzzy rules are designed based on existing logical knowledge and expert experience, so different standards are set during the control process, resulting in different results. There are a total of 64 fuzzy control rules in the fuzzy inference machine, and the surface diagram of the fuzzy control rules is shown in Figure 7. Table 4 further provides a table of fuzzy control rules.

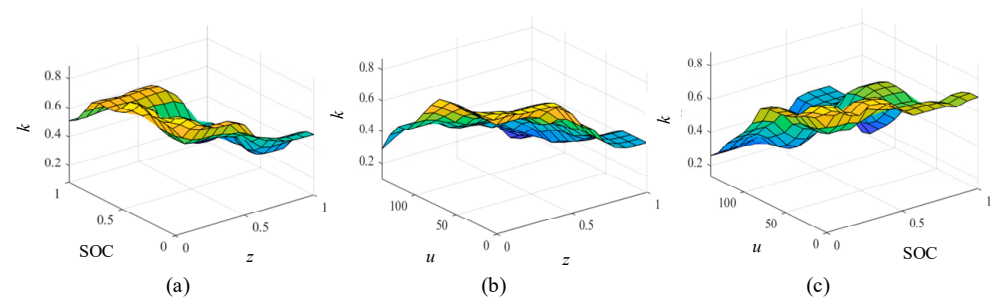


Figure 7. Surface diagram of the fuzzy control rules: (a) z -SOC; (b) z - u ; (c) SOC- u .

Fuzzy logic reasoning is based on fuzzy logic, which is an uncertainty reasoning method, and methods such as Zadeh's method, Baldwin's method, Tsukamoto's method, Yager's method, and Mizumoto's method have been proposed [80–82]. The Zadeh operator includes maximum and minimum operations [83]. The function $\min(A, B)$ is used to parse statements A and B. The membership value of k is expressed as follows:

$$\mu_{W^i}(k_i) = \min\{\mu_{N_1^i}(z), \mu_{N_2^i}(SOC), \mu_{N_3^i}(u)\}. \quad (45)$$

Table 4. Fuzzy control rules.

z	Input SOC	u	Output k	z	Input SOC	u	Output k
L	L	L	SH	M	L	L	SH
		M	SH			M	H
		H	H			H	M
		SH	M			SH	L
	M	L	SH		M	L	SH
		M	SH			M	M
		H	M			H	L
		SH	L			SH	L
	H	L	SH		H	L	H
		M	H			M	H
		H	H			H	M
		SH	L			SH	M
	SH	L	H		SH	L	H
		M	M			M	M
		H	L			H	L
		SH	SL			SH	SL
H	L	L	H	SH	L	L	H
		M	M			M	M
		H	M			H	M
		SH	L			SH	L
	M	L	M		M	L	M
		M	M			M	L
		H	L			H	L
		SH	L			SH	SL
	H	L	M		H	L	L
		M	L			M	L
		H	L			H	SL
		SH	SL			SH	SL

Table 4. Cont.

z	Input SOC	u	Output k	z	Input SOC	u	Output k
		L	M			L	L
		M	L			M	SL
		H	SL			H	SL
		SH	SL			SH	SL
	SH				SH		

The process of selecting a single value that relatively best represents the fuzzy set obtained through inference is called fuzzy decision. Fuzzy decision can adopt different methods: the center of gravity method, maximum membership degree method, weighted average method, and limited element average method of membership degree. In the center of gravity method, the membership degree of each variable represents its importance in the fuzzy set, while the value of the variable represents its position in the fuzzy set. By multiplying the membership degree of variables and their values and summing all variables, the center of gravity position of the fuzzy set can be obtained. Specifically, the formula for the center of gravity method can be expressed as [84]

$$k = \frac{\sum_{i=1}^n k_i \mu(k_i)}{\sum_{i=1}^n \mu(k_i)}, \quad (46)$$

where $\mu(k_i)$ is the membership value of k_i .

3.2.3. Structural Analysis of Fuzzy Controllers

For example, when $z = 0.1$, $SOC = 0.6$, and $u = 100$, z activates “L” and “M”, SOC activates “M” and “H”, and u activates “M”, “H”, and “SH”. Therefore, a total of 12 fuzzy control rules are activated. Table 5 provides specific fuzzy control rules. For Rule R_1 : IF z is L AND SOC is M AND u is M, the membership value of k_1 can be obtained from Equation (37). Since the membership function corresponding to $\mu(k_1)$ is “SH”, k_1 can be solved inversely. The remaining fuzzy control rules R_i can be solved similarly. Finally, an explicit value of k is obtained through Equation (46).

Table 5. Fuzzy control rules for $z = 0.1$, $SOC = 0.6$, and $u = 100$.

z	Input SOC	u	Output k	z	Input SOC	u	Output k
		M	SH			M	H
		H	H			H	M
		SH	M			SH	L
		M	SH			M	M
		H	M			H	L
		SH	L			SH	L
L	M			M	M		
	H				H		

Stability is one of the important indicators for evaluating the performance of a control system. The performance of a fuzzy controller mainly depends on factors such as its structure, fuzzy rules, inference algorithms, and fuzzy decision. Due to the inherent nonlinearity of fuzzy control and the lack of a unified system description, it is difficult to analyze and design fuzzy control systems using existing control theories and analysis methods. Therefore, stability analysis of the fuzzy control theory has always been a difficult topic and has not formed a relatively complete theoretical system, especially the Mamdani-type fuzzy controller [85,86].

3.3. Construction of Simulink Simulation

We established the model of the regenerative braking control strategy using Simulink, which mainly includes the battery charging module, the power generation module of the

motor, the braking force distribution module of front/rear axles, the maximum regenerative torque model of the front-axle motor, and the regenerative braking distribution module of the front axle. As shown in Figure 8, a Simulation platform was established relying on the regeneration control strategy (see Supplementary Materials).

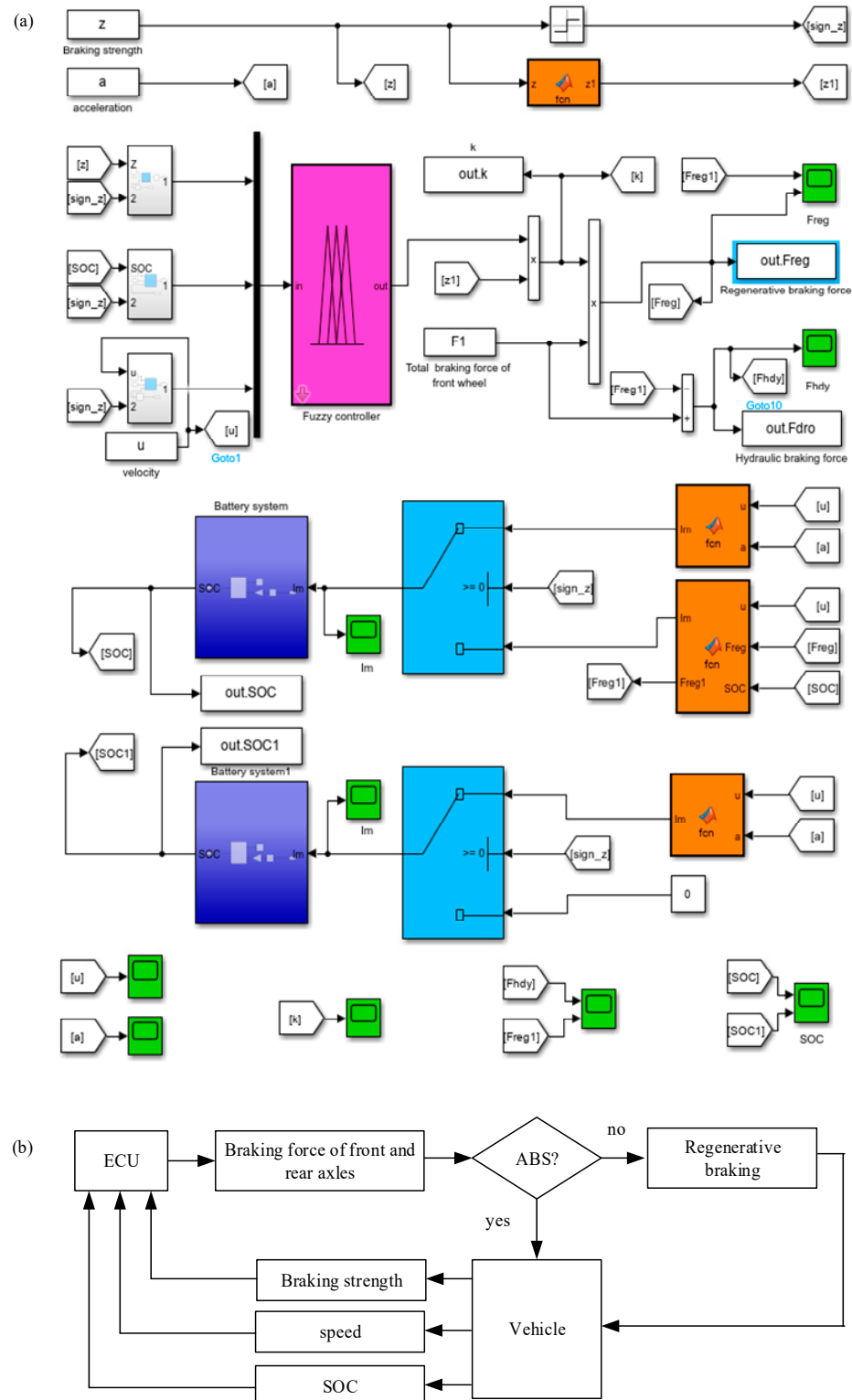


Figure 8. Regenerative braking control strategy model based on the Simulation platform: (a) Simulink blocks and (b) flow diagram of control program.

4. Results and Analysis

4.1. Variations in Regenerative Braking Coefficient

For validating the control strategy feasibility of regenerative braking energy distribution in electric vehicles, different braking force tests were conducted by simulating six different cycle conditions and calculating SOC changes. Figure 9 shows the variation in the regenerative braking coefficient. It can be seen that the smaller the time between two adjacent braking intervals, the denser the change in the regenerative braking coefficient. The smaller the braking intensity, the greater the regenerative braking coefficient. At the same time, it can be seen that the time between two adjacent braking intervals under the NEDC condition is relatively long, and braking is not frequent.

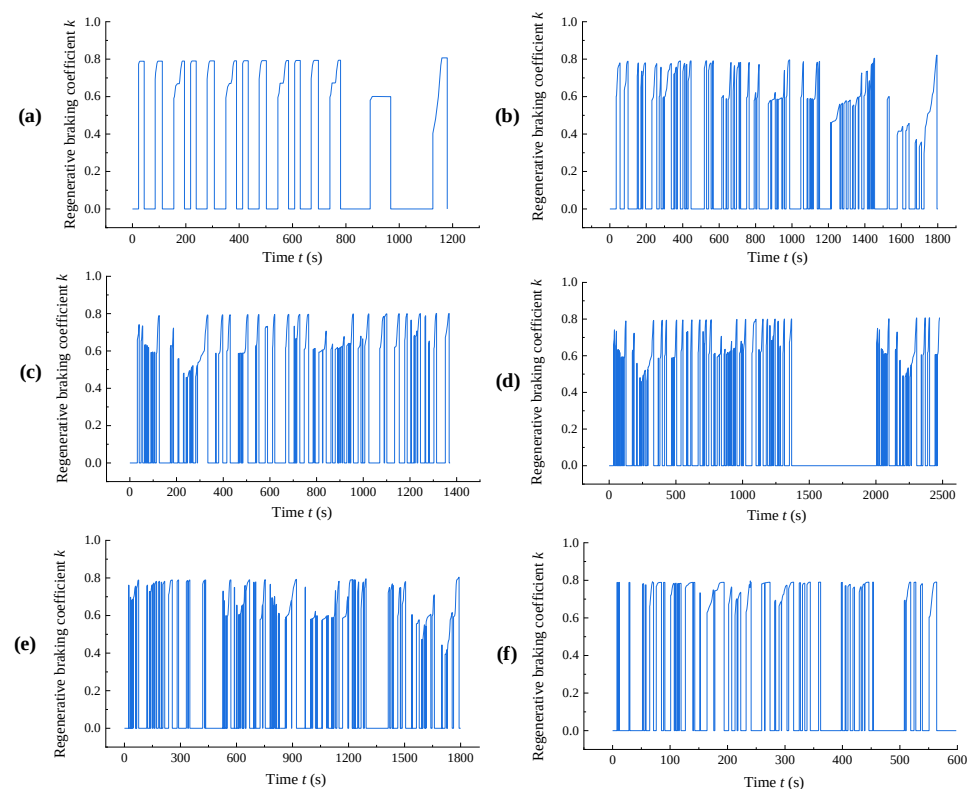


Figure 9. Variations in regenerative braking coefficient: (a) NEDC; (b) WLTC; (c) FTP-72; (d) FTP-75; (e) CLTC-P; and (f) NYCC.

Due to the constraints of SOC and maximum motor braking torque T_{emax} on the regenerative braking torque, according to the distribution rules of the front $F_1 = F_{reg} + F_{hdy}$ and rear braking force F_2 designed in Section 3.3, the braking force caused by F_{reg} during the braking process may exceed the constraint of maximum motor braking torque T_{emax} . F_{reg} is the regenerative braking force of the motor, and F_{hdy} is the hydraulic braking force. One key point is that when the braking force caused by F_{reg} during the braking process exceeds the constraint of the maximum motor braking torque T_{emax} , F_{reg} should be corrected and calculated based on the maximum motor braking torque T_{emax} (regarded as a threshold), and the part of the braking force that exceeds the maximum motor braking torque T_{emax} should be loaded onto the hydraulic braking force F_{hdy} . The specific expression is as follows:

$$\begin{cases} F_{reg} = T_{emax} i_{min} / r, F_{hdy} = F_1 - F_{reg}, F_{reg} r / i_{min} \geq T_{emax} \\ F_{reg} = F_1 k, F_{hdy} = F_1 - F_{reg}, F_{reg} r / i_{min} < T_{emax} \end{cases} \quad (47)$$

Figure 10 shows the distribution of regenerative braking force and hydraulic braking at the front axle. It can be seen that the regenerative braking force is greater than the

hydraulic braking force, and the proportion of motor braking during the braking process is larger, so the effect of energy recovery is better.

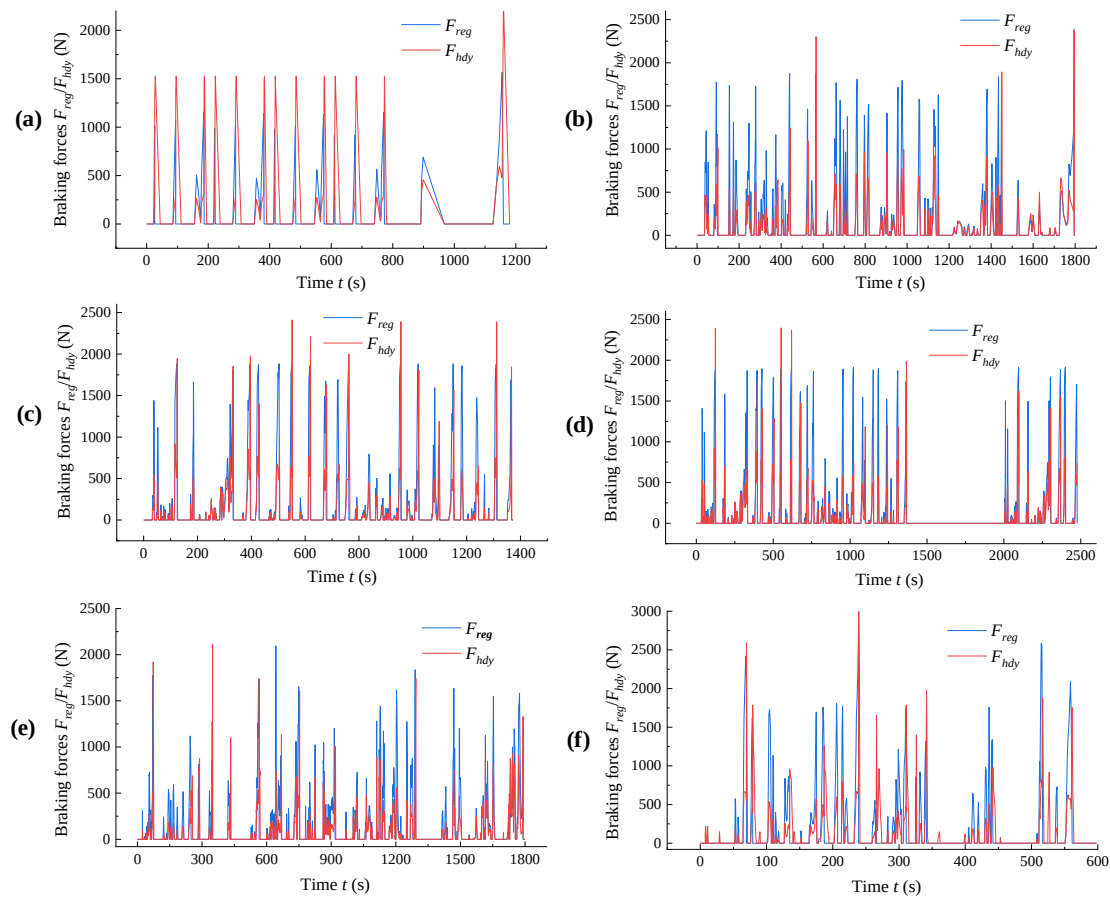


Figure 10. Braking force distribution of F_{reg} and F_{hdy} : (a) NEDC; (b) WLTC; (c) FTP-72; (d) FTP-75; (e) CLTC-P; and (f) NYCC.

4.2. Energy Recovery Performance of Regenerative Braking

According to Figure 11a, in the NEDC condition, the hydraulic braking is responsible for the majority of the braking, while the motor braking is only responsible for a minor portion. Hydraulic braking is mainly employed when the braking strength of a vehicle is too high, and motor braking is less involved or not involved in braking. The motor brake serves as the primary brake when the braking strength of the vehicle is medium, while the hydraulic brake may also be utilized. When the braking strength of the vehicle is low, just the motor contributes to the braking process. As presented in Figure 11b, in the WLTC working cycle, the frequency of engine start and stop increases, which elevates the braking frequency and the motor force, thereby increasing the motor braking efficiency. As described in Figure 11c,d, the braking force of the front axle in the FTP-72 and FTP-75 cycles ranges from 0 to 2500 N, and the proportion of motor braking force to the total braking force of the front axle is reasonable. The increase in motor braking frequency elevates its braking efficiency. As depicted in Figure 11e, in the CLTC-P cycle, the proportion of vehicles in the high-speed phase decreases, while the proportion in the idle phase significantly increases. Therefore, the usage efficiency of regenerative braking is relatively low in this driving cycle. The NYCC driving condition is shorter, but there is a frequent braking process, which consumes more energy, but the energy recovery efficiency is also larger, as shown in Figure 11f.

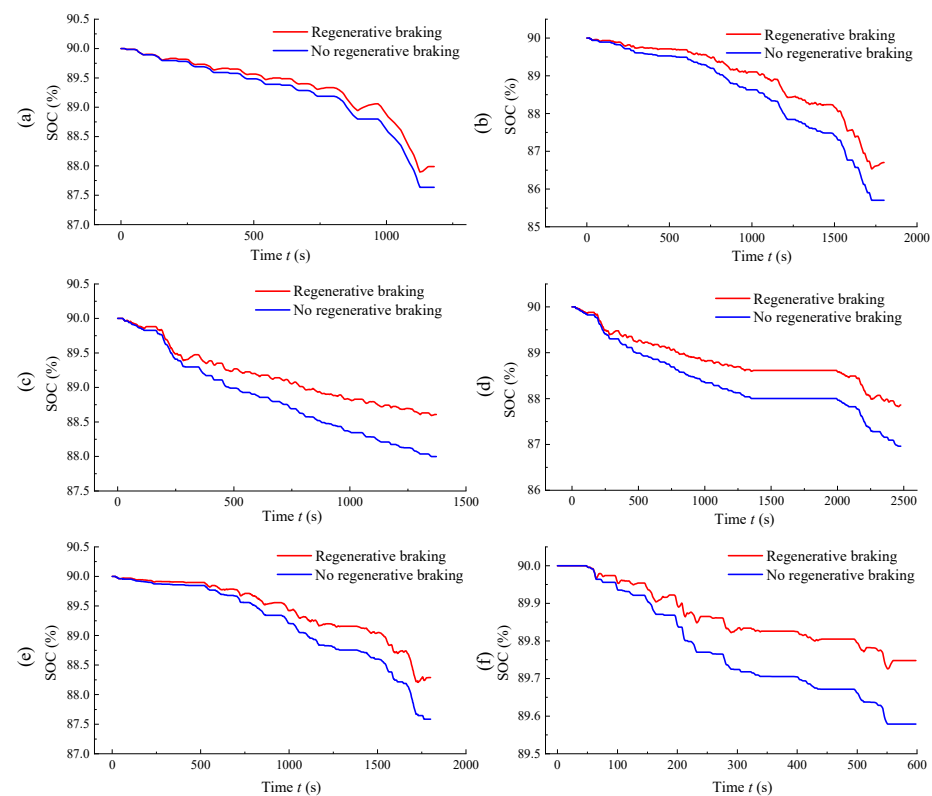


Figure 11. SOC variations: (a) NEDC; (b) WLTC; (c) FTP-72; (d) FTP-75; (e) CLTC-P; and (f) NYCC.

The trends of driving distance and energy saving efficiency for the NEDC, WLTC, FTP-72, FTP-75, CLTC-P, and NYCC conditions are given in Figure 12. Table 6 shows that the values of SOC at the end of the NEDC with and without regenerative braking are $SOC_{end} = 87.98\%$ and 87.63% . The WLTC, FTP72, FTP-75, CLTC-P, and NYCC conditions correspond to $86.70\%/85.70\%$, $88.60\%/87.99\%$, $87.86\%/86.96\%$, $88.28\%/87.58\%$, and $89.74\%/89.57\%$, respectively. Their energy saving efficiencies and driving ranges are $\varepsilon = 15.01\%/s = 11.01$ km, $23.20\%/23.26$ km, $30.51\%/11.99$ km, $29.59\%/17.77$ km, $29.16\%/14.47$ km, and $40.13\%/1.89$ km, respectively. Under the conditions of five driving cycles, the regenerative braking efficiency of electric vehicles has significantly improved, and the efficiency of regenerative braking reaches more than 15%. In addition, under the conditions of NYCC circular roads, the energy saving efficiency of regenerative braking has reached more than 40%. It can be seen that the WLTC has the longest driving range, but its energy recovery is not the highest. The driving distance of the WLTC reached 23.26 km, indicating that its braking process accounts for a relatively small proportion and the driving speed is relatively high. The NYCC has the shortest driving range but the highest energy recovery. The driving ranges of FTP-72, FTP-75, and the CLTC-P are relatively similar, and their energy recovery efficiencies are also close to 30%. The energy saving efficiency of the NEDC is the smallest, about 15%.

Table 6. SOC comparison and energy saving efficiency of braking recovery.

Driving Cycle	No Regenerative Braking			Regenerative Braking			$\varepsilon/\%$
	$SOC_{int}/\%$	$SOC_{end}/\%$	$\Delta SOC_n/\%$	$SOC_{int}/\%$	$SOC_{end}/\%$	$\Delta SOC_y/\%$	
NEDC	90	87.63	2.37	90	87.98	2.02	15.01
WLTC	90	85.70	4.30	90	86.70	3.30	23.20
FTP-72	90	87.99	2.01	90	88.60	1.40	30.51
FTP-75	90	86.96	3.04	90	87.86	2.14	29.59
CLTC-P	90	87.58	2.42	90	88.28	1.72	29.16
NYCC	90	89.57	0.43	90	89.74	0.26	40.13

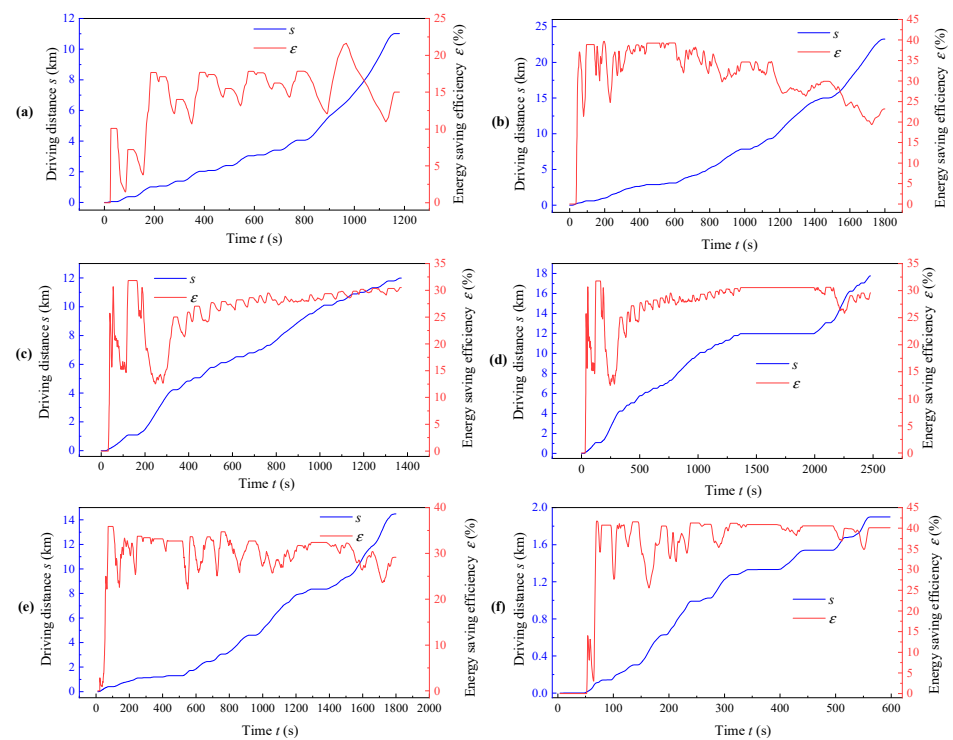


Figure 12. Diving distance s and energy saving efficiency ε curves: (a) NEDC; (b) WLTC; (c) FTP-72; (d) FTP-75; (e) CLTC-P; (f) NYCC.

4.3. Energy Consumption Analysis

As shown in Figure 13, the total energy consumptions E_{tol} and total energy recoveries E_{reg} of the NEDC, WLTC, FTP-72, FTP-75, CLTC-P, and NYCC conditions are 2145.76 kJ/322.25 kJ, 3897.38 kJ/904.27 kJ, 1816.07 kJ/554.14 kJ, 2755.22 kJ/815.39 kJ, 2191.04 kJ/639.04 kJ, and 382.18 kJ/153.381 kJ, respectively. From Figure 13, it can be seen that the WLTC has the highest total energy consumption, followed by the FTP-75, CLTC-P, NYCC, NEDC, and FTP-72 conditions. The NYCC has the smallest total energy consumption due to its short operating time.

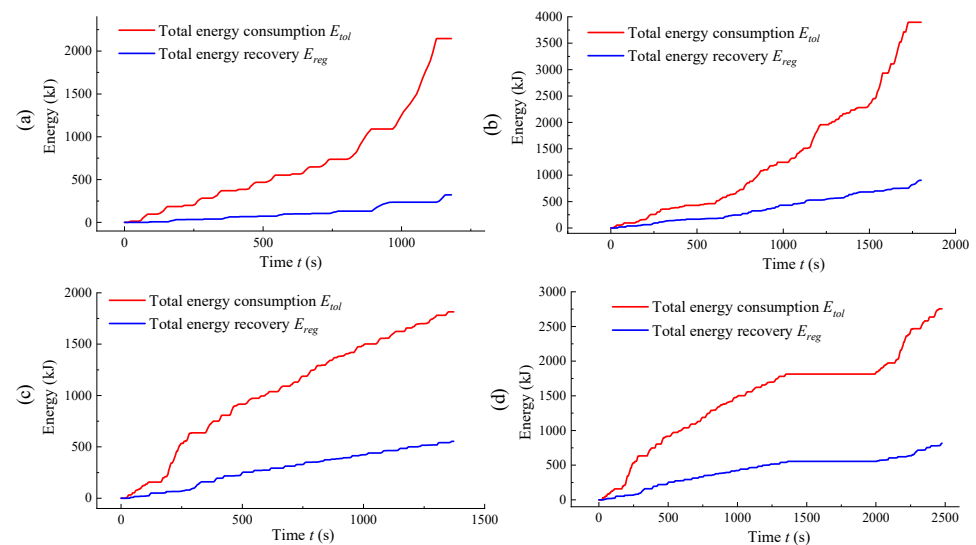


Figure 13. Cont.

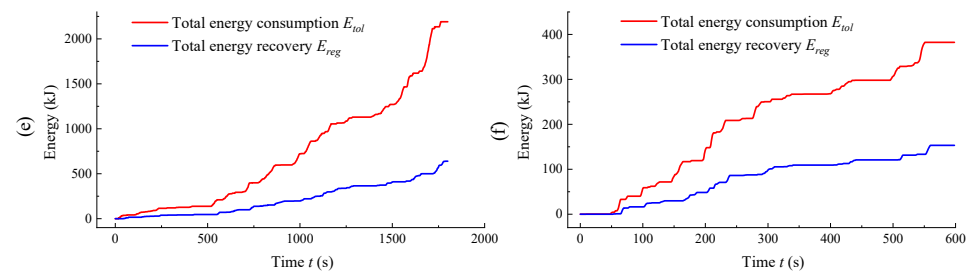


Figure 13. Variations in total energy consumption E_{tol} and total energy recovery E_{reg} : (a) NEDC; (b) WLTC; (c) FTP-72; (d) FTP-75; (e) CLTC-P; (f) NYCC.

In order to unify and compare their energy utilization rates, we introduced the energy consumption rate per 100 km and the energy recovery rate per 100 km, defined as $P_{tol} = E_{tol}/s$ (kJ/km) and $P_{reg} = E_{reg}/s$ (kJ/km). After calculation, the energy consumption rates and energy recovery rates per 100 km for the NEDC, WLTC, FTP-72, FTP-75, CLTC-P, and NYCC conditions are $P_{tol} = 194.89$ kJ/km/ $P_{reg} = 29.26$ kJ/km, 167.55 kJ/km/38.87 kJ/km, 151.46 kJ/km/46.21 kJ/km, 155.04 kJ/km/45.88 kJ/km, 151.41 kJ/km/44.16 kJ/km, and 202.21 kJ/km/81.15 kJ/km, respectively. From the above data, it can be concluded that the NYCC has the highest energy consumption rate, followed by the NEDC, WLTC, FTP-75, FTP-72, and CLTC-P conditions. The NYCC has the highest energy recovery rate, followed by the FTP-72, FTP-75, CLTC-P, WLTC, and NEDC conditions. In the NEDC, the energy consumption rate is high, while the energy recovery rate is low.

5. Comparison and Discussion

5.1. Performance of Regenerative Braking

Reference [87] investigated the energy consumption and recovery rates of different powertrain vehicle architectures, and the RESC system in the FTP-75 and NEDC urban conditions was also performed to study the energy recovery. As shown in Figure 14a, in the NEDC, the braking intensity is smaller, and the recovered braking energy is less. However, with a higher initial braking speed, the kinetic energy consumed during braking is greater, resulting in a lower braking energy recovery. The braking energy recovery is generally showing an upward trend. At $t = 1200$ s, the energy recovery efficiency almost reaches $\varepsilon = 10\%$. However, Yildiz's braking energy recovery efficiency is relatively low, and at $t = 0$ –1100 s, the energy recovery efficiency does not exceed $\varepsilon = 3\%$. As shown in Figure 14b, in FTP-75, the current braking energy recovery efficiency is relatively high due to the high braking intensity and the corresponding amount of recovered braking energy. The energy recovery efficiency shows a roughly horizontal trend and remains above $\varepsilon = 15\%$. Yildiz's braking energy recovery efficiency is also relatively low, and within $t = 0$ –2500 s, its energy recovery does not exceed $\varepsilon = 5\%$. In summary, the braking energy recovery control strategy in the present work has significant energy saving effects under two cycle conditions compared to Yildiz's work.

Research has shown that in urban driving conditions, approximately 50% or even more of the driving energy is lost during the braking process, and in suburban driving conditions, up to 20% of the driving energy is also lost during the braking process [88]. The cycle ratio of braking energy to driving energy describes the promotion of recyclable mechanical energy. The cycle ratio of ECE-15 is about 27.5%, while the cycle ratio of the NYCC is about 86% [89]. The cycle ratio of the WLTC and CLTC is about 50% [90]. Martyushev et al. [91] studied the dynamic patterns of battery charging and discharging in heavy-duty electric vehicles under various driving conditions (urban cycle and out-of-city driving conditions). The mathematical model of the battery is based on a model that includes active and reactive elements, which can be used to calculate the electrical and thermal characteristics of the battery. The input signals to the mathematical model are the current and ambient temperature obtained during the testing of the electric vehicle, and the

output signals are the voltage, electrolyte temperature, and charge. Therefore, brake energy recovery is an effective measure to improve the energy utilization efficiency of automobiles.

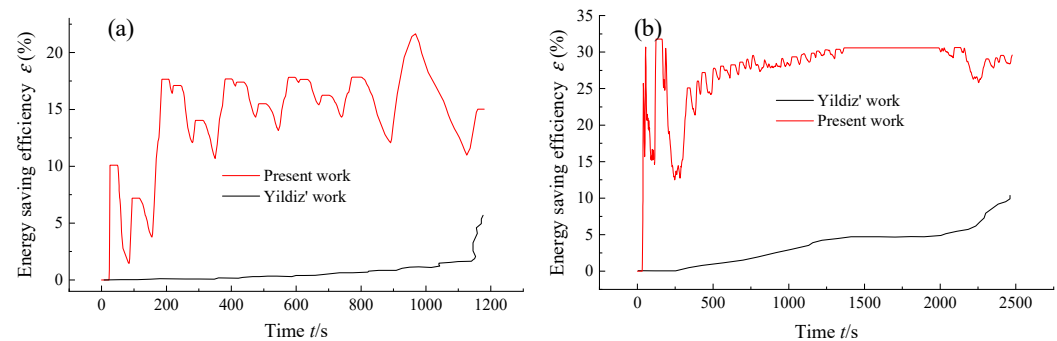


Figure 14. Comparison of energy recovery between Yildiz's work [87] and present work: (a) NEDC and (b) FTP-75.

In order to compare the energy saving efficiency of regenerative braking more comprehensively, 21 previous studies on regenerative braking are listed in Table 7 [10,11,18–21,21–26,70,92–105]. It can be seen that the energy recovery efficiency of He et al. [10], Yang et al. [11], Jiang et al. [21], Geng et al. [26], Ning et al. [27], Zhao et al. [28], Li et al. [70], Yin et al. [93], Chen et al. [94], Shang et al. [98], Chang et al. [99], Chun et al. [100], Liu et al. [101], Heydari et al. [102], and Gang et al. [105] was less than 15%. The energy recovery efficiency of Wu et al. [92], Ashok et al. [95], Liu et al. [96], Sandrini et al. [97], Chun et al. [98], Ji et al. [103], and He et al. [104] exceeded 20%, with Liu et al. [96] having an energy recovery efficiency of over 45%.

Table 7. Comparison of energy saving efficiency.

Work	Vehicle Category	Control Algorithm	Drive Cycle	Recovery Efficiency
He et al. [10]	pure electric vehicles	electro-hydraulic coordinated	WLTC	3.35%
Yang et al. [11]	electric vehicles	minimum loss	NYCC	1.18%
Jiang et al. [21]	pure electric bus	parallel regenerative braking	NEDC	17.4%
Geng et al. [26]	hybrid electric vehicles	multi parameters fuzzy	NEDC	15.55%
Ning et al. [27]	electric vehicles	fuzzy Q-learning	WLTC	11.71%
Zhao et al. [28]	hybrid electric vehicles	fuzzy optimization	UDDS	8.91%
Li et al. [70]	electric vehicles	fuzzy control method	NEDC	1.22%
Wu et al. [92]	dual-motor EVs	genetic algorithm	NEDC	9.12%
Yin et al. [93]	hybrid electric vehicles	Q-learning network	self-defined braking	22.8%
Chen et al. [94]	distributed drive electric vehicles	neural network and least square algorithm	self-defined braking	7.4%
Ashok et al. [95]	electric two wheelers	fuzzy PID	US06	9.62%
Liu et al. [96]	electric vehicles	adaptive distribution control	EUDC	5.04%
Sandrini et al. [97]	electric vehicle	RB logic	REP05	3.13%, 17%
Shang et al. [98]	electric vehicles	multi-source information fusion	WLTP Class 2	44%
Chang et al. [99]	electric vehicles	PSO fuzzy	NYCC	52.62%
Chun et al. [100]	electric vehicles	nonlinear model predictive control	NEDC	47.45%
Liu et al. [101]	range-extended electric vehicles	revised regenerative braking control strategy	WLTC	29.5–30.3%
Heydari et al. [102]	electric vehicles	optimal brake allocation	US06	23.9–24.4%
Ji et al. [103]	electric vehicles	energy recovery mode A	self-defined braking	16.1%
He et al. [104]	electric vehicles	optimization neural network	NEDC	2.5%
Gang et al. [105]	electric vehicles	energy saving control	CLTC-P	1.56%
			WLTC	30.4%
			WLTP	16.6%
			UDDS	8.09%
			FTP-75	20.39%
			NEDC	26.15%
			NEDC	6%
			UDDS	5.17%
			J1015	4.67%

Zhang et al. [106] designed a Sugeno fuzzy logic controller which has three inputs, the driver's braking requirements, vehicle speed, and battery SOC, and one output, regenerative braking force. They indicate that in the UDDS drive cycle, the energy saving efficiency reaches 22.29%. Similar to the work of Zhang et al. [106], Tao et al. [107] reported that under the NEDC, the energy recovery efficiency of four-wheel electric vehicles based on fuzzy control reached 17.6%. However, in the work of Zhang et al. [106] and Tao et al. [107], the braking force of the front and rear wheels is allocated according to a fixed ratio, which is not conducive to braking stability. In addition, both Zhang et al. [106] and Tao et al. [107] had 27 fuzzy control rules, while we achieved 64 fuzzy control rules. The accuracy of the dynamic mode of the control system is the most important factor affecting the quality of control. The more detailed the dynamic information of the system, the more precise the control that can be achieved. Cao and Ishikawa [108] used Taguchi method to optimize the fuzzy control model and claimed that they achieved an energy saving efficiency of 49.7% in driving cycles in Japan. However, the domain of fuzzy variables they involve is also too limited, and the specific expression of the regenerative braking distribution coefficient k is not mentioned in their article.

In the work of Liu et al. [96], the energy saving efficiency of the NEDC reached 52.62%, while that of the NYCC was 47.45%. In our work, the energy saving efficiency of the NEDC is 15.01%, and the NYCC is 40.13%. Sandrini et al. [97] and Chun et al. [100] reported that in the WLTC driving condition, the energy saving efficiency can reach 30%, while in our work, the energy saving efficiency of the WLTC driving condition is 23.20%. Ji et al. [103] reported an energy saving efficiency of 20.39% in the FTP-75 driving cycle, while our energy saving efficiency was 29.59%. Overall, the energy saving efficiency of regenerative braking in the current work is relatively good, and the energy saving efficiency can reach 30% under the FTP-72, FTP-75, and CLTC-P conditions. On the premise of ensuring the electrical safety of the vehicle and power battery, this strategy not only reduces the ineffective charging of the power battery during the energy recovery process and avoids damage to the battery, but also recovers more braking energy.

5.2. Prospects for other Technologies to Improve Energy Saving Efficiency

Thus far, some key technologies of power batteries have not made effective breakthroughs, and the range and charging time of power batteries have greatly restricted the development and popularization of electric vehicles. In addition to regenerative braking, some energy saving measures have been put forward one after another. Recently, Zhu et al. [109] proposed a path planning method for electric vehicles considering traffic information. This approach models real transportation networks and enables energy consumption prediction with the help of deep learning. The authors claimed a 9.9% reduction in vehicle energy consumption. Martyushev et al. [110] reviewed the energy conservation measures in terms of regenerative braking, battery charge consumption, electric transport complex, energy storage devices, and traction drive operation. The energy saving methods of new energy vehicles mainly include the following aspects:

(1) A composite energy storage system: In order to reduce the power burden of power batteries and extend their service life, a feasible method is to use different types of energy sources to form a composite energy storage system, so that different energy sources can play their respective advantages and improve the comprehensive performance of the energy storage system. According to the characteristics of different energy sources, composite energy storage systems mainly consist of fuel cells and supercapacitors, fuel cells and supercapacitors with lithium-ion batteries, flywheel energy storage and lithium-ion batteries, lithium-ion batteries and supercapacitors, and other forms.

(2) The comprehensive utilization of multiple energy sources: New energy vehicles can be synergistically utilized with renewable energy sources such as solar energy and wind energy for multi-energy approaches. The effective utilization of renewable energy reduces dependence on traditional energy sources. However, solar power generation efficiency is extremely low, and is also susceptible to factors such as weather (cloudy), environment

(with trees or building shading), and other factors; therefore, the power generation effect is quite bad.

(3) An optimized transmission management system: The scientific parameter matching of drive motors and the design of electric vehicle transmissions can ensure higher expenditure on electric vehicle power as well as energy application efficiency. In order to meet the requirements of climbing, high speed, and acceleration, the power demand can be accurately matched and managed by the intelligent control system.

(4) Autonomous driving technology: A well-planned vehicle speed is of great significance in reducing vehicle driving energy consumption. The driving energy consumption of cars in urban driving conditions mainly occurs during the starting and accelerating stages. Through the Internet of Vehicles, intelligent cars can obtain information on congestion situations and the signal light change cycle of future road sections, thereby reducing driving energy consumption by avoiding parking. Transportation big data information is a key technology to be utilized in improving the energy efficiency level of intelligent vehicles.

(5) Hybrid electric vehicles: Hybrid vehicles have high fuel economy and superior driving performance. The engine of hybrid vehicles requires fuel, and during starting and accelerating, these vehicles can reduce fuel consumption with the assistance of electric motors. The plug-in hybrid electric vehicle adopts a design of electric and fuel hybrid systems combined with advanced energy management systems and intelligent control technology, making energy utilization more efficient.

(6) Intelligent charging technology: The core of intelligent charging lies in connecting the information of vehicles, batteries, navigation maps, and charging networks to achieve intelligent charging. A charging facility management system based on the internet of vehicles and big data technology can monitor, schedule, and manage charging stations as well as provide path optimization technical support for charging vehicles. Intelligent charging technology can optimize the energy usage process, thereby achieving energy conservation and reducing waste.

Martyushev et al. [110] reported that in the composite energy storage system, the application of electro-mechanical storage increased the energy saving coefficient by 40.61%. By optimizing the power distribution between supercapacitors and batteries, the energy consumption has been reduced by 5%. By optimizing the parameters of the flywheel device and energy management strategy, the energy efficiency has been improved by 4.1–6.7%. In the comprehensive utilization of multiple energy sources, based on the energy management model of solar cells, solar cells can output 450 to 900 watts of energy for electric vehicles. Liu et al. [111] showed that hydrogen fuel cell electric vehicles have higher operating efficiency than traditional gasoline internal combustion engine vehicles, and well-to-wheel experiments have shown that using hydrogen fuel cell electric vehicles can reduce fossil fuels by 5–33%. In the optimized power management system, Martyushev et al. [110] indicated that through transmission optimization, energy saving efficiency can reach 3–8%, while the implementation of in-wheel motor technology on electric vehicles can achieve energy savings of up to 21.4%. Regarding autonomous driving technology, Martyushev et al. [110] showed that through the use of a quasi-optimal cycle based on dynamic planning, battery degradation was reduced by 15.5%, and through the automation of vehicle processes, energy efficiency was improved by 10–15%. Regarding hybrid electric vehicles, by applying plug-in hybrid vehicles, energy management strategies can reduce energy consumption by 48%. Regarding intelligent charging technology, Fotouhi et al. [112] demonstrated that driving data and traffic information have significant benefits for vehicle energy efficiency. The authors discussed the promotion of energy conservation efficiency in electric vehicles from three aspects: traffic monitoring and management systems, intelligent energy management systems in vehicles, and the intelligent management of charging issues. Inci et al. [113] reviewed the application of electric vehicles in vehicle grid integration (VGI). The authors supported this VGI technology, as virtual power plants will be a practical and economical solution for the energy sector.

6. Conclusions

The common high-performance electric vehicles have a range of up to 600 km, but the gap between the operating range and actual range is very large, especially in low- and high-temperature environments where the problem of range attenuation is particularly evident. With the increase in service life and driving distance, the battery life of electric vehicles is reduced by nearly 50%. The range of new energy vehicles is relatively short compared to traditional fuel vehicles, which has raised concerns about long-distance travel. Regenerative braking, composite energy storage systems, the comprehensive utilization of multiple energy sources, optimized transmission management systems, autonomous driving technology, hybrid electric vehicles, intelligent charging technology, and other technologies have been proposed to relieve the mileage anxiety problem of electric vehicles.

The advantages of regenerative braking energy recovery are that it not only improves energy recovery efficiency, but also reduces mechanical wear and tear in mechanical and hydraulic braking, achieving more precise braking control. In order to fully utilize the energy recovery capacity of the motor and improve energy recovery efficiency, it is necessary to increase the proportion of regenerative braking torque of the motor in the braking torque of the entire vehicle as much as possible. Inspired by this, the braking force distribution of the front and rear axles in electric-vehicle-integrated front-wheel driving was studied under various braking intensities relying on the I curve, f curve, and ECE rules. The regenerative braking torque of the motor was used to allocate the regenerative braking force of the front-axle motor based on fuzzy control. The MATLAB/Simulink simulation platform was used to build the experimental models, and six different cycle conditions were selected for a comparative analysis of regenerative braking and non-regenerative braking. The main conclusions are as follows:

(1) Considering the electrical characteristics of the motor and battery, the maximum braking force of the motor is used as a logical threshold in the distribution of hydraulic braking force and regenerative braking force to optimize the participation of regenerative braking.

(2) Our findings revealed that the distribution strategy of regenerative braking force can significantly increase the energy saving efficiency of electric vehicles, with an energy recovery efficiency of over 15%. Under the conditions of NYCC driving, the energy saving efficiency of regenerative braking has reached over 40%. The energy recovery efficiency of the FTP-72, FTP-75, and CLTC-P conditions has also reached 30%.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/pr11102985/s1>, Procedure: procedure (main.m, procedure.slx, and lock.fis).

Author Contributions: Writing—original draft, writing—review and editing, Z.Y.; writing—review and editing, funding acquisition, project administration, supervision, X.M.; investigation, visualization, R.S.; writing—original draft, Z.H.; visualization, C.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the University Natural Science Research Project of Anhui Province, grant numbers KJ2020A0826, 2022AH051885, 2022AH051891, 2022AH030160, and 62303231, and Intelligent Detection Research Team Funds for the Anhui Institute of Information Technology, grant number AXG2023_kjc_5004. The APC was funded by the University Natural Science Research Project of Anhui Province, grant number 2022AH051885.

Data Availability Statement: The data used to support the findings of this study are available from the corresponding author upon request.

Acknowledgments: The author thanks the developers of MATLAB software.

Conflicts of Interest: The authors declare no conflict of interest.

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