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SIMULATION STUDY ON REGENERATIVE BRAKING SYSTEM IN ELECTRIC VEHICLE (EV)

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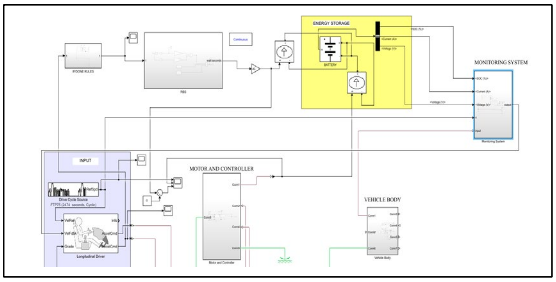
Graphical Abstract



Abstract

The acceptance of electric vehicles (EVs) is rapidly growing in today's era, driven by the imperative to curtail carbon emissions and embrace environmentally friendly alternatives. Consequently, profound significance is attached to researching energy regeneration systems within EVs. This paper focuses on a simulation study involving an integrated electric vehicle (EV) model and a regenerative braking system (RBS). The EV model was meticulously crafted using MATLAB Simulink to investigate the impact of the RBS on recharging the battery with recaptured energy. Furthermore, the study delved into comprehending how the size and weight factors influence the RBS performance. The study leveraged a 72 V Lithium-ion battery model, valued for its substantial capacity and charging efficiency. Employing Simulink's driving cycle sources, the simulation accurately mirrored real-world scenarios. The pivotal parameters scrutinized in this simulation encompassed the magnitude of current replenishing the battery and the battery's State of Charge (SOC) percentage. The results of this study showed that a good design for electric vehicles, focused on putting more energy back into the battery, needs to be heavier, more aerodynamic, and have a smaller front end.

Keywords

Regenerative Braking, Electric Vehicles, Energy Return, State of Charge, MATLAB Simulink

Introduction

The regenerative braking system (RBS) is a technology that efficiently converts wasted kinetic energy during deceleration into useful electrical energy. In contrast to conventional braking systems that generate heat and energy loss, RBS minimizes wear on braking components and harnesses the energy to charge the vehicle's battery. Although electric vehicles (EVs) have a long history, they face challenges with the rise of internal combustion engines. However, recent developments, such as the Toyota Prius and Tesla's electric cars, reignited interest in EVs and the optimization of RBS. Conventional brakes dissipate energy as heat, but RBS captures and stores the kinetic energy in the battery, offering significant advantages. Regeneration occurs when the driver presses or releases the brake pedal, with the amount of energy regenerated directly related to the force applied. Factors like vehicle speed, pedal usage, and weight influence the optimization of RBS to enhance its performance. The primary objective of this study is to carry out a simulation study that can investigate the effect of energy returned from RBS towards the current and SOC of the battery. This study also will investigate the effect of parameter changes on the performance of regenerative braking systems (RBS) in electric vehicles (EV).

The problem or issue concerning the regenerative braking system (RBS) depends on driving conditions. According to [1], the RBS experiences a 16.04% reduction in torque distribution during regular city driving, indicating an issue with traffic jams. Therefore, conducting a simulation study of the RBS in electric vehicles is crucial to evaluate performance and address this problem. The focus of building the simulation model for this study is the braking methods, such as plugging braking, dynamic braking, and regenerative braking. Paper [2] suggests that a combination of a "plugging + regenerative" system optimizes energy consumption, while the "dynamic + regenerative" system enhances braking ability. This paper highlights the structure of the regenerative braking system and its components, such as the electrical motor, power inverter, batteries, and control system, which may affect performance and efficiency. Paper [3] highlights the significance of various parameters like calliper surface area and effective disc radius in determining the amount of friction braking force. To discuss RBS efficiency, we must focus on the wasted energy produced by the system. The power generated by a fully charged battery (100%) is dissipated as heat. Therefore, this simulation study will provide the necessary data for improvement.

METHODOLOGY

The main objective of this paper is to study the effect of energy regeneration from regenerative braking systems (RBS) on the current and state of charge (SOC) of the batteries in electric vehicles (EV). This paper also investigates the effect of parameter changes on the performance of regenerative braking systems (RBS) in electric vehicles (EVs). All the objectives were achieved using the simulation parameter tuning in Simulink. By implementing the mathematical models in MATLAB/Simulink, data can be calculated and verified, aiding in the analysis and optimization of EV systems [4].

Mathematical Modelling For EV

The methodologies process starts with Mathematical Modelling for EV Development in Simulink. The EV model developed in this project followed the tutorial in [5]. The block section of the mathematical model for the electric vehicle (EV) consists of various components, including driver input, controller, motor, battery, gearbox, and tires, which are shown in Figure 1.

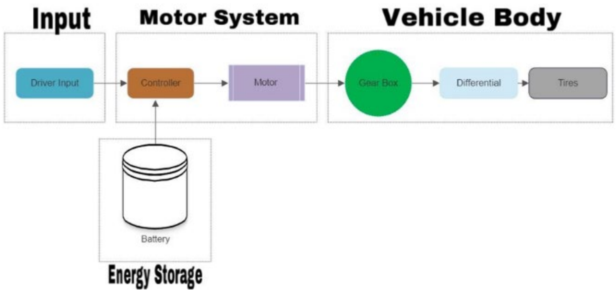


Figure 1: Subsystem Connection for Electric Vehicle Mathematical Modelling

The driver input system allowed the user to adjust the input speed over time, enabling the monitoring of driver behaviour during acceleration and deceleration. The vehicle body component adjusted parameters such as the vehicle's mass. The motor and controller system processed the driver input, which employed a PWM (Pulse Width Modulation) controller. This processing of the driver input impacted the energy storage system, which was connected to a monitoring system that displayed the Percentage of State of Charge (SOC), voltage, and current of the battery. The integrated mathematical model in Simulink allowed for analysing and evaluating the EV's performance, particularly in regenerative braking, and provided valuable insights into the system's behaviour and efficiency.

According to a paper referenced in [6], the driver model was classified into longitudinal, lateral, and integrated driver models, depending on the dimensions of vehicle dynamics. The developed EV model utilized the longitudinal driver model to analyse the input from the driving cycle and investigate how the driver adjusted the vehicle's acceleration and deceleration.

The model also employed a PWM voltage signal controller for the motor and controller system. This controller received input from the longitudinal driver model and supplied power to the motor driver, which was connected to a DC Motor. The combination of PWM voltage control and DC Motor proved to be highly suitable for their simulation tests, particularly in the context of battery charge and discharge monitoring. The vehicle body parameters were set according to Table 1, and the energy storage parameters were provided in Table 2.

Table 1: Parameters for Vehicle Body of the EV model [5]

Parameters	Value
Mass	600 kg
Distance from COG to front axle	1.4 m
Distance from COG to rear axle	1.6 m
Height of COG from the ground	0.5
Frontal Area	2 m^2
Coefficient Drag	0.25
Air Density	1.18 kg/m^3

Table 2: Parameters for Lithium- Ion battery of the EV model verification test [5]

Parameter	Value
Nominal Voltage (V)	72
Rated Capacity (Ah)	695
Initial state-of-charge (%)	50
Battery response time (s)	1

To calculate the amount of energy returned through regenerative braking, the equation primarily focuses on the initial and final speeds of the electric vehicle (EV). This approach aims to analyse the impact of acceleration and deceleration on the energy returned to the batteries. In this analysis, brake-related parameters like brake torque and coefficient of friction are assumed to remain constant. By isolating the effects of speed changes, the equation enables a better understanding of the energy regeneration process and its connection to vehicle dynamics. Figure 3 shows the block diagram of RBS. The derived equation to calculate the energy return to the battery is given in Eq. (1)

$$0.01072\mathrm{W_e}({V^2}_1 - {V^2}_2) + 27.25GSW + 0.2778\, WrS \quad (1)$$

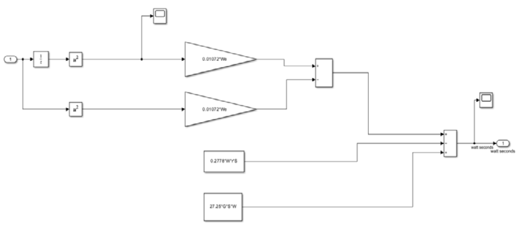


Figure 2: Block Diagram for RBS Integration

Performance Analysis of The Regenerative Braking System

The size and weight of the vehicle significantly influence the effectiveness of the regenerative braking system. Numerous studies have demonstrated that electric regenerative braking can enhance fuel efficiency by 20-50%, depending on the size of the electric machine [7].

A performance analysis will be carried out to gather the data to conduct the simulation study. A comparison will be made between an EV without a regenerative braking system (RBS) and an EV equipped with RBS. This analysis will focus on the current usage and the battery's state of charge (SOC) percentage. The second comparison will be considering EVs with different weights. Specifically, EVs weighing 580 kg, 600 kg, and 620 kg, all equipped with RBS, will be compared regarding current usage and percentage of SOC. The performance analysis will also be a comparison between EVs with varying coefficients of drag. EVs with made drag coefficients set at 0.2, 0.25, and 0.3 will be evaluated based on current usage and percentage of SOC. Lastly, a comparison will be made among EVs with different frontal areas. EVs with frontal areas of 2.0 m^2, 2.5 m^2, and 3.0 m^2 will be assessed regarding current usage and percentage of SOC. By examining these different scenarios, the performance analysis aims to provide a comprehensive understanding of the impact of RBS, weight, coefficient of drag, and frontal area on EVs' current usage and SOC percentage.

RESULTS AND DISCUSSIONS

The first outcomes of this project discuss the comparison between the current and state of charge (SOC) of batteries in electric vehicles (EVs) equipped with a regenerative braking system (RBS) and those without. Figure 3 shows that EVs with RBS show negative current values, while EVs without RBS display positive ones. During acceleration, the vehicle's kinetic energy increases exponentially with its velocity. As the vehicle coasts, the kinetic energy gradually decreases until it reaches zero. When the brakes are applied in an electric vehicle, the motor controller works to bring the motor to a stop or reduce its speed. This involves reversing the motor torque's direction, opposing its rotation. Referring to Figure 4, we can observe that the line trend for the electric vehicle (EV) equipped with a regenerative braking system (RBS) consistently increases throughout the simulation. In contrast, the EV without RBS shows a decreasing trend. This suggests that the battery in the EV model with RBS is charged during the driving cycle, while the battery without RBS discharges.

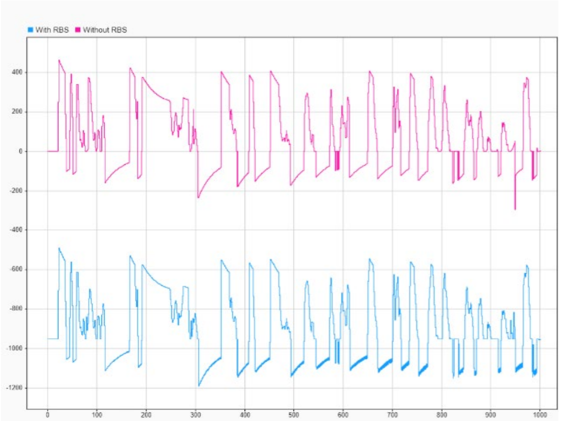


Figure 3: Comparison of the current of the Battery between EVs with and without RBS

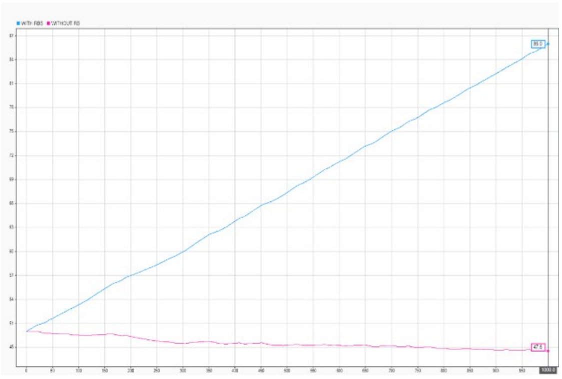


Figure 4: Comparison of the SOC (%) of the battery between EVs with and without RBS

Continuing with the results, we compare the batteries' current and state of charge (SOC) (%) after varying the vehicle weight. The study includes three different weights, which are 550 kg, 600 kg, and 650 kg. Figure 5 illustrates the current results for all three weights after simulating 1000 seconds. At 187 seconds, the negative current values for the weights of 550 kg, 600 kg, and 650 kg are 1003 A, 1084 A, and 1165 A, respectively. These findings suggest that the vehicle with the heaviest weight (650 kg) generates the highest negative current, indicating a greater extent of battery recharging. This observation is further supported by Figure 6, which reveals that after 1000 seconds, EVs with a weight of 650 kg have recharged up to 89.18%, while those with weights of 600 kg and 550 kg have recharged up to 86% and 83%, respectively. From this observation, the regenerative braking system returns more energy as the vehicle's weight increases. This suggests that a greater vehicle weight results in a higher potential for energy recovery through the regenerative braking system.

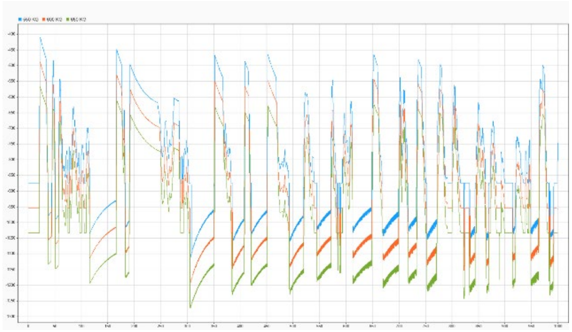


Figure 5: Comparison of the current of the batteries between different weights of vehicles

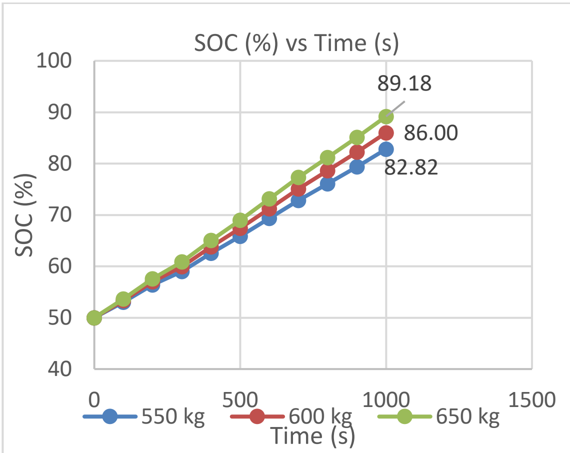


Figure 6: Comparison of SOC (%) of the batteries between different weights of vehicles

The analysis proceeds by comparing the outcomes of the current and state of charge (SOC) (%) of the batteries after 1000 seconds with varying drag coefficients. Figure 7 indicates that the current values do not differ significantly across the drag coefficients. For example, at 187 seconds, the battery current (in Amperes) for drag coefficients 0.2, 0.25, and 0.3 are -1085.02, -1084.03, and -1083.08, respectively. Although these values show minor differences, they are still sufficient to study the effect of the coefficient of drag on the performance of the regenerative braking system. This observation is further supported by the data presented in Figure 8, which compares the SOC percentage of the batteries for different drag coefficients. The figure demonstrates that the vehicle with a drag coefficient of 0.2 achieves the highest SOC at the end of the simulation (1000 seconds), reaching 86.41%. This is followed by the vehicle with a drag coefficient of 0.25, which attains a SOC of 86.00%, and the vehicle with a drag coefficient of 0.3, which achieves a SOC of 85.61%. While the differences in current and SOC (%) values may not be significant, they offer valuable insights into the impact of the coefficient of drag on the performance of the regenerative braking system. The findings highlight the importance of minimizing the drag coefficient to enhance energy recovery in the vehicle, emphasizing the significance of aerodynamic design in optimizing the efficiency of the regenerative braking system.

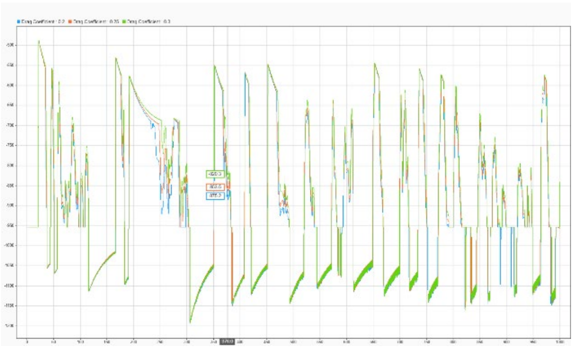


Figure 7: Comparison of the current of the batteries between different coefficients of drag

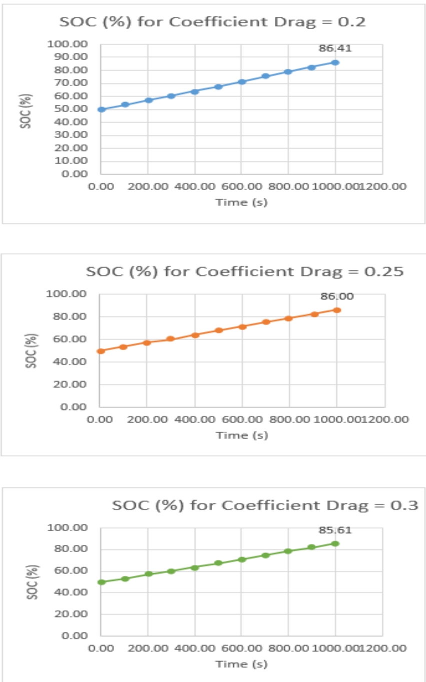


Figure 8: Comparison of SOC (%) of the batteries between different coefficients of drag

In the final analysis, we examine the frontal area's effect on the battery's current and SOC. We consider three frontal areas, which are 2.0 m², 2.5 m², and 3.0 m². Figure 9 shows that smaller frontal areas result in higher negative current values. For example, at 187 seconds, the current values for 2.0 m², 2.5 m², and 3.0 m² are -1084.03 A, -1082.84 A, and -1081.64 A, respectively. This indicates that a smaller frontal area yields greater energy return through regenerative braking. Figure 10 shows that EVs with a frontal area of 2.0 m² achieve a higher SOC of 86% after the 1000-second simulation, compared to 85.52% and 85.07% for 2.5 m² and 3.0 m², respectively. These findings highlight how reducing the frontal area enhances battery recharging. It reduces air resistance, enabling a more efficient conversion of kinetic energy into electrical energy during deceleration, leading to more energy stored in the batteries.

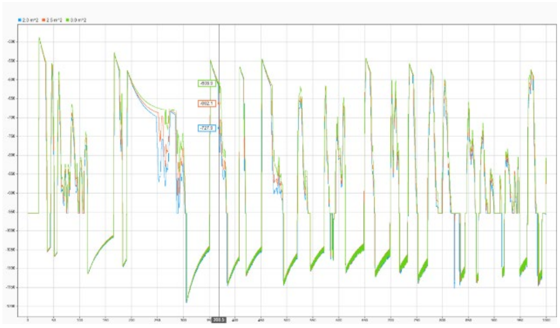


Figure 9: Comparison of the current of the batteries between different frontal areas

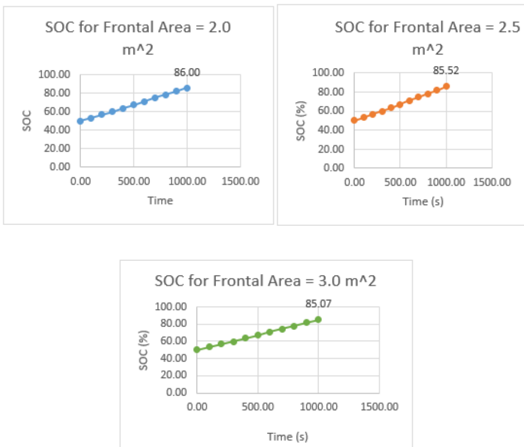


Figure 10: Comparison of SOC (%) of the batteries between different frontal areas

Conclusion

In conclusion, this study provides comprehensive data on the impact of the regenerative braking system (RBS) on energy regeneration in electric vehicles (EVs). The findings show that EVs equipped with RBS have higher battery current returns and achieve a higher charge at the end of the simulation period. This indicates the effectiveness of the RBS in recharging the batteries during the driving cycle. Furthermore, the analysis reveals that parameters such as the weight of the vehicle, coefficient of drag, and frontal area significantly influence the performance of the regenerative braking system. To improve energy recovery and increase current values returned to the battery, having a heavier weight, lower drag coefficient, and smaller frontal area in EV design is beneficial. These factors contribute to more efficient energy regeneration and enhance the overall performance of the regenerative braking system.

However, further research and development are needed to advance the knowledge and application of regenerative braking systems (RBS). This includes improving braking algorithms and control strategies, exploring integration with other energy storage technologies and conducting real-world testing on physical EV prototypes. These efforts will optimize RBS performance and enhance energy efficiency in electric vehicles, contributing to a more sustainable transportation future.

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