

CHALLENGES IN IMPLEMENTATION OF REGENERATIVE BRAKING IN PASSENGER VEHICLES

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ABSTRACT

Regenerative braking has become an important technology in electric cars because it lets them turn kinetic energy back into electrical energy when they slow down. This system cuts down on the energy losses that come with regular friction braking, which greatly increases the range and efficiency of the vehicle. Depending on the architecture of the drivetrain, the power electronics, and the battery technology, different regenerative braking strategies have been used by passenger vehicle manufacturers. This paper reviews the principles of regenerative braking, compares control strategies used in battery-electric vehicles (BEVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs), and examines advancements in blended braking, one-pedal driving, and predictive energy recuperation. The study emphasizes contemporary trends and forthcoming challenges, such as the consistency of braking feel, battery thermal management, and integration with autonomous driving systems.

KEYWORDS: Regenerative braking, battery electric vehicles, hybrid vehicles, energy recovery, blended braking, one-pedal driving, electric powertrain, braking control algorithms

INTRODUCTION.

The quick rise in the use of electric and hybrid passenger cars has made the need for efficient energy recovery systems even greater [1]. Electric vehicles use battery power instead of an internal combustion engine (ICE), so changes in energy efficiency have a direct effect on driving range [2]. When you slow down, regenerative braking lets electric traction motors act like generators, turning kinetic energy into electricity that is stored in the battery or supercapacitor [3].

The automotive industry's move toward electrification has sped up research into how well regenerative braking works, how reliable it is, and how well it works with advanced driver-assistance systems (ADAS) [4]. This paper examines the concepts, technologies, and control strategies of regenerative braking currently employed in passenger vehicles, highlighting enhancements in energy recovery, ride comfort, and braking safety [5], [6].

WORKING PRINCIPLE OF REGENERATIVE BRAKING

The idea behind regenerative braking is to turn a car's kinetic energy into electrical energy that can be stored and used again [7], [8]. Traditional friction braking systems turn kinetic energy into heat, but regenerative braking uses the electric traction motor to get back some of the energy that would be lost. When the driver lets go of the gas pedal or presses the brake, the traction motor changes to generator mode and creates an electromagnetic torque that pushes the wheels in the opposite direction. This counter-torque slows the car down while also turning rotational mechanical energy into electrical power [9].

During the regeneration process, the power inverter sends the recovered electrical energy to the vehicle's battery or another energy storage device, like a supercapacitor. There are a number of things that affect how much energy can be recovered, such as the speed of the vehicle, the state of charge (SOC) of the battery, the characteristics of the traction motor, and the capabilities of the power electronics. When a vehicle is moving at a moderate to high speed, there is more kinetic energy available, which usually leads to a higher recovery efficiency [10]. Regenerative capability goes down at low speeds or high SOC, and the system switches to friction braking to keep up braking performance.

Mathematically, the regenerative power can be expressed as:

$$P_{regen} = T_m \cdot \omega_m \cdot \eta_{gen}$$

where T_m is the motor braking torque, ω_m is the motor angular speed, and η_{gen} represents generator efficiency. This relationship illustrates that both torque and speed strongly influence energy recovery potential, emphasizing why regenerative systems are most effective during higher-speed deceleration.

Modern passenger cars have both traditional hydraulic brakes and regenerative braking systems. Advanced electronic control units control how the two types of brakes work together. This makes sure that the brakes feel the same, stay stable, and are safe no matter what the road, battery, or traction conditions are. Ultimately, regenerative braking enhances vehicle efficiency, extends driving range, and reduces wear on mechanical brake components, making it a fundamental element of electric and hybrid powertrains [12].

PERFORMANCE CHALLENGES

There are a number of operational and technical problems that affect both energy recovery and braking quality in passenger vehicles with regenerative braking systems. One of the main problems is that batteries have limits. The ability to recover energy depends a lot on the battery's state of charge, temperature, and maximum charging current. When the SOC is high or the temperature is low, the regenerative current is limited to protect the battery. This means less energy is recovered and more reliance on mechanical braking [13].

Another important thing to think about is how to mix regenerative and friction braking. Regenerative braking alone can't always provide enough stopping power, especially when going slowly, in an emergency, or when traction is limited. That's why hydraulic braking needs to be added or replaced. One of the biggest engineering problems is still how to make a smooth transition without any noticeable changes in pedal feel. Also, regenerative braking works with traction control and stability systems. When the roads are slippery, the system has to slow down regeneration to keep the wheels from slipping and the car stable [14].

Thermal management of the powertrain is also very important. Power electronics and electric machines can get hotter when they are constantly or at high power, which means they need advanced cooling methods to stay reliable and work well. Also, driving at low speeds makes it harder to regenerate energy because less kinetic energy means that mechanical braking is needed at the end of a stop.

Driver comfort and perception are equally important, especially in cars that have one-pedal driving modes. To meet user expectations, car makers have to find

a balance between energy recovery and predictable deceleration, smooth torque modulation, and consistent braking response. Because of this, modern regenerative braking systems use advanced control algorithms, brake-by-wire systems, and predictive logic to make braking feel and work better in all driving situations.

CONCLUSION

Regenerative braking has become a key technology in the development of electric and hybrid passenger cars. It has directly led to better energy efficiency, longer driving ranges, and less reliance on friction brakes. Regenerative systems turn kinetic energy into usable electrical energy when the car slows down. This is a big advantage over regular brakes, especially in cities and on roads where you have to stop and go a lot. Modern systems use electric motor control, power electronics, and advanced brake-by-wire systems to provide smooth braking while getting the most energy back.

Even though regenerative braking has its advantages, its performance is affected by a number of operational limitations, such as the ability to charge the battery, temperature limits, traction conditions, and the need to work well with mechanical braking systems. Keeping the best braking feel and stability in different driving situations is still a big engineering problem. As energy storage systems, motor control algorithms, and predictive braking strategies continue to improve, they will be even more useful thanks to vehicle connectivity, ADAS integration, and machine learning.

As the global car industry moves faster toward electric cars and self-driving cars, regenerative braking will keep changing as a key part of eco-friendly vehicle powertrains. Future advancements in solid-state batteries, thermal management, and intelligent control systems will enhance energy recovery capabilities and strengthen the function of regenerative braking in attaining reduced emissions, increased efficiency, and enhanced driving comfort for passenger vehicles.

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