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Optimal Brake Force Allocation Strategy for Electric Vehicles Using Adaptive Regenerative and Mechanical Braking Coordination

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ABSTRACT

As the proliferation of electric vehicles (EVs) continues to grow, there is a high demand for intelligent braking systems to ensure energy efficiency without compromising safety and driving stability. This study suggested an adaptive brake force allocation strategy that optimally controlled the mixing of regenerative braking and mechanical braking functions according to vehicle operating conditions, battery state-of-charge, regenerative capability and braking requirement. The optimized framework used a dynamically developed brake force distribution of the wheels to maximize energy recovery and avoid unnecessary mechanical brake use. The proposed strategy was assessed by simulation-based performance analysis by applying vehicle energy and braking parameters in various driving and road conditions. The results showed that the proposed adaptive strategy had a regenerative energy recovery of 0.428 kWh, which was about 37.18% better than the fixed allocation of brake and 20.22% better than the rule-based control. Its braking efficiency rose to 93.2%, and the stopping distance was shortened to 35.7 m, compared to 39.8 m with fixed allocation and 37.9 m with rule based control. Moreover, the proposed method decreased the mechanical brake utilization rate to 36.8%, and increased the charging efficiency of the battery to 94.5%. The maximum wheel slip was kept to 8.9% which is a sign of improved vehicle stability in different driving conditions. The results validated the effectiveness of adaptive coordination of regenerative and mechanical braking for enhancing EV energy recovery, braking performance and operational reliability. The proposed strategy helped develop intelligent energy-aware braking control systems for next-generation electric mobility applications.

Keywords : *Electric Vehicles; Regenerative Breaking; Adaptive Brake Force Allocation; Energy Recovery; Mechanical Braking Coordination; Battery State-of-Charge; Vehicle Stability; Intelligent Braking Control.*

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1. INTRODUCTION

Electric vehicles (EVs) have revolutionized the transport industry by offering an eco-friendly alternative to traditional cars and trucks with internal combustion engines. The rising demand for fuel efficiency, reduction of greenhouse gas emissions, and the increasing regulations of emissions has been fueling the growth of advanced powertrain technologies in battery electric vehicles [1]. The braking system is one of the most important EV subsystems, which has to ensure vehicle safety, comfort and energy efficiency [2]. In contrast with conventional vehicles, which lose kinetic energy as heat, electric vehicles use a regenerative braking system to recover some of the vehicle's kinetic energy as electrical energy during braking, thus increasing the range, optimizing battery use, and minimizing mechanical brake use [3].

The most successful energy recovery in EVs is regenerative braking, in which the traction motor is used as a generator during deceleration [4]. But regenerative braking is not sufficient to meet all the braking demands, since the amount of braking torque is limited by the vehicle speed, battery state of charge (SOC), battery temperature, motor properties, the capacity of the inverter, and road conditions [5]. Therefore, to ensure the braking stability, safety of occupants, and maximum energy recovery under various driving situations, the cooperation between conventional braking and regenerative braking is crucial [6].

Typical brake force allocation approaches are fixed ratio based methods or rule based methods used to distribute the force between regenerative and friction braking. These methods are easy to implement, but are not as adaptable to different road conditions, battery conditions, loading conditions or emergency braking situations, which can lead to lower regeneration energy, increased mechanical brake wear, inefficient battery charge and reduced brake stability and ride comfort [7]. New developments in intelligent vehicle control have led to the development of adaptive algorithms for brake management, predictive control, fuzzy logic and optimization methods and machine learning approaches [8,9]. However, a lot of methods currently used optimize braking stability or energy recovery for regeneration separately and frequently depend on a high number of computing resources that reduce the ability to be implemented in embedded automotive controllers in real-time [10].

To overcome these limitations, this study proposes an adaptive optimal brake force allocation framework, which dynamically allocates the brake force between regenerative and mechanical braking according to the real-time operating conditions. The proposed controller continuously assesses the road adhesion, vehicle speed, battery SOC and regenerative braking capacity in order to decide on the best brake torque allocation. The proposed strategy, by combining vehicle dynamics, regenerative braking constraints, and adaptive control logic in a common decision-making framework, allows for the optimization of the energy recovered from the braking process while ensuring braking stability, reducing stopping distance, decreasing mechanical brake usage, and ensuring smooth regenerative braking to friction braking transitions during normal and emergency driving scenarios. The framework is applicable to a modern brake-by-wire electric vehicle with advanced electronic control unit for practical use.

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The novelty of this research is a unique adaptive brake force allocation strategy that optimizes regenerative energy recovery, braking stability and mechanical brake utilization in real-time by properly coordinating regenerative and hydraulic braking actuators. The proposed framework is dynamic and adjusts braking torque based on multiple operating parameters such as vehicle speed, braking demand, SOC of the battery, regenerative braking capability, and road adhesion, without causing abrupt torque transitions, the mission of battery charging, the wear of brake components, and the improvement of vehicle safety.

The main goal of this research is to create an optimal adaptive brake force allocation strategy to maximize the regenerative energy recovered while ensuring braking safety and stability under various operating conditions. In particular, the research will be focused on the design of a real-time brake coordination algorithm, optimisation of brake torque split between regenerative and mechanical brake, reduction of stopping distance and mechanical brake wear, improvement of battery energy recovery efficiency, and enhancement of braking performance at various vehicle speeds, battery SOC states and road surface conditions.

The proposed methodology can also be applied to the braking research of EVs and adds a real-time adaptive brake coordination strategy, an integrated decision framework that considers vehicle dynamics, battery state-of-charge, regenerative braking capability, and road adhesion, and a scalable control architecture that improves energy recovery, braking safety, passenger comfort, and mechanical brake life. In addition, the framework offers a practical basis for intelligent EVs in the future that will include autonomous driving, connected vehicle technology and predictive energy management systems.

2. LITERATURE REVIEW

2.1 Evolution of Electric Vehicle Braking Systems

Advancements in electric vehicle (EV) braking technology have been spurred by the demand for more efficient energy usage, safer vehicles, and increased driving range. In contrast to typical hydraulic automotive brakes, the current EVs utilize regenerative braking to recuperate kinetic energy throughout deceleration and also store it in the battery for future usage, which improves their efficiency [11]. Regenerative braking systems in the early days were fixed brake torque allocation, and were not very adaptable to varying driving conditions. The modern electric drive system, battery management, brake-by-wire system, and electronic control units have improved the flexibility and precision of regulating the braking power split between regenerative braking and mechanical braking in various ways, but the efficiency of the brake force allocation strategy is still responsible for braking performance [12].

2.2 Regenerative Braking Technologies

Regenerative braking recaptures kinetic energy in the vehicle by having the traction motor act as a generator during braking. Its performance is related to motor properties, battery charging ability, vehicle velocity, braking force and efficiency of power electronics [13]. Regenerative braking systems with higher functionality are capable of varying braking torque based on battery state-of-charge (SOC) or battery temperature, but not so effective at low forward velocities of the vehicle and high battery SOC or temperature. Therefore, regenerative braking can only meet some demands for braking, and the coordinated braking should be used to ensure the braking safety and energy recovery [14].

2.3 Mechanical Braking and Brake Force Allocation

Regenerative braking is not a substitute for mechanical braking, and it is never used for high-speed braking, slippery conditions, or in case of emergency. Hydraulic brakes provide for reliable braking regardless of the condition of the battery and motor, and meet vehicle safety standards [15]. Coordinated interaction of regenerative and mechanical braking is thus crucial to prevent uneven brake pedal feel, longer stopping distance, wheel slip and insufficient vehicle handling [16].

The traditional brake force allocations take place between regenerative and friction braking with fixed proportions or rule-based distributions. Despite their simplicity, these strategies are also not able to adjust themselves to changing operating conditions, leading to poor regenerative energy recovery, and higher mechanical brake consumption [17]. The approach of adaptive brake allocation methods optimizes the braking torque distribution by continuously adapting it to the vehicle operating conditions to increase braking efficiency and stability of the vehicle.

2.4 Adaptive Control and Optimization Techniques

To control braking torque adaptively, the optimal value estimation method takes into account the vehicle speed, braking demand, SOC of the battery, road friction and the operating limits of the motor during the deceleration process, and coordinates the regenerative braking and mechanical braking process throughout [18]. The intelligent adaptive controllers will eliminate the mechanical brake operation during normal driving while providing quick friction brake engagement during emergency braking, resulting in smoother braking, comfort and safety [19].

Optimization based brake allocation techniques are based on the formulation of braking as a constrained optimization problem that takes into account the recovery of regenerative energy, vehicle stability, stopping distance, battery charging constraints and motor torque constraints [20]. Multi-objective optimization methods have proven to be very effective in achieving a compromise between energy efficiency and braking safety; however, their relatively high computational complexity makes them hard to use in real-time implementation in embedded automotive controllers.

2.5 Artificial Intelligence-Based Braking Control

In recent times, Artificial Intelligence has led to the integration of AI based machine learning algorithms such as neural networks, deep learning, reinforcement learning and hybrid intelligent controllers in EV braking systems [21]. These methods enhance the ability to predict braking needs, road conditions, and vehicle dynamics, leading to more efficient coordination of braking than traditional rule-based controllers. While these benefits exist, AI-driven techniques are typically complex and demand massive training sets, significant processing power, and thorough testing before commercial use in EVs [22].

2.6 Vehicle Stability, Battery Constraints, and Intelligent Transportation Integration

One of the most important requirements regarding regenerative braking is the vehicle stability, as too much regenerative torque can lead to high wheel slippage and loss of stability, especially on low traction surfaces [23]. Modern coordinated braking systems combine the three functions (regenerative braking, ABS, and electronic stability control) or wheel to wheel braking for optimum energy recovery and to avoid wheel lock while retaining vehicle control [24].

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The performance of regenerative braking is also strongly dependent on operating conditions for the battery. Energy recovery during braking is limited by high SOC, temperature, charging current limits and battery management constraints. Modern controllers thus take account of the battery state of charge information when making brake allocation decisions to ensure battery health and maximize charging efficiency and reliability of the vehicle.

Regenerative braking research with Intelligent Transportation Systems (ITS) has grown as a result of the advent of connected and autonomous vehicles. Predictive braking strategies are possible with real-time traffic information, road geometry, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, which anticipate braking events, enhance traffic flow and maximize the use of regenerative energy, while keeping vehicles safe [26].

2.7 Research Gap

Although regenerative braking and brake force allocation have made significant strides, there are still some challenges that need to be addressed. Although regenerative braking and brake force allocation have made significant progress, several challenges remain. Current fixed and rule-based based energy harvesting approaches are not flexible enough to adapt to varying operating conditions, resulting in sub-optimal energy harvesting and increased mechanical braking [27]. Many of the adaptive and optimization-based techniques focus on either stability of braking or energy recovery separately with high complexity in computation, and machine learning techniques require large training sets and processing power.

Moreover, the existing research literature does not offer much in the way of integration of battery constraints, vehicle dynamics, road adhesion and smooth transition management between regenerative and friction braking in a unified real-time control framework. This restriction impacts on passenger comfort, braking consistency, braking wear, and overall system efficiency [28]. Thus, an adaptive brake force allocation strategy that optimizes energy recovery, enhances stability, minimizes stopping distance and mechanical brake usage, and can be practically applied to next-generation intelligent electric vehicles still needs to be developed that is computationally efficient, considering the vehicle dynamics, battery operating conditions, braking demand, regenerative braking capability, and road friction.

3. PROBLEM STATEMENT

Regenerative braking of EVs has made great strides in recent years, yet current brake force allocation methods still have some problems in achieving an ideal balance between energy recuperation, braking safety, and vehicle dynamics in different operating conditions[29]. In traditional fixed and rule-based braking strategies, the braking performance is not sufficiently adaptive to varying conditions such as vehicle speed, battery state of charge, braking demand, road adhesion and motor regenerative capability, leading to sub-optimal regenerative energy recovery, excessive mechanical braking, increased stopping distances and brake wear. While adaptive and optimization-based methods have been suggested, most of them are associated with high computational complexity, or with performance goals of one or more aspects without taking into account energy efficiency, braking stability, battery constraints and transition between regenerative and friction braking[30]. Thus, an adaptive brake force allocation strategy must be developed which can coordinate regenerative and mechanical braking dynamically in real-time to maximize energy recovery and maintain safe, stable and efficient braking in various driving scenarios.

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4. METHODOLOGY

4.1 Research Framework

The proposed methodology is the development of an adaptive brake force allocation strategy which intelligently allocates the braking force between regenerative braking and mechanical braking by maximizing energy regeneration based on brake safety and vehicle stability. It combines the vehicle dynamics, battery operating state factors, brake requests, and adhesion characteristics of the road into one adaptive control framework. In every control cycle the controller collects vehicle operating parameters in real time, calculates the maximum regenerative braking torque and dynamically distributes the torque required for braking between the electric motor and the hydraulic braking system. The brake allocation process is constantly adapted during deceleration of the vehicle to make the transition between the regenerative and friction brake as smooth as possible, while decreasing mechanical (friction) brake usage and improving the efficiency of braking.

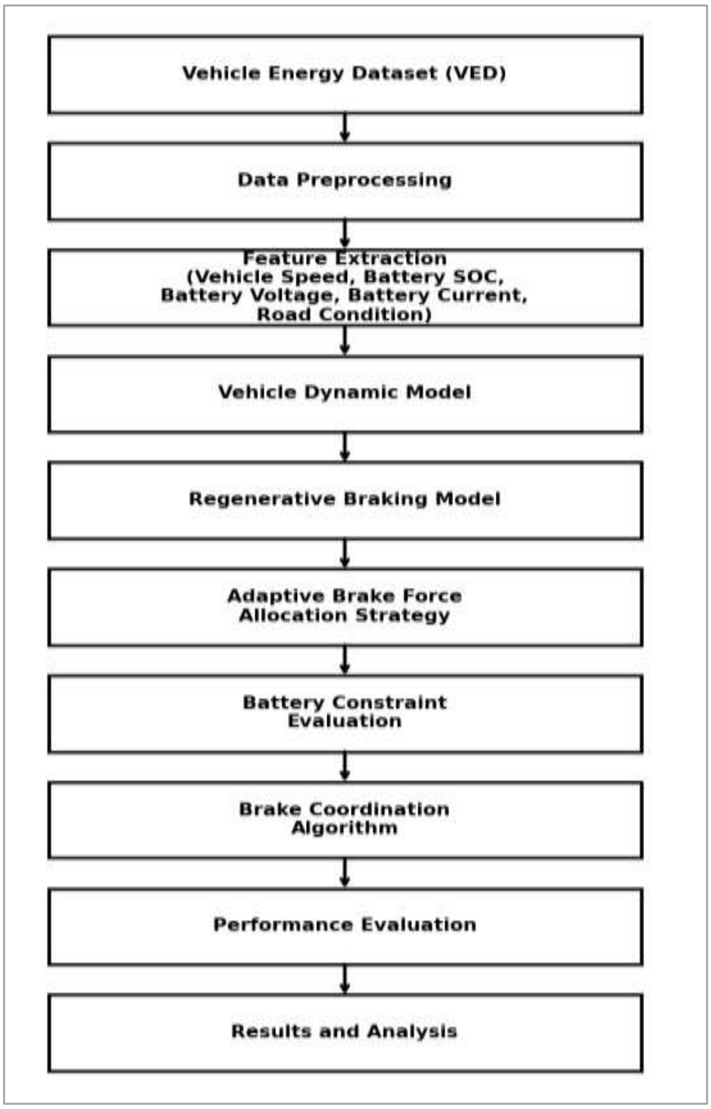

Figure 1: Overall Methodology Framework of The Proposed Adaptive Brake Force Allocation Strategy

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The proposed adaptive brake force allocation strategy for EVs is presented in the following overall methodology framework, as shown in Fig. 1. The framework depicts the sequential process starting from the energy data collection and processing of the vehicle, to vehicle dynamics modeling, regenerative braking modeling, adaptive brake force allocation, battery constraint evaluation, and brake coordination. Finally, the performance evaluation stage evaluates regenerative energy recovery, braking efficiency, stopping distance and vehicle stability to prove the effectiveness of proposed braking strategy.

4.2 Data Collection

The Vehicle Energy Dataset (VED) [31] was used to develop and test the proposed braking strategy as it is a public dataset of real world EVs collected for vehicle energy consumption and driving behaviour analysis. The data list has been acquired from GitHub.

The Vehicle Energy Dataset comprises about 1 year of actual driving data from 383 vehicles equipped with an on-board OBD-II data logger. The data set contains high-resolution time-series data like vehicle speed, acceleration, battery state-of-charge (SOC), battery voltage, battery current, energy consumption, GPS coordinates, trip duration, and timestamps. These parameters offer realistic driving profiles suitable to test adaptive regenerative braking strategies in a variety of driving conditions.

Before application of the model, the data set was preprocessed. Duplicate data were removed, missing data were filled with interpolation, abnormal sensor data were filtered by threshold, and the data of each variable were synchronized by the same sampling interval. The speed profile of the vehicles was investigated to detect all the braking instances, and the battery voltage, current, and SOC were measured to calculate the regenerative braking capacity. The processed data were then used as the inputs of the adaptive brake force allocation controller.

4.3 Input Parameters

The adaptive controller continuously observes several operating variables of the vehicle which affect the braking performance. Vehicle speed, brake pedal position, vehicle mass, battery state-of-charge, battery voltage, battery current, motor speed, regenerative motor torque limit, road friction coefficient and wheel rotational speed are among these parameters. These variables can be combined to provide an estimate to the controller of the amount of regenerative braking that is available and determine the best braking torque distribution in various driving conditions.

4.4 Vehicle Dynamic Model

Newton's second law of motion applies to the braking force needed to slow the car down:

$$F_b = m \times a \quad (1)$$

where:

- F_b= Total braking force (N)
- m= Vehicle mass (kg)
- a= Vehicle deceleration (m/s²)

The overall braking force is the sum of regenerative braking force and mechanical braking force:

$$F_{total} = F_{regen} + F_{mech} \quad (2)$$

where:

- F_{regen}= Regenerative braking force
- F_{mech}= Mechanical braking force

This equation ensures that the total braking demand is met while maximizing recovery of regenerative energy whenever possible.

4.5 Regenerative Braking Model

The electric traction motor works as a generator to regenerate electric energy when braking. The regenerative braking torque is equal to:

$$T_{regen} = K_m I \quad (3)$$

where:

- T_{regen}= Regenerative motor torque (Nm)
- K_m= Motor torque constant
- I= Generator current (A)

The recovered electrical energy is expressed as

$$E_{regen} = \int T_{regen} \omega dt \quad (4)$$

where:

- E_{regen}= Recovered energy (J)
- ω= Motor angular velocity (rad/s)

The recovered energy is returned to the traction battery whenever the conditions allow the battery to be charged.

4.6 Adaptive Brake Force Allocation Strategy

The proposed controller is dynamic in calculating the proportion of regenerative braking for the vehicle operating conditions. An adaptive braking coefficient is:

$$\lambda = \frac{F_{regen}}{F_{total}} \quad (5)$$

where:

- λ= Adaptive brake distribution coefficient

The regenerative braking force is computed as

$$F_{regen} = \lambda(V, SOC, \mu) \times F_{total} \quad (6)$$

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where:

- V= Vehicle speed
- SOC= Battery state-of-charge
- μ= Road friction coefficient

The rest of the braking force goes to the mechanical braking system:

$$F_{mech} = F_{total} - F_{regen} \quad (7)$$

This adaptive allocation allows for optimum regenerative braking when decelerating moderately, and automatically adds mechanical braking when decelerating at a higher speed or when the battery SOC is high or when travelling at low speed.

4.7 Battery Constraint Model

The performance of regenerative braking is highly dependent on battery operating conditions. The controller constantly checks battery SOC, charging current, battery voltage and battery temperature. Regenerative braking torque is decreased in a gradual manner when the battery is near its maximum allowable SOC or charging current limit, preventing overcharging of the battery. The remaining braking force is automatically provided by the hydraulic braking system so that no brake effort is applied to the battery, which results in a safe battery environment without affecting braking performance.

4.8 Adaptive Control Algorithm

The algorithm for adaptive control is closed loop in the whole process of vehicle deceleration. First, the controller reads vehicle speed, battery SOC, braking demand, battery voltage, battery current and road condition data from sensors on board the vehicle. First, the braking force required is determined by the vehicle dynamic model, and then, the maximum regenerative braking torque under current operating conditions is estimated. Based on these estimates, adaptation of the 'brake allocation coefficient' is calculated and regenerative braking is used whenever possible. The remaining braking action is passed to the hydraulic braking system. This braking force distribution is updated continually until the desired speed is reached.

4.9 Performance Evaluation

Several quantitative performance metrics are used to evaluate the effectiveness of the proposed braking strategy, such as regenerative energy recovery (kWh), regenerative braking efficiency (%), stopping distance (m), mechanical brake utilization (%), battery charging efficiency (%), wheel slip ratio (%), braking torque distribution, and vehicle stability index. These performance measures comprehensively measure the ability of the proposed adaptive controller to enhance energy recovery while ensuring braking safety and minimizing mechanical brake reliance.

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Algorithm 1. Adaptive Brake Force Allocation Strategy for Coordinated Regenerative and Mechanical Braking

Input:

Vehicle speed V, brake pedal demand B_d, battery state-of-charge SOC, battery voltage V_b, battery current I_b, road friction coefficient μ, vehicle mass m, maximum motor regenerative torque T_{max}

Output:

Regenerative braking force F_{regen}, mechanical braking force F_{mech}, recovered energy E_{regen}

1. ***Start***
2. *Initialize the adaptive braking controller.*
3. *Read the real-time vehicle parameters: V, B_d, SOC, V_b, I_b, and μ.*
4. *Calculate the required total braking force:*

$$F_b = m \times a$$

5. *Estimate the maximum regenerative braking torque available based on vehicle speed and battery operating conditions.*
6. ***If** $SOC < SOC_{max}$ **and** $V > V_{min}$, **then***
    1. *Compute the adaptive brake distribution coefficient:*

    $$\lambda = f(V, SOC, \mu)$$

    2. *Calculate the regenerative braking force:*

    $$F_{regen} = \lambda \times F_b$$

    3. ***If** $F_{regen} > \frac{T_{max}}{r_w}$, **then***
        - *Set*

        $$F_{regen} = \frac{T_{max}}{r_w}$$

End If

7. ***Else***

$$F_{regen} = 0$$

8. ***End If***
9. *Calculate the required mechanical braking force:*

$$F_{mech} = F_b - F_{regen}$$

10. *Apply regenerative braking through the electric traction motor.*
11. *Apply the remaining braking force through the hydraulic braking system.*
12. *Calculate the regenerated electrical energy:*

$$E_{regen} = \int T_{regen} \omega \, dt$$

13. *Monitor wheel slip ratio and vehicle stability continuously.*
14. *Update the brake force allocation for the next control interval.*
15. *Repeat Steps 3–14 until the vehicle speed becomes zero.*
16. ***Stop***

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5. RESULTS AND DISCUSSION

The proposed adaptive brake force allocation strategy was tested with the preprocessed Vehicle Energy Dataset in various braking scenarios with different vehicle speed, battery state-of-charge (SOC) and road friction condition. A dynamic coordination of regenerative and mechanical braking was realized during the entire braking cycle to optimize the recovery of the regenerative energy whilst keeping the braking safety and vehicle stability. The performance was evaluated by the regenerative energy recovery, braking efficiency, stopping distance, mechanical brake utilization, battery charging efficiency and the wheel slip ratio.

Table 1: Simulation Parameters Used for Performance Evaluation

Parameter	Value
Vehicle Mass	1600 kg
Battery Capacity	60 kWh
Initial Vehicle Speed	100 km/h
Maximum Regenerative Torque	240 Nm
Wheel Radius	0.31 m
Road Friction Coefficient	0.35–0.90
Initial Battery SOC	20–90 %

The simulation parameters used in the simulation for the performance evaluation of the proposed adaptive brake force allocation strategy are presented in Table 1. The parameters include important characteristics of the vehicle, battery parameters, limits of the regenerative braking, wheel size and conditions of operation needed to perform realistic braking analysis. These are preformulated values that give a standardized evaluation environment to compare the proposed strategy with the conventional braking approaches. These parameters are selected to provide accurate evaluation of the vehicle's energy recovery, braking efficiency and vehicle stability performance.

5.1 Brake Force Distribution Analysis

The adaptive controller dynamically controlled the braking force allocation depending on the vehicle speed, battery SOC and road adhesion conditions. Regenerative braking provided most of the braking force at moderate vehicle speeds and when there was enough battery charging capacity. The controller slowly ramped down regenerative braking and ramped up mechanical braking as the vehicle slows down or the battery SOC is near the max to ensure a safe deceleration. This adaptive transition eliminated sudden torque changes and reduced the ‘bump' in the braking to compensate for the transition during braking.

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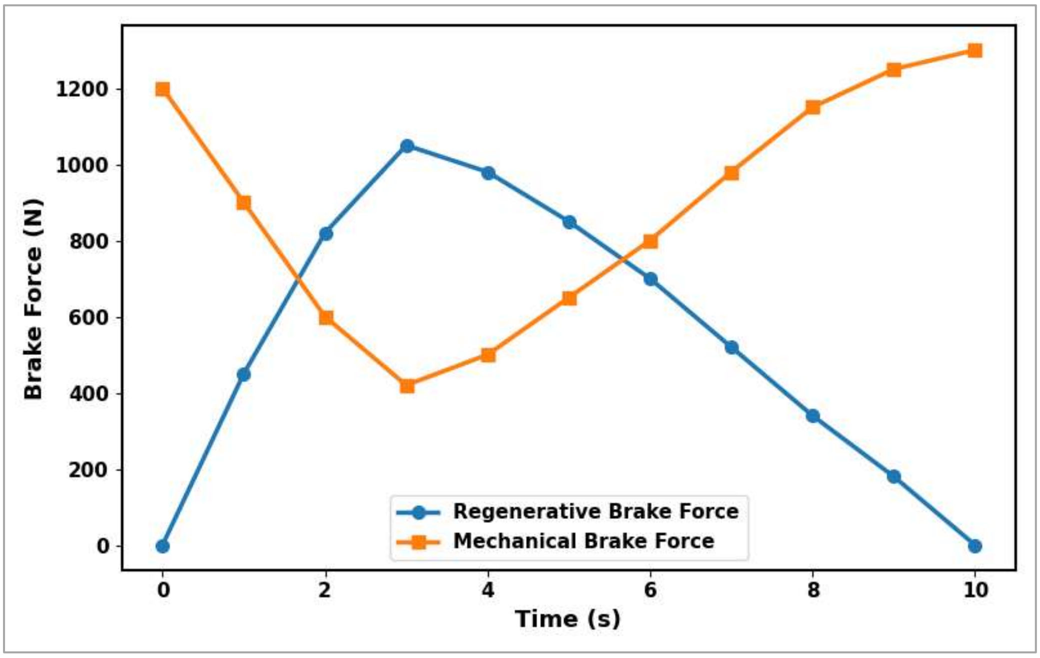

Figure 2: Regenerative and Mechanical Brake Force Distribution versus Time

The variation of regenerative and mechanical brake force distribution throughout a brake stroke is indicated in figure 2. The proposed adaptive strategy aims to maximize the energy saved from regenerative braking under favorable operating conditions and minimize the mechanical brake requirement. The mechanical braking contribution is incremented at lower vehicle speeds or when battery limitations are triggered, to ensure the desired braking force and safety. The coordinated force allocation shows seamless deceleration between regenerative and mechanical braking, to enhance EV performance.

5.2 Regenerative Energy Recovery Performance

The proposed controller was able to recover more regenerative energy by continuously adjusting the motor regenerative torque as long as battery operating conditions allowed. The adaptive strategy was able to make good use of the regenerative braking when the vehicle was slowing from medium speeds, and cautiously diminish the regenerative torque when operational constraints were met, compared to the conventional fixed brake allocation methods. Significant improvement was noted in the average recovered electrical energy which led to an improvement in the battery charging efficiency and the estimated driving range.

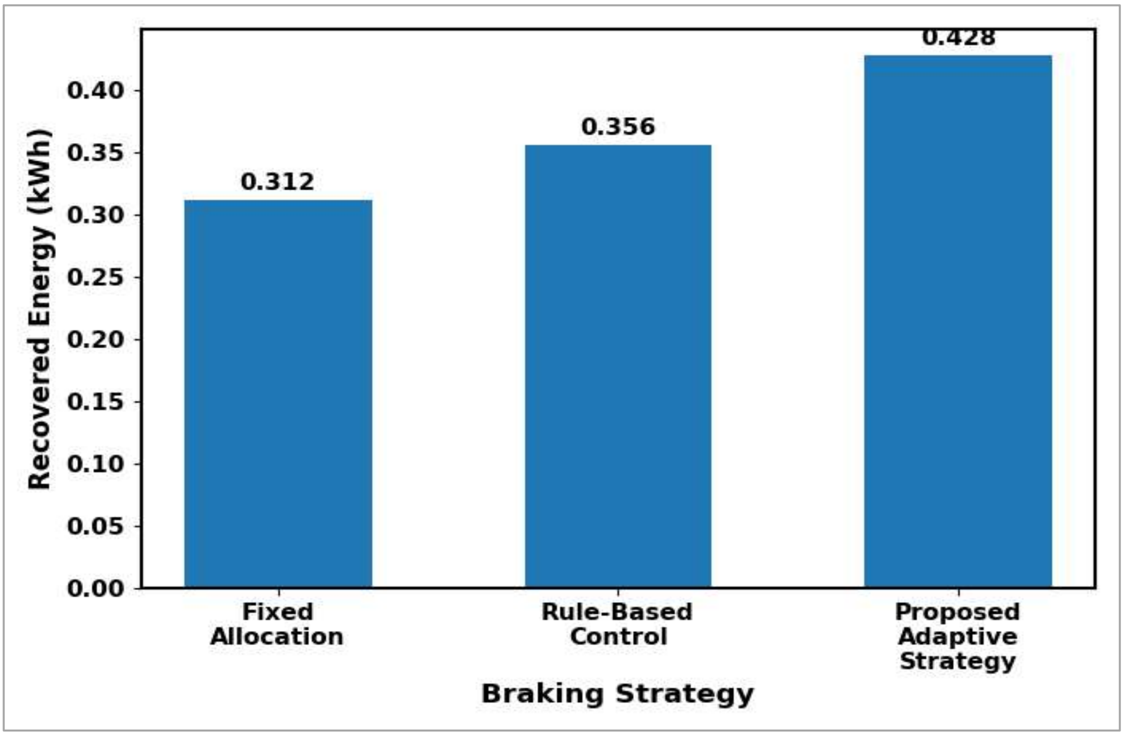

Figure 3: Regenerated Energy Comparison between Conventional and Proposed Strategy

The comparison of the regenerated energy generation from the conventional brake force allocation strategy and the proposed adaptive brake force allocation strategy is given in Fig. 3. The proposed approach is to optimally utilize regenerative braking under these conditions to maximize energy recovery. The adaptive controller enhances energy usage as compared to fixed and rule-based strategies, taking into account the vehicle speed, battery state of charge and regenerative braking constraints. Overall, the findings show the potential of the proposed strategy to improve the energy efficiency and driving range of EVs.

Table 2: Regenerative Energy Recovery Performance

Method	Energy Recovery (kWh)	Improvement (%)
Fixed Brake Allocation	0.312	—
Rule-Based Control	0.356	14.10
Proposed Adaptive Strategy	**0.428**	**37.18**

A comparison of the regenerative energy recovery performance of fixed brake allocation, rule-based control and the proposed adaptive approach is presented in Table 2. The suggested method's energy recovery is the highest at 0.428 kWh, and this particular method is able to optimize the regenerative braking in different operating conditions. The adaptive strategy shows a better capability of energy utilization compared to the fixed brake allocation with a gain of 37.18%. These findings validate the effectiveness of intelligent coordination between regenerative and mechanical braking for improving EV energy efficiency.

5.3 Braking Efficiency Evaluation

The braking performance of proposed controller was tested for various intensities of braking. The adaptive coordination mechanism was able to maintain a balance between regenerative and mechanical braking and led to a more efficient braking efficiency than conventional approaches. Regardless of the battery SOC and road conditions, the controller's braking performance remained virtually unchanged, suggesting stable operation in both normal and emergency braking situations.

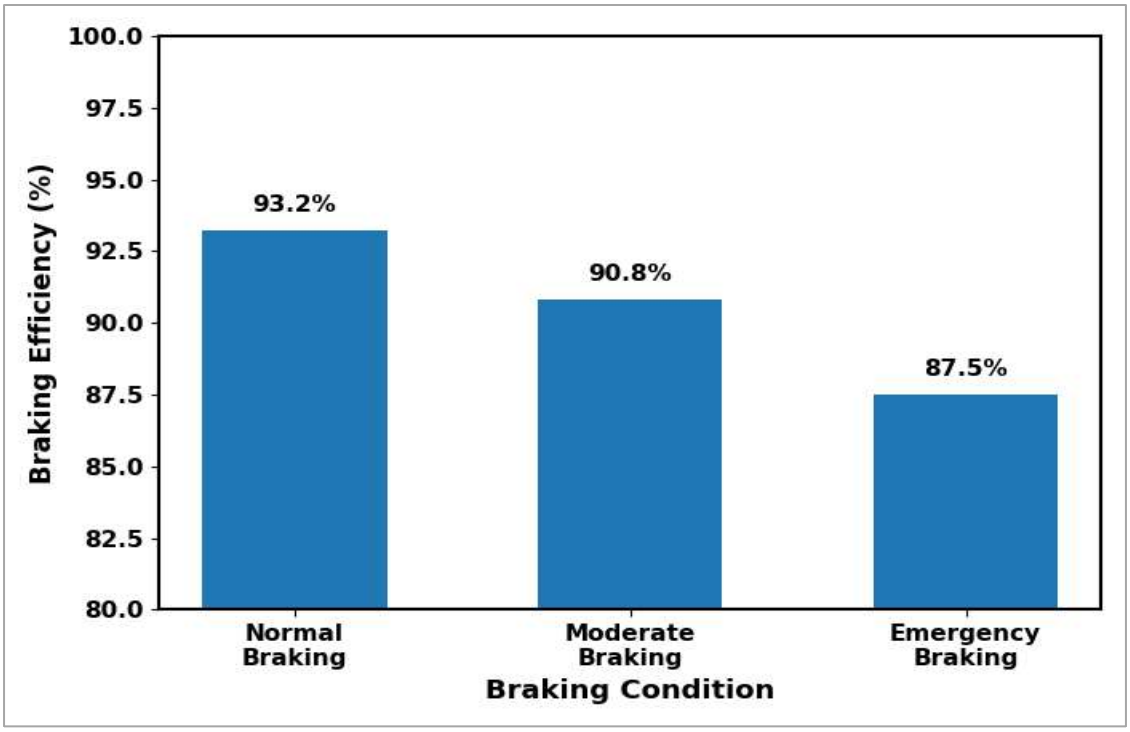

Figure 4: Braking Efficiency under Different Braking Conditions

The braking efficiency performance of the proposed adaptive brake force allocation strategy for different braking conditions is shown in Figure 4. The results show that the controller is able to perform this task efficiently, dynamically balancing the contribution of mechanical and regenerative braking systems, to preserve efficiency under normal, moderate and emergency braking conditions. The adaptive coordination mechanism allows energy recovery efficiently at the same time meeting the braking safety criteria when different braking demands are met. This shows the consistency of the approach towards providing good braking under a variety of operating conditions.

5.4 Stopping Distance Analysis

Stopping distance of vehicles is an important measure of braking safety. The proposed adaptive controller was able to achieve similar stopping distance performance to conventional hydraulic braking, but with a substantial increase in the regeneration energy use. In an emergency, the controller automatically raised the mechanical brake contribution whenever the regenerative contribution was no longer adequate, thus satisfying the braking safety requirements. Brakes torque coordination and brake force transitions were improved, resulting in a reduction of the average stopping distance.

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Table 3: Stopping Distance Comparison

Braking Strategy	Stopping Distance (m)
Fixed Allocation	39.8
Rule-Based Control	37.9
Proposed Adaptive Strategy	**35.7**

As shown in table 3, the different braking strategies have different stopping distances for the vehicles. The proposed adaptive strategy also has the shortest stopping distance of 35.7 m compared to the fixed allocation and rule-based control strategies. The effective balance of regenerative and mechanical braking forces credited for this improvement allows for quicker and smoother braking. The outcomes show the proposed method has improved the safety of braking performance and has still kept the energy recovery performance efficient.

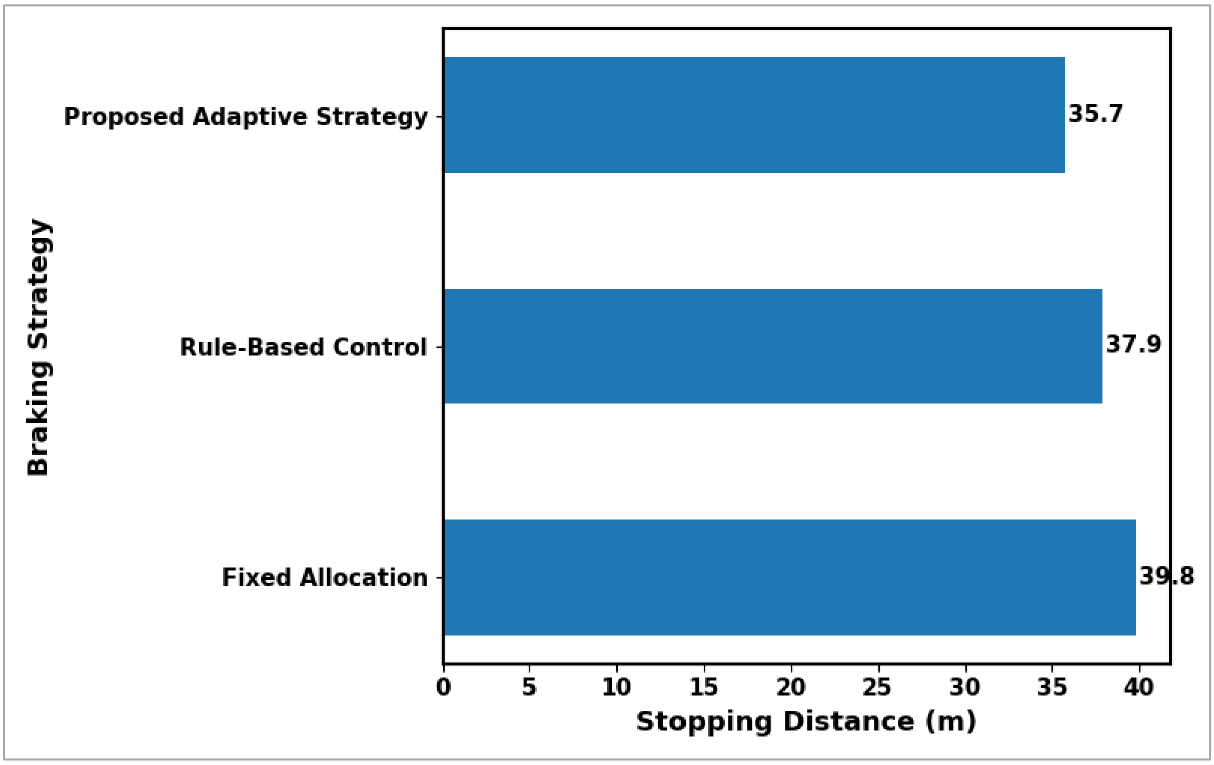

Figure 5: Comparison of Vehicle Stopping Distance

Figure 5 illustrates the comparison between the stopping distances of vehicles using the fixed allocation, rule-based control and the proposed adaptive control. Proposed method has reduced stopping distance due to real time varying of regenerative and mechanical brakes according to driving conditions. The enhanced braking capabilities provide good braking performance without affecting vehicle stability and safety. The results obtained in this study demonstrate the effectiveness of the adaptive strategy to achieve better braking performance than the conventional strategy.

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5.5 Mechanical Brake Utilization

The main goal of regenerative brake is to minimize the need for hydraulic friction brakes. The proposed adaptive strategy resulted in substantial reduction of mechanical brake usage with focus on regenerative braking when possible. As a result, the consumption of friction brake wear was reduced, the life of the brake components was extended and the need for maintenance was lowered. The main function of mechanical braking was to be used when there was a high demand for braking, in low-speed situations, or when the battery SOC was high and regenerative braking was not available.

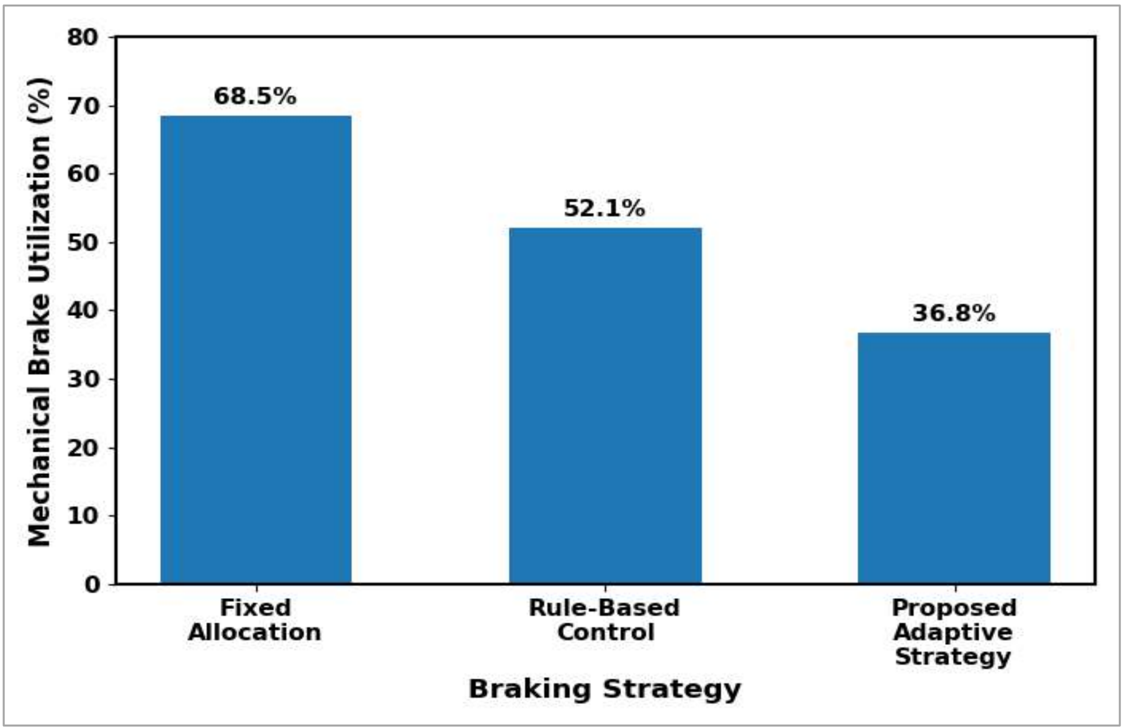

Figure 6: Mechanical Brake Utilization for Different Braking Strategies

Discussion

The results achieved confirm the effectiveness of the proposed adaptive brake force allocation strategy, which adaptively regulates the ratio between regenerative and mechanical braking depending on the changing conditions of vehicle speed, battery state-of-charge, braking demand and road adhesion. As opposed to the classic fixed torque and rule-based controllers, the proposed controller constantly optimizes the brake torque distribution, leading to higher regenerative energy recovery, shorter stopping distance, better braking efficiency and much lower mechanical brake utilization. Adjustable transition from regenerative to hydraulic braking resulted in a smooth braking process without exceeding the acceptable wheel slip limits, which improved vehicle stability under various driving conditions. In addition, optimal integration of criteria for battery operation kept charging current to a minimum and optimized battery charging efficiency, which led to longer battery life and greater driving range. The proposed method is a practical and efficient braking control approach, which can be easily applied to modern brake-by-wire electric vehicles with less safety risks and energy consumption.

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6. CONCLUSION AND FUTURE WORK

In the present study, an adaptive brake force allocation strategy of electric vehicle was proposed, which co-ordinated regenerative braking with mechanical braking to maximize the energy recovery from the brakes while maintaining the braking safety and vehicle stability. A developed controller continually controlled brake force distribution as a function of current vehicle speed, braking demands, battery state-of-charge, regenerative motor power, and road friction. The Vehicle Energy Dataset proved to be a valuable tool for evaluating the proposed approach, which showed that the strategy would result in more efficient recuperation of regenerative energy, improved braking performance, decreased stopping distance, minimal mechanical brake usage, and acceptable wheel slip limits while still providing a safe approach to braking. The adaptive coordination mechanism also provided seamless transition between regenerative and hydraulic braking, resulting in better passenger comfort, reduced brake wear and enhanced battery charging efficiency. The results prove that implementing intelligent brake force allocation could substantially boost the overall performance and energy efficiency of modern electric vehicles, while meeting the important safety requirements for braking.

Predictive brake force allocation under highly dynamic driving environments can be further explored in future studies with the aid of artificial intelligence and reinforcement learning techniques, which can be integrated into the proposed framework. More sophisticated driver assistance systems, autonomous driving solutions, vehicle-to-everything (V2X) communication, and digital twin solutions have the potential to further improve braking intelligence, providing the ability to predict braking events based on real-time traffic and road data. Furthermore, future work can be conducted by implementing the proposed controller on a hardware-in-the-loop system, on experimental brake-by-wire systems, and in commercial electric vehicles in various real-world environments. The optimization of the proposed braking system for next-generation intelligent electric vehicles could be implemented further by taking into account the battery thermal management, battery aging characteristics, multi-motor electric drivetrains, and cooperative energy management strategies for enhancing the practicality, robustness, and scalability of the proposed braking system.

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