Enhancing Regenerative Braking efficiency in electric vehicles: a simulation study of cooperative braking systems

Bruno Romão
Emerson Batagini
Robert Bosch Ltda.

E-mails: Bruno.Romao@br.bosch.com, Emerson.Batagini@br.bosch.com

ABSTRACT

xEV vehicles contains various configurations of electric propulsion. The electric motor in these vehicles can provide traction and can also function as a power generator during deceleration, which is known as regenerative braking. The vehicle control unit, battery management system, electric motor and inverter are essential components for the proper operation of this function. Furthermore, to enhance the efficiency of regenerative braking, improvements have been made to the braking system, allowing it to cooperate with the function, including the electronic stability control with the brake booster. This paper aims to present simulation results of regenerative braking in xEV vehicles to highlight its efficiency through different braking system configurations. Comparative results demonstrate approximately 17% additional range and over 95% efficiency in regeneration with cooperation in homologated driving cycles.

INTRODUCTION

In recent years, the growing concern with sustainability and energy efficiency has driven the evolution of vehicle propulsion systems, leading to the emergence of a new category of automobiles known as xEVs (electrified vehicles). xEVs include different categories, each with specific characteristics that contribute to energy efficiency and sustainability.

Mild hybrid electric vehicles (mHEVs) combine an internal combustion engine with an auxiliary electric system, which does not enable the vehicle to be powered solely by electricity but assists during acceleration, deceleration, and can recover energy during braking, thereby increasing efficiency [1]. Hybrid electric vehicles (HEVs) integrate the electric motor with the combustion engine, allowing them to operate either jointly or separately, and they are recharged by the combustion engine and through regenerative braking, resulting in fuel savings from 25% to 30% [2].

Plug-in hybrid electric vehicles (PHEVs) feature larger capacity batteries, enabling external charging and providing greater electric range compared to HEVs [1]. Finally, battery electric vehicles (BEVs) are fully electric, with the electric motor as the sole source of propulsion and can be recharged from external sources and through regenerative braking [2].

xEVs utilize advanced components such as electric motors, inverters and battery management systems, which play crucial roles in the overall efficiency and performance of automobiles. Regenerative braking, a technology that allows for energy recovery during deceleration, is one of the key features that contribute to the energy efficiency of these vehicles. By converting kinetic energy into electricity, regenerative braking not only increases the range of electric vehicles but also reduces wear on braking components, promoting more sustainable operation [3].

In the Brazilian context, the adoption of xEV vehicles and the implementation of technologies such as regenerative braking are on the rise, driven by environmental policies and growing awareness of the importance of sustainable mobility. This article aims to explore the benefits of regenerative braking and the significance of cooperative regenerative braking in enhancing efficiency. Additionally, it discusses the status of the Brazilian market, challenges and prospects for the adoption of these technologies. The proposed analysis seeks to contribute to the understanding of innovations in the automotive sector and their impact on sustainability and energy efficiency.

VEHICLE BRAKE SYSTEM

The conventional vehicle braking system is fundamental for ensuring the safety of the vehicle, allowing it to decelerate, stop and remain stationary. The first component that the driver interacts with when applying the brakes is the brake pedal. By pressing the pedal, the driver increases the friction forces at the wheels, reducing the vehicle's speed. The first component activated by the brake pedal is the brake booster, whose main function is to amplify the applied force, facilitating the braking process. This booster utilizes the vacuum generated by the engine or an external vacuum pump to increase the applied force [4].

Connected to the brake booster is the master cylinder, which compresses the brake fluid, converting the amplified force into hydraulic pressure. From the master cylinder, the pressurized fluid is distributed to the braking systems at the wheels, which can be either disc brakes or drum brakes. In disc brakes, the brake cylinder receives the pressurized fluid and applies pressure to the brake pads, which are pressed against the fixed brake disc, reducing the wheel's rotation. In drum brakes, the operation is similar but involves additional components, such as brake shoes, which create friction against the fixed drum. The hydraulic system uses brake fluid as a means of force transmission, allowing the driver to effectively control the vehicle's stopping [4].

With the advancement of vehicles, new components have been added to the conventional hydraulic system. The anti-lock braking system (ABS) prevents wheel lock-up during braking. A more recent component is the electronic stability control (ESC), which operates the brakes of each wheel individually through the activation of internal valves. This provides enhanced control and stability for the vehicle [5].

The demand for more efficient and adaptable braking systems has become increasingly evident, especially in vehicles with improved combustion engines, hybrid and electric propulsion systems, as well as advanced driver assistance features. In this context, the need for independent vacuum solutions for braking systems stands out as a crucial aspect for ensuring the safety and energy efficiency of these modern vehicles [6].

One of the developments in this field is the electromechanical brake force amplifier (EBA), which meets the requirements of a contemporary braking system. This device uses an electric motor to generate braking pressure independently of the driver's request, allowing for a faster and more precise response compared to conventional systems. This ability to generate pressure more efficiently not only improves the effectiveness of driver assistance systems but also offers significant advantages for autonomous emergency braking systems [6].

Furthermore, the implementation of electromechanical brake boosters in hybrid and electric vehicles enables the elimination of various peripheral components that are necessary in vacuum-dependent braking systems, such as auxiliary vacuum pumps, vacuum hoses, vacuum sensors, and electrical connectors. This simplification not only reduces the weight and maintenance of the system but also contributes to an increase in energy efficiency of around 3% [7].

REGENERATIVE BRAKING

Regenerative braking is a technology that has been utilized for decades, particularly in railway systems, where the energy generated during deceleration is converted into electricity and stored for later use. This innovative approach is also applied in electric and hybrid vehicles, allowing kinetic energy, which would normally be dissipated as heat during braking, to be repurposed to recharge the vehicle's battery. During deceleration, the electric motor acts as a generator, converting kinetic energy into electrical energy. When the driver presses the brake pedal, the electric motor reverses its operation, generating an electromotive force which creates braking torque, decelerating the vehicle while simultaneously recharging the battery [8].

The operation of regenerative braking occurs in specific operational modes of the electric motor. It is important to note that in high demand braking situations, especially at low speeds, conventional braking is still necessary, as the electromotive force generated may not be sufficient to decelerate the vehicle effectively. Additionally, factors such as the battery's capacity to absorb electrical energy and the distribution of traction among the wheels can influence the efficiency of regeneration [8].

To optimize the regenerative braking process, many modern vehicles utilize electronic stability control (ESC) as an essential controller. The ESC plays a crucial role in modulating the flow of brake fluid, ensuring that regenerative braking and hydraulic braking are efficiently combined. When the driver applies the brake pedal, the ESC controls a set of internal valves that regulate the flow of brake fluid, allowing for an appropriate mix between regenerative and conventional braking. If the braking is entirely regenerative, the ESC stores this brake fluid in an accumulator chamber [9].

During regenerative braking, it is undesirable for braking torque to be applied simultaneously to the brake discs, as this would result in excessive deceleration that does not correspond to the driver's request. Therefore, the ESC adjusts the flow of brake fluid for each situation, ensuring that the braking system's response is precise and safe. The device also features an accumulator that stores the fluid displaced by its actuation, allowing it to be used in the braking circuit when necessary [9].

Figure 1 presents a comparison of regenerative braking with and without cooperation. On the left side of the figure, a typical curve of a regenerative braking system without cooperation is observed. As the vehicle decelerates, the electric motor exhibits a characteristic torque curve, which translates into torque that can be used to brake the vehicle. However, this torque from the electric motor cannot be fully utilized without the cooperation system. When the driver activates the hydraulic braking system, the vehicle's deceleration increases, and the driver perceives the combined deceleration from both the motor's braking system and the hydraulic system. The greater the potential deceleration torque of the electric motor, the more significant the change in deceleration felt by the driver. For this reason, the regenerative torque of the electric motor is limited in the regenerative braking system without cooperation.

On the right side of Figure 1, in the regenerative braking system with cooperation, it is possible to adapt the torque generated by the hydraulic system using the electronic stability control (ESC) to control the fluid going to the wheels and maximize the utilization of the electric motor's regenerative torque. Initially, to meet the driver's deceleration demand with a constant application of the pedal, the regenerative braking of the electric motor is supplemented with the torque from the hydraulic braking system to generate the desired deceleration. When the electric motor's potential is maximized, the torque generation by the hydraulic brake is reduced, allowing for the full utilization of the electric motor's regenerative braking.

It is important to note that this system allows up to 0.3 g of deceleration through purely regenerative braking, for vehicle stability safety reasons. To bring the vehicle to a complete stop, a combination of the electric motor's regenerative braking and the hydraulic brake is used. In this type of system, the driver can decelerate the vehicle without perceiving abrupt changes in deceleration, ensuring that the maximum regenerative braking of the electric motor is utilized.

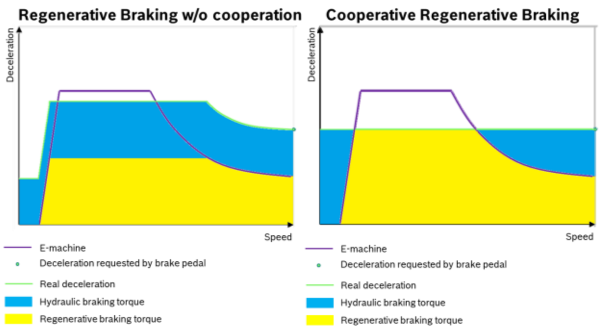

Figure 1. Regenerative braking with and without cooperative system.

In addition to the control of the ESC, the electromechanical brake force amplifier (EBA) also contributes to the cooperative regenerative braking system. When the driver applies force to the brake pedal, they should not perceive whether the braking is being performed by the electric motor, the hydraulic braking system, or a combination of both. The EBA features an electric motor controlled by its electronic control unit, which amplifies the force applied to the pedal and generates hydraulic pressure for the braking system. Thus, when braking is performed purely by the electric motor, the force amplification of the EBA is adjusted to maintain the relationship between force and travel, ensuring that the driver does not notice any changes in pedal feel. It allows the regenerative braking of the electric motor to remain effective, without changing the pedal feeling, if the electric motor achieves the desired deceleration, according to Figure 2.

On the other hand, using a vacuum brake force booster makes this impossible. After a certain point on the characteristic force and travel curve, the driver directly feels a decrease in hydraulic pressure at the pedal due to fluid accumulation in the ESC, as the vacuum force booster does not have electronic control over the amplification of braking force.

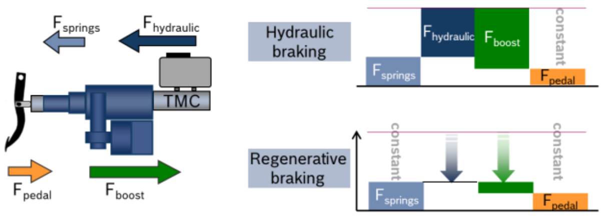

Figure 2. EBA control to maintain pedal feel during regenerative braking.

The frequency inverter plays a fundamental role in regenerative braking. It is responsible for converting the direct current from the battery into alternating current for the electric motor and vice versa. During regenerative braking, the inverter reverses the flow of energy, allowing the motor to function as a generator. This not only facilitates the recovery of kinetic energy but also controls the amount of energy returned to the battery, optimizing the system's efficiency [10].

The vehicle control unit (VCU) is also essential in this process, as it coordinates the operations between the electric motor, the inverter and the ESC. The VCU constantly monitors the vehicle's conditions and the driver's requests, adjusting the parameters of regenerative braking to maximize efficiency and safety. This integration allows the braking system to respond dynamically to driving conditions, ensuring a smooth and safe driving experience [10].

This advanced control system enables regenerative braking to operate effectively, maximizing energy recovery and improving the overall efficiency of the vehicle. The combination of regenerative and conventional braking, known as volume blending, is crucial for meeting the driver's deceleration demands, ensuring a smooth and safe driving experience. Thus, the integration of the ESC, frequency inverter, and VCU with regenerative braking not only enhances energy efficiency but also contributes to the safety and performance of electric and hybrid vehicles.

INSTRUMENTATION

The equipment used for vehicle data collection included the OBD connector, the VN1640 from Vector, a data acquisition computer, and the CANalyzer acquisition software. The vehicle used for the measurements was a plug-in hybrid model with a combustion engine rated at 110 kW and an electric motor rated at 120 kW, providing a combined power output of 230 kW.

The OBD (On-Board Diagnostics) connector is a standard interface found in modern vehicles that allows communication between the vehicle and external diagnostic devices. It provides access to information regarding engine performance, emissions systems, and other critical parameters, facilitating fault detection and maintenance [11].

The VN1640 from Vector is an interface device that enables the connection between the OBD connector and the data acquisition computer. It is designed to capture and transmit vehicle network communication data, allowing for detailed analysis of the signals and messages exchanged between electronic modules [12].

The CANalyzer software is a tool used to monitor, analyze, and simulate communication networks in vehicles. It allows real-time visualization of the collected data, as well as the configuration of tests and fault analysis, making it essential for engineers and technicians working with automotive systems [13].

Real-time data is acquired via the CAN network, providing a comprehensive understanding of the operation of the vehicle's electronic systems, as illustrated in Figure 3.

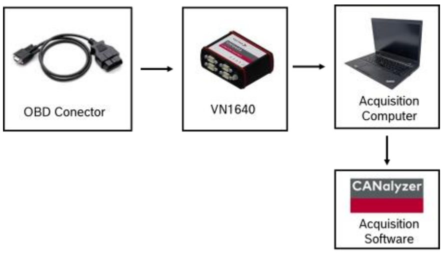

Figure 3. Instrumentation Diagram.

MEASUREMENT RESULTS

The measurements were conducted using vehicle instrumentation. The objective of this experiment was to practically verify how regenerative braking occurs in conjunction with the cooperation of the braking system, allowing for a detailed analysis of the interaction between hydraulic and regenerative braking, and how this synergy contributes to the efficiency and performance of the plug-in hybrid vehicle.

In Figure 4, the behavior of the vehicle during an acceleration and braking test is observed. Initially, the vehicle is accelerated to approximately 35 km/h, as indicated by the speed signals represented in blue and the pedal percentage in black. After this acceleration, the regenerative braking system (shown in gray) is activated, allowing the electric motor to begin decelerating the vehicle efficiently, achieving up to 389 Nm (approximately 39 kW). During this process, the driver applies the brake pedal, which is represented in purple. However, due to the deceleration provided by the electric motor, no hydraulic pressure is generated, as indicated by the light green line, even with the constant application of the pedal, which shows a travel of 2 mm, represented in dark green (Figure 4 – I). As the electric motor begins to lose its deceleration potential and the driver desires additional deceleration, hydraulic pressure is then generated to complement the regenerative braking. This results in a phenomenon known as torque blending, where hydraulic braking combines with regenerative braking, optimizing the efficiency of the vehicle's braking system (Figure 4 – II).

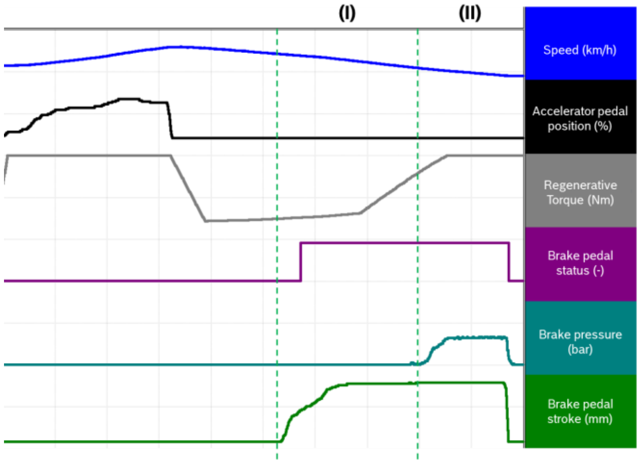

Figure 4. Regenerative Braking with Blending.

In Figure 5, the performance of the vehicle during an acceleration and braking test is presented. The vehicle is accelerated to approximately 50 km/h, with the speed signals represented in blue and the pedal percentage in black. After this acceleration, the electric motor initiates the deceleration of the vehicle through regenerative mode, managing to regenerate about 143 Nm (approximately 14 kW) of power. Although the driver applies the brake pedal, indicated in purple, no hydraulic pressure is generated, as shown by the light green line, due to the action of the electric motor that is already decelerating the vehicle. Even with the constant application of the pedal, which shows a travel of about 3 mm (represented in dark green), the braking occurs purely electrically, highlighting the efficiency of the cooperative regenerative braking in operation.

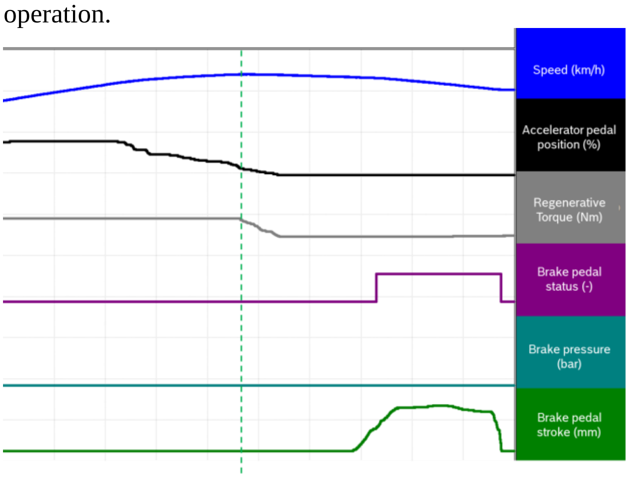

Figure 5. Purely Regenerative Braking.

The regeneration of the electric motor not only contributes to the deceleration of the vehicle but also increases the range by charging the battery during braking.

This energy recovery process is fundamental for maximizing the system's efficiency, allowing the vehicle to utilize the energy generated during braking to extend its electric operation. By employing this cooperative regenerative braking system, the efficiency of energy recovery can reach higher levels, increasing the electric vehicle's range by up to 20% (considering the WLTP cycle and according to the response of the brake caliper) [9, 14].

BRASILIAN MARKET

The national market for electric and hybrid vehicles has shown significant growth in recent years, driven by an increasing awareness of sustainability and energy efficiency. This system not only improves energy consumption efficiency but also contributes to reducing emissions, aligning with the national environmental goals.

Regenerative braking allows electric and hybrid vehicles to recover some of the energy that would otherwise be wasted during braking, converting it into electricity to recharge the battery. This feature is especially relevant in urban traffic conditions that often require frequent stops and starts. The ability to regenerate energy during these maneuvers not only increases the vehicles' range but also reduces the dependence on frequent recharges, making the user experience more convenient.

However, challenges still need to be addressed, such as dimensioning the charging infrastructure and consumer awareness of the benefits of electric and hybrid vehicles. In summary, the application of regenerative systems in electric and hybrid vehicles represents a significant opportunity for the national market, promoting not only energy efficiency but also contributing to a more sustainable future. Continued investment in technology and infrastructure will be crucial to consolidating this trend and ensuring that Brazil keeps pace with global innovations in the automotive sector.

CONCLUSION

The evolution of vehicle propulsion systems, especially with the introduction of xEV vehicles, represents a significant milestone in the pursuit of sustainable mobility solutions. Regenerative braking stands out as an essential technology that not only improves energy efficiency but also contributes to reducing wear on braking components and optimizing the driver experience. The ability to recover energy during deceleration and convert it into electricity to recharge the battery is an advancement that aligns with contemporary demands for more efficient vehicles. With the potential to increase range by up to 20% and achieve higher levels of energy recovery; cooperative regenerative braking becomes an important component in the architecture of electric and hybrid vehicles.

In the Brazilian context, the growing adoption of xEV vehicles, driven by environmental policies and increased awareness of sustainability, opens new opportunities for the automotive industry. However, for this transition to be successful, it is essential to develop adequate charging infrastructure and promote about the benefits of emerging technologies, such as regenerative braking. The future of mobility in Brazil depends on the continuous integration of technological innovations and collaboration among manufacturers and society. Thus, the effective implementation of regenerative braking systems will not only contribute to energy efficiency but also position Brazil as a key player in the global sustainable vehicle landscape, promoting less emissions and more efficient future for all.

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