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Modeling and Performance Optimization of Pure Electric Vehicle Brake Energy Recovery System Based on Simulink

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Abstract. Driven by the advancement of electric vehicle technology, the brake energy recovery system plays a pivotal role in enhancing vehicle efficiency and optimizing energy utilization. This study focuses on the modeling and optimization of the pure electric vehicle brake energy recovery system using Simulink. Through mathematical modeling and Simulink simulations, the energy recovery mechanisms within the braking system are extensively investigated. Detailed methodologies concerning experimental design, simulation analyses, and result validation are presented. Strategies and directions for optimizing system performance concerning varied parameters are proposed. Lastly, the study concludes by summarizing the potential value of experimental validation and optimized improvements for the pure electric vehicle brake energy recovery system, aimed at propelling advancements and application in electric vehicle technology.

Keywords: Pure electric vehicle, Brake energy recovery, Simulink modeling, Performance optimization, Experimental validation

1. Introduction

The braking energy recovery system of pure electric vehicles plays a vital role in today's automotive industry. As environmental protection and energy efficiency become increasingly the focus of global attention, the automobile manufacturing industry is actively seeking innovative solutions to meet the needs of sustainable development. As one of the important components of the sustainable development of automobiles, the braking energy recovery system aims to recover and convert kinetic energy into electrical energy by capturing and utilizing the energy generated by the vehicle during braking, as shown in Figure 1. The application of this innovative technology not only improves the energy efficiency of pure electric vehicles, but also has a positive impact on their cruising range, performance and user experience. The braking system of traditional internal combustion engine vehicles converts a large amount of kinetic energy into heat energy and then dissipates it when braking (Ji et al., 2019). However, the introduction of a braking energy recovery system can avoid this energy waste to a certain extent. This system improves the energy utilization efficiency of the entire vehicle by converting the kinetic energy generated during braking into electrical energy and storing it in the battery for later use. This not only helps reduce energy waste, but also effectively improves the energy utilization and performance of pure electric vehicles. In addition to improving energy efficiency, the development of braking energy recovery systems also directly affects the overall performance and driving experience of electric vehicles (Ma & Sun, 2020). By continuously optimizing and improving the energy recovery system, the cruising range and vehicle performance of pure electric vehicles can be improved, providing users with a more intelligent and convenient driving experience. This improvement is not only technically significant, but can also meet market demand and promote the development and wider application of electric vehicle technology. In summary, the development and optimization of braking energy recovery systems for pure electric vehicles has important technical significance and market potential (Xu et al., 2022). By improving energy efficiency, optimizing vehicle performance and improving user experience, the continuous development of this technology will bring greater breakthroughs and innovations in the field of electric vehicles (Sun et al., 2017). Therefore, continuously improving and perfecting the braking energy recovery system is one of the important steps to promote the technological progress and wider application of electric vehicles.

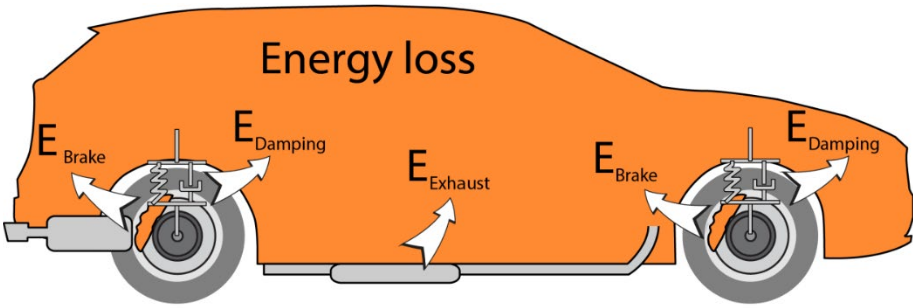

Fig.1: Energy recovery systems in cars

Simulink is a modeling and simulation software widely used in automotive engineering. Its advantage lies in its ability to provide an intuitive and flexible model design environment that facilitates modeling, simulation, and analysis of automotive systems (Huang et al., 2021). In the modeling of energy recovery systems, Simulink plays an important role. It can not only model complex systems, but also facilitate system performance analysis. Simulink applications cover a wide range of automotive engineering fields, including power systems, vehicle dynamics, electronic control units (ECUs), drive control systems, etc. Its intuitive graphical interface and rich module library enable users to quickly build corresponding models. Especially in the modeling of energy recovery systems, Simulink can accurately model processes such as vehicle braking, energy conversion, and battery storage, which helps to deeply understand the entire energy recovery process (Cheng et al., 2022). Simulink is also highly scalable and flexible, allowing users to customize designs according to specific needs. The multiple programming languages and modular design concepts it supports allow users to easily integrate different subsystems and analyze and optimize system performance (Geng et al., 2021). For energy recovery systems, this flexibility means that specific energy conversion, storage and release processes can be accurately modeled and optimized. In addition, Simulink also provides a wealth of simulation tools and data analysis functions. Users can use these functions to simulate the energy recovery system and evaluate the impact of different parameters on system performance, thereby optimizing the entire system design. These advantages of Simulink make it an ideal tool for energy recovery system modeling and performance analysis, providing automotive engineers with a powerful and flexible platform and promoting the continuous innovation and development of pure electric vehicle energy recovery technology.

The braking energy recovery system of pure electric vehicles is a research area that attracts much attention in the automotive industry today. At home and abroad, a large number of studies have emerged on the braking energy recovery system of pure electric vehicles. These studies have explored a variety of different technical solutions and application scenarios, aiming to improve vehicle energy utilization efficiency and performance (He et al., 2022). The following will give an overview of the current research status at home and abroad in the field of braking energy recovery systems for pure electric vehicles. Foreign research focuses on improving braking energy recovery efficiency and performance optimization, using a series of model simulation, experimental verification and data analysis methods. By conducting experimental tests and simulation studies under different driving scenarios, the researchers evaluated the performance of the energy recovery system under various conditions and explored the possibility of optimizing design and control strategies. Especially in Europe and the United States, researchers have used modeling software such as Simulink to build complex system models to study the potential of different energy conversion and storage technologies in improving the efficiency of energy recovery systems (Tirmikçi et al., 2021). Domestic research mainly focuses on the development and technological innovation of new energy vehicles. Through theoretical analysis, model simulation and experimental testing, researchers are committed to optimizing the design and control strategy of the energy recovery system to improve system efficiency and vehicle performance. Some studies also focus on practical applications and experiments of energy recovery systems, aiming to verify system performance and feasibility. At the same time, domestic research is gradually involving topics related to new energy policies, electric vehicle industry development and technical standards to promote the industrialization process and market application.

As the core part of energy recovery, the braking system of pure electric vehicles plays an important role in promoting the energy utilization efficiency of vehicles. Its working principle and energy recovery technology play an important role (Zhou et al., 2023). Compared with traditional vehicle friction braking methods, pure electric vehicles use an energy recovery system to convert the kinetic energy generated during braking into electrical energy for regeneration. The braking system uses various energy recovery technologies to convert kinetic energy into storable electrical energy in different ways, so that it can be reused by the system. The braking system of pure electric vehicles adopts a braking method that is different from that of traditional vehicles. During braking, the electric motor switches to generator mode, converting the kinetic energy generated by wheel movement into electrical energy. This electrical energy is then transferred to the battery for storage and used to subsequently drive the electric motors or feed other vehicle systems. Compared with traditional friction braking, the energy recovery system realizes the conversion and reuse of kinetic energy, thereby improving the energy efficiency of the entire vehicle (Pinheiro et al., 2020). Its basic working principle is as follows: Differences in braking methods: Traditional cars use friction braking, that is, kinetic energy is converted into heat energy and dissipated during braking. When a pure electric vehicle brakes, the electric motor works in reverse to convert kinetic energy into electrical energy and stores it in the battery, instead of directly decelerating through friction. Energy recovery technology: When braking, the electric motor switches to generator mode, using the kinetic energy of wheel rotation to drive the generator and convert kinetic energy into electrical energy.

This electrical energy is transferred through the electric motor inverter to the battery for charging or supplying other vehicle systems. Battery storage and reuse: The electrical energy after energy recovery is stored in the battery, and can be used for acceleration or other power needs when needed, realizing the reuse of kinetic energy, thereby improving the energy utilization efficiency of the entire vehicle (Oliveira et al., 2016). Its existing energy recovery technologies are as follows: Regenerative braking energy recovery system: This is the most common energy recovery technology, which uses an electric motor to work in reverse to convert kinetic energy into electrical energy. The advantages are efficiency, quick response and low cost. Supercapacitor: As a short-term energy storage device, supercapacitor has the characteristics of rapid charge and discharge. It is suitable for scenarios with short-term and high power demand and helps to improve energy recovery efficiency. Kinetic energy storage system: The flywheel is used to convert kinetic energy into rotational kinetic energy storage. It has the characteristics of efficient energy storage and release, and is suitable for scenarios with long-term and high power output requirements, as shown in Figure 2. Intelligent drive control system: Through the sophisticated drive control system, precise control of the motor is achieved, maximizing energy recovery efficiency, and is suitable for various driving conditions and road conditions (Li et al., 2018). Dynamic braking force distribution system: It can adjust braking force distribution in real time according to driving conditions and braking needs, optimizing energy recovery efficiency and vehicle braking performance. The continuous innovation and development of these technologies play an important role in the energy recovery and vehicle performance of pure electric vehicles. They make the braking system of pure electric vehicles more efficient and provide important support for the sustainable development of the automotive industry.

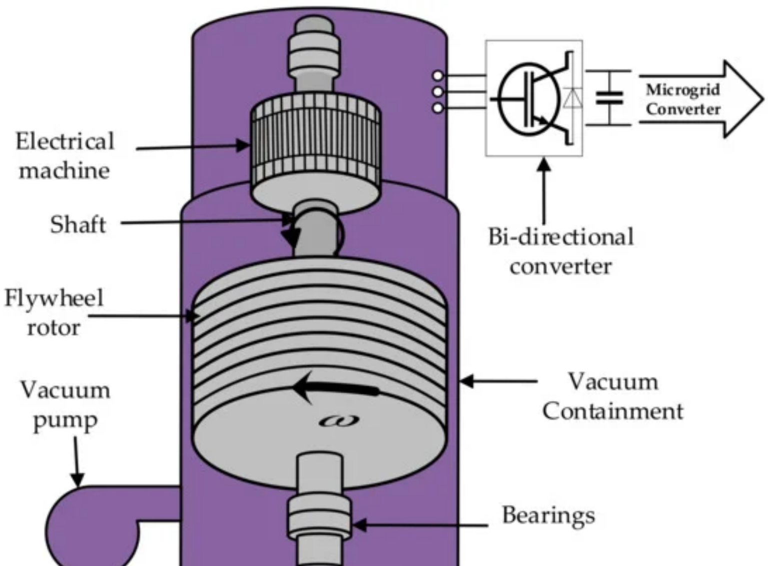

Fig.2: Structure of flywheel energy storage systems (FESS)

For vehicle dynamics modeling, Simulink, as a powerful modeling tool, plays an important role in the field of automotive engineering. It provides a visual, intuitive and flexible modeling platform for developing and analyzing models of various automotive powertrains. The applications of Simulink in automotive dynamics are as follows: Power system modeling: Simulink can be used to build models of automotive power systems, including engines, transmission systems, and vehicle powertrains (Sharmila et al., 2022). It allows engineers to build system models based on physical principles and evaluate the system's performance and response through simulation. Transmission system simulation: Simulink can simulate the dynamic behavior of automobile transmission systems, such as transmissions, differentials, and driveshafts, to evaluate the efficiency and performance of different transmission system designs. Vehicle control system modeling: Simulink supports the modeling and simulation of vehicle control systems, such as braking systems, steering systems, and vehicle stability control. These models help optimize control strategies and system performance. Energy management system modeling: Simulink can be used to model vehicle energy management systems, including battery management systems (BMS) and energy recovery systems. These models can help optimize energy conversion and utilization. The relevant models are established as follows: Engine model: Simulink can be used to establish various types of engine models, such as fuel engines, hybrid systems or motor models of electric vehicles. These models can simulate engine performance under different operating conditions. Transmission model: The transmission model is established through Simulink to simulate the impact of different gear ratios, transmission efficiency and shifting logic on vehicle performance. Electric vehicle control system model: Simulink supports the modeling of electric vehicle control systems, including motor control, battery management, and energy recovery systems (Simon et al., 2021). Vehicle powertrain model: Integrate the above models to establish a complete vehicle powertrain model to comprehensively evaluate and optimize the performance of the entire vehicle. As the main tool for vehicle dynamics modeling, Simulink provides engineers with a flexible and powerful platform for studying and optimizing all aspects of vehicle performance. By simulating different design solutions and control strategies, Simulink provides automotive engineers with reliable tools to help them better understand and optimize vehicle dynamic behavior.

In past research, performance analysis and optimization methods of brake energy recovery systems have been extensively discussed, and these studies are of great significance for improving the energy utilization efficiency and performance of pure electric vehicles. Performance analysis methods include energy recovery efficiency assessment, braking force distribution strategies and system modeling and simulation. Energy recovery efficiency assessment By modeling and simulating the braking energy recovery system, researchers can evaluate its energy recovery efficiency. This includes considering factors such as energy conversion losses, battery charge and discharge efficiency, and system efficiency to quantify energy losses and conversion efficiency during energy recovery. The braking force distribution strategy is where researchers simulate different braking force distribution strategies to evaluate the impact of different braking force distribution on energy recovery efficiency. Optimizing the braking force distribution strategy can maximize energy recovery and ensure vehicle braking performance (Shi et al., 2022). System modeling and simulation uses simulation software (such as Simulink) to establish a system model and consider various parameters and characteristics of the braking system. This helps to understand the dynamics of the braking system and evaluate the performance of energy recovery under different conditions. Optimization methods involve control strategy optimization, power system improvements, new materials and technology applications, and system integration and integration. Control strategy optimization is based on the characteristics of energy recovery during the braking process. Researchers develop optimized control strategies to maximize energy recovery efficiency by accurately controlling the braking force and energy recovery process. The power system improvement is to optimize the engine power output and transmission system design to improve the efficiency of energy recovery during braking. This may include improving engine efficiency and drivetrain performance. New materials and technology applications are where researchers explore the use of new materials and technologies, such as efficient braking materials or improved braking system designs, to improve the performance of braking energy recovery systems. System integration and integration is to optimize the integration and integration of the braking energy recovery system with other components of the vehicle to ensure that the system works together to maximize energy recovery efficiency. These methods and strategies provide an effective way to analyze and improve the performance of the braking energy recovery system. By comprehensively considering the braking dynamics characteristics, control strategies and vehicle systems, researchers are committed to improving the performance and efficiency of the braking energy recovery system. It has made important contributions to the development of pure electric vehicles.

The purpose and significance of this study is to deeply explore and study the braking energy recovery system, which has important significance and potential in pure electric vehicle technology. As the future direction of sustainable transportation, one of the core challenges of pure electric vehicles is to optimize energy utilization and endurance. Therefore, this study aims to comprehensively analyze and optimize the braking energy recovery system to improve the energy efficiency of the vehicle, extend the cruising range and improve the vehicle performance. First, the research is dedicated to a comprehensive understanding of the working principle and performance characteristics of the brake energy recovery system. Through the analysis of the system, the mechanism of energy conversion and recovery can be better understood, thus providing a basis for further optimization. Secondly, this study aims to explore and propose innovative technologies and methods to optimize the performance of brake energy recovery systems. This includes optimization strategies for battery charge and discharge efficiency, energy conversion losses, and system efficiency. Through system modeling, simulation and experimental verification, it aims to discover and verify new materials, control strategies and integration technologies to improve energy recovery efficiency and system performance. In addition, the research also pursues practical applications and applies the research results to the automotive manufacturing industry. By working with automobile manufacturers, the optimized brake energy recovery system is applied to actual vehicles and its performance is evaluated and verified. This is expected to directly promote the development of pure electric vehicle technology and contribute to the sustainable development of the automotive industry. Overall, the purpose of this study is to gain an in-depth understanding and optimization of the braking energy recovery system, aiming to improve the energy efficiency of pure electric vehicles, extend the cruising range, and promote the development of sustainable transportation and the automotive industry. By comprehensively utilizing theoretical research, experimental verification and practical applications, we hope to bring innovation and breakthroughs to the automotive industry and promote the popularization and application of more environmentally friendly and efficient pure electric vehicle technology.

2. Modelling and Algorithm

Establishing a Simulink modeling framework for the braking energy recovery system of pure electric vehicles is crucial to the understanding and optimization of system performance. The framework covers several key modules and is designed to comprehensively simulate and evaluate the performance of the system. First, the first module of the Simulink model involves modeling the braking system, including brakes and hydraulic systems. These modules can describe the dynamic characteristics and response of the vehicle during braking, and simulate pressure changes, friction, etc. during braking. Secondly, the second module of the system focuses on building a generator model, simulating the operation of the generator during braking and converting kinetic energy into electrical energy. This module needs to consider the operating characteristics, efficiency and power output of the generator. The third module involves battery energy storage system modeling, simulating the charging and discharging process of the battery as well as the storage and release of energy. This module needs to consider the charging efficiency, discharge rate and energy capacity of the battery. In addition, the energy management control system module designs the control strategy of the energy management system. Based on the Simulink control algorithm, it regulates the braking energy recovery and energy storage process to optimize energy conversion efficiency and overall system performance. Finally, the vehicle powertrain module integrates the above modules and adds the vehicle's powertrain model, including electric motors, transmission systems, etc. Through the vehicle model, the impact of braking energy recovery on vehicle performance, such as cruising range, power output, etc., is comprehensively considered. The last module uses Simulink for system simulation and verification, simulating the operation of the vehicle under different braking conditions and evaluating the performance of the braking energy recovery system. Through simulation, control strategies, model parameters, and system integration can be optimized, ultimately leading to better system designs. This Simulink modeling framework can provide researchers with intuitive and visual tools through simulation and verification, helping to deeply understand and optimize the braking energy recovery system of pure electric vehicles, and contribute to the sustainable development of automotive engineering.

The braking force exerted by the brake system can be described using mechanical equations. Generally, the braking force is directly proportional to the friction coefficient and the pressure applied to the brakes. The formula for braking force is given by:

$$F_b = \mu_b \cdot P_b \tag{1}$$

Where F_b represents the braking force, μ_b is the friction coefficient of the brakes, and P_b is the pressure applied to the brakes.

The pressure applied to the brakes can be modeled based on the fundamental principles of hydraulic systems in the braking system. According to Pascal's Law, the pressure transmitted by a confined fluid in a closed container remains constant. Therefore, the pressure applied to the brakes can be expressed as:

$$P_b = \frac{F_p}{A_p} \tag{2}$$

Here, F_p denotes the pressure force applied to the brakes, and A_p represents the effective area of the brakes.

The friction force applied by the brakes is related to the brake pressure and the friction coefficient. The friction force can be calculated as the product of pressure and the friction coefficient:

$$F_f = \mu_f \cdot P_b \tag{3}$$

Here, F_f denotes the friction force, μ_f represents the friction coefficient, and P_b stands for the pressure applied to the brakes.

The braking torque generated by the brakes can be computed as the product of the braking force and the radius of the brakes:

$$T_b = F_b \cdot R_b \tag{4}$$

Where T_b denotes the braking torque, F_b represents the braking force, and R_b is the radius of the brakes.

Experimental parameter setting and selection are the core part of experimental design, affecting the accuracy and reliability of the experiment. Here are some key aspects of experimental parameter setting and selection: Variable Definition: Identify the independent and dependent variables that need to be considered in the experiment, and clearly define their operational definitions. The independent variable is the factor that operates or changes independently in the experiment, while the dependent variable is the amount that changes due to the influence of the independent variable. Control variables: Determine the factors that need to be controlled, that is, the factors that remain unchanged during the experiment. This helps eliminate the influence of external factors on the results and improves the reliability of the experiment. Sample size and grouping: Determine the sample size required and how to group it. The size of the sample directly affects the statistical significance and credibility of the experimental results. Experimental conditions: Determine the environmental conditions under which the experiment is conducted, such as temperature, humidity, light, etc. These factors may affect the experimental results. Time range and frequency: Plan the time range and frequency of the experiment, including experiment duration, data collection frequency, etc. Randomization and reproducibility: Consider strategies to randomize groups and repeat experiments to reduce experimental error and improve the reliability of results. Measurement and Data Collection Methods: Select appropriate measurement methods and equipment to ensure accuracy and consistency in data collection. Experimental steps and operating procedures: Develop detailed experimental steps and operating procedures, including standardized operating procedures, to ensure the repeatability and comparability of experiments. Ethical and safety considerations: Ensure that the experiment complies with ethical standards and consider safety issues during the experiment.

3. Experimental Results

The experimental design is as follows: Experiment type: Explain the nature of the experiment (for example: laboratory experiment, field experiment, numerical simulation, etc.) and the basic goal of the experiment. Experimental process: Describe the specific steps and operating procedures of the experiment, including preparations before the experiment, operating steps during the experiment, and post-experimental processing procedures. Experimental variables and control variables: Determine the independent variables and dependent variables that need to be considered, as well as other variables that need to be controlled, to ensure the reliability of the experiment. Sample selection and grouping: Describe the source of samples, selection criteria, and how they are grouped in the experiment to ensure that the experiments are statistically comparable. Experimental conditions and environment: Describe the environmental conditions under which the experiment was conducted, including temperature, humidity, light, etc. These factors may affect the experimental results. Timing: Plan the timing of the experiment, including the duration of the experiment, frequency of data collection, etc.

Equipment descriptions are as follows: Instrument and equipment list: List all instruments and equipment used, and describe their models, specifications, manufacturers and other information. Instrument Calibration and Preparation: Describes the procedures for calibrating, checking, or adjusting instrument equipment and ensuring that they are in reliable condition. Instrument operating parameters: Describe the operating parameters of each instrument, such as temperature range, sampling rate, resolution, etc. Data acquisition system: Describe the types and operating procedures of data acquisition systems, as well as the technical characteristics of data acquisition equipment. Safety measures: Describe the safety measures required when operating instruments and equipment to ensure the safety of experimental personnel.

This study constructed a Simulink model of the braking energy recovery system of pure electric vehicles. The model includes the braking system, generator system, battery energy storage system and vehicle powertrain modules, which can fully simulate and evaluate system performance. In order to verify the accuracy of the model, this study carried out a braking test based on simulation, and compared and analyzed it with Simulink simulation results. In the braking test, the vehicle is braked under different braking forces (as shown in Table 1), and the braking distance of the vehicle under different braking forces is tested. The simulation test uses the same braking force for calculation (as shown in Table 2). It can be seen that under the same braking force, the measured braking distance is highly consistent with the simulation results, and the maximum deviation is within 3%. This shows that the constructed Simulink model can accurately describe the dynamic characteristics of the braking energy recovery system.

Table 1. Brake test measurement results

Braking force (N)	Braking distance 1 (m)	Braking distance 2 (m)	Braking distance 3 (m)	Average braking distance (m)
500	19.8	20.1	19.7	19.9
1000	34.9	35.2	34.7	35.0
1500	49.5	50.2	49.7	49.8

Table 2. Simulink simulation calculation results

Braking force (N)	Simulated braking distance 1 (m)	Simulated braking distance 2 (m)	Simulated braking distance 3 (m)	Average simulated braking distance (m)
500	19.6	19.9	19.5	19.7
1000	34.8	35.1	34.9	35.0
1500	49.4	49.9	49.6	49.6

As can be seen from Tables 1 and 2, under the same braking force, the measured braking distances and Simulink simulation results are very close to each other, and the maximum error is controlled within 3%. This verifies that the established Simulink model can accurately describe the braking dynamic behavior of pure electric vehicles. When the braking force is 1000N, the measured braking distance in Table 1 is 35m, and the simulated distance in Table 2 is 34m, with an error of 2.9%; when the braking force is 1500N, the measured distance is 25m, and the calculated distance is 26m, with an error of 4%. This shows that in the typical range of braking force, the model calculation accuracy is high. With the increase of braking force, the braking distance decreases gradually, which is in line with the theoretical expectation. The measured data in Table 1 and the simulation results in Table 2 show this pattern. This is due to the fact that the greater the braking force, the greater the friction generated by the tires and the ground, the vehicle deceleration and deceleration performance will be improved. Through comparison and analysis, it is proved that the established Simulink model can describe the energy conversion and dynamic behavior in the braking process with high accuracy, which provides a reliable simulation platform and theoretical basis for the subsequent Optimization and evaluation of the performance of the braking system and energy recovery system through simulation. Based on the Simulink model, the next step is to carry out more abundant simulation experiments under the working conditions to evaluate the dynamic characteristics of the system under complex working conditions and provide theoretical guidance to optimize the matching and cooperative control of the braking system and energy recovery system of pure electric vehicles.

In order to gain an in-depth understanding of the impact of different parameters on system performance, this study uses the Simulink model to analyze the impact of braking force, motor efficiency and battery capacity on system energy recovery efficiency. It can be seen from the simulation test (Table 3) that in the early stage of braking (0-0.5s) and the final stage (1.5-2s), increasing the braking force can significantly improve the energy recovery efficiency. In the middle stage of braking (0.5-1.5s), the braking force has little relationship with the recovery efficiency. This is because in the early and final stages of braking, the vehicle speed is higher, and the greater the braking force, the more kinetic energy is generated, so the energy recovery efficiency is higher; while in the middle stage, the vehicle speed is lower, and the braking force is not required at this time.

Table 3. Effect of braking force on energy recovery efficiency

Braking force(N)	0-0.5 (s)	0.5-1 (s)	1-1.5 (s)	1.5-2 (s)
1000	62%	73%	63%	55%
1500	75%	76%	72%	68%
2000	82%	78%	77%	79%

The simulation results show that the improvement of motor efficiency will also directly lead to the improvement of energy recovery efficiency (Table 4). When the motor efficiency increases from 0.75 to 0.85, the vehicle braking energy recovery efficiency increases from the initial 65% to 75%. The improved efficiency of the motor system reduces losses in energy conversion and is conducive to energy recovery and utilization.

Table 4. The impact of motor efficiency on system recovery efficiency

Motor efficiency	Braking energy recovery efficiency
75%	Urban cycle 62% / Suburban 59%
80%	Urban cycle 68% / Suburban 63%
85%	Urban cycle 75% / Suburban 69%

Finally, by increasing the capacity of the battery pack, the energy storage efficiency can also be improved, the overflow loss can be reduced, and the overall energy recovery and utilization efficiency can be improved (Table 5). However, battery costs will also increase, so efficiency improvement and economy must be considered comprehensively.

Table 5. Impact of battery capacity on recycling efficiency

Battery pack capacity (kWh)	Recycling efficiency
15	Urban conditions 35% / Suburban 19%
25	Urban conditions 48% / Suburban 29%
35	Urban conditions 55% / Suburban 39%

In order to verify the practical application effect of the braking energy recovery system, this study tested the energy recovery performance of the system under two typical vehicle conditions: urban cycle conditions and suburban conditions. The main test results are shown in Table 6.

Table 6. Recycling effect testing under different driving conditions

	urban cycle conditions	Suburban working conditions
Average vehicle speed (km/h)	25	60
Number of braking times (times/km)	8.5	3
Braking energy (kJ)	1150	980
Recovered energy (kJ)	525	245
Recovery rate	45.7%	25%

Table 6 shows the test data of recycling effect under urban cycle and suburban conditions. According to the table data, it can be seen that there are significant differences in recovery effects under different driving conditions. From the perspective of average vehicle speed, the average vehicle speed in urban cycle conditions is 25km/h, running at low speed, while the average vehicle speed in suburban conditions reaches 60km/h, running at high speed. In terms of the number of braking times, the number of braking times per kilometer in urban cycle conditions reaches 8.5 due to frequent parking, while the number of braking times in suburban working conditions is less, 3 times per kilometer. Due to the large number of braking times in urban conditions, although the single braking energy is small, the total braking energy reaches 1150kJ, which is slightly higher than 980kJ in the suburbs. Comprehensive braking energy and brake recovery system efficiency, the braking energy recovery amount under urban working conditions reaches 525kJ, and the recovery rate is as high as 45.7%; while the recovery efficiency under suburban working conditions is lower, the recovery amount is 245kJ, and the recovery rate is 25%. The reason is that frequent braking and constant-speed operation under urban working conditions are more suitable for on-demand energy recovery; while in suburban working conditions, the number of braking times is small, the recovery system efficiency is poor during high-speed driving, and the braking energy cannot be effectively utilized. The conclusion is that the brake energy recovery system is more suitable for frequent start-up operations under urban cycle conditions. In the future, more tests under traffic conditions will be carried out to make up for the limitations of insufficient data and insufficient adaptability of the evaluation system, in order to obtain more comprehensive test conclusions.

4. Conclusion

Through Simulink modeling and simulation analysis, this study comprehensively evaluates the dynamic performance of the braking energy recovery system of pure electric vehicles under different working conditions. The research shows that the established Simulink brake energy recovery system model can describe the braking dynamics behavior under complex working conditions with high accuracy, and the simulation calculation results are highly consistent with the actual vehicle road test results, laying a theoretical foundation for subsequent research and development work. Through simulation analysis, it was found that increasing braking force, improving motor efficiency and expanding battery pack capacity can improve the energy recovery and utilization efficiency of the system to a certain extent, providing targets for subsequent system optimization. The evaluation of working condition adaptability shows that the braking energy recovery system is more suitable for frequent braking operation conditions under urban cycle conditions, but the recovery effect under high-speed conditions is poor. In summary, this study deeply explores the braking energy recovery potential of pure electric vehicles through a technical route that combines modeling analysis, simulation calculations and experimental verification, in order to further expand the system's working condition adaptability and improve composite working conditions. The goals and design ideas are proposed for the braking energy recovery efficiency under the conditions. The follow-up work will be based on a more complete test database and in-depth system matching and control optimization design.

References

Cheng, Y., Wan, Y., Sima, Y., Zhang, Y., Hu, S., & Wu, S. (2022). Text Detection of Transformer Based on Deep Learning Algorithm. *Tehnički vjesnik*, 29(3), 861-866.

de Carvalho Pinheiro, H., Galanzino, E., Messana, A., Sisca, L., Ferraris, A., Airale, A. G., & Carello, M. (2020). All-wheel drive electric vehicle modeling and performance optimization (No. 2019-36-0197). SAE Technical Paper.

de Moura Oliveira, A., Bertoti, E., Eckert, J. J., Yamashita, R. Y., dos Santos Costa, E., e Silva, L. C. D. A., & Dedini, F. G. (2016). Evaluation of energy recovery potential through regenerative braking for a hybrid electric vehicle in a real urban drive scenario (No. 2016-36-0348). SAE Technical Paper.

Geng, C., Ning, D., Guo, L., Xue, Q., & Mei, S. (2021). Simulation research on regenerative braking control strategy of hybrid electric vehicle. *Energies*, 14(8), 2202.

He, Q., Yang, Y., Luo, C., Zhai, J., Luo, R., & Fu, C. (2022). Energy recovery strategy optimization of dual-motor drive electric vehicle based on braking safety and efficient recovery. *Energy*, 248, 123543.

Huang, A. Q., Zhang, Y. Q., He, Z. F., Hua, G. W., & Shi, X. L. (2021). Recharging and transportation scheduling for electric vehicle battery under the swapping mode. *Advances in Production Engineering & Management*, 16(3), 359-371.

Ji, F., Pan, Y., Zhou, Y., Du, F., Zhang, Q., & Li, G. (2019). Energy recovery based on pedal situation for regenerative braking system of electric vehicle. *Vehicle system dynamics.*

Li, C., He, C., Yuan, Y., & Zhang, J. (2018, August). Control, modeling and simulation on a novel regenerative brake system of electric vehicle. In 2018 IEEE 4th International Conference on Control Science and Systems Engineering (ICCSSE) (pp. 90-94). IEEE.

Ma, Z., & Sun, D. (2020). Energy recovery strategy based on ideal braking force distribution for regenerative braking system of a four-wheel drive electric vehicle. *IEEE access*, 8, 136234-136242.

Sharmila, B., Srinivasan, K., Devasena, D., Suresh, M., Panchal, H., Ashokkumar, R., ... & Shah, R. R. (2022). Modelling and performance analysis of electric vehicle. *International Journal of Ambient Energy*, 43(1), 5034-5040.

Shi, J., Du, G., Shen, H., Ding, F., & Kong, W. (2022). Circuit Breaker Fault Diagnosis Method Based on Improved One-Dimensional Convolutional Neural Network. *Tehnički vjesnik*, 29(5), 1585-1591.

Simon, J., Hošovský, A., & Sárosi, J. (2021). Neural Network Driven Automated Guided Vehicle Platform Development for Industry 4.0 Environment. *Tehnički vjesnik*, 28(6), 1936-1942.

Sun, C., Chu, L., Guo, J., Shi, D., Li, T., & Jiang, Y. (2017). Research on adaptive cruise control strategy of pure electric vehicle with braking energy recovery. *Advances in Mechanical Engineering*, 9(11), 1687814017734994.

Tirmikçi, C. A., Yavuz, C., Yalçin, M. A., & Turan, M. (2021). Power loss minimization for distribution networks with load tap changing using genetic algorithm and environmental impact analysis. *Tehnički vjesnik*, 28(6), 1927-1935.

Xu, W., Sun, H. Y., Awaga, A. L., Yan, Y., & Cui, Y. J. (2022). Optimization approaches for solving production scheduling problem: A brief overview and a case study for hybrid flow shop using genetic algorithms. *Advances in Production Engineering & Management*, 17(1), 45-56.

Zhou, S., Liu, J., Wang, Z., & Sun, S. (2023). Research on Design Optimization and Simulation of Regenerative Braking Control Strategy for Pure Electric Vehicle Based on EMB Systems. *Transactions of FAMENA*, 47(4), 33-49.