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# Analysis of regenerative braking efficiency in an electric vehicle through experimental tests

# Análisis de la eficiencia del freno regenerativo en un vehículo eléctrico mediante pruebas experimentales

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## Abstract

This paper presents a regenerative braking analysis of efficiency in real driving conditions and different road geographies. Factors affecting or benefiting energy recovery were identified, these are: the weight of the vehicle, torque, speed, inclination of road, and braking time; however, the sport and Eco driving modes were not considered because the same driving pace was chosen for the different routes. These results are intended to collaborate with real energy regeneration data and help investigators, academics, and automotive engineering, improving this system's efficiency. In the driving process, the state of charge (SOC), speed, torques, and road geography effect the efficiency of regenerative braking, as driving a vehicle on a road with irregular geography exposes it to aggressive physical factors, which considerably reduces its energy autonomy. The main aspects of recovery and regenerative braking efficiency were determined through quantitative data analysis, resulting in experimental surfaces and curves, which present the performance of current and deceleration during vehicle braking. Thus, it is shown that the energy recovery during braking is 78% considering the low autonomy of the electric vehicle.

***Keywords***: Brake pedal, electric vehicle, energy recovery, regenerative braking

## Resumen

Este artículo presenta un análisis de la eficiencia del frenado regenerativo en condiciones reales de conducción y en diferentes geografías de carretera. Se identificaron los factores que afectan o benefician a la recuperación de energía, estos son: el peso del vehículo, el par, la velocidad, la inclinación de la calzada y el tiempo de frenado; no obstante, no se consideraron los modos de conducción deportivo y Eco debido a que se optó por un mismo ritmo de conducción en las diferentes rutas. Estos resultados pretenden colaborar con datos reales de regeneración de energía y ayudar a los investigadores, académicos e ingenieros de automoción, a mejorar la eficiencia de este sistema. En el proceso de conducción, el estado de carga (SOC), la velocidad, torques y la geografía de la carretera afectan a la eficiencia del frenado regenerativo, ya que conducir un vehículo por una carretera con una geografía irregular lo expone a factores físicos agresivos, lo que reduce considerablemente su autonomía energética. Se determinaron los principales aspectos de la recuperación y la eficiencia del frenado regenerativo mediante análisis de datos cuantitativos, dando como resultado superficies y curvas experimentales, que presentan el rendimiento de la corriente y la desaceleración durante el frenado del vehículo. Así, se demuestra que la eficiencia de recuperación de energía durante el frenado es de un 78 % considerando la baja autonomía del vehículo eléctrico.

***Palabras clave***: pedal de freno, vehículo eléctrico, recuperación de energía, freno regenerativo

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# 1. Introduction

Electric vehicles (EV) are very attractive and have generated interest in science, academia, and public and private transportation systems at a global scale [1–3]. In this type of vehicle, the search to improve the system efficiency is essential; since it presents an important alternative of transport compared to conventional vehicles with internal combustion engines. Nevertheless, these vehicles have a limited driving autonomy, and this factor continues to be the main obstacle for the mass acceptance and use of EVs [1], [2], [4], [5].

As opposed to conventional vehicles and in addition to reducing air contamination, EVs can recover part of the energy lost in the braking process thanks to the regenerative braking system, thus improving the driving autonomy of electric vehicles [6].

Irregular road geography exposes vehicles to factors at an altitude on the mountain road. In relation to energy consumption, these factors require more performance of batteries in electric vehicles, especially on mountain routes. In this sense, the slope of the road is a factor that cannot be neglected in the design of strategies for optimizing regenerative braking [7, 8].

In a regenerative braking system, energy is transferred to generators under a strategy of integrated control, which consists of generating an estimate for the deceleration by the driver and distributing the needed braking force between the regenerative system and mechanical braking [9].

In literature, the authors consider that the deceleration rate and the mass of the vehicle have significant effects in the regenerative braking threshold at low speeds, as it is considered that a regenerative brake at low speed is effective in the city, because more action is needed in the braking system for the heavy traffic, thus increasing the power and autonomy of the vehicle [4], [10]. Strategies of regenerative braking that take into account the slope of the road, are considered by other authors to be more efficient. A noticeable improvement can be seen in the recovery of energy [8].

In other literature they show through simulations that the lowest energy consumption happens with a complete braking system in series, due to better use of the braking torque and therefore less energy is consumed [11]. The potential energy consumption is lower in road travel than in a driving in the urban area, where there is little brake actuation affecting the energy recovery in the EV vehicle [12].

In the present work, experiments are carried out on the EV on established routes to determine the efficiency of the regenerative brake, its performance and its influence on the autonomy of the EV. Behavior maps were used to analyze the influence of factors such as braking time, initial braking speed, and road grade on energy recovery. The maximum and minimum recovery energy percent per range will be estimated numerically.

The paper is organized as follows: In Section 2, the mathematic support of regenerative braking is presented, describing with detail subsystems such as the dynamical model; in Section 3, the energy efficiency and performance on regenerative braking are presented. Finally, the conclusions of this study are presented in Section 4.

# 2. Materials and methods

## 2.1. Traditional SOC estimation

This method mainly uses the battery discharge current as input and integrates the current discharge over a period to calculate the SOC state [13], the equation (1) is as follows.

$$SOC = SOC_o - \frac{1}{C_n}\int_{t_0}^{t} i(t)dt \qquad (1)$$

Where $C_n$ corresponds to the nominal capacity of the battery, $i(t)$ corresponds to the current flowing in and out the battery and t is the time. On the other hand, this other calculation method requires a variation to Equation (11), multiplying a coulombic efficiency factor ($\mu i$) to the integral, which is represented between the discharge capacity and load capacity, represented in the equation (2).

$$SOC = SOC_o - \frac{\mu i}{C_n}\int_{t_0}^{t} i(t)dt \qquad (2)$$

## 2.2. SOC status

The charge is expressed in the equation (3).

$$Chatge = (Current) \times (time)\ [Ah] \qquad (3)$$

The SOC is the charge level of a battery expressed as a percentage, the equation (4) is.

$$SOC(\%) = \frac{Charge\ [Ah]\ (100\%)}{Total\ battery\ capacity\ [Ah]} \qquad (4)$$

## 2.3. Evaluation of the recovery of the energy

Evaluating energy recovery in regenerative braking mainly includes the energy recovery capacity during braking and the energy recovery rate during braking [14]. Where, $E_m$ is the energy recovery presented in Equation (5).

$$E_m = \int_{t_0}^{t} U_b(t) i_b(t)dt \qquad (5)$$

Where, $U_b(t)$ is the voltage at the motor controller while recovering braking energy, $i_b(t)$ is the motor controller current present in the braking action, and $t$ time of braking of the motor.

### 2.4. Measure of energy recuperation of braking

Braking energy recovery measurement, $n_b$ is the relation between energy $E_m$ and the total consumed energy. $E_b$ is the energy lost calculated as a function of the velocity of the start and end of braking, as shown in the equation (6).

$$E_b = \frac{1}{2} m \left( V_f^2 + V_0^2 \right) \tag{6}$$

Where, $m$ is the mass of the vehicle, $V_0$ is the initial velocity of braking, $V_f$ is the final velocity of braking, and $n_b$ is the efficiency shown in the equation (7).

$$\frac{E_m}{E_b} = \frac{\int_{t_0}^{t} U_b(t) i_b(t) dt}{\frac{1}{2} m \left( V_f^2 + V_0^2 \right)} (100\ \%) \tag{7}$$

Equation (7) allows to determine efficiency values of regenerative braking mainly using the initial velocity used by the vehicle to start the braking process.

## 3. Results and discussion

The results in real driving experimental tests are represented in this section with the use of Matlab and Electric Mobility Laboratory (Emolab) software to determine the parameters that affect the efficiency of regenerative braking [15].

### 3.1. Variables involved in energy recovery process

Emolab was used in order to obtain the variables of the vehicle. Emolab registers in real time are: the battery current, the vehicle speed, the motor torque, and the SOC [14]. Matlab was used to model this data in the braking process in real driving. Performance surfaces were generated, where the relationship between torque and speed is observed. In this manner, when values for torque and speed are changed, the system outputs a new value of energy recuperation charge, which influences the autonomy of the vehicle.

The geography of route one presents a higher slope which translates into a higher power demand of the vehicle in order to overcome pronounced inclinations. The principal variable of route two was a high degree of traffic which caused braking more often. Meanwhile, route three presented a combination of these two factors, considerable slopes and traffic of the routes one and two.

Figures 1, 2 and 3 show that variables such as velocity and motor torque play key roles in energy recovery during the braking process; since during the braking action the system generates current by means of an AC motor, which is represented with negative values. In this case, energy regeneration in the vehicle is affected by the speed, and therefore the braking torque applied to the vehicle.

Figure 1 indicates a greater recovery of energy, because the geography of route one has different types of roads and inclinations. These characteristics also allow higher vehicle speeds, and consequently, longer times of brake application, resulting in greater motor torques and greater currents.

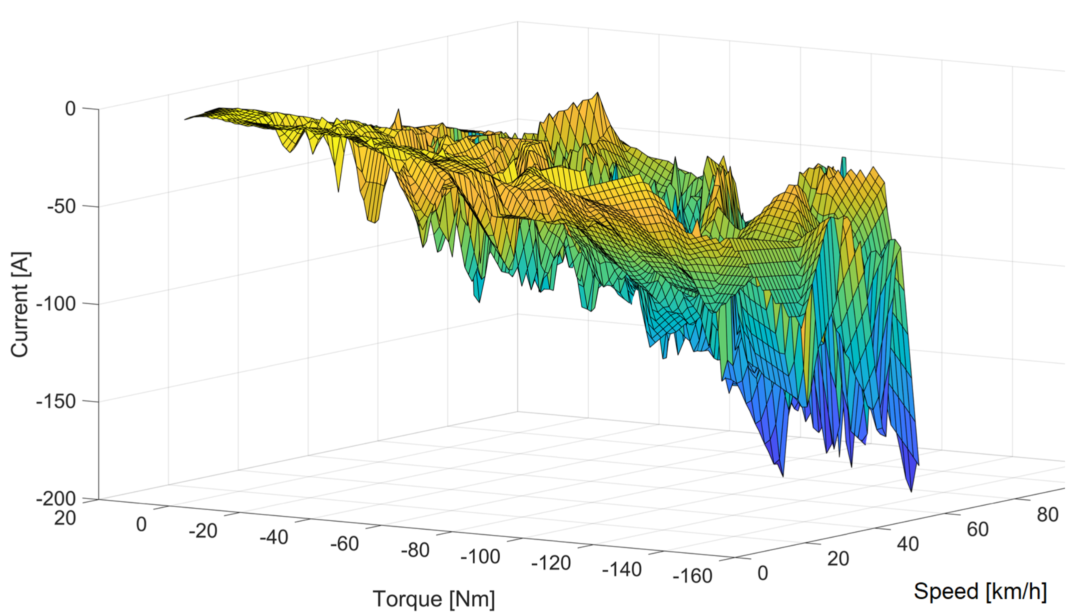


**Figure 1.** Variables affecting energy recovery in route 1

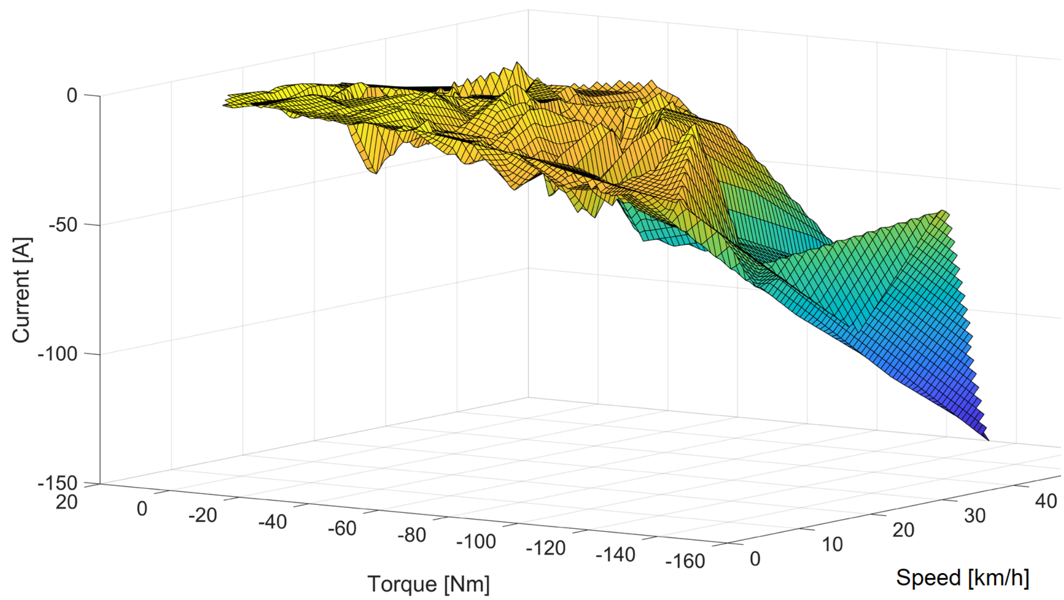


**Figure 2.** Variables affecting energy recovery in route 2

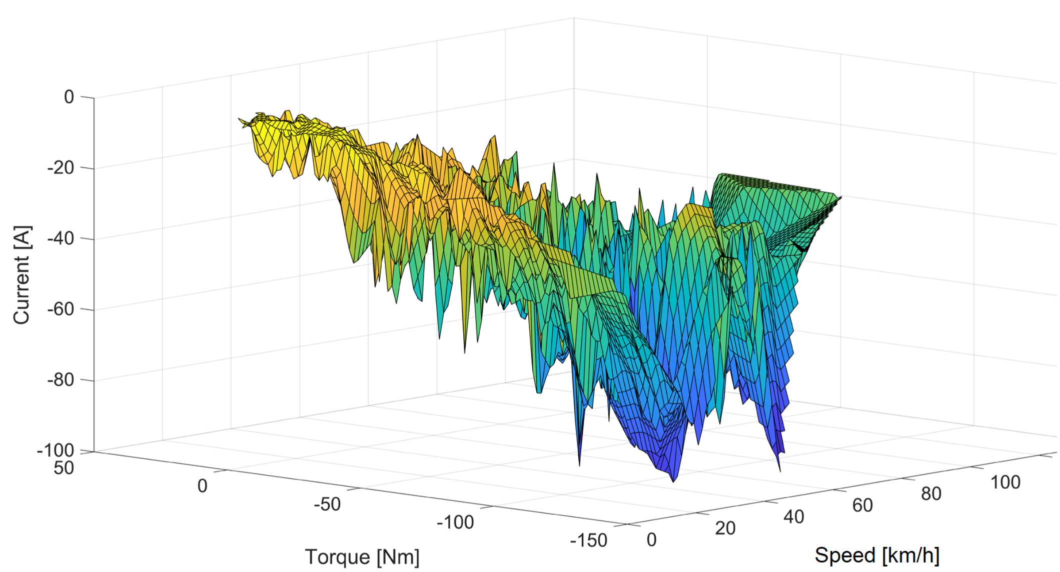


**Figure 3.** Variables affecting energy recovery in route 3

### 3.2. SOC behavior

This section presents the SOC performance of the three types of routes, taking into account the type of road and the elapsed driving time during each route.

In Figure 4, the different SOC performances can be seen for each route and different length. Route one has a greater inclination across all its trajectory, and it tends to discharge at a rate of 47%. The battery of the vehicle was discharged aggressively because of the high-power demand it endures in overcoming the considerable route geography. After a certain point, the geography of this route changes to an only downward slope. While descending, the vehicle recovers 9% of its charge because of the longer brake times and high speeds up to 70km/h, as can be seen in Figure 1 and the resulting elevated motor torques. Route two only has a discharge process. Figure 2 shows low velocities in the range of 30 - 60 km/h. The added amount of traffic results in a more extended brake usage. The battery discharge tendency is almost lineal during its entire trajectory since there is a variation of 5% of the charge from its initial value. Route three presents a more abrupt discharge process compared to route two. The road type is rural; it has more pronounced slopes, a moderate power demand on the vehicle, less traffic and speeds in the range of 50 - 100 km/h as shown in Figure 3. In this route, there is low brake usage. Figure 4 shows certain points along this route where the discharge is significant, reaching a 32% level until its end point.

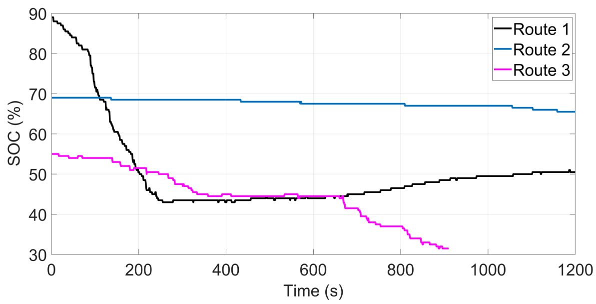


**Figure 4.** Behavior of SOC with respect to recovered energy

### 3.3. Deceleration Performance

In this section, the deceleration comportment during braking is explained.

Figure 5 presents a 1600 seconds sample of deceleration values during the regenerative braking process, rendered with MATLAB. Results tend to vary with factors such as inclination, driving style, and the road geography, provoking a heterogeneous deceleration. The deceleration values observed favor energy recuperation, because the state of the charge increases when the brake is used, thus the vehicle recovers energy to continue moving forward.

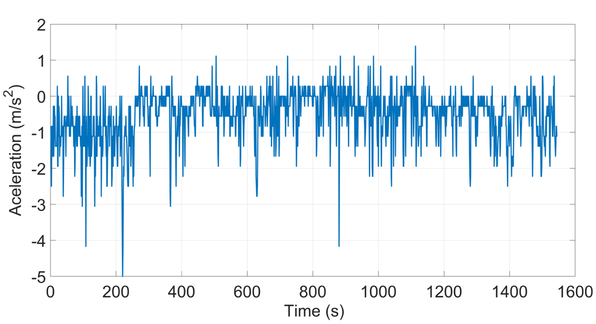


**Figure 5.** Deceleration regarding regenerative system application

### 3.4. Efficiency of regenerative braking

The efficiency of regenerative braking was calculated using Eq (7). The most significant values are the initial and final braking velocities, the recovered charge, and the weight of the vehicle.

Figure 6 shows the relationship between the initial braking velocity and the efficiency for each route. These values are sampled at specific points to better observe the behavior of the efficiency. In routes 1, 2 and 3 in the driving process the different types of road geography, slopes, and initial braking speeds have an impact on the variability of the obtained efficiencies as shown in Figure 6. In route 1, the result of the average efficiency in the specific sample is 23%, and due to the type of geography of the road it is necessary the use of more power by the vehicle, so the brake pedal is not used with high frequency The brake efficiency at its peak reaches up to 76%, this is due to a longer braking time and the final speed reached.

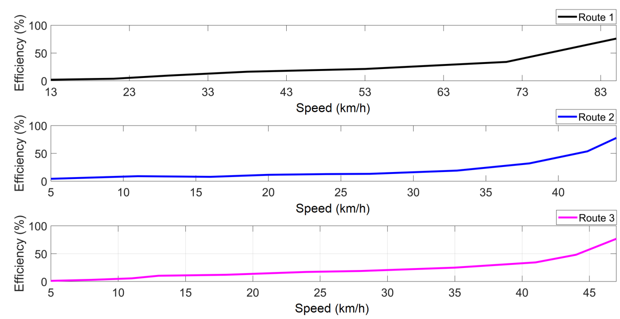


**Figure 6.** Efficiency of regenerative braking at specific speeds

According to Figure 6, values vary in route 2 because it presented a high vehicular flow, low driving speeds and high use of the brake pedal, hence there is greater efficiency of the regenerative system. In turn, this efficiency tends to stabilize, resulting in greater energy recovery, since it has optimal load values reaching an average of 24% and its highest efficiency reaching a value of 78%.

The efficiency of route three shows values that vary with the road geography, average braking velocities, and the amount of traffic. The average efficiency was of 22% with a max value of 77%. In routes 1 and 3, the efficiency decreases significantly and does not stabilize, resulting in low values close to zero.

The regenerative braking efficiency of each route is shown to be dependent on the loss and recovered energy of the vehicle. The road geographies, the initial braking velocity, and the time of brake application, summarized in Table 1, are the main variables that affect the values of loss and recovered energy. The values presented in Table 2 are greatly improved by the extended use of the brake pedal even though its velocity values are lower due to high traffic. There is lower consumption of energy because there is no need for a high-power demand. Energy recovery and high efficiencies are favored by a lack of aggressive changes in the route. Table 3 shows that the vehicle has high energy loss compared to Table 2, due to the geography of the road, high power when overcoming slopes and moderate use of the brake pedal, resulting in lower energy recovery compared to Table 2.

**Table 1.** Minimum, average and maximum efficiency of the regenerative braking system in route 1

| Speed (km/h) | Recovery braking energy $E_m$ (J) | Braking energy loss $E_b$ (J) | Efficiency (%) |
|---|---|---|---|
| 9 | 3053,4 | 409 842,90 | 0,07 |
| 44 | 6930,63 | 19 275,92 | 36 |
| 74 | 44472 | 55 819,86 | 79 |

**Table 2.** Minimum, average and maximum efficiency of the regenerative braking system in route 2

| Speed (km/h) | Recovery braking energy $E_m$ (J) | Braking energy loss $E_b$ (J) | Efficiency (%) |
|---|---|---|---|
| 9 | 111,72 | 8261,11 | 1,35 |
| 22 | 6346,1 | 17210,64 | 37 |
| 44 | 8030,25 | 10 326,39 | 78 |

**Table 3.** Minimum, average and maximum efficiency of the regenerative braking system on route 2

| Speed (km/h) | Recovery braking energy $E_m$ (J) | Braking energy loss $E_b$ (J) | Efficiency (%) |
|---|---|---|---|
| 9 | 346,96 | 56 9041,39 | 0,06 |
| 22 | 1748,81 | 4818,98 | 36 |
| 52 | 34224 | 44 059,25 | 77 |

## 4. Conclusions

In this paper, an analysis of the regenerative braking system was carried out through real driving experiments, where variables such as: current, torque and speed influence with respect to the vehicle's energy recovery were considered in order to determine the efficiency and performance of the regenerative braking system . The difference between the routes is the type of road geography, the vehicle driving time and brake pedal actuation, so in route 1 it was possible to observe a greater energy recovery due to the factors mentioned.

With respect to the state of charge (SOC) of the vehicle, it was observed that the different powers used for each route and the type of geography are significant variables for a greater energy loss. The results obtained indicate that the use of the vehicle in route 2 has a progressive energy loss, which at a certain time tends to stabilize because of the greater use of the brake due to the high vehicular flow; while in route 1 a small energy recovery was achieved due to the use of the brake due to the descent of steep slopes.

In the efficiency of the regenerative braking system, the results demonstrate that the type of road geography, initial braking speeds, brake usage, and vehicle mass are variables that greatly influence the efficiency of this system. Additionally, driving in route 2 is more efficient than in routes 1 and 3, as it has lower energy loss values and high energy recovery values.

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