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THE ANALYSIS OF ENERGY RECOVERED BY AN ELECTRIC VEHICLE DURING SELECTED BRAKING MANOEUVRES

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Abstract

Electrical vehicles have the ability to partially recover some kinetic energy during braking. Kinetic energy is transformed into electric energy, which is fed to the battery by the control system and stored there for further use. The aim of this paper was to analyse the levels of energy recovered by an electric vehicle during braking at various speeds and with different braking intensities. The first phase of testing consisted of vehicle braking tests in real-life conditions. The registered speed profiles were then used as input data for the simulation software. The authors have also analysed the effect of the state of charge of the battery and of the vehicle's load on the amount of energy recovered during braking. The performed simulation tests demonstrated that the level of recovered energy is significantly affected by the initial braking speed and by the force of pressure applied to the brake pedal. The amount of recovered energy is less affected by the state of charge (SOC) of the battery and by the vehicle's load. Energy regeneration during braking is currently an important research topic. The efficiency of an electric vehicle depends on the range, which can be extended thanks to the additional energy recovered during braking maneuvers. The presented preliminary simulation results are intended to assess the level of energy recovery in electric vehicles. The authors are aware that a full, comprehensive analysis requires additional research using electric vehicles that will verify the results presented in the paper.

Keywords: regenerative braking; regenerative energy; electric vehicle; vehicle testing

1. Introduction

The number of electric vehicles currently in use is growing and these vehicles are experiencing increasingly high sales. In 2021, the number of electric vehicles in the EU increased by approximately 63% in relation to 2020 [27]. In Poland, the number of electric-only powered

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vehicles in use in 2021 was 18,795. In the period between January and December 2021, 8,038 new electric-only powered vehicles were registered [1].

The benefits of battery electric vehicles primarily include the absence of emissions in the operating location and high engine efficiency. The users of BEVs are offered many different benefits, such as the possibility of free entry into city centres, free city parking, or the possibility of using bus lanes. However, apart from many such benefits, the users of electrical vehicles are also aware of their disadvantages [36]. One of these is undoubtedly their limited range on a single battery charge and the resulting need of route planning [4]. A vehicle's range is closely associated with the conditions in which the vehicle is used [28]. The factors that affect energy consumption, and therefore the range, include ambient temperature [3, 12]. The need to use the cabin heating and cooling system requires additional energy to be drawn from the battery [13]. It was also observed that higher wind exposure (especially to headwind) affects energy consumption during driving [2]. Another factor that affects a vehicle's range is the route topography. Driving in hilly and mountainous terrain increases energy consumption, which as a result reduces the driving range [17]. Urban driving, which requires numerous acceleration and braking events, also affects energy consumption. The driver's driving style may also significantly reduce an electric vehicle's range [5].

An effect called "range anxiety" has been observed among new users of electric vehicles. It is a psychological, subjective feeling of the driver of an electric vehicle, which is expressed by anxiety and fear that the state of charge of the battery will not be sufficient to complete the planned route [14, 21]. The issue of "range anxiety" is currently the subject of much research [23, 35]. Fear connected with limited range can also be analysed as a factor that affects the travel chain. We can also find articles in which the feeling of range anxiety has been analysed in connection with the charging infrastructure and the charging time [20, 37].

Electrical vehicles have the ability to partially recover some kinetic energy during braking. Recuperation, also known as regenerative braking, is the recovery of kinetic energy released during braking or during thrust [19]. In electrical vehicles, the electrical traction machine acts as a generator. Kinetic energy is transformed into electric energy, which is fed to the battery by the control system and stored there for further use. Because of physical reasons, only a percentage of this braking energy can be recovered. This is caused by factors such as the state of charge of the battery and limitations resulting from the voltage characteristics of the electrical machine and the battery [6, 11, 30].

Information on braking systems with regenerative energy is provided in documents such as Regulation 13-H of the United Nations Economic Commission for Europe (UNECE). This document explains the terms connected with the recuperation of energy during braking and describes the action of the individual system elements, such as the transmission of signals. This regulation also defines two categories of braking systems with energy recuperation [11]:

- Category A – in which this system does not represent a part of the main braking system. It is activated by one of the two available solutions:
  - the gear level, when positioned in the neutral gear,
  - the acceleration control device.

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- Category B – the regenerative braking system is integrated with the main braking system. In this situation, the system is equipped with one control device and the disconnection of any part of the main system must be automatic. In the event of any malfunction of the main braking system, the driver must be informed of such an event via a visual warning signal.

One of the main advantages of regenerative braking is the ability to improve propulsion system efficiency without adding any new components. In contrast to conventional vehicles, in which braking energy is dispersed in the form of heat, the function of regenerative braking in electric vehicles allows this energy to be recovered and stored during braking. Current research on regenerative braking is concentrate on achieving the best possible efficiency of energy conversion. In plug-in hybrids, regenerative braking can also extend the electric range, thereby reducing fuel consumption and emissions [24]. With this in mind, different strategies and algorithms are implemented to distribute the braking force between the regenerative and mechanical braking systems in a way that would enable the recovery of the highest possible level of energy from regenerative braking [25, 29, 32].

The aim of this paper was to analyse energy levels recovered by an electric vehicle during braking at various speeds and with different values of forces applied to the brake pedal, with the use of vehicle simulation software. The authors have also analysed the effect of the state of charge of the battery and of the vehicle load on the amount of energy recovered during braking.

2. Methodology

In this work, the value of energy recovered during braking tests was analysed. The research was divided into two stages. In the first, real braking on the straightway tests were carried out at specific initial speeds. Using specialized equipment, speed profiles from the braking of a passenger car with a conventional drive were collected. In the second stage, simulation tests of the electric vehicle were carried out using recorded speed profiles.

1.1. Braking tests in real-life conditions

The first stage of testing consisted of braking tests in real-life conditions. The test vehicle (Audi A6) was equipped with a measuring system for the registration of the vehicle's dynamic parameters. The measuring apparatus consisted of:
- a Corrsys Datron S-350® Aqua optoelectronic sensor;
- a three-axis TAA® acceleration sensor;
- a Datron uEEP12® data acquisition station;
- a control tablet equipped with ARMS® software,
- a pressure sensor located on the brake pedal.

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The following parameters were measured during the braking tests: instantaneous speed, instantaneous acceleration, time, instantaneous location of vehicle. The tests were carried out on testing yards with asphalt pavement. Hard braking tests were carried out with the following initial speeds: 40 km/h, 50 km/h, 60 km/h and 70 km/h. Velocity profiles collected during the tests are shown in Figure 1.

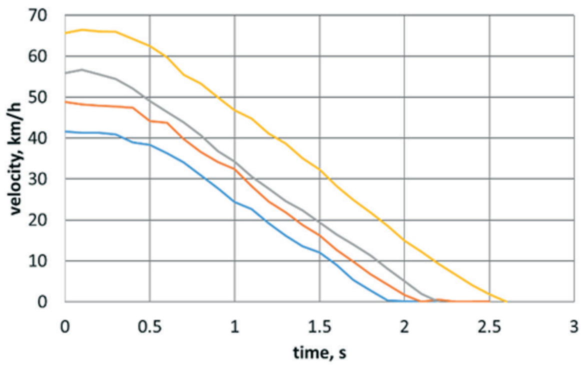

Fig. 1. Velocity profiles during braking tests

The highest deceleration value was registered during braking tests with an initial speed of 70 km/h. The value of deceleration was 9.94 m/s^2.

Further tests included braking at different intensities, expressed as brake pedal force. The pressure forces of 150 N and 400 N were implemented. The driver was supposed to stop the vehicle by pressing the brake pedal without exceeding the implemented force. The tests were carried out with the initial braking speeds of 40 km/h and 50 km/h. Figure 2 shows the speed profiles registered during testing.

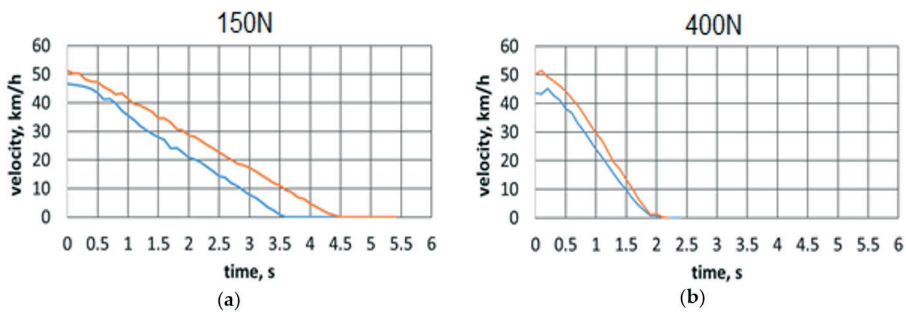

Fig. 2. Velocity profiles during braking tests with brake pedal forces of (a) 150 N and (b) 400 N

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When the force of 150 N was applied to the brake pedal, maximum deceleration registered during braking from 40 km/h was 5.24 m/s^2 and during braking from 50 km/h – 4.01 m/s^2. Approximately two times higher deceleration values were registered during braking tests with the force of 400 N applied to the brake pedal. Deceleration in this case was 9.81 m/s^2 when braking from the speed of 40 km/h and 10.32 m/s^2 when braking from the speed of 50 km/h.

1.2. Simulation tests

Speed profiles generated during these tests were then used during simulation tests, to determine the values of energy recovered during the braking of an electric vehicle. Simulations were carried out using the AVL Cruise software. This programme enables an analysis of the energy consumption of vehicles in different driving conditions. The model of the simulated electric vehicle is shown in Figure 3.

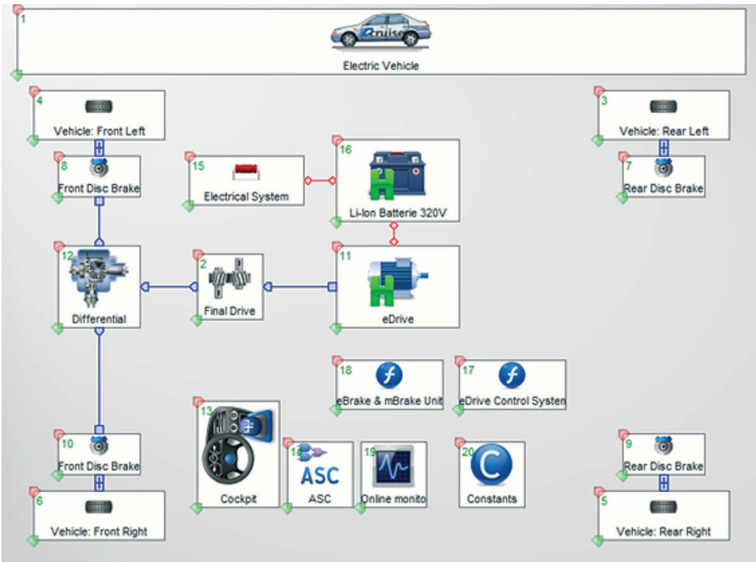

Fig. 3. Electric vehicle model in AVL Cruise

The test vehicle was an electric vehicle with a kerb weight of 1250 kg and a frontal area of 1.97 m^2. The source of energy in the vehicle was a lithium-ion battery, and the drive unit was an asynchronous motor (ASM). Some of the vehicle's technical parameters are shown in Table 1. The model reflects the actual Nissan Leaf I vehicle. The characteristics of the drivetrain components available in the model are modelled after those of the Leaf.

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Tab. 1. Electric drive components specifications

Electric drive component	Parameter	Value
asynchronous motor	maximum torque	240 Nm
motor mode	maximum power	80 kW
generator mode	maximum torque	240 Nm
	maximum power	75 kW
Li-ion battery	nominal voltage	320 V
	maximum voltage	420 V
	minimum voltage	220 V
	maximum charge	10 Ah

In the simulation test investigate the values of energy recovered by an electric vehicle during braking:

- with different initial speeds (40 km/h, 50 km/h, 60km/h, 70 km/h);
- with different forces applied to the brake pedal (150 N, 400 N);
- with different battery state of charge levels (40%, 50%, 60%, 70%, 80%, 90%);
- with different vehicle loads (50 kg, 100 kg, 150 kg, 200 kg, 250 kg).

3. Results

Figure 4 shows the values of energy recovered with different initial braking velocity. Simulations were carried out with an electrical vehicle of the weight of 1300 kg and a battery state of charge of 60%.

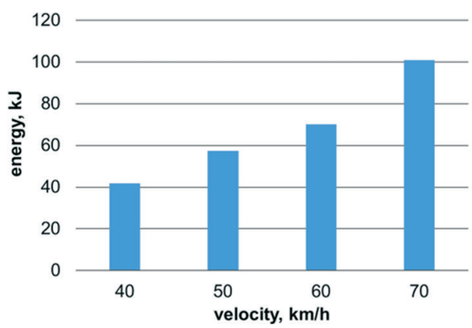

Fig. 4. Values of energy recovered at different initial braking velocity

As shown in Figure 4, higher initial braking velocity results in higher amount of recovered energy. Out of all the performed tests, the highest value of recovered energy was registered when braking from 70 km/h – the highest test speed. The difference between the values

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of energy recovered during braking with the initial speeds of 40 km/h and 70 km/h was approximately 60%.

Energy recovered during braking with different state of charge (SOC) presents Figure 5. The simulations were carried out for an electrical vehicle of the weight of 1,300 kg. The initial braking speed was 40 km/h.

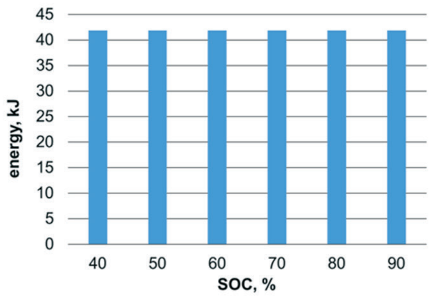

Fig. 5. Values of energy recovered at different battery state of charge (SOC) during braking

Tab. 2. The state of charge (SOC) before and after braking from the initial velocity of 40 km/h

Initial SOC, %	40	50	60	70	80	90
Final SOC, %	40.228	50.226	60.224	70.222	80.220	90.218

The level of energy recovered during the braking tests does not significantly affect the battery state of charge. The completed simulation tests demonstrate that the values of energy recovered during braking with different battery state of charge vary slightly. As can be seen from the Table 2, the amount of energy in the battery after the braking tests increased by 0.218% – 0.228%.

Figure 6 shows the values of energy recovered during braking with different forces applied to the brake pedal. Simulated braking was carried out using a vehicle of the weight of 1,300 kg, with the initial speeds of 40 km/h and 50 km/h and with the battery state of charge level of 60%.

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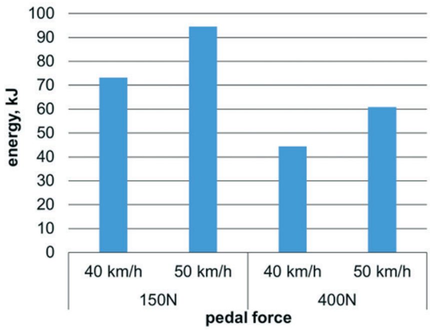

Fig. 6. Values of energy recovered during braking with different forces applied to the brake pedal

The results of simulation tests shown in Figure 6 demonstrate that the amount of force applied to the brake pedal significantly affects the level of energy recovered during the braking of an electric vehicle. When braking with the force of 150 N applied to the brake pedal, the amount of recovered energy is approximately 40% higher than when braking with the force of 400 N.

Energy recovered during braking with different vehicle loads presents Figure 7. Simulated braking was performed with the initial speed of 40 km/h and the battery state of charge level of 60%.

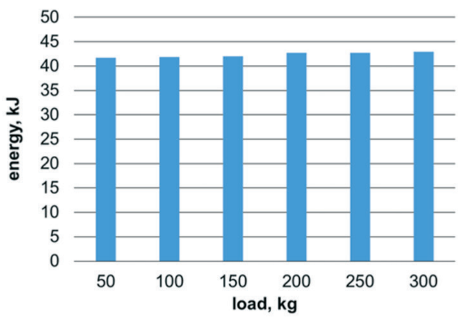

Fig. 7. Values of energy recovered during braking with different loads

The results of simulation tests performed on an electric vehicle indicate that the amount of load in the vehicle does not significantly affect the amount of recovered energy. The lowest amount of recovered energy was registered with the lowest load, whereas the highest amount of energy was recovered during braking with the highest load. The values of recovered energy varied by 3%.

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4. Conclusions and discussion

The authors of this paper analysed the effect of selected factors on the amount of energy recovered during braking. The presented results reveal information that is of significance to the users of electric vehicles. It has been stated in many articles that recuperation extends the range of an electric vehicle. The presented results show that the amount of recovered energy depends primarily on the initial speed at which the vehicle starts braking and on the method of braking, represented by the amount of force applied to the brake pedal. The results of simulation tests indicate that higher initial braking speed translates into higher levels of recovered energy. On the basis of the performed tests, we can conclude that increasing the initial braking speed by 10 km/h can increase the amount of energy recovered from braking by approximately 25%. Similar conclusions were presented in [18]. The higher the speed, the greater the energy recovered and the higher the energy recovery efficiency. According to the results published in [7–9], regenerative braking from low initial speeds is not very effective. As confirmed by the results presented in [34], energy recovery at speeds below 16 km/h is not implemented, because the motor voltage is low in the area of low rotational speed. Therefore, many studies and projects are devoted to the methodology and control algorithms in order to increase the efficiency of regenerative braking at low speeds [30, 31].

The tests have revealed that higher forces applied to the brake pedal translate into lower amounts of recovered energy. During this research it was observed that in the case of braking with the force of 150 N applied to the brake pedal, the amount of recovered energy is approximately 40% higher than when braking with the force of 400 N. According to the research carried out by the authors of papers [16, 33, 38], properly adjusted force on the brake pedal, the depth and time of pressing the brake pedal during braking can affect the comfort of braking and the efficiency of regeneration. This is obvious, because in most electric vehicle braking systems, the first system to be activated is the electrical system which converts kinetic energy into electric energy using the electric machine [15]. The amount of recovered energy is limited by the current-voltage characteristic of the electric machine and the battery. The mechanical braking system is then activated, which disperses the remaining braking energy through friction processes. Therefore, when the braking intensity is lower, the level of recuperated energy is higher.

The authors if this research also analyzed the values of energy recovered with different state of charge (SOC) values. The results of the performed simulation tests indicate that the state of charge of the battery does not significantly affect the amount of recovered energy. The values of energy recovered with the same initial braking speed and vehicle weight, but with different initial battery state of charge values, differ by 0.03 %.

The amount of energy recuperated during braking is less affected by the vehicle's weight. The results of simulation tests performed on an electric vehicle during braking with the same initial speed and constant battery SOC, but with different loads (in 50 kg increments), have shown that the values of recovered energy differ by 3%. According to the results presented in [22], as the weight of the vehicle decreases, the amount of available energy that can

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be recovered decreases. Reducing the weight of the vehicle by 10% reduces the total amount of energy recovered by 7%.

In summary, the paper presents the results of energy recovered during EV braking with different initial speeds and different intensity of brake pedal pressure. The study presents the results of simulation tests conducted only for selected braking maneuvers. It is worth noting that due to the possibility of regenerative braking, it is possible to recharge the battery while driving. This contributes to extended range. When taking braking action, the driver usually does not consider how the braking system works. The driver is only interested in stopping or slowing down the vehicle. It is worth making drivers aware of the fact that the braking process in an electric vehicle can further recharge the battery while driving. Due to different driving styles and behavior, it is worth pointing out to EV drivers to adjust the braking method to ensure effective energy recovery. Authors are aware that comprehensive analyses of electric vehicle operation require more extensive research. In future work, it is planned to expand the study of electric vehicle energy efficiency. In addition to simulation studies, it is also planned to use actual electric vehicles.

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