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“ANALYSIS OF REGENERATIVE BRAKING EFFICIENCY IN AN ELECTRIC VEHICLE THROUGH EXPERIMENTAL TESTS”

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DEDICATORIA

Este proyecto va dedicado a mis padres Milton Calle y Rosa Salinas, familia, novia y amigos ya que ustedes han sido el pilar fundamental en mi proceso de educación. Les dedico este triunfo que fue hecho con el corazón, mucha dedicación y empeño por ser el mejor.

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Angel Geovany Guiracocha Cajamarca

Articulo Científico / Scientific Paper

ANÁLISIS DE LA EFICIENCIA DEL FRENO REGENERATIVO EN UN VEHÍCULO ELÉCTRICO MEDIANTE PRUEBAS EXPERIMENTALES

ANALYSIS OF REGENERATIVE BRAKING EFFICIENCY IN AN ELECTRIC VEHICLE THROUGH EXPERIMENTAL TESTS

Mauricio Calle[1], Angel Guiracocha[2], Juan Diego Valladolid[3]

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 y el tiempo de frenado, no obstante, no se consideró 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 a 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.

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, 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.

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1. Introduction

Electric vehicles (EV) are generating great interest in science, academia, and automotive groups at a global scale [1]. In this type of vehicle, the search improves the system efficiency; they present an important alternative of transport compared to conventional vehicles with internal combustion engines. Nonetheless, thesevehicles have a limited driving autonomy, this factor continues to be the main obstacle for the mass acceptance and use of EVs [1–3].

As opposed to conventional vehicles and in addition to reducing air contamination, EVs can recuperate part of the energy lost in the braking process thanks to the system of regenerative braking, improving the driving autonomy of electric vehicles [4].

Irregular road geography exposes vehicles to aggressive physical factors at an altitude. In relation to energy consumption, these factors demand more power of vehicles to be able to cross mountain sector. In this respect, the slope of the road is a factor that cannot be neglected in the design of optimization strategies of regenerative braking [5,6].

In a system of regenerative braking, energy is transferred to generators under a strategy of integrated control, this consists of generating an estimate for the deceleration by the driver and distributing the needed braking force between the system of regenerative and mechanical braking [7].

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's considered a regenerative brake a low speed is what is effective in the city now that more action in the system of braking is needed for the heavy traffic, in this way by increasing the power of the vehicle [2]. Strategies of regenerative braking which consider the slope of the road, are considered by other authors to be more efficient. A noticeable improvement can be seen in the recuperation of energy [6].

In other literature they show through simulations that the lowest energy consumption is with a complete braking system in series, this is given by a better use of the braking torque and therefore less energy is consumed. 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 [8].

The present paper is based in obtaining of EV data about the behavior of regenerative braking, and its influence in driving autonomy. Behavioral maps will be used to analyze the influence of factors such as time of braking, initial velocity of braking, and the slope of the road in the recuperation of energy. The maximum and minimum recovery energy percent per range will be estimated numerically.

The paper is composed by a literature review, so that important mathematical models are obtained for the analysis, finally, the data obtained in the driving tests are studied, to then obtain the results of the regenerative braking efficiency in a quantitatively.

2. Methods

2.1. Traditional SOC estimation

This method mainly uses the battery discharge current as input and integrates the current discharge over a period of time to calculate the SOC state [9], the equation is as follows:

$$\mathrm{SOC} = \mathrm{SOC_0} - \frac{1}{\mathrm{C_n}}\int_{\mathrm{t_0}}^{\mathrm{t}} \mathrm{I} * \mathrm{dt} \tag{1}$$

Where $\mathrm{C_n}$, corresponds to the nominal capacity of the battery, I, corresponds to the current flowing in and out of the battery and t, is the time.

On the other hand, generally this other method of calculation is made a variation, multiplying to the integral a coulombic efficiency factor (μi), which is represented between the discharge capacity and load capacity, is represented in the following equation:

$$\mathrm{SOC} = \mathrm{SOC_0} - \frac{\mu\mathrm{i}}{\mathrm{C_n}}\int_{\mathrm{t_0}}^{\mathrm{t}} \mathrm{I} * \mathrm{dt} \tag{2}$$

2.2. SOC status

The charge is expressed in the following equation:

$$Charge = I * t \tag{3}$$

The SOC is the charge level of a battery expressed as a percentage, the following equation is:

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

2.3. Evaluation of the recovery of the energy of the regenerative breaks

Evaluating energy recuperation in regenerative braking mainly includes the capacity of energy recuperation during braking and the rate of energy recuperation during braking [10]. Where, E_m is the energy recovery the equation is as follows:

$$E_m = \int U_b I_b * dt \tag{5}$$

Where, U_b is the voltage at the motor controller while recovering braking energy, I_b 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 that 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 next equation:

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

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 following equation:

$$n_b = \frac{E_m}{E_b} = \frac{\int U_b I_b * dt}{\left(\frac{1}{2}\right)(m)\left(V_0^2 - V_f^2\right)} \,(100\%) \tag{7}$$

Equation (7) allows determinate efficiency values of regenerative braking using mainly the initial velocity with which the vehicle starts 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 Lab (Emolab) softwares in the determination of the parameters that affect the efficiency of regenerative braking.

3.1. Variables that affect energy recuperation

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 [10]. 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 can be seen. 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.

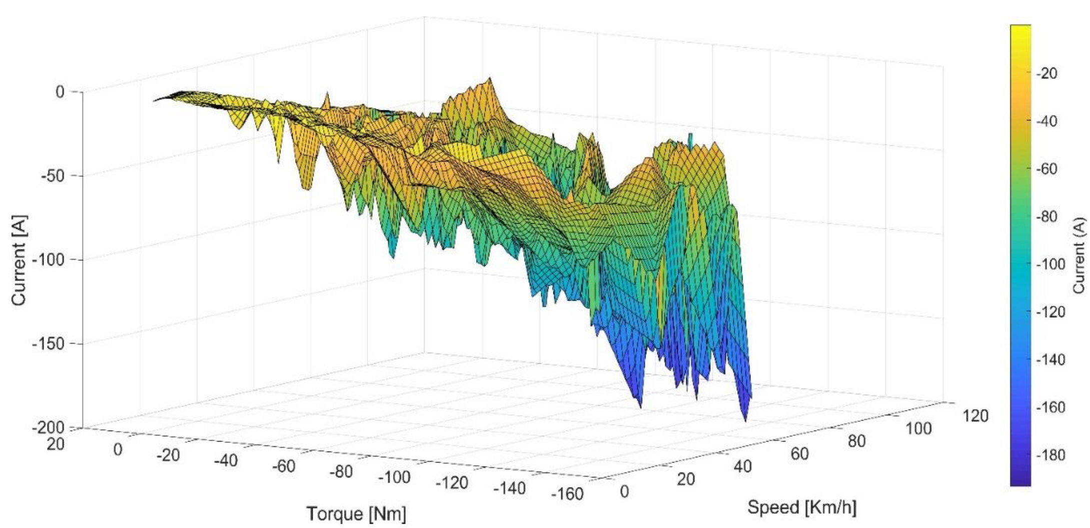

Figure 1. Variables affecting energy recovery in route 1.

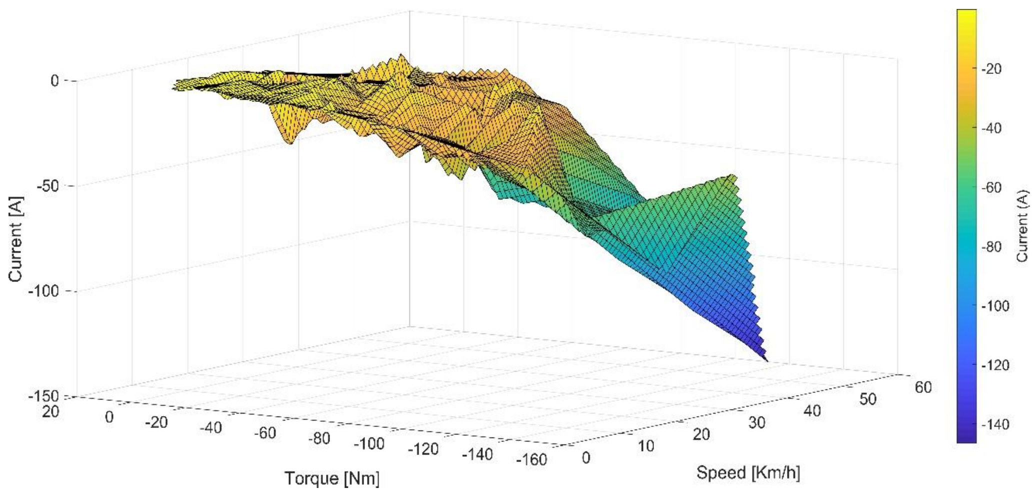

Figure 2. Variables affecting energy recovery in route 2.

Fig. 1, 2, and 3 show that, during the braking process,

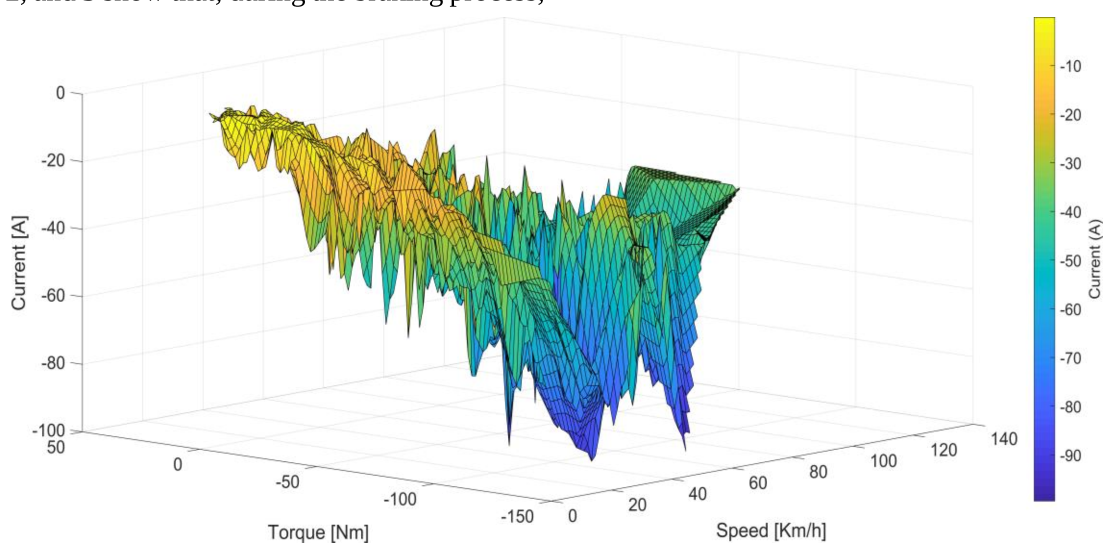

Figure 3. Variables affecting energy recovery in route 3.

variables such as velocity and motor torque play key roles in energy recuperation; since during the braking action the system generates current gradually by means of an AC motor, this 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.

Fig. 1 indicates a greater recuperation of energy. This is due to the fact that the geography of route one has different types of roads and inclinations. These characteristics also permit higher vehicle speeds, and consequently, longer times of brake application, resulting in greater motor torques and greater currents.

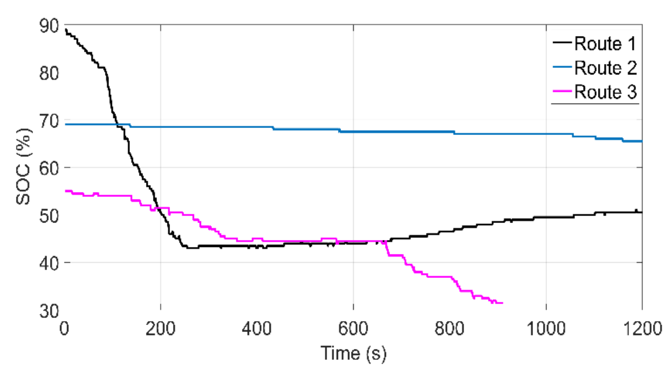

Figure 4. Behavior of SOC with respect to recovered energy.

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 Fig. 4, the different SOC performances can be seen for each route, each with a different length. Route one has a greater incline across all its trajectory, 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 recuperates 9% of its charge because of the longer brake times, high speeds up to 70Km/h as can be seen on Fig. 1 and the resulting elevated motor torques.

Route two only has of a discharge process. Fig. 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 discharge tendency is almost lineal 5% until the end of its trajectory. 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 Fig. 3. In this route, there is low brake usage, Fig. 4 shows certain points along this route where the discharge is attenuated, reaching a 32% level until its end point.

3.3. Deceleration performance

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

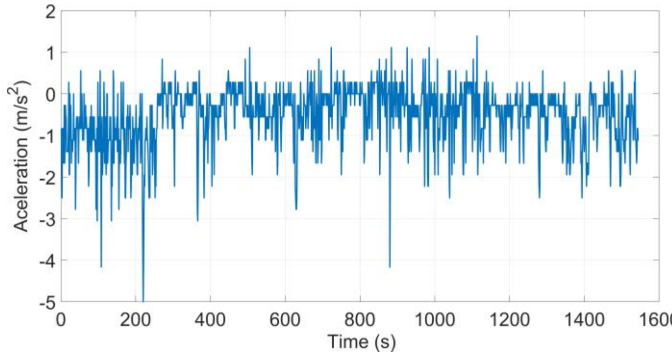

Figure 5. Deceleration with respect to regenerative system application.

Fig. 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 when the brake is used the state of the charge increases, a thus the vehicle recuperates energy to continue moving forward.

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 recuperated charge, and the weight of the vehicle.

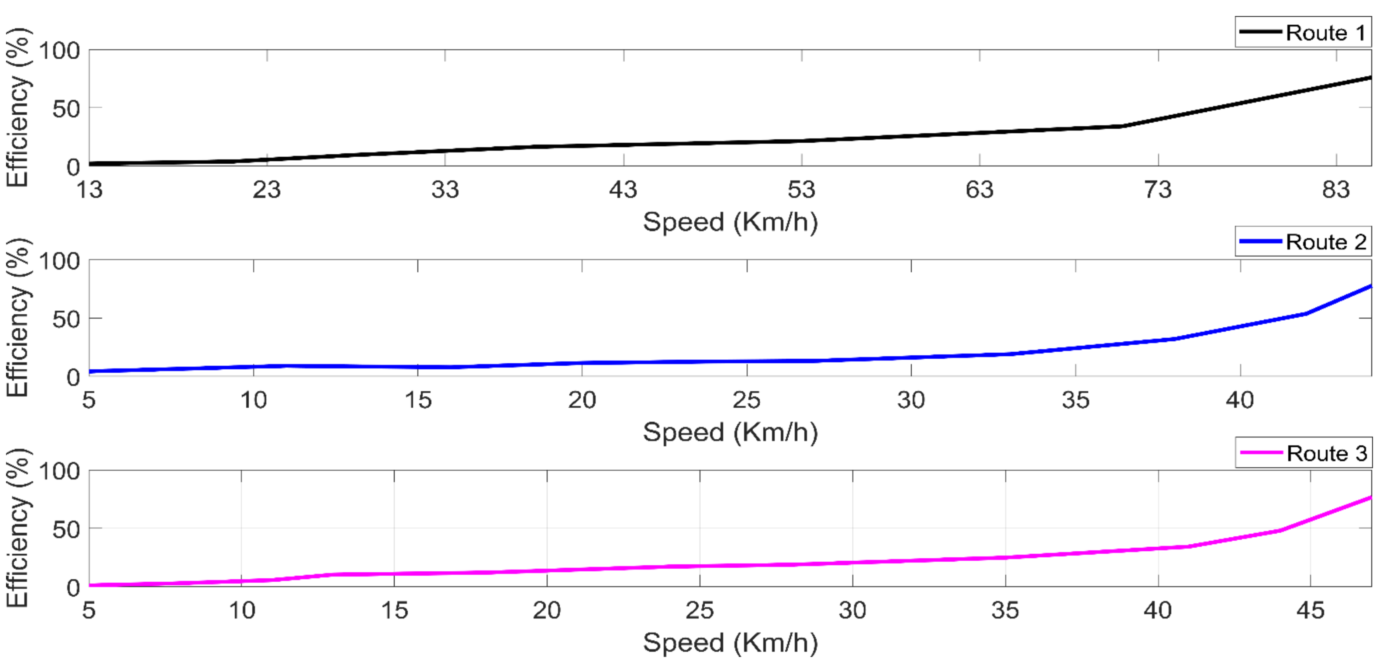

Figure 6. Deceleration with respect to regenerative system application.

Fig. 6 shows the relationship between the initial velocity of braking 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, initial braking speeds have an impact on the variability of the obtained efficiencies as shown in Fig. 6. In route 1 the result of the average efficiency in the specific sample is 23% 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.

In route 2, according to Fig. 6, its values vary because it presented a high vehicular flow, conditions of low driving speeds and high use of the brake pedal. So there is greater efficiency of the regenerative system, this efficiency in turn tends to stabilize, which results in greater energy recovery. Since it has optimal load values reaching an average of 24% and its highest efficiency reaches 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 one and three, the efficiency falls aggressively and it does not stabilize, resulting in low values near zero.

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

Speed (Km/h)	Recovery braking energy Em (J)	Energy loss of braking Eb (J)	Efficiency (%)
9 (Km/h)	3053.40 J	409842.90 J	0.07 %
44 (Km/h)	6930.63 J	19275.92 J	36 %
74 (Km/h)	44472 J	55819.86 J	79 %

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

Speed (Km/h)	Recovery braking energy Em (J)	Energy loss of braking Eb (J)	Efficiency (%)
9 (Km/h)	111.72 J	8261.11 J	1.35 %
22 (Km/h)	6346.10 J	17210.64 J	37 %
44 (Km/h)	8030.25 J	10326.39 J	78 %

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

Speed (Km/h)	Recovery braking energy Em (J)	Energy loss of braking Eb (J)	Efficiency (%)
9 (Km/h)	346.96 J	569041.39 J	0.06 %
22 (Km/h)	1748.81 J	4818.98 J	36 %
52 (Km/h)	34224 J	44059.25 J	78 %

The regenerative braking efficiency of each one of the routes is shown to be dependent on the lost and recuperated energy of the vehicle. The road geographies, the initial braking velocity, and the time of brake application, summarized in Table 1, are the principal variables that affect the values of lost and recuperated energy.

The values summarized 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 recuperation 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.

4. Conclusions

In this paper an analysis of the regenerative braking system was carried out through real driving tests, where variables such as: current, torque and speed influence with respect to the vehicle's energy recovery. 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 on route 2 has a progressive energy loss, which at a certain time tends to stabilize due to the greater use of the brake due to the high vehicular flow, while on 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. So a driving on route 2 due to the high vehicle flow the system is more efficient than route 1 and 3, as it has lower energy loss values and high energy recovery values.

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