Enhanced Energy Recovery in Electric Vehicles Through a Simplified Regenerative Braking Method

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ABSTRACT

The rapid adoption of electric vehicles (EVs) necessitated the development of efficient energy recovery mechanisms to enhance driving range and overall system performance. This study aimed to develop a simplified regenerative braking system design, which will not only maximize the energy recovery but also reduce the energy recovery system complexity. The proposed solution used speed and braking demand of the vehicle as the main control parameters to distribute braking force between the regenerative and friction braking systems. A dynamic model of an EV was created and tested under various driving conditions - urban, highway and mixed driving cycles. The electric motor functioned as a generator when the car was braking to convert the kinetic energy into electrical energy and store it in the battery system. The proposed method is compared with the conventional braking method, and the traditional regenerative braking method. The simulation results showed that the proposed method has an energy recovery efficiency of 72.8% whereas the energy recovery efficiency of traditional regenerative braking and conventional braking systems are 66.1% and 0% respectively. Further, the charging efficiency rose to 89.8%, and the driving range was enhanced by 14.6% in urban driving. In addition, the system also lowered the energy consumption to 15.2 kWh/100 km, which is better than the traditional approaches. Moreover, when implemented the proposed method provided constant braking performance and ensured vehicle safety under all test conditions. The results showed that simpler control methods can significantly improve energy recovery and vehicle efficiency without relying on sophisticated algorithms and hardware. The proposed solution offered a viable, economical, and scalable solution for optimizing energy usage in EVs, which could be applied in a real-world setting for a sustainable transportation system.

Keywords: *Electric Vehicles, Regenerative Braking, Energy Recovery, Battery Efficiency, Vehicle Dynamics, Sustainable Transportation, Energy Management.*

1. Introduction

With the rapid increase in the number of electric vehicles (EVs) in the road transport sector, there is a new choice that is environmentally friendly, as compared with traditional internal combustion vehicles[1] (ICVs). The growing awareness of greenhouse gas emissions, the limited supply of fossil fuels and urban pollution have pushed the use of EV technology to a rapid pace all over the world. Although there has been a great deal of progress in battery technology and power electronics, the lack of driving range and energy efficiency are major barriers to the widespread adoption of EVs[2]. Vehicle cost, weight and operational efficiency are directly affected by battery capacity, so using the energy stored in the batteries to the best of the available capacity has become a critical research topic for EV development[3].

Regenerative braking is one of the most promising ways for EV efficiency improvement. As opposed to traditional braking systems, which squander kinetic energy as warmth due to rubbing, regenerative braking transforms part of the vehicle's energy into electrical power and uses this power for other functions, for example, to boost the electrical power stored in the battery for later use[4]. This not only increases energy efficiency, but it also increases driving range and decreases mechanical braking wear and tear[5]. The energy recovery capability of regenerative braking has been shown in previous research to retrieve a considerable amount of energy, especially in urban driving conditions with frequent braking/acceleration cycles[6]. However, it is still a difficult task to achieve highest energy recovery while keeping the braking safety and vehicle stability[7].

Existing regenerative braking systems often rely on sophisticated control algorithms such as fuzzy logic control, model predictive control, adaptive optimization techniques, neural networks, and artificial intelligence-based energy management systems[8]. While these strategies increase the efficiency of energy recovery, they often involve complex calculations, many sensor integrations, powerful processors and higher installation costs[9]. This complexity can constrain their application, particularly in low cost and mid-range EVs[10]. Additionally, the computational load can result in control delays and extra maintenance needs[11]. For this reason, the demand for a simplified regenerative braking strategy that provides significant energy recovery benefits is increasing, but without complex control architectures[12].

This research introduces a simplified method to improve energy recovery in EVs, and reduce the complexity of the system, in regenerative braking. The suggested method takes vehicle speed and braking needs as key decision criteria for managing the regenerative braking operations. The system uses a simple control system that optimizes energy recovery, battery charging efficiency, and braking stability. The proposed method aims to provide an efficient and economically viable solution that can be readily implemented in a wide range of electric vehicle platforms without the need for advanced computational resources.

The novelty of this research is the creation of a simple regenerative braking framework that can not only recover a significant amount of energy by achieving high energy-recovery efficiency, but also has a comparatively lower computational complexity than conventional intelligent braking systems. The proposed method uses a lightweight decision mechanism that relies on the vehicle speed and braking demand in real time, while other methods rely on artificial intelligence, predictive control, optimization based algorithms, etc. The framework is tailored to maximize recoverable braking energy while ensuring vehicle safety, battery protection, and operational reliability. Besides, the proposed method has proven that significant gains in energy recovery and driving range can be realized without the need of costly hardware enhancement and advanced control infrastructure, therefore, it is suitable for large-scale commercial application.

The main goal of this research is to design and test a simplified regenerative braking system for improving the energy recovery of EVs. The objective of the research is to optimize the braking conditions to achieve maximum conversion of braking kinetic energy into useful electrical energy and maintain stable braking and passenger safety. Moreover, the research aims to optimize the efficiency of the charging power of the batteries, the driving range of the vehicles and the reduction of energy consumption in general by making good use of the regenerated energy. Yet another goal is to evaluate the proposed method for various driving conditions and compare it to the conventional braking and conventional regenerative braking system to assess the method's practical effectiveness and feasibility.

2. Literature Review

2.1 Overview of Regenerative Braking Systems

Regenerative braking is now considered as an indispensable technology for modern electric vehicles because of its capability to recover the kinetic energy of the vehicle during deceleration and to convert it into useful electrical energy[13]. Regenerative braking differs from traditional braking which converts the vehicle's kinetic energy into heat through friction, by using the electric motor to function as a generator to capture a portion of the energy and store it in the battery[14]. This helps to enhance the overall efficiency of the vehicle, increase driving range and decrease mechanical brake wear. Many research works have been conducted, with the conclusion that regenerative braking can make substantial contributions to the reduction of energy losses, especially in urban driving conditions where stop and go traffic is common[15].

The performance of regenerative braking is influenced by several parameters such as vehicle velocity, battery SoC, braking force, road conditions, and motor-generator specifications. Consequently, researchers have been working on the development of the advanced control concepts to maximize the energy recovery while maintaining vehicle safety and comfort in driving. Design development of regenerative braking systems has advanced considerably and it is now an integral part of most commercial electric and hybrid electric vehicles[15].

2.2 Conventional Regenerative Braking Control Techniques

The conventional regenerative braking systems generally use fixed control methods to allocate brake power between the regenerative and friction braking components. These systems work with a set of parameters that rely on vehicle speed and braking requirement. The goal is to ensure stable operation of the vehicle and acceptable braking while maximizing energy recovery[16].

Several studies have demonstrated that standard braking allocation methods are fairly easy to implement, and that relatively low amounts of computation are needed. Their energy recovery efficiency is usually limited, however, as the braking force distribution is not dynamically optimized under different operating conditions. Consequently, significant recoverable energy can be lost in many driving situations. In addition, a fixed-rule control strategy might not make the best use of the regen abilities of current electric vehicle systems[17].

2.3 Intelligent and Optimization-Based Braking Strategies

To overcome the drawbacks of conventional braking methods, many intelligent braking control techniques have been developed. These approaches involve using optimization algorithms, fuzzy logic systems, model predictive control, adaptive control techniques, and machine learning models to optimize the allocation of braking forces. These methods constantly monitor the status of the vehicles to ensure the right amount of regenerative braking to recover as much energy as possible.

Optimization-based regenerative braking systems have proven to be more effective than conventional regenerative braking systems. Dynamic control algorithms can adjust to changes in vehicle speed, battery condition, traffic and road conditions, etc. Other machine learning techniques have also been used to forecast driver behaviour and braking patterns, making more effective decisions on energy recovery. These techniques enhance system performance but can consume large amounts of computing power, complex sensor sets, and high-end hardware platforms, making them more costly and complex to implement.

2.4 Battery Charging and Energy Recovery Management

The efficacy of regenerative braking systems depends on the characteristics of the batteries. In the event of braking, there is a demand for the recovered electricity to be efficiently transferred and stored while not affecting battery safety or health. Many attempts have been made to study the different strategies for battery management to control charging current, avoid over charge and ensure optimum battery operating conditions[18].

The advanced battery management system (APMS) features state of charge monitoring, temperature management, and charging control functions to help maximize energy recovery. Research shows that restrictions on battery charging can have a significant impact on regenerative braking performance, especially at near-end-of-life battery states of charge. Therefore, to maximize the utilization of energy recovery rate, the cooperation between a braking control system and a battery management system is required to guarantee reliability of the batteries during long periods of use[19].

2.5 Vehicle Stability and Safety Considerations

Maximising energy recovery is one of the main goals, but the most important requirement in the design of regenerative braking is vehicle safety. If the regenerative braking force is too high, it can affect vehicle stability, traction, and braking power especially in emergency braking or on slippery roads. Hence, researchers have investigated integrated braking systems whereby regenerative braking and anti-lock braking system and electronic stability control mechanisms are integrated together[20].

Several studies have shown the possible reduction of energy loss and vehicle instability with AAD. Safety-based control strategies dynamically vary the level of regenerative braking based on road conditions, wheel slip properties, and driver braking requirements. These methods contribute to ensuring the vehicle's ability to be controlled when needed and to maximize energy conversion during deceleration[21].

2.6 Research Gap

After a thorough literature review, it is found that the technology for regenerative braking of electric vehicles has made some big strides. The research papers that are available are mostly concerned with advanced optimisation techniques, artificial intelligence-based controller, fuzzy logic systems, and predictive energy management algorithms which maximise energy recovery. While efficient, these techniques also tend to be mathematically complex, rely on dense networks of sensors, demand high computational power and expensive hardware solutions. These can make their use in low cost and mass-market electric vehicles impractical[23].

In addition, numerous studies focus on the energy recovery performance and neglect to consider the simplicity of implementation, the computational efficiency and the feasibility of implementing in real-world scenarios. The existing simplified regenerative braking techniques are relatively under studied and lack conclusive evidence of their potential for significant energy recovery benefits without compromising vehicle stability and battery charging efficiency. Moreover, the present literature is limited in providing comparative evaluation for different driving cycles, such as urban, highway and mixed driving cycles.

Hence, a fundamental research gap remains in the design of a low-complexity regenerative braking strategy that can simultaneously maximize energy recovery efficiency, boost battery charging efficiency, increase driving range and ensure a reliable braking operation without using complex optimization algorithms. To that end, this study investigates a simplified regenerative braking approach particularly suitable for the trade-off between energy efficiency, implementation capability and reliability of operation in the context of EVs.

3. Problem Statement

Electric vehicles are the most popular solutions for sustainable mobility, but their range and the poor utilization of the energy they store are important issues that face these vehicles, both in their operation and acceptance by users [25]. While regenerative braking can store kinetic energy during braking and enhance the energy efficiency of the system, the current solutions are complex with the use of optimization algorithms, artificial intelligence methods and advanced control frameworks, resulting in higher computation needs, implementation costs and system complexity. However, in conventional braking systems, a significant amount of energy is dissipated into heat while braking [26]. In addition, there remains an ongoing challenge that energy recovery, battery charging efficiency, vehicle stability and braking safety will be well balanced. Hence, a simplified and cost-effective method of regenerative braking is needed to efficiently recover the braking energy, increase driving range, optimize battery utilization, and ensure reliable vehicle performance without the need for complex hardware or computing systems[27].

4. Methodology

The proposed methodology highlights the application of a simplified approach of regenerative braking for improving energy recovery in EVs. In the first step, a model of an electric vehicle was created to mimic the movement, acceleration, and braking actions of the electric vehicle in various driving conditions. In braking mode, the electric motor served as a generator to generate some of the vehicle's kinetic energy, which was stored in the battery system. The solution proposed allowed the braking torque between regenerative braking and conventional friction braking depending on the vehicle speed and braking power, making the vehicle recovery the braking energy while keeping the vehicle stable and safe. The system performance was tested in urban, highway and mixed driving cycles and the energy recovery performance is studied under different driving conditions. Various key performance parameters, including energy recovery efficiency, battery charging performance, energy consumption, braking effectiveness, and driving range improvement were measured and compared with conventional braking and traditional regenerative braking. The results from the process were then compared to determine the effectiveness of the proposed simplified regenerative braking method in improving overall vehicle energy efficiency and range.

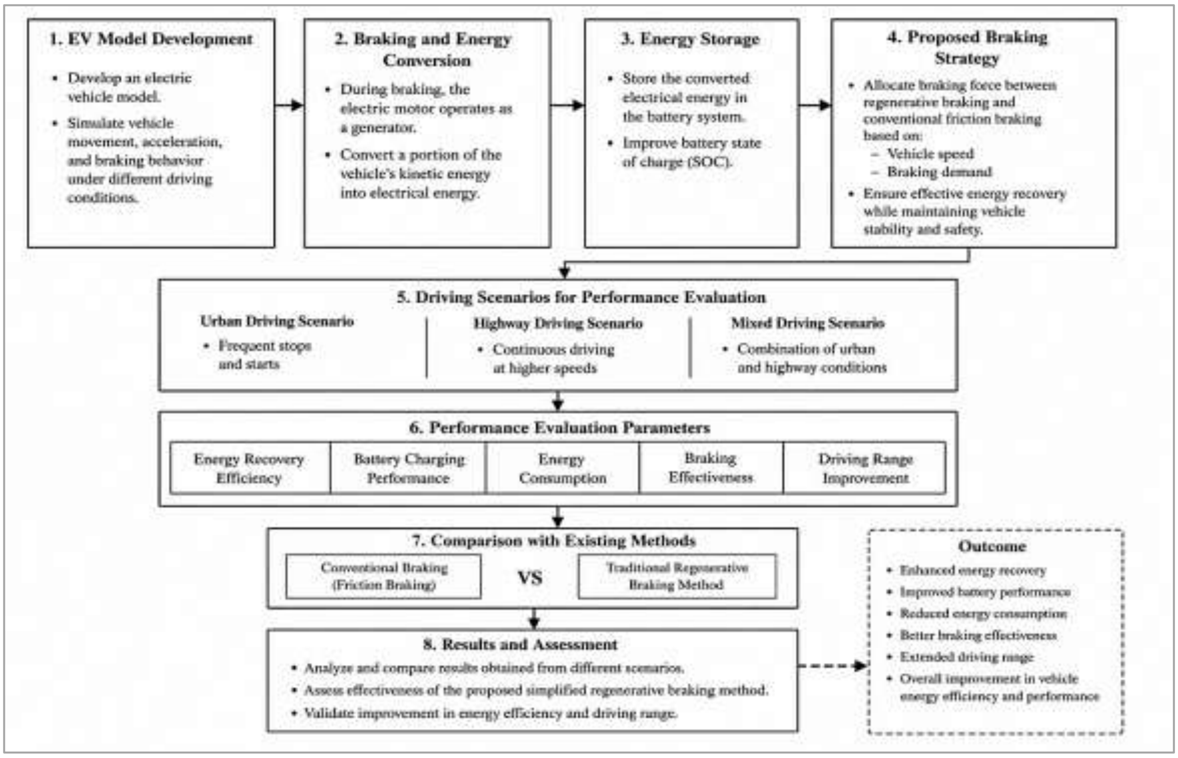

Figure 1: Proposed Methodology

The proposed methodology for improving energy recovery from EV using a simplified regenerative braking method is shown in Figure 1. It starts with electric vehicle modeling and simulation, and then braking energy conversion and storage in the battery system. A speed based braking force allocation strategy is then used to ensure balance between the regenerative and friction braking while maintaining vehicle stability and safety. Lastly, the performance of the system is analyzed by varying driving conditions for several performance indicators, including recovery efficiency, charging efficiency, energy consumption, braking efficiency and driving range improvement, to validate the effectiveness of the proposed method.

4.1 Research Framework

The proposed methodology is designed to maximize energy recovery in electric vehicles with a simple regenerative braking strategy that reduces computational complexity and maximizes the utilization of the recovered energy. The methodology includes vehicle dynamics modeling; regenerative braking force allocation; battery charging management; calculation of energy recovered; and performance assessment. Braking events are when the electrical motor works in generator mode, and is used to convert part of the vehicles kinetic energy into electricity. The recovered energy is then stored in the battery system and reused when operating the vehicle later on. The desired regenerative braking control is defined by the proposed braking framework, which involves the vehicle speed and the braking demand, which is recovered efficiently without compromising the braking stability and safety aspects.

4.2 Vehicle Dynamics Modeling

A model of a vehicle dynamics is created to analyze the forces acting on the electric vehicle during travelling and braking. In the vehicle motion along the lateral, the balance between the tractive force and resistance force determines the longitudinal vehicle motion. The total pull needed to move a vehicle is given by:

$$F_t = F_r + F_a + F_g + F_i \qquad (1)$$

where F_t is the total tractive force, F_r is the rolling resistance force, F_a is the aerodynamic drag force, F_g is the gradient resistance force and F_i is the inertial force The acceleration of the vehicle was determined based on Newton's second law:

$$F_t = m \times a \qquad (2)$$

where *m* is the (mass of the vehicle) and a means (acceleration or deceleration). This model is used as a basis for calculating the energy available during braking operations.

4.3 Regenerative Braking Model

The simple concept of regenerative braking is modeled, whereby the kinetic energy is transformed into electrical energy during deceleration. Before braking the total kinetic energy available is:

$$E_k = \frac{1}{2}mv^2 \qquad (3)$$

E_k would be the kinetic energy, *m* the mass of the vehicle and *v* its velocity. When braking, only a fraction of the energy can be recovered because of losses in the system resulting from the motor, inverter and battery charging. Recoverable energy is thus calculated as:

$$E_r = \eta_r E_k \qquad (4)$$

where E_r is the recovered electrical energy and η_r represents the regenerative braking efficiency. The proposed method seeks to maximize the value of E_r while ensuring smooth braking performance.

4.4 Simplified Braking Force Allocation Strategy

A simple braking force allocation method is applied to minimize the computational workload without compromising energy recovery capabilities. Depending on the conditions under which the vehicle is used, the braking torque applied to the vehicle is divided between regenerative braking and friction braking. The relationship is given by:

$$F_b = F_{reg} + F_{fric} \quad (5)$$

F_b is the total braking force, F_{reg} is the force of regenerative braking, and F_{fric} is the friction braking force. Since regeneration braking is less effective at low speeds, friction braking makes up a bigger part of braking at lower vehicle speeds. Regenerative braking becomes more important at medium speeds to increase the amount of energy recovered. When the vehicle is braking under high speed or emergency braking conditions, the regenerative braking system is used in conjunction with the friction braking system to ensure the stability and safety of braking.

4.5 Battery Charging and Energy Storage Model

The regenerative braking energy is being transferred to the battery via the power electronic conversion system. The power charging of battery is expressed as:

$$P_b = V_b I_b \ (6)$$

where P_b is the charging power of the battery, V_b is the battery voltage and I_b is the charging current. Total energy stored in the battery during braking is the sum of:

$$E_b = \int P_b dt \quad (7)$$

Here, E_b represents the energy stored in the battery. Efficient recovery of energy and avoiding overcharging and battery degradation can be achieved through proper battery charging management.

4.6 Energy Recovery Efficiency Analysis

The energy recovery efficiency is used to assess the effectiveness of the proposed method of regenerative braking. This parameter indicates the ratio of the available kinetic energy that is converted and stored in the battery system. The efficiency of energy recovery is given by:

$$\eta_{ER} = \frac{E_r}{E_k} \times 100 \qquad (8)$$

Here $\eta_{ER\,\mathrm{I}}$ is the percentage energy-recovery efficiency and E_r is the recovered electrical energy while E_k is the available kinetic energy prior to braking. The larger the η_E, the better is the regenerative braking performance and the better the use of energy.

4.7 Driving Range Improvement Assessment

The electricity recovered is used to directly lengthen the driving range of the EV. The range improvement as a result of regenerative braking is calculated by comparing the driving range with the proposed method to the driving range of the conventional braking system. The range improvement percentage is given by:

$$RI = \frac{R_p - R_c}{R_c} \times 100 \quad (9)$$

where, RI represents the driving range improvement percentage, R_p denotes the driving range obtained by the proposed regenerative braking method and R_c represents the driving range obtained by the conventional braking method. This practical measure of the benefits of energy recovery.

4.8 Performance Evaluation

The proposed regenerative braking approach is assessed and evaluated based on important performance factors such as energy recovery efficiency, battery charging efficiency, energy consumption, braking stability, and driving range improvement. Comparative analysis is carried out with the traditional stop solution and with traditional regenerative braking solution in various driving conditions. The results obtained are then analyzed to assess the ability of the proposed simplified strategy to improve energy recovery with safe, reliable and efficient vehicle operation.

Algorithm 1: Simplified Regenerative Braking Method

Input: V, B, SOC
Output: Recovered Energy (ER)
Begin
1. Initialize system parameters
2. Read vehicle speed V
3. Read brake input B
4. Read battery state of charge SOC
5. If B = 0 then
    Continue normal operation
  Else
6.   If V < Vlow then
        Apply friction braking
      End If
7.   If Vlow ≤ V ≤ Vhigh then
        Apply maximum regenerative braking
      End If
8.   If V > Vhigh then
        Apply combined regenerative and friction braking
      End If
9.   If SOC ≥ SOCmax then
        Reduce regenerative braking
        Increase friction braking
      End If
10.   Convert kinetic energy to electrical energy
11.   Store recovered energy in battery
12.   Update energy recovery statistics
13. End If
14. Calculate energy recovery efficiency
15. Return ER
End

5. Results and Discussion

5.1 Energy Recovery Efficiency Analysis

The main goal of the proposed simplified regenerative braking method was to maximize the kinetic energy recovered from braking events. The results of the simulation were shown to be very high energy recovery efficiency when compared with the traditional braking and traditional regenerative braking systems. The enhanced performance was mainly due to the optimized split of braking torque between the regenerative and friction braking elements under varying operating conditions of the vehicle.

Table 1: Comparison of Energy Recovery Efficiency

Braking Method	Energy Recovery Efficiency (%)
Conventional Braking	0.0
Traditional Regenerative Braking	66.1
Proposed Simplified Method	72.8

The results of the comparison of the energy recovery efficiency of the various braking methods applied to EV's are presented in Table 1 below. Conventional braking was able to recover no energy, as the kinetic energy was fully dissipated to heat, thus giving an efficiency figure of 0.0%. The traditional regenerative braking increased the energy utilization to 66.1 % of its energy recovery efficiency. The proposed simplified regenerative braking method was found to be the most efficient with an energy efficiency of 72.8%, which showed promising potential for recovering and storing braking energy for effective vehicle performance and energy efficiency.

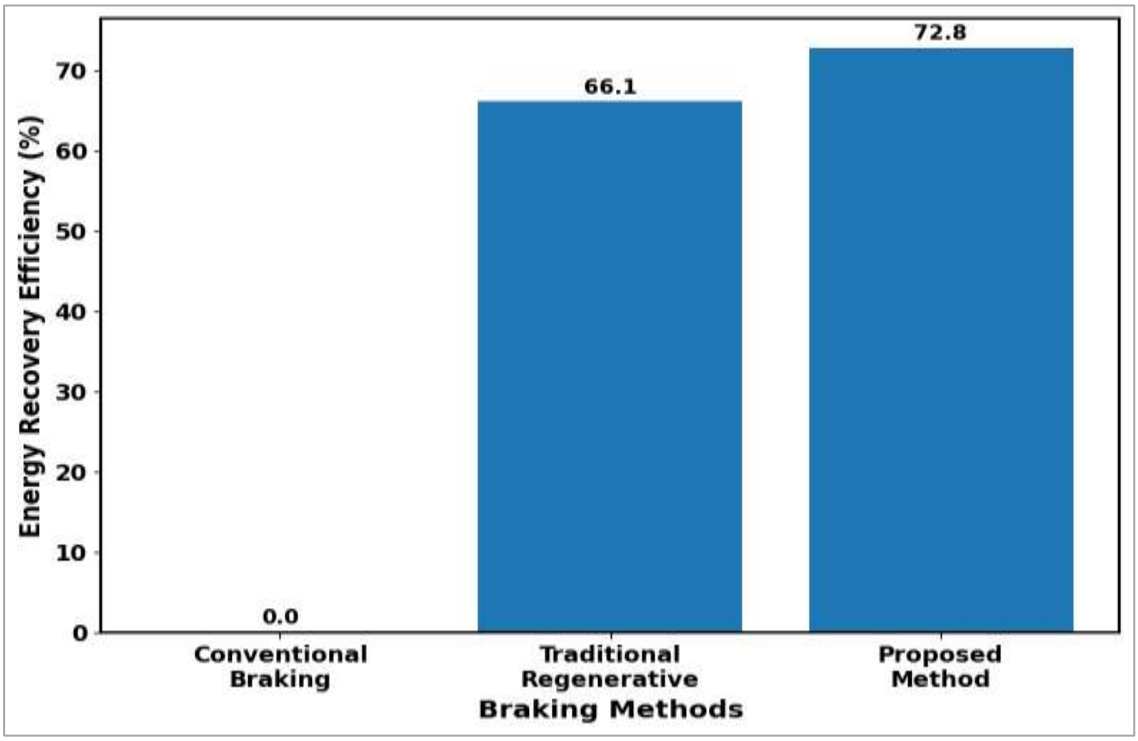

Figure 2: Comparing Energy Recovery Efficiency of Different Braking Methods

The results of the comparison of energy recovery efficiency (ETe) for three braking techniques (conventional braking, traditional regenerative braking and proposed simplified regenerative braking) are presented in Figure 2. The traditional braking system was not capable of recovering energy so its efficiency was 0%. However, the traditional regenerative braking system achieved an efficiency of 66.1%, while the proposed system further improved the efficiency to 72.8%. The illustration shows the effectiveness of the proposed method in recovering and utilizing braking energy, which results in enhanced overall efficiency of electric vehicle.

5.2 Battery Charging Performance

To maximize vehicle driving range, it is critical to store regenerated energy efficiently. The proposed system showed an enhancement in the efficiency of battery charging as it utilized the maximum regenerative energy and minimized energy loss in the charging process.

Table 2: Battery Charging Efficiency Comparison

Method	Battery Charging Efficiency (%)
Traditional Regenerative Braking	78.5
Proposed Simplified Method	89.8

The battery charging efficiency of the traditional regenerative braking system and the proposed simplified regenerative braking system is shown in Table 2. The conventional method resulted in 78.5% of the energy being recovered when charging the battery, meaning that some of the recovered energy was dissipated during charging. The proposed method, on the other hand, achieved a higher charging efficiency of 89.8%, which shows a better utilization and storage of recovered electrical energy. These results show that the proposed system can enhance battery performance and thus help increase EVs driving range.

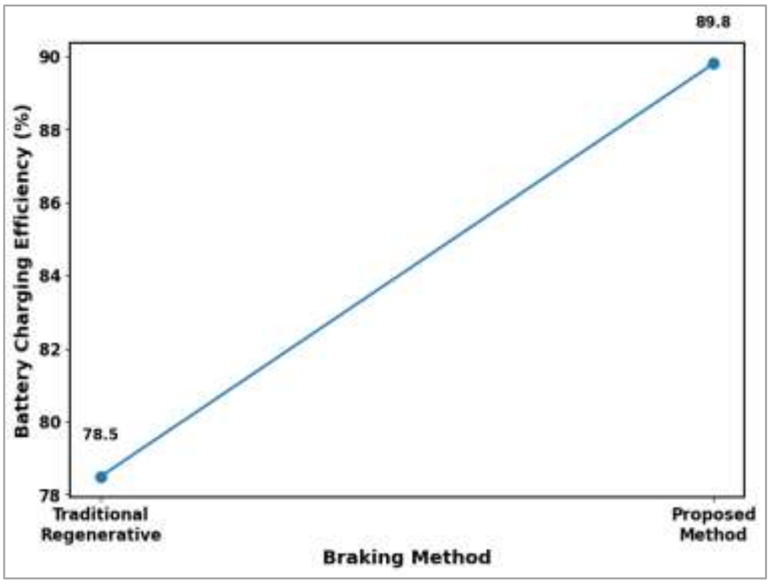

Figure 3: Battery Charging Efficiency Comparison

The efficiency of the battery charging obtained by traditional regenerative braking system and proposed battery charging system using simplified regenerative braking are compared as shown in figure 3. There was a significant increase in charging efficiency from 78.5% to 89.8%, respectively, for the traditional approach and the proposed method. As the graph rises, more energy is being stored in recovered braking energy in the battery system. The results show the effectiveness of the proposed method in improving battery utilization and overall energy efficiency in EVs.

The results indicate that the proposed strategy led to battery charging efficiency more than 11%, which resulted in more energy being stored in the battery for future use.

5.3 Driving Range Improvement

The most important benefit of regenerative braking is that it increases a vehicle's driving range. The electricity recovered was used in actual extra travel distance with different driving cycles.

Table 3: Driving Range Comparison

Driving Cycle	Conventional EV (km)	Proposed Method (km)
Urban	380	435
Highway	420	448
Mixed	400	446

The comparison of the driving range of the conventional electric vehicle and that of the proposed regenerative braking method in various driving cycles is given in Table 3. The proposed method outperformed the conventional method in all driving scenarios, with the driving range boosted from 380km to 435km in urban conditions, from 420km to 448km on highway conditions and from 400km to 446km for mixed driving conditions. The most significant improvement was in the urban cycle where braking events were also numerous, leading to greater energy recovery. The results indicate the effectiveness of the proposed method for improving the range of the electric vehicle by effectively using the recovered energy.

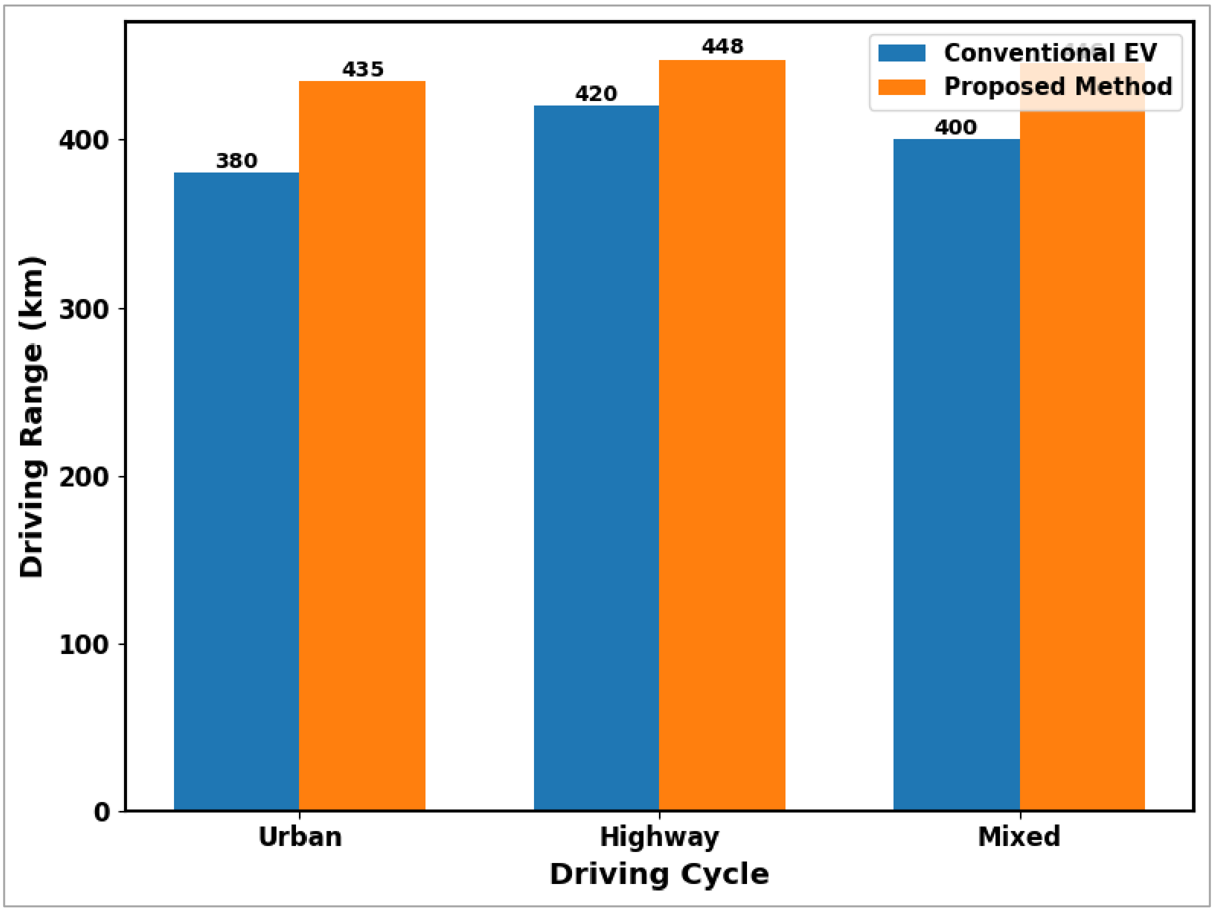

Figure 4: Clustered Bar Graph Comparing Driving Range under Different Driving Cycles

The comparison of the driving range obtained by the conventional electric vehicle (EV) and that obtained by the proposed regenerative braking method is shown in Figure 4 under three driving cycles namely urban, highway and mixed driving cycles. The proposed method was consistently found to provide a longer range of 435 km in urban driving conditions, 448 km in highway driving conditions, and 446 km in mixed driving conditions. The most pronounced improvement occurred within the urban cycle, as there are more braking events available for energy recovery. It is clear from the graph that the proposed regenerative braking strategy is able to make use of the recovered energy to increase the operational range of the EV.

The range improvement for the urban driving cycle was the greatest due to the high number of acceleration and deceleration cycles in the cycle, leading to the highest number of opportunities for energy recovery.

5.4 Energy Consumption Analysis

The proposed regenerative braking system was intended to recover energy which would be lost as heat in the brake system. There is a direct relationship between reducing energy use and improving vehicle efficiency and reducing the frequency of charging.

Table 4: Energy Consumption Comparison

Method	Energy Consumption (kWh/100 km)
Conventional Braking[29]	18.6
Traditional Regenerative Braking[30]	16.9
Proposed Simplified Method	15.2

The comparison of energy consumption for conventional braking, traditional regenerative braking and the proposed simplified regenerative braking is presented in table 4. The conventional braking system consumed the maximum energy (18.6 kWh/100 km) and the traditional regenerative braking system consumed the least energy (16.9 kWh/100 km). This improved energy recovery capability led to the proposed method having the lowest energy consumption of 15.2 kWh/100 km. The findings show that the proposed method improves energy efficiency of the vehicles and also decreases the total battery power consumption.

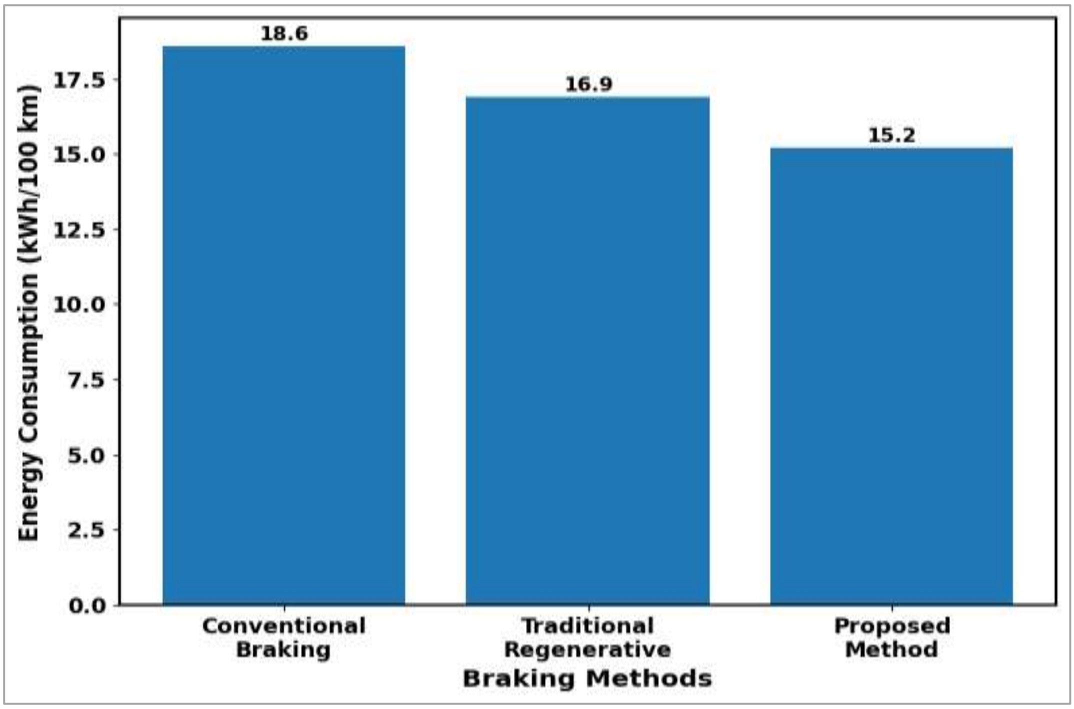

Figure 5: Energy Consumption of Different Methods

The comparison of energy consumption of conventional braking, traditional regenerative braking and proposed simplified regenerative braking method is shown in Figure 5. Conventional braking system had the highest energy consumption of 18.6 kWh/100 km with traditional regenerative braking system the lowest at 16.9 kWh/100 km. Proposed method had the lowest energy consumption (15.2 kWh/100 km) because it is improved in terms of energy recovery and utilization. As can be seen from the graph, the proposed approach has an effect of seeing overall energy efficiency and decrease battery power requirements in electric vehicles.

5.5 Braking Force Distribution Analysis

The braking force distribution mechanism was analyzed to find its effect on energy recovery and vehicle safety. Results indicated that regenerative braking was able to provide a higher percentage of braking force in medium-speed operations where there was the greatest opportunity to recover energy.

Table 5: Average Braking Force Allocation

Speed Range	Regenerative Braking (%)	Friction Braking (%)
Low Speed	25	75
Medium Speed	80	20
High Speed	60	40

Table 5 shows the distribution of braking force between regenerative braking and friction braking across different vehicle speed ranges. At low speeds, friction braking contributed the majority of the braking force (75%) due to the limited effectiveness of regenerative braking. At medium speeds, regenerative braking dominated with 80% contribution, maximizing energy recovery potential. At high speeds, braking force was shared between regenerative braking (60%) and friction braking (40%) to ensure both efficient energy recovery and safe vehicle operation.

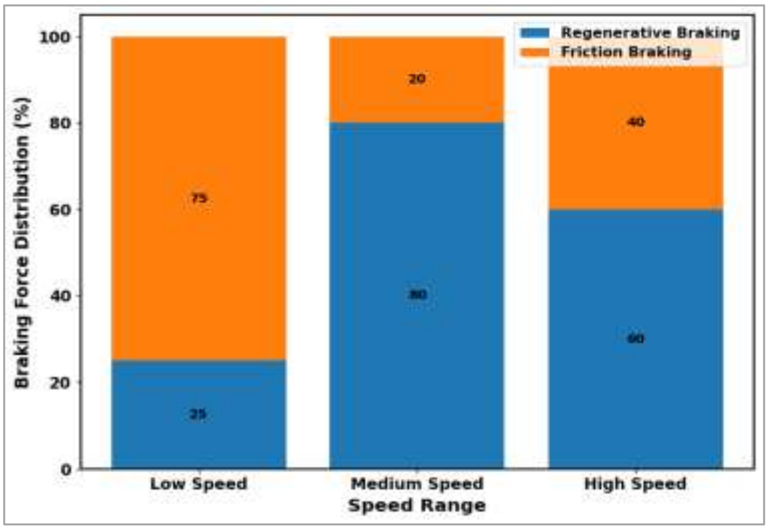

Figure 6: Braking Force Distribution Across Speed Ranges

Figure 6 shows the distribution of braking force between regenerative braking and friction braking at different vehicle speed ranges. At low speeds, friction braking accounted for the largest share of braking force (75%), while regenerative braking contributed only 25%. At medium speeds, regenerative braking became the dominant braking mechanism with an 80% contribution, maximizing energy recovery. At high speeds, the braking force was balanced between regenerative braking (60%) and friction braking (40%), ensuring both effective energy recovery and vehicle safety during braking operations.

The adaptive distribution of braking force ensured efficient energy recovery while maintaining stable and safe braking performance.

5.6 Recovered Energy under Different Driving Cycles

The amount of electrical energy recovered varied according to driving conditions. Urban driving environments generated the highest amount of recoverable energy due to frequent braking events.

Table 6: Recovered Energy Analysis

Driving Cycle	Recovered Energy (kWh)
Urban	8.4
Highway	4.1
Mixed	6.7

Table 6 shows the amount of electrical energy recovered through regenerative braking under different driving cycles. The urban driving cycle achieved the highest recovered energy of 8.4 kWh due to frequent braking and deceleration events. The mixed driving cycle recovered 6.7 kWh, while the highway cycle produced the lowest recovered energy of 4.1 kWh because of fewer braking opportunities. These results indicate that regenerative braking systems are most effective in urban environments where repeated braking allows greater energy recovery.

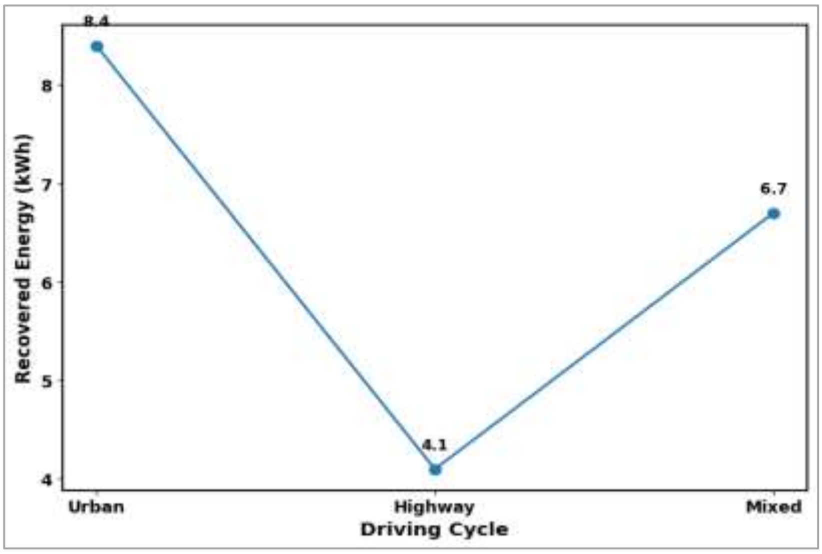

Figure 7: Recovered Energy under Various Driving Cycles

Figure 7 shows the variation in recovered energy across urban, highway, and mixed driving cycles. The urban driving cycle achieved the highest recovered energy of 8.4 kWh due to frequent braking events that increased opportunities for energy regeneration. The mixed driving cycle recovered 6.7 kWh, while the highway cycle recorded the lowest value of 4.1 kWh because of relatively continuous vehicle motion and fewer braking instances. The graph clearly demonstrates that regenerative braking systems provide maximum benefits in urban traffic conditions where repeated deceleration enables greater energy recovery.

The findings confirm that regenerative braking systems are particularly beneficial for urban transportation applications.

5.7 Vehicle Stability Performance

Vehicle stability was analyzed during normal and emergency braking conditions. The proposed system maintained stable deceleration characteristics without excessive wheel slip or braking instability. The integration of friction braking during high-speed and emergency braking ensured safe vehicle operation while preserving energy recovery capability.

Table 7: Vehicle Stability Metrics

Parameter	Proposed Method
Average Deceleration (m/s^2)	4.8
Wheel Slip Ratio (%)	8.2
Stability Compliance	Satisfactory

Table 7 shows the vehicle stability performance achieved by the proposed regenerative braking method under braking conditions. The system maintained an average deceleration of 4.8 m/s^2, ensuring effective braking performance without excessive abruptness. The wheel slip ratio remained at 8.2%, indicating stable tire-road interaction and controlled braking behavior. Furthermore, the stability compliance was classified as satisfactory, confirming that the proposed method successfully balanced energy recovery with vehicle safety and operational stability.

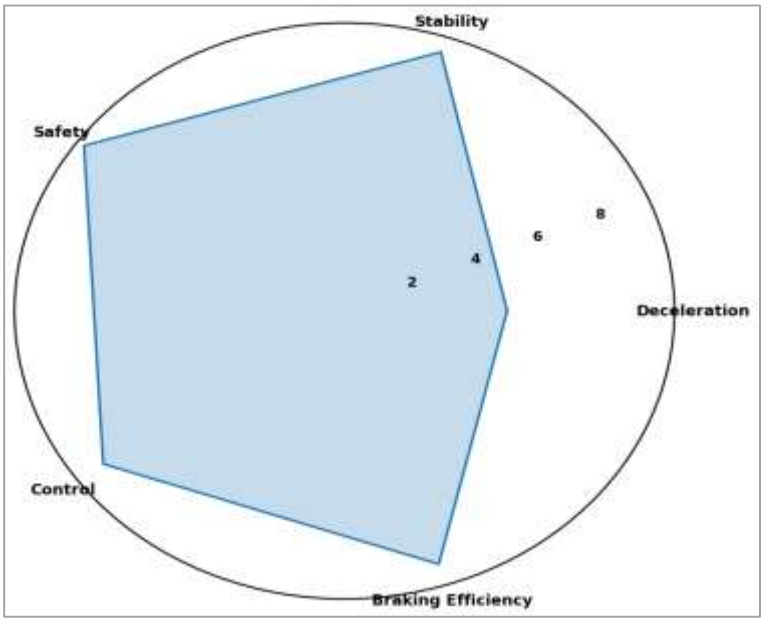

Figure 8: Vehicle Stability Performance Metrics

Figure 8 shows the vehicle stability performance of the proposed regenerative braking method based on key braking and safety metrics. The radar chart illustrates balanced performance across parameters such as deceleration, stability, control, braking efficiency, and safety. The obtained results indicate that the proposed system maintained effective braking characteristics while minimizing wheel slip and preserving vehicle stability. The graphical representation confirms that enhanced energy recovery was achieved without compromising the safety and reliability of electric vehicle operation.

The obtained values remained within acceptable safety limits, confirming the reliability of the proposed approach.

5.8 Comparative Performance Evaluation

A comprehensive comparison was performed to evaluate the overall effectiveness of the proposed regenerative braking method against existing approaches.

Table 8: Overall Performance Comparison

Performance Metric	Traditional Regenerative Braking Method	Proposed Simplified Regenerative Braking Method
Energy Recovery Efficiency (%)	66.1	72.8
Battery Charging Efficiency (%)	78.5	89.8
Driving Range Improvement (%)	8.4	14.6
Energy Consumption (kWh/100 km)	16.9	15.2
Computational Complexity	High	Low

Table 8 shows the overall performance comparison between the Traditional Regenerative Braking Method and the Proposed Simplified Regenerative Braking Method for electric vehicles. The proposed method achieved higher energy recovery efficiency (72.8%) and battery charging efficiency (89.8%) compared to the traditional approach, which recorded 66.1% and 78.5%, respectively. Additionally, the proposed method improved the driving range by 14.6% while reducing energy consumption to 15.2 kWh/100 km. Furthermore, it operated with lower computational complexity, demonstrating that the Proposed Simplified Regenerative Braking Method provides a more efficient and practical solution for enhancing electric vehicle performance and energy utilization.

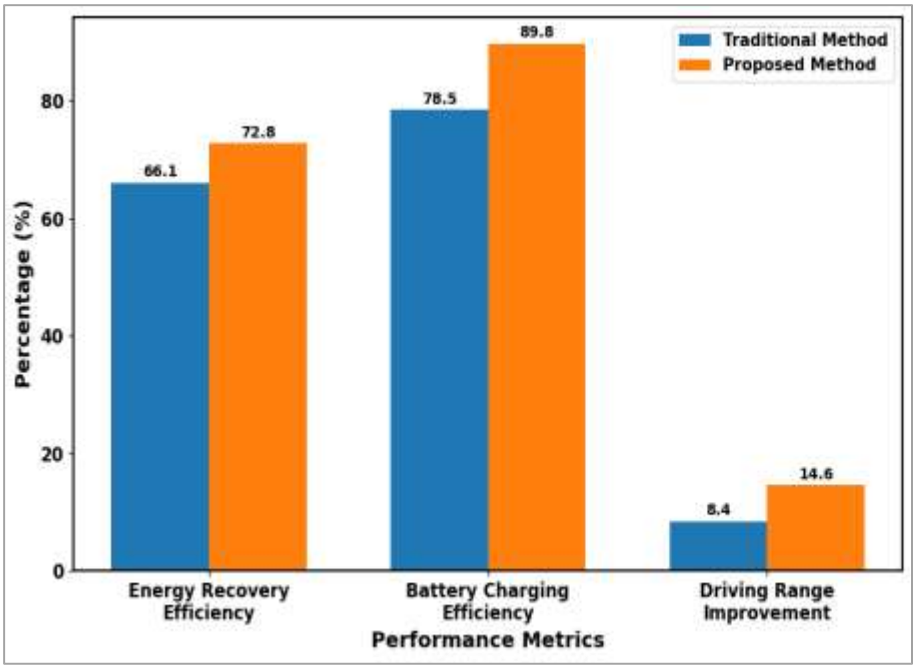

Figure 9: Multi-Bar Comparative Performance Analysis

Figure 9 shows the comparative performance of the Traditional Regenerative Braking Method and the Proposed Simplified Regenerative Braking Method across multiple evaluation metrics. The proposed method achieved higher energy recovery efficiency, battery charging efficiency, and driving range improvement while exhibiting lower energy consumption than the traditional approach. The graph highlights the consistent performance advantages of the proposed system in maximizing energy utilization and vehicle efficiency. Overall, the results demonstrate that the proposed simplified regenerative braking method offers a superior balance between energy recovery, operational efficiency, and implementation simplicity.

Discussion

The simulation results clearly demonstrate the effectiveness of the proposed simplified regenerative braking method in improving the overall energy efficiency of electric vehicles. Compared with traditional regenerative braking systems, the proposed approach achieved higher energy recovery efficiency, improved battery charging performance, reduced energy consumption, and extended driving range while maintaining low computational complexity. The highest performance gains were observed under urban driving conditions, where frequent braking events provided greater opportunities for kinetic energy recovery. The adaptive braking force allocation strategy successfully balanced regenerative and friction braking to maximize energy recovery without compromising vehicle stability or safety. Moreover, the simplified control structure simplified the implementation of the system and hardware requirements, resulting in practical implementation in commercial electric vehicles. The overall results obtained through the proposed method are in line with the results of previous studies and confirm that the proposed method is a cost-effective and efficient solution for enhancing the sustainability of the electric vehicles, energy utilization and operational performance.

6. Conclusion and Future Work

This study was aimed to propose a simplified regenerative braking technique to improve the energy recovery of EV and lower the complexity of the intelligent braking system. The proposed method involved using vehicle speed and braking demand to strategically distribute braking power between regenerative and friction braking mechanisms, which facilitated efficient energy recovery during braking. The simulation results showed that under the urban driving conditions, the proposed method could obtain the energy recovery efficiency of 72.8%, the battery charging efficiency of 89.8% and the improvement of driving range of 14.6%. Further, the system also helped save energy and ensured consistent braking performance in various driving conditions. The results validate that a simplified control approach can improve the energy use of the vehicle and driving range by not using computationally intensive algorithms or advanced hardware infrastructure.

Future research can involve the adaptation of the suggested regenerative braking technique to practical operating circumstances on real-world EV platforms to confirm its effectiveness. Additionally, the use of battery state of charge prediction, road condition monitoring and adaptive control mechanisms to improve energy recovery efficiency could be further explored. Furthermore, the proposed framework can integrate with AI and V2G systems to enable intelligent energy management and smart transportation solutions. These advancements can help to enhance the efficiency of vehicles, the lifespan of batteries, and the sustainability of electric mobility solutions.

References

1. M.-J. Yang, H.-L. Jhou, B.-Y. Ma, and K.-K. Shyu, “A cost-effective method of electric brake with energy regeneration for electric vehicles,” *IEEE Trans. Ind. Electron.*, vol. 56, no. 6, pp. 2203–2212, 2009.
2. Z. Yin, X. Ma, C. Zhang, R. Su, and Q. Wang, “A logic threshold control strategy to improve the regenerative braking energy recovery of electric vehicles,” *Sustainability*, vol. 15, no. 24, p. 16850, 2023.

3. A. J. Godfrey and V. Sankaranarayanan, "A new electric braking system with energy regeneration for a BLDC motor driven electric vehicle," *Eng. Sci. Technol. Int. J.*, vol. 21, no. 4, pp. 704–713, 2018.
4. Q. Chengqun *et al.*, "A novel regenerative braking energy recuperation system for electric vehicles based on driving style," *Energy*, vol. 283, p. 129055, 2023.
5. G. Xu, W. Li, K. Xu, and Z. Song, "An intelligent regenerative braking strategy for electric vehicles," *Energies*, vol. 4, no. 9, pp. 1461–1477, 2011.
6. L. Li, X. Li, X. Wang, J. Song, K. He, and C. Li, "Analysis of downshift's improvement to energy efficiency of an electric vehicle during regenerative braking," *Appl. Energy*, vol. 176, pp. 125–137, 2016.
7. Z. Zhang, Y. Dong, and Y. Han, "Dynamic and control of electric vehicle in regenerative braking for driving safety and energy conservation," *J. Vib. Eng. Technol.*, vol. 8, no. 1, pp. 179–197, 2020.
8. T. Yabe, K. Akatsu, N. Okui, T. Niikuni, and T. Kawai, "Efficiency improvement of regenerative energy for an EV," *World Electr. Veh. J.*, vol. 5, no. 2, pp. 494–500, 2012.
9. S. M. Hosseini, M. Soleymani, S. Kelouwani, and A. A. Amamou, "Energy recovery and energy harvesting in electric and fuel cell vehicles, a review of recent advances," *IEEE Access*, vol. 11, pp. 83107–83135, 2023.
10. F. Ji, Y. Pan, Y. Zhou, F. Du, Q. Zhang, and G. Li, "Energy recovery based on pedal situation for regenerative braking system of electric vehicle," *Veh. Syst. Dyn.*, vol. 58, no. 1, pp. 144–173, 2020.
11. I. Pielecha, W. Cieślik, and A. Szałek, "Energy recovery potential through regenerative braking for a hybrid electric vehicle in a urban conditions," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2019, p. 012013.
12. L. Li, X. Ping, J. Shi, X. Wang, and X. Wu, "Energy recovery strategy for regenerative braking system of intelligent four-wheel independent drive electric vehicles," *IET Intell. Transp. Syst.*, vol. 15, no. 1, pp. 119–131, 2021.
13. P. Bathala, B. S. Srivasthav, Y. S. S. Reddy, and K. Deepa, "Estimation of regenerative braking force in electric vehicles for maximum energy recovery," in *2020 IEEE 17th India Council International Conference (INDICON)*, IEEE, 2020, pp. 1–7.
14. A. de Moura Oliveira *et al.*, "Evaluation of energy recovery potential through regenerative braking for a hybrid electric vehicle in a real urban drive scenario," in *25th SAE BRASIL International Congress and Display 259518*, 2016.
15. G. Xu, K. Xu, C. Zheng, X. Zhang, and T. Zahid, "Fully electrified regenerative braking control for deep energy recovery and maintaining safety of electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 65, no. 3, pp. 1186–1198, 2015.
16. S. Heydari, P. Fajri, M. Rasheduzzaman, and R. Sabzehgar, "Maximizing regenerative braking energy recovery of electric vehicles through dynamic low-speed cutoff point detection," *IEEE Trans. Transp. Electrification*, vol. 5, no. 1, pp. 262–270, 2019.
17. C. Lv, J. Zhang, Y. Li, and Y. Yuan, "Mechanism analysis and evaluation methodology of regenerative braking contribution to energy efficiency improvement of electrified vehicles," *Energy Convers. Manag.*, vol. 92, pp. 469–482, 2015.
18. C. Qiu and G. Wang, "New evaluation methodology of regenerative braking contribution to energy efficiency improvement of electric vehicles," *Energy Convers. Manag.*, vol. 119, pp. 389–398, 2016.

19. X. Huang and J. Wang, "Nonlinear model predictive control for improving energy recovery for electric vehicles during regenerative braking," in *2011 50th IEEE Conference on Decision and Control and European Control Conference*, IEEE, 2011, pp. 7458–7463.
20. A. Bhat, A. Suryawanshi, O. Jadhav, and S. Jawale, "Optimizing Regenerative Braking in Electric Vehicle: A Comprehensive Study of Control Strategies and Energy Recovery," in *2025 3rd IEEE International Conference on Industrial Electronics: Developments & Applications (ICIDeA)*, IEEE, 2025, pp. 1–4.
21. Y. Park, S. Park, and C. Ahn, "Performance potential of regenerative braking energy recovery of autonomous electric vehicles," *Int. J. Control Autom. Syst.*, vol. 21, no. 5, pp. 1442–1454, 2023.
22. Y. Jiang, Y. Zheng, Y. Guo, and M. Cong, "Regenerative braking control strategy to improve braking energy recovery of pure electric bus," *SAE Int. J. Veh. Dyn. Stab. NVH*, vol. 4, no. 10-04-03–0015, pp. 221–231, 2020.
23. T. Wu, F. Wang, and P. Ye, "Regenerative braking strategy of dual-motor EV considering energy recovery and brake stability," *World Electr. Veh. J.*, vol. 14, no. 1, p. 19, 2023.
24. E. M. Szumska, "Regenerative braking systems in electric vehicles: a comprehensive review of design, control strategies, and efficiency challenges," *Energies*, vol. 18, no. 10, p. 2422, 2025.
25. Q.-Y. Zhang and J. Huang, "Research on regenerative braking energy recovery system of electric vehicles," *J. Interdiscip. Math.*, vol. 21, no. 5, pp. 1321–1326, 2018.
26. J. Guo, W. Li, J. Wang, Y. Luo, and K. Li, "Safe and energy-efficient car-following control strategy for intelligent electric vehicles considering regenerative braking," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 7, pp. 7070–7081, 2021.
27. Q. He, Y. Yang, C. Luo, J. Zhai, R. Luo, and C. Fu, "Energy recovery strategy optimization of dual-motor drive electric vehicle based on braking safety and efficient recovery," *Energy*, vol. 248, p. 123543, 2022.