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A COMPARATIVE STUDY OF REGENERATIVE BRAKING EFFICIENCY BETWEEN AUTOMATED AND HUMAN DRIVEN ELECTRIC VEHICLES TO MINIMIZE BATTERY DEGRADATION

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Abstract: Recently, lithium-ion batteries has been becoming essential components in electric vehicles and hybrid electric vehicles however, their degradation significantly impacts the battery's lifespan, reliability, safety, and overall performance. Accurately evaluating and quantifying the extent of degradation is crucial for determining the true state of health of lithium-ion batteries. As a key component of electric vehicles, the regenerative braking system improves energy efficiency and extend the range of electric vehicles by capturing kinetic energy during braking and converting it into stored energy in the batteries or other storage systems. In this comparative study, regenerative braking efficiency between automated and human driven electric vehicles to review and analyze the chance of minimize battery degradation and assess the battery state of health.

Keywords: electric vehicles, lithium-ion battery, regenerative braking system, degradation, state of health.

AVTOMATLASHTIRILGAN VA INSON TOMONIDAN BOSHQARILADIGAN ELEKTROMOBILLARDA REGENERATIV TORMOZLASH SAMARADORLIGINI TAQQOSLASH BO‘YICHA TADQIQOT, AKKUMULYATORNING YEMIRILISHINI MINIMALLASHTIRISH MAQSADIDA

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Annotatsiya: So‘nggi yillarda lityum-ionli akkumulyatorlar elektromobillar va gibrid elektromobillar uchun muhim komponentga aylangan bo‘lsa-da, ularning eskirishi akkumulyatorning ishlash muddati, ishonchliligi, xavfsizligi va umumiy samaradorligiga salbiy ta’sir ko‘rsatmoqda. Akkumulyatorning asl texnik holatini aniqlash uchun uning eskirish darajasini to‘g‘ri baholash va miqdoriy ifodalash muhim hisoblanadi. Elektromobillarning asosiy qismlaridan biri bo‘lgan regenerativ tormozlash tizimi harakat vaqtida kinetik energiyani saqlab qolib, uni batareyalarda saqlanadigan elektr energiyasiga aylantirib, avtomobilning energiya samaradorligini oshiradi va yurish masofasini uzaytiradi. Ushbu taqqoslov tadqiqotda avtomatlashtirilgan va inson tomonidan boshqariladigan elektromobillarda regenerativ tormozlash samaradorligi o'rganilib, akkumulyator eskirishini kamaytirish imkoniyatlari va akkumulyator sog'lig'ining holati baholandi.

Kalit so'zlar: Elektromobillar, lityum-ion batareya, regenerativ tormozlash tizimi, yemirilish, sog'lik holati.

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I. INTRODUCTION.

Electric vehicles are playing a crucial role in shifting the transportation sector towards sustainability, offering a real chance to cut down on greenhouse gas emissions and reduce our dependence on fossil fuels. One key element in improving the energy efficiency and range of electric vehicles is the energy recovery system, which captures kinetic energy during braking and converts it into electrical energy to be stored in the vehicle's battery. While this technology has been in use for years in both hybrid and electric vehicles, there are still challenges to overcome, such as making the energy recovery process more efficient under different driving conditions, ensuring it works well with traditional braking systems, and dealing with the limitations of batteries and electric motors [1].

In recent years, both scientific research and industry interest in this area have grown significantly, leading to exciting developments and a surge in related publications. In this study, we will first examine the structure of regenerative braking systems and analyze how they improve energy efficiency and extend the driving range of electric vehicles. Next, we will analyze human driving behavior in urban environments and, in comparison, evaluate the impact of regenerative braking on automated driving, with the goal of minimizing battery degradation. This comparative study seeks to offer a comprehensive analysis of the scientific literature on energy recovery systems in electric vehicles, focusing specifically on their structure, control strategies, energy storage technologies, and the impact of external factors and kinematic parameters on recovery efficiency. The study is based on a systematic review and modeling of battery performance, aiming to synthesize key insights from existing research to better understand the dynamics of energy recuperation in electric vehicles [2].

II. HUMAN DRIVING BEHAVIOR OF ELECTRIC VEHICLES IN URBAN ENVIRONMENTS

In cities, the way electric vehicles are driven is shaped by things like traffic, road types, and how the driver behaves. Urban driving often involves frequent stops, congested roads, and short trips, which bring both challenges and advantages for electric vehicles, especially when it comes to energy efficiency and regenerative braking. These factors play a key role in how well the vehicle recovers energy and how far it can go on a single charge. City driving mode often involves a lot of quick starts and stops, which can put a strain on a vehicle's energy system. However, electric vehicles can take advantage of regenerative braking in these stop-and-go situations. This system allows the vehicle to capture the energy that's normally lost during braking and turn it into electrical energy to recharge the battery. In urban settings, where frequent braking is common, this is a great way to recover energy. How well regenerative braking works depends a lot on how smoothly and often the vehicle stops and starts. In the Fig 1, the structure of regenerative braking system outlined and the green color identifies here when the braking pedal is applied, the kinetic energy changes to electric energy and the red color shows how electric energy converts to kinetic energy. How a driver behaves behind the wheel is key to the energy efficiency of electric vehicles. Aggressive driving, like speeding up quickly and braking suddenly can make regenerative braking systems less effective and cause the battery to degradation faster. On the other hand, driving more smoothly, with gradual acceleration and braking, helps the regenerative braking system work more efficiently and reduces energy loss. In cities, where traffic often leads to frequent stops and starts, promoting smoother driving through driver education that encourage calm driving can improve the overall performance of electric vehicles [3].

In cities with heavy traffic, electric vehicles often spend a lot of time idling and the during these moments, the regenerative braking system doesn't operate, and energy is instead used for things like air conditioning, entertainment systems, and lights, which can drain the battery. While modern electric vehicles are designed to minimize energy loss when idling, the impact of traffic congestion and long periods of idling on energy efficiency is still significant. To address these challenges, urban planning that includes more electric vehicles charging stations and efforts to reduce traffic congestion could be key to improving overall energy efficiency. Regenerative braking systems are especially effective in urban environments due to the frequent braking events that occur in city driving. The energy captured during braking is stored in the battery, which helps improve overall energy efficiency and extends the vehicle's driving range. However, the effectiveness of these systems largely depends on how well the driver manages braking force. In some electric vehicles, the regenerative braking system is adaptive, automatically adjusting the braking force based on the driver's inputs and the driving conditions. External elements such as road conditions, weather, and terrain also influence both driving behavior and the efficiency of regenerative braking systems. For example, on rainy or slippery roads, drivers may brake more gently, limiting the energy recovery potential. On the other hand, hilly terrains may cause more frequent braking, which can enhance regenerative braking efficiency, although it may also increase battery consumption due to the extra energy needed to ascend hills. The incorporation of autonomous driving technologies in urban environments could further optimize regenerative braking and energy recovery. Automated systems can make braking decisions more precisely and consistently, smoothing out driving patterns and reducing energy loss caused by erratic braking. This increased accuracy in braking could maximize the benefits of regenerative braking, particularly in stop-and-go traffic situations [4].

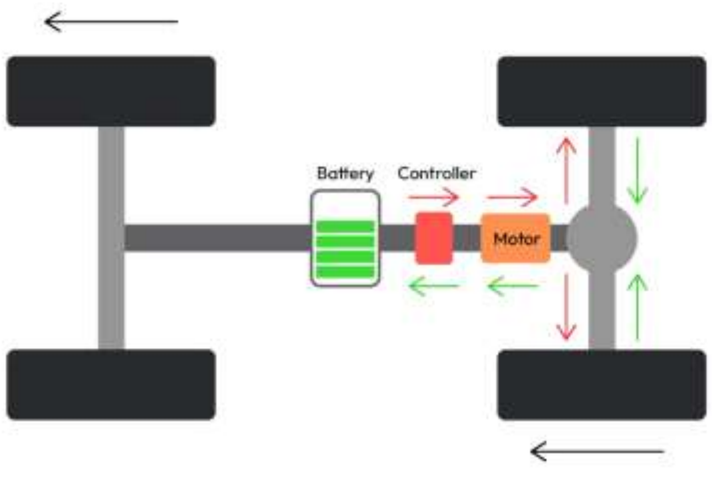

Fig 1: The Structure of regenerative braking system

Normal driving is all about steady acceleration and braking. Drivers typically go with the flow of traffic and try to maintain a consistent speed. This kind of driving is great for both regenerative braking and battery health. During smooth, controlled braking, the regenerative braking system can efficiently capture the energy from slowing down and send it back to the battery without putting too much strain on it. Regenerative braking works well in normal driving, allowing energy to be consistently recovered. Since the braking is usually not too forceful, the system operates at its best, improving energy efficiency. Normal driving with moderate braking and acceleration helps reduce degradation on the battery compared to more aggressive driving. By utilizing regenerative braking, the system reduces the load on the battery, preventing deep discharges and heavy, high-load use, which helps slow down battery degradation [5].

Comparing to the sport mode is designed for a more exciting driving experience. It makes the vehicle more responsive by increasing the sensitivity of the accelerator and, in some cases, reducing the effectiveness of regenerative braking. This mode often appeals to drivers who enjoy a quicker, more dynamic response from their vehicle. However, it can lead to more aggressive acceleration and braking, which may affect both the efficiency of regenerative braking and the health of the battery. In sport mode, regenerative braking might be less effective or even turned off in some cars, which limits the amount of energy that can be recovered. The aggressive acceleration and braking reduce the opportunities for regenerative braking to do its job, as the system doesn't get enough time or conditions to recover energy. Frequent hard accelerations and rapid braking increase energy consumption and cause more significant battery discharges. This means the battery goes through more charge cycles, which speeds up degradation over time. Sport driving generates more heat in the battery, which can cause it to degrade faster. Higher energy demand means deeper discharges and more frequent charging, which can shorten the battery's lifespan. Over time, the constant charging and discharging at high rates can cause the battery to lose its capacity and efficiency.

Aggressive driving, like rapid acceleration, speeding, and sudden braking has the biggest negative impact on regenerative braking and battery life and the sudden or harsh braking reduces the effectiveness of regenerative braking. The system works best when the deceleration is gradual, but aggressive braking forces the system to work harder and prevents energy from being fully recovered. Aggressive acceleration, followed by quick braking, results in less efficient energy recovery since the system can't adjust smoothly to the rapid changes in speed. Constant aggressive driving puts a lot of stress on the battery. Rapid acceleration demands a lot of power, and harsh braking strains the regenerative braking system, forcing it to work harder and draining the battery faster. The high rate of charge and discharge cycles accelerates battery degradation. Deep discharges followed by fast charging generate heat, which negatively impacts the battery's long-term health. Over time, this continuous stress compromises the battery's capacity and efficiency, shortening its overall lifespan.

On the flip side, smooth and gentle driving is the least taxing on both regenerative braking and battery health. Drivers who avoid sudden accelerations and hard braking allow the regenerative braking system to function at its best and minimize the strain on the battery. Smooth driving allows regenerative braking systems to work efficiently. When the acceleration and deceleration are gentle, the vehicle can recover more energy and store it in the battery. This behavior improves overall energy efficiency, making the most out of the regenerative braking system. Smooth driving causes less stress on the battery, leading to more moderate charge cycles. This reduces the likelihood of deep discharges and long recharging times. As a result, the battery stays healthier for longer, avoiding extreme temperature fluctuations and wear caused by rapid charge cycles [6].

$$E_{regen} = \frac{1}{2}mv^2 \times \eta_{regen} \quad (1)$$

Where;

- E_{regen} is recovered through regenerative braking (in joules)
- m is mass of the vehicle (in kilograms)
- v is speed of the vehicle before braking (in meters per second)
- η_{regen} is efficiency of the regenerative braking system (dimensionless, typically between 0 and 1)

In different driving modes (e.g., Normal, Sport, Eco), the efficiency η_{regen} and the level of deceleration may vary. In normal mode the regenerative braking system typically operates at moderate efficiency, with η_{regen} between 0.5 and 0.7, and deceleration is smooth.

$$E_{regen} = \frac{1}{2}mv^2 \times 0{,}6 \quad (2)$$

where η_{regen} is equaled 0.6 reflects a balanced, moderate energy recovery.

In sport mode, the regenerative braking might be less aggressive, or even disabled, leading to lower efficiency. The vehicle may also experience more rapid acceleration, resulting in less energy to recover.

$$E_{regen} = \frac{1}{2}mv^2 \times 0{,}3 \quad (3)$$

where η_{regen} is equaled 0.3 reflects a more conservative energy recovery in sport mode.

In eco mode, the regenerative braking system is typically maximized for energy recovery to optimize range, so

η_{regen} could be higher, typically in the range of 0.7 to 0.9 [7].

Driving Mode	**Speed (m/s)**	**Acceleration (m/s²)**	**Deceleration (m/s²)**	**Energy Recovery (Joules)**	**Energy Loss (Joules)**
Normal	16.67	2.0	4	125050.005	83366.67000000001
Sport	16.67	4.0	2	62525.0025	145891.67250000002
Eco	16.67	1.5	6	166733.34000000003	41683.33499999999

Fig 2: The table of energy recovery, loss, speed, acceleration, and deceleration by driving mode.

Driving Mode	**Regenerative Braking Efficiency (%)**
Normal	60.0
Sport	30.0
Eco	80.0

Fig 3: The table of regenerative braking efficiency for each human driving mode.

III. AUTOMATION DRIVING OF ELECTRIC VEHICLES IN URBAN ENVIRONMENTS.

The combination of autonomous driving technology and electric vehicles is transforming transportation, especially in cities. Self-driving cars, or automated driving systems, use advanced sensors, algorithms, and machine learning to navigate and make decisions without the need for a human driver. When paired with electric vehicle technology, these systems have the potential to make driving more energy-efficient, safer, and smoother. They can also help reduce traffic congestion and improve the overall driving experience in the busy and often unpredictable environments of urban areas. Autonomous driving includes a variety of systems that allow a vehicle to take over driving tasks that would usually be done by a human. The Society of Automotive Engineers (SAE) has created a classification system with levels of automation, ranging from Level 1 (basic driver assistance) to Level 5 (full self-driving). For city driving, most vehicles are expected to operate at Level 3 or Level 4, meaning they can handle most driving tasks in certain situations but might still need a human driver to step in when things get complicated.

In cities, where traffic can be unpredictable and constantly changing, automated driving systems bring a lot of benefits that make electric vehicles even more efficient and practical. One of the main advantages of automation in electric vehicles is its ability to fine-tune regenerative braking. This system uses the electric motor to slow the car down, turning its kinetic energy into electrical energy. In urban settings, with all the frequent stops and starts, automated systems can handle braking and acceleration more smoothly and efficiently than human drivers. One of the primary benefits of automated driving is its ability to decelerate smoothly and consistently. In traditional driving, human drivers may apply the brakes abruptly or inconsistently, leading to inefficient energy recovery and increased wear on the braking system. However, autonomous systems can anticipate upcoming traffic conditions, such as stoplights, turns, and pedestrian movement, allowing them to apply regenerative braking at the optimal moment and with the ideal intensity. With regenerative braking working more efficiently, the battery experiences fewer deep discharge cycles, which reduces the strain on it. This helps the battery last longer and prevents rapid degradation, ultimately extending its lifespan. When the car decelerates smoothly, energy is recovered more effectively, ensuring the vehicle stays efficient. This also prevents energy loss that often happens with abrupt or inefficient braking.

Automated driving systems are designed to adapt in real-time, adjusting the regenerative braking force based on factors like road conditions, traffic flow, and the battery's charge level. For instance, if the battery is nearly full, the system will reduce the amount of energy recovered to avoid overcharging. On slippery roads, the system will dial back the regenerative braking to prevent slipping, and on downhill slopes, it will increase braking to capture as much energy as possible. By adjusting the regenerative braking based on the battery's charge level, autonomous systems ensure the battery stays in a healthy range, preventing overcharging or deep discharges—both of which can speed up degradation. Since regenerative braking reduces reliance on traditional friction brakes, there’s less heat generated. This helps prevent wear and tear on the brakes and also reduces strain on the battery, making energy use more efficient overall.

$$SOC_{final} = SOC_{inital} + \frac{E_{regen}}{C_{battery}} \quad (4)$$

The battery’s state of charge is crucial for understanding how regenerative braking impacts battery degradation. The energy recovery process keeps the battery within an optimal range of charge, preventing overcharging or deep discharges that can cause damage [8].

Where:

- SOC_{final} is the final state of charge of the battery (as a percentage)
- $SOC_{initial}$ is the initial state of charge of the battery (as a percentage)
- E_{regen} is the energy recovered through regenerative braking (in joules)
- $C_{battery}$ is the capacity of the battery (in joules or watt-hours)

Driving Mode	Energy Recovery (Joules)	SOC Initial (%)	SOC Final (%)
Normal (Autonomous)	131302.5	80	80.06079
Sport (Autonomous)	65651.25	80	80.03039
Eco (Autonomous)	175070	80	80.08105

Fig 4: The table of regenerative braking efficiency for each autonomous driving mode at 80% SOC Initial.

Driving Mode	Energy Recovery (Joules)	SOC Initial (40%)	SOC Final (40%)
Normal (Autonomous)	131302.5	40	40.06079
Sport (Autonomous)	65651.25	40	40.03039
Eco (Autonomous)	175070	40	40.08105

Fig 5: The table of regenerative braking efficiency for each autonomous driving mode at 40% SOC Initial.

Driving Mode	Regenerative Braking Efficiency (%)
Normal (Autonomous)	63
Sport (Autonomous)	31.5
Eco (Autonomous)	84

Fig 6: Regenerative Braking Efficiency for Autonomous Driving Modes.

Driving Mode	Human Driving Efficiency (%)	Autonomous Driving Efficiency
Normal	60	63
Sport	30	31.5
Eco	80	84

Fig 7: Summarize of Regenerative Braking Efficiency for Autonomous Driving Modes.

IV. MATHEMATICAL FORMULATION OF THE OPTIMIZATION

The optimization model was developed using MATLAB/Simulink, following the schematic structure shown in Figure 8. The key components of the model include the Powertrain model, the Resistance model, and the Track model.

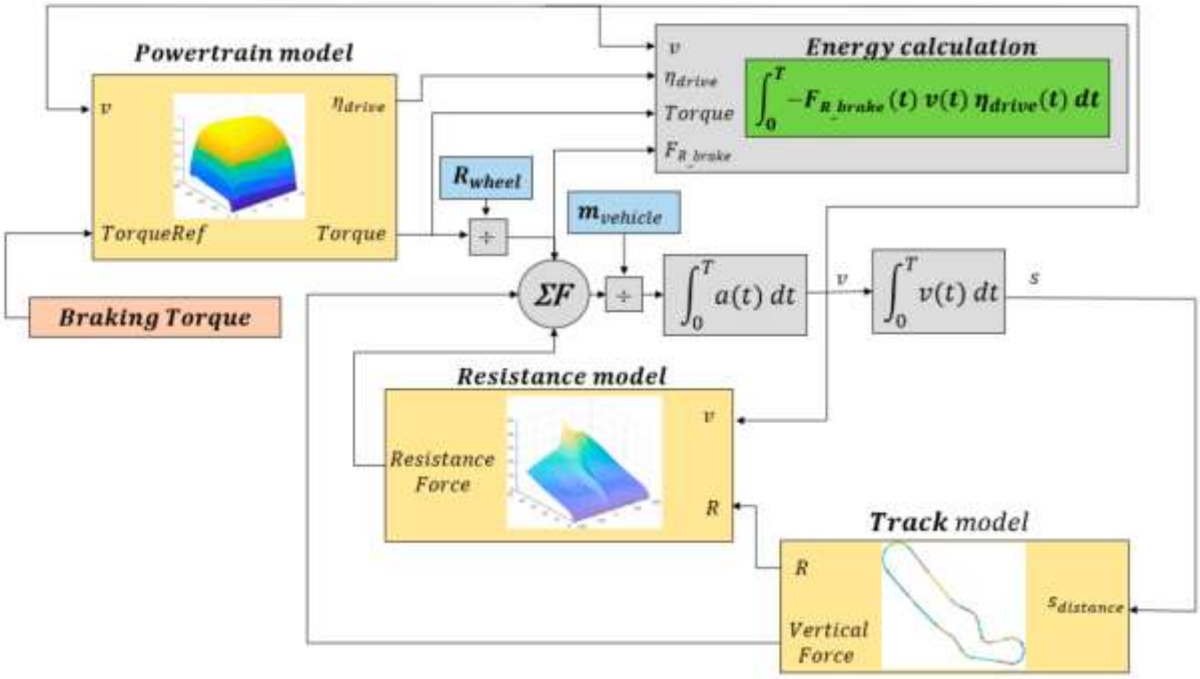

Fig 8: Schematic of optimization framework for regenerative braking system.

The model was designed to be adaptable for future applications, such as optimizing driving strategies, which is why the track model is included. The version of the model shown in Figure 8 operates with direct torque input. While this setup is not suitable for driving strategy optimization, it is ideal for determining the optimal regenerative braking-torque function. The electric powertrain operates in a dual mode, allowing both motor and generator functions depending on the control method used. The unique aspect of the model is its powertrain subassembly, which is capable of functioning in both motor and generator modes.

Figure 9 provides an overview of this powertrain subassembly. The operation mode of the powertrain is determined by the desired torque reference for the vehicle. The process starts by evaluating the required torque based on whether the system is functioning as a motor or a generator. In this step, the desired torque reference is examined and adjusted according to physical limitations, ensuring that the model accurately reflects real-world vehicle operation. Efficiency is then calculated using an efficiency map for the drivetrain, which was previously measured. If the powertrain is in generator mode, a negative torque value is applied to the model. The final step of the subassembly involves a set of logical operators that match the correct values to the initial torque reference, ultimately providing the output of the subassembly [9].

$$E_{recovered} = \int_0^T F_{R\_braking}\,(t) v(t)_{\eta drive}(t) dt \quad (5)$$

The goal of optimization is to determine the optimal regenerative braking-torque function, which enables the maximum available kinetic energy to be converted into recovered energy by the electric powertrain. Minimizing the negative value of recovered energy, $E_{\text{recovered}}$, as shown in Equation (5), is mathematically equivalent to maximizing the positive value of recovered energy in practical applications. This means that to achieve the best performance, we aim to maximize the recovered energy. For computational ease in optimization software, the objective function can be formulated as a minimization problem, which is represented by Equation (6). This approach is more convenient for optimization algorithms, making the task of maximizing the recovered energy more efficient to implement.

$$\text{Minimize: } E = \int_0^T -F_{R\_braking}(t)v(t)_{\eta drive}(t)dt \quad (6)$$

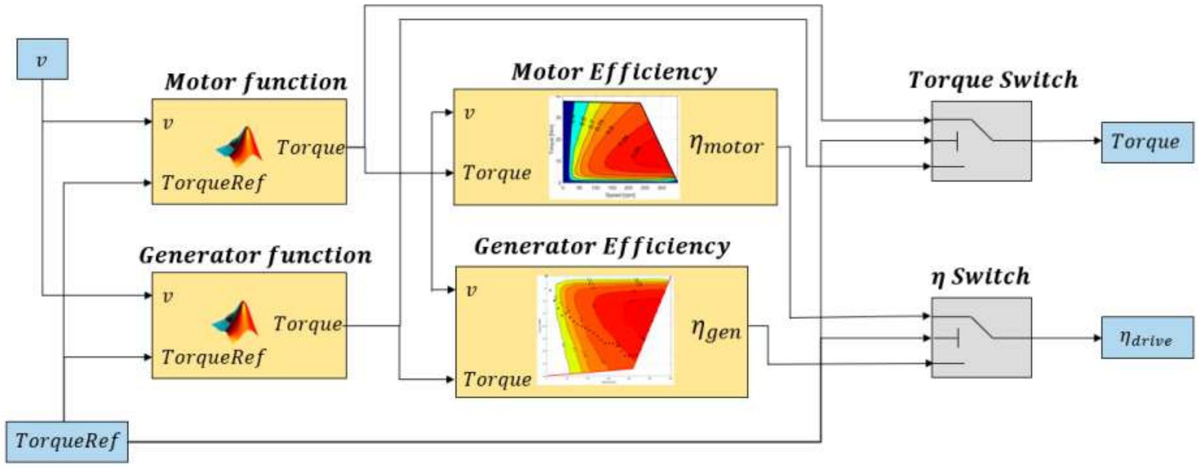

Fig 9: Overview of the powertrain subassembly in the optimization model.

The track model does not impose any optimization constraints, as it is assumed to be flat, and the vehicle path is considered straight. This simplification removes the complexity of terrain or road curvature from the optimization process. The optimized torque function defines discrete torque values at corresponding vehicle speeds, with the aim of maximizing the energy recovered during regenerative braking. Essentially, for each specific speed, the model calculates the optimal torque that ensures the maximum possible energy is recovered by the powertrain, thus enhancing the overall efficiency of the regenerative braking process.

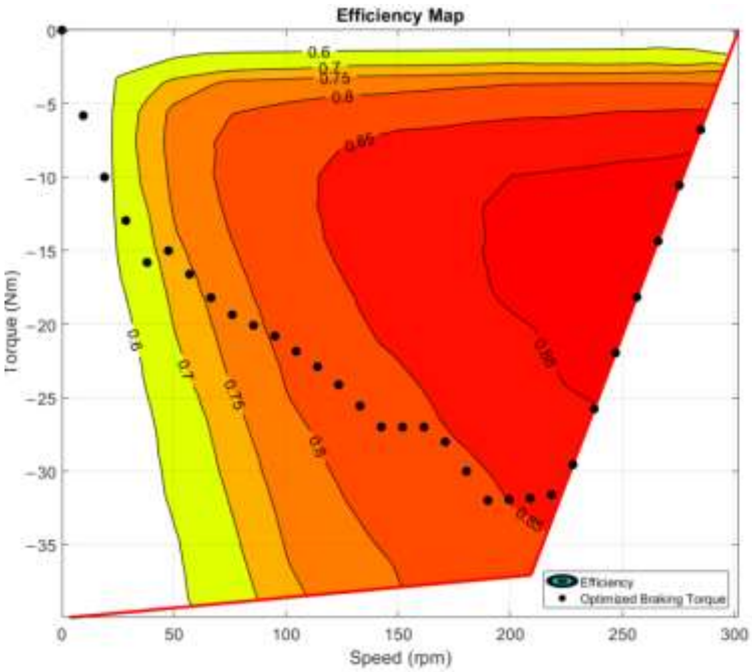

Fig 10: Optimized braking-torque on the efficiency map.

The Fig 10 presents an efficiency map of the electric powertrain during regenerative braking. The contour plot illustrates the system's efficiency across a range of motor speeds (in rpm) and torque values (in Nm), with efficiency levels indicated by color gradients from yellow (lower efficiency) to dark red (higher efficiency). The black dots represent the optimized braking torque values at various speeds, which were determined through the optimization model. These discrete torque-speed points define the optimal torque inputs that maximize energy recovery during braking. As shown, the optimized points align with regions of higher efficiency (0.85–0.9), confirming that the model successfully targets the most energy-effective operating zones. The map assumes a flat road and straight path, with no external constraints from the track model.

Speed (km/h)	Initial SOC (%)	Recovered Energy (Joules)	Final SOC (%)
150	90	1041667	90.48225
150	80	1041667	80.48225
150	70	1041667	70.48225
150	60	1041667	60.48225
150	50	1041667	50.48225
100	90	462963	90.21433
100	80	462963	80.21433
100	70	462963	70.21433
100	60	462963	60.21433
100	50	462963	50.21433
80	90	296296.3	90.13717
80	80	296296.3	80.13717
80	70	296296.3	70.13717
80	60	296296.3	60.13717
80	50	296296.3	50.13717
60	90	166666.7	90.07716
60	80	166666.7	80.07716
60	70	166666.7	70.07716
60	60	166666.7	60.07716
60	50	166666.7	50.07716
40	90	74074.07	90.03429
40	80	74074.07	80.03429
40	70	74074.07	70.03429
40	60	74074.07	60.03429
40	50	74074.07	50.03429

Fig 11: Efficiency of regenerative braking system in different speed limits and initial SOCs.

V. MINIMIZE BATTERY DEGRADATION

Regenerative braking helps recharge the battery while you're driving by capturing energy that would otherwise be lost during braking. This means your battery doesn't have to work as hard throughout a trip. Because the battery isn't drained as deeply, it experiences less stress. Studies have shown that batteries last longer when they're kept in a moderate charge range rather than being fully drained and recharged frequently. So, by topping up the battery during driving, regenerative braking helps reduce wear and tear. Every time a battery goes through a full charge and discharge cycle, it loses a tiny bit of its overall capacity. Over time, this adds up. Since regenerative braking adds small amounts of charge as you drive, it reduces how often you need to plug in and do a full recharge. Fewer full cycles mean the battery degrades more slowly, helping it stay healthier for longer. Braking the traditional way using friction creates heat, and that heat can spread to other parts of the vehicle, including the battery. Too much heat can be harmful to batteries, especially when they're already close to fully charged.

Regenerative braking avoids this by turning braking energy into electricity instead of heat. That helps keep temperatures lower, which is better for both battery health and overall vehicle efficiency. One of the biggest advantages of autonomous driving systems is how smoothly they operate. These systems can brake gently and predictably, which makes regenerative braking even more effective. Human drivers, on the other hand, often brake too late or too hard, which limits how much energy can be recovered. With automated systems, energy recovery is more efficient, and the stress on the battery is reduced because the flow of energy is more controlled and consistent.

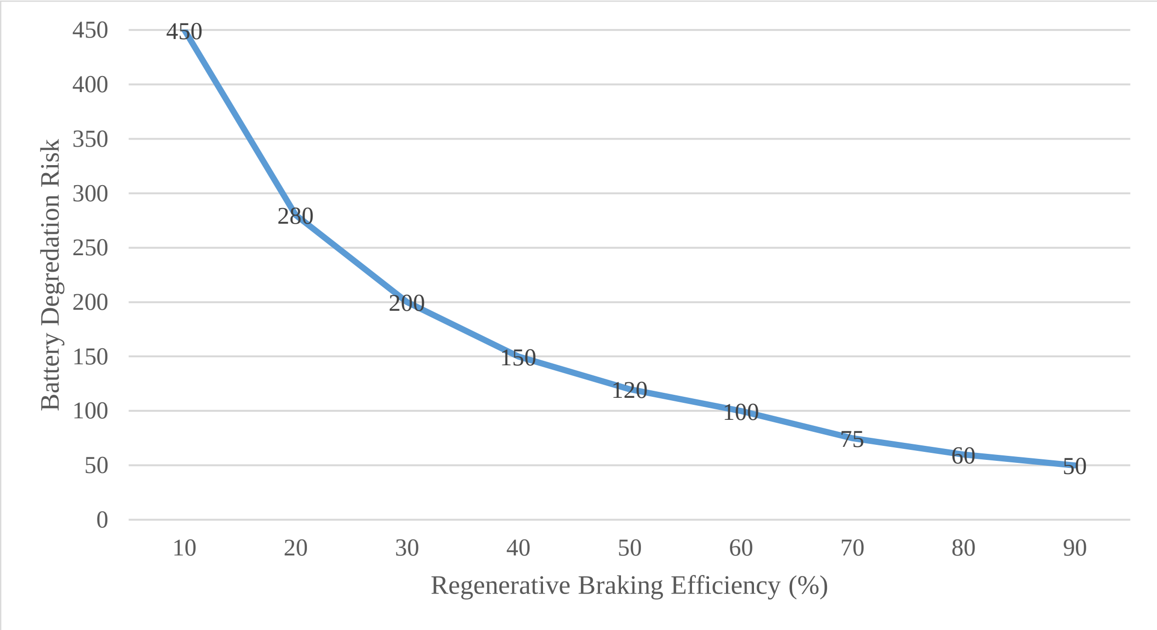

Fig 12: The Connection of regenerative braking system and battery degradation

VI. CONCLUSION

Regenerative braking plays a key role in helping electric vehicle batteries last longer. By reducing how much the battery is drained during trips, cutting down on the need for full charging cycles, lowering heat buildup, and enabling smoother energy flow, especially when paired with autonomous driving, it helps slow down the wear and tear on battery cells. While there are some limitations to how and when regenerative braking can be used, smart energy recovery systems offer a practical and effective way to protect battery health and extend the overall life of an electric vehicle's powertrain.

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Muassislar: "SCIENCEPROBLEMS TEAM" mas'uliyati cheklangan jamiyati;
Jizzax politexnika insituti.

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