INVESTIGATION INTO REGENERATION REGIMES FOR CONVERTED ELECTRIC VEHICLE IN ROAD TESTS

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Abstract. As fossil energy deposits are exhausted, internal combustion engine vehicles tend to be replaced by electric ones. Electric vehicles have several advantages over internal combustion ones: no exhaust emissions at the site of exploitation, emissions from energy production could be located in less populated areas, emissions are much lower, quieter operation and a two-fold higher efficiency factor of the motor. One of the most significant advantages of operating an electric vehicle in a city is the possibility of energy recovery, which allows the energy regenerated during braking to be charged into the batteries, thus increasing the range. An original research methodology for road testing has been developed and tested. Since regenerative braking usually occurs in parallel with braking by applying the service or friction brakes, it is difficult to determine the maximum amount of energy regenerated, as part of the kinetic energy is also transformed into thermal energy when braking. Therefore, a braking experiment with a converted electric vehicle Renault Clio Electro was performed by braking at different speeds only by means of regenerative braking, using no friction brakes. The experiment was performed in two of the most commonly used gears – second and third. The experiment recorded both the energy consumed to reach a certain speed and the energy returned to the battery during the braking cycle. The highest regenerative braking efficiency was achieved in second gear at a 100% regenerative braking setting, on average 35.1%, yet this regenerative braking setting was difficult to use in real driving conditions due to excessive braking and difficulty in controlling the braking torque and the deceleration of the electric vehicle. Therefore, a regenerative braking setting of no more than 80% is recommended for the experimental prototype in road traffic, reaching a regenerative braking efficiency of 32.5%.

Keywords: electric vehicle; current, voltage, controller, data logger.

Introduction

As global oil deposits are exhausted, the use of other kinds of energy in vehicles is being considered. An electric motor is one of the ways for replacing vehicles with internal combustion engines. Although electric vehicles have historically emerged alongside internal combustion engine vehicles more than 120 years ago, internal combustion engine vehicles progressed faster, and electric vehicles were disregarded. The last decade, when the first modern electric vehicles began to appear in the streets, could be considered to be a mass revival of electric vehicles. Prototypes of electric vehicles are currently designed by almost every auto manufacturer. Over the next decade, auto manufacturers plan to reduce the manufacture of internal combustion vehicles and increase the manufacture of electric motor vehicles. Electric vehicles have several advantages, e.g. quiet emission-free operation, relatively simple motor design, low maintenance cost, as well as the possibility to regenerate and store energy from regenerative braking. Owing to regenerative braking, energy is saved and, in urban driving, electric vehicles usually have a longer range per charge than in non-urban driving. Several research papers are available on regenerative braking for electric vehicles.

A parallel or a series control strategy could be used to control regenerative braking system of an electric vehicle. Relevant research studies have used several sensors, e.g. a voltage sensor, a current sensor, a pedal pressure sensor, a gyroscope and a motor slip sensor. Experiments have been conducted in urban driving in a specially designed regenerative braking cycle. The experiments found that a series control strategy resulted in higher efficiency. The experiments were conducted also under critical braking conditions, identifying improvement in the braking efficiency of up to 14.71% under low adhesion conditions if using regenerative braking [1; 2].

A power-based model for electric vehicles has been designed. The model has been calibrated. The calibration was performed by using experimental data on a prototype of an experimental Nissan Leaf. Simulation experiments were performed in different driving cycles. An energy recovery of up to 31% was achieved during the UDDS driving cycle. If using additional systems, e.g. the climate control system, the overall recovery effect was lower, only 21.3%. The model could also simulate the range of an electric vehicle with fully charged batteries [3].

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Precise coordination between the electric and the hydraulic braking systems is required to achieve a larger recovery of regenerative energy to be charged into the batteries. Such a braking system considers changes in weight distribution on the axles during braking. During intensive regenerative braking, the braking force of an all-wheel drive vehicle is reduced for the rear axle [4].

Chinese scientists have developed a mathematical model for operating the regenerative braking system of an electric vehicle, which evaluates the performance of all systems involved in the process. To test the algorithm, experiments were conducted on a roller test bench, performing a combined New European Driving Cycle (NEDC). The experiments were conducted on the roller test bench with and without regenerative braking, measuring changes in the battery voltage, current and motor torque. The energy recovery efficiency of 12.58% was obtained on the roller test bench by performing a modification of power flow control [5].

Several mathematical models for electric vehicle control systems and power distribution are available in the literature. The models have two main driving regimes for an electric vehicle: acceleration and steady cruising when energy is needed from the batteries. The regime of regenerative braking when kinetic energy is converted into electrical energy has also been researched using the models [6].

To research the process of regenerative braking, special roller test benches were also designed to simulate the main parameters of regenerative braking: the braking torque, regeneration time and the amount of energy recovered. The brake pedal was equipped with four fixed positions providing different braking forces [7; 8].

Chinese scientists have designed a regenerative braking system in which the standard ABS module is replaced with a special adapted ABS block. The module is connected to the inverter and operates according to the driving regime and motor parameters set. One of the functions of the new module is to control the efficiency of energy recovery so that it is similar to an internal combustion vehicle using engine braking. Experiments with regenerative braking have also been conducted to record data on the vehicle speed, deceleration and regenerative current. The conventional braking system is activated when the regenerative braking torque is not sufficient to provide the required braking force [9].

Chinese scientists have designed a mathematical model for regenerative braking for a DC electric motor. The performance of the model has been tested on a special test bench [10].

A calculation model for electric and hybrid vehicles has been designed in Sweden. A vehicle weighing 1500 kg was chosen as a prototype. The experiments used a GPS logger installed on the vehicle, which recorded the movement of 430 cars in real driving conditions in Sweden. The potential savings of energy for electric and hybrid vehicles were calculated based on the data recorded. The average savings were estimated at EUR 430 per vehicle per year [11].

There have been conducted relatively few experiments to identify the effect of the energy recovery setting on the amount of energy recovered during regenerative braking; therefore, it is useful to conduct such experiments. The aim of the present research is to design and test a research methodology for determining the maximum amount of energy recovered for an electric vehicle performing braking only by means of the electric motor and to identify the amount of energy recovered by the electric vehicle operated in two of the most frequently used gears.

Materials and methods

A converted electric vehicle Renault Clio was used in the experiment. The electric vehicle had a standard 5-speed gearbox, with second and third gears being used. Shifting a gear was done when the vehicle was stopped, as the standard clutch was not used. The main technical parameters of the electric vehicle are summarized in Table 1.

The electric vehicle was equipped with a switch that had three positions: forward, neutral and reverse. If switched to the neutral position while the electric vehicle was moving, regenerative braking occurred without activating the brake pedal. The Sigma Drive inverter of the electric vehicle could be adjusted at an increment of 1% for regeneration braking setting. The adjustment could be done by means of a diagnostic device connected to the electric vehicle.

Table 1

Main technical characteristics of the electric vehicle Renault Clio

No	Parameter characteristics	Parameter value
1	Motor nominal power	30 kW
2	Controller type	Sigma Drive PAC950TL02
3	Gear ratios used: 2 3 Final drive	 1.864 1.321 4.067
4	Maximum speed	120 kmh^{-1}
5	Battery cells	$LiFePO_4$, 32pcs.
6	Nominal battery voltage	102.4 V
7	On-board power	10.5 kWh
8	Nominal voltage of a battery cell	3.2 V
9	Voltages set in the BMS	U_{min} = 2.6 V; U_{max} = 3.8 V;
10	Range per charge	60 km
11	Battery capacity	100 Ah
12	Curb weight	1080 kg
13	Weight in the experiment	1230 kg

A Graphtec midi Logger GL220 data logger was used to record electrical data. The logger's data logging frequency could be set within a range of 100 ms to 24 h. The logger was equipped with a 4.3-inch screen (TFT LCD display). The logger supply voltage was within a range of 8.5 to 24 V. The data logger had 10 input channels, of which 6 were used in the experiment: for storing the voltage, current, motor speed, battery temperature, inverter temperature and ambient temperature data (temperature data were not analysed by the research). Circuit diagram of the experimental equipment is shown in Fig. 1.

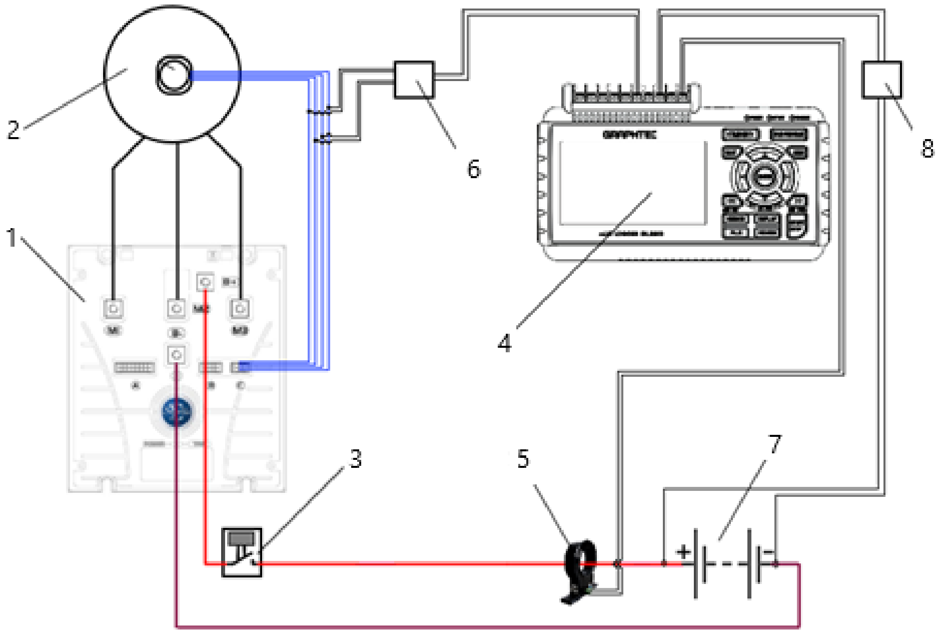

Fig. 1. **Electrical circuit of the experimental equipment:** 1 – controller Sigma Drive; 2 – electric motor; 3 – electromagnetic safety switch; 4 – data logger Graphtec GL220; 5 – current sensor; 6 – speed sensor; 7 – 102.4 V batteries; 8 – voltage sensor

A Garmin Edge 830 GPS logger was used to accurately determine the speed of the vehicle in cruising regime. The logger could record the route, speed and distance travelled.

The experiment was conducted on 28 October 2021 on the light traffic road section between Jelgava city and the village of Brankas at an ambient temperature of +10 to +12 ºC. The experiment was performed by two operators. One operator drove the vehicle, while the other was responsible for activating the data logger. To easily control the driving regime of the electric vehicle, the vehicle's standard tachometer was used, which was calibrated using the GPS logger. The calibration was performed at one speed, at $v = 50$ km·h^{-1}. The vehicle ran smoothly, reached a speed of 50 km·h^{-1}, controlled by the GPS logger. This driving regime was maintained for at least 10 seconds, and the tachometer reading could be recorded. During the experiment, the speed was controlled by means of the tachometer, as it was the most comfortable instrument for the driver to do it, and his reaction speed was sufficient for correctly conducting the experiment.

The experiment was performed with fully charged batteries. The experiment was started with the electric vehicle being stationary. The electrical parameter logger was activated, and the movement was started. After reaching a speed of 50 kmh^{-1}, it was maintained for 1-2 seconds, and regenerative braking was activated by means of the regime switch. The braking was done until the electric vehicle completely stopped. After the vehicle stopped, the data logger was stopped for on average 2-3 seconds to save the data. The experiment was replicated 5 times. The experiment was performed in gear 2 and 3 at the energy regeneration settings of 20%, 40%, 60%, 80% and 100%. For safety reasons, the experiment was performed when there were no other vehicles on the road at least 300 m behind the electric vehicle, as the stop lights were not activated during the regeneration braking.

After the experiment, the data stored in the data logger were copied to a computer and processed, calculating the energy consumed and recovered during the experiment. The calculations used instantaneous current and voltage values.

Results and discussion

The duration of each replication of the experiment was significantly influenced by the gear engaged as well as the energy regeneration setting. At 100% setting, the average experiment duration was 22.6 seconds in second gear and 27.3 seconds in third gear, while at 20% setting, 67.7 seconds and 75.3 seconds, respectively (see Fig. 2). The lower the setting and the longer the regenerative braking time, the higher the proportion of the braking force during braking due to the rolling resistance because part of the kinetic energy was dissipated in the form of rolling friction.

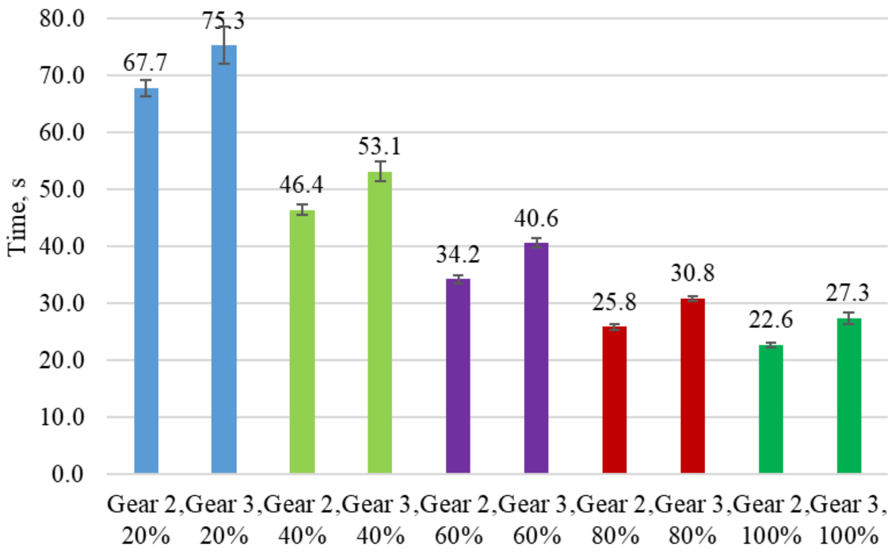

Fig. 2. **Total acceleration- regeneration time**

One of the indicators of energy recovery is the maximum current that is allowed by the inverter to be converted into electricity using the kinetic energy that the vehicle has accumulated when accelerating. In the experiment, the acceleration was performed with maximum intensity and on average in all the driving regimes the current in the third gear ranged from 370.2 A to 388.1 A (see Fig. 3). When accelerating in second gear, the instantaneous current ranged from 448.7 A to 512.0 A. The acceleration current did not depend on the percentage of the energy regeneration set in the controller, but only on the gear engaged.

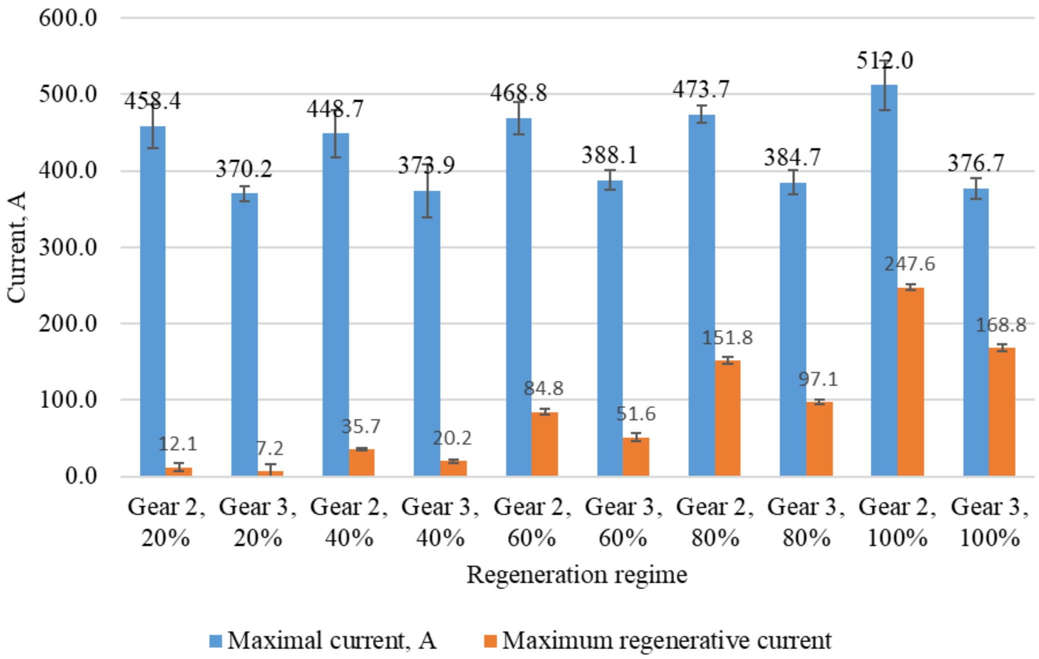

Fig. 3. **Maximum current values when accelerating and applying regenerative braking**

The data logger recorded the regenerative current as a negative value, yet for simpler graphical perception, the regenerative current was displayed as positive values. In both second and third gears, the maximum values of regenerative current at the settings of 20% and 40% ranged from 7.2 A to 35.7 A. Such a regenerative current was not able to significantly contribute to energy supply to the battery. At the setting of 60%, a maximum of 84.8 A was already reached in second gear and only 51.6 A in third gear. The highest regenerative current value, 247.6 A, was reached in second gear at the 100% setting, while in third gear it was 31.8% lower. However, at 80% setting, the maximum current was reached in gear 3, which was 36.0% less than in the second gear (151.8A).

One of the most important indicators of regenerative braking for an electric vehicle is the energy balance during the vehicle trip, while in this particular experiment – during one experimental cycle. When the electric vehicle accelerated up to 50 km·h^{-1} in the experiment, energy was consumed from the battery, while when braking, it was returned (see Fig. 4).

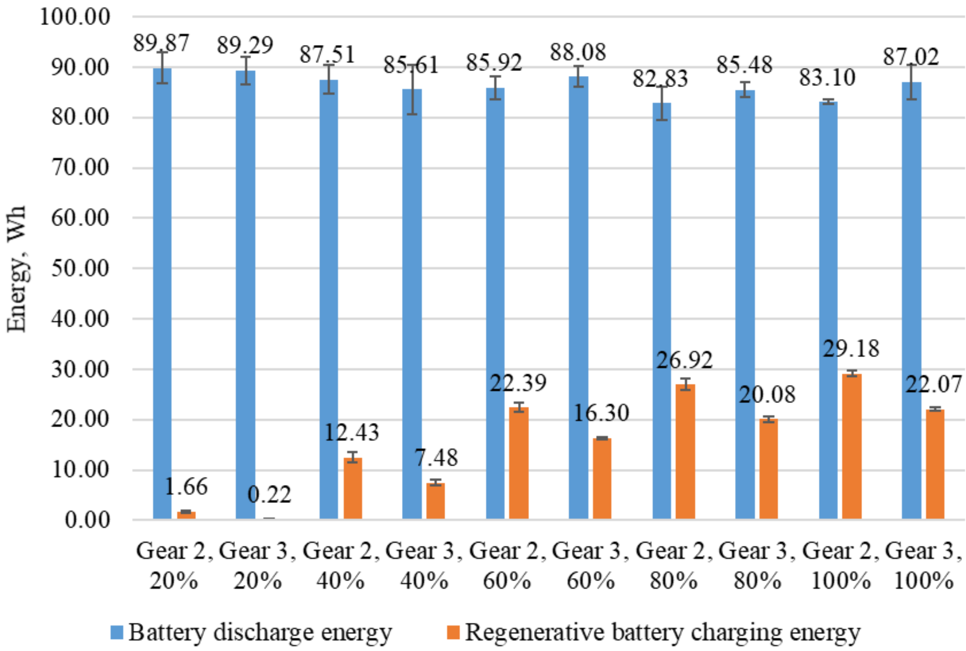

Fig. 4. **Energy consumed and regenerated in the experiment**

The amounts of energy consumed per cycle in all the experimental regimes were similar, ranging from 82.83 Wh to 89.87 Wh in second gear and from 85.48Wh to 89.29 Wh in third gear. At the 20% setting, the amount of energy recovered was very small due to the long regenerative braking time and the fact that a significant part of the kinetic energy was dissipated by rolling resistance. Even at 40% setting, the amount of energy regenerated did not exceed 12.43 Wh, and the braking deceleration was very insignificant according to the “feel”. The regenerative effect was already felt at the 60% setting, as 22.39 Wh of energy was recovered in second gear and 16.30 Wh in third gear. At the 80% setting in second gear, 26.92 Wh was charged into the battery, while in third gear it was 25.4% less energy. At 100% setting, the amount of energy recovered in second gear was 29.18 Wh and in third gear 22.07 Wh, which was 24.4% less. However, such a regenerative setting is not applicable for everyday driving, as the regenerative braking effect is difficult to control with the pedal and causes discomfort during braking due to the excessive braking force. According to preliminary studies in a city, the highest adjustable regenerative braking setting, which provides a good feeling and control of braking with the pedal is 70-77% in second gear and 75-80% in third gear.

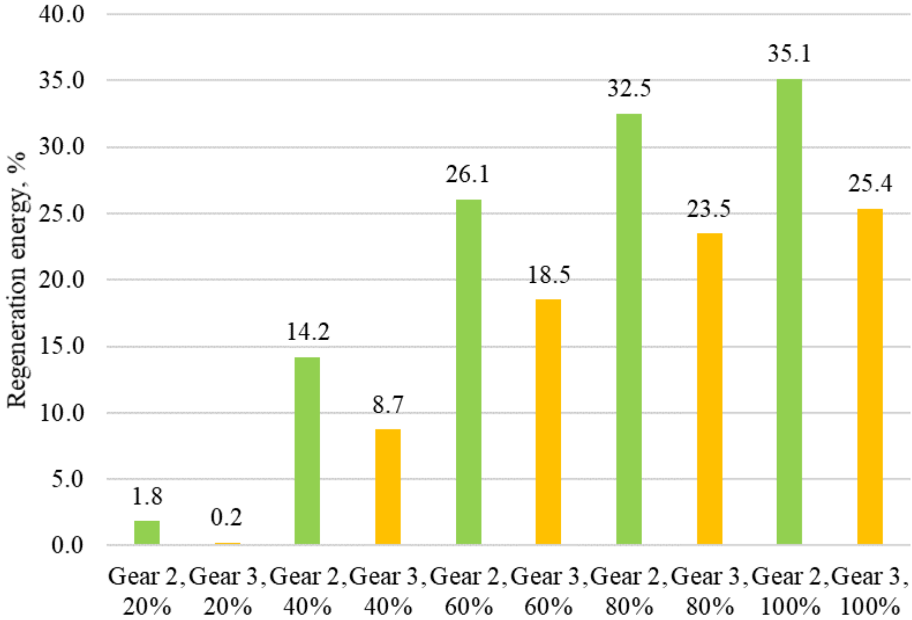

Fig. 5. **Energy regenerated, as% of battery energy consumed during the experimental cycle**

The highest percentage of energy regenerated compared with the energy consumed from the battery could be reached in the second gear at the 100% setting, 35.1% (see Fig. 5). At the 80% setting, the proportion of the energy regenerated was only 2.6% lower, while at the 60% setting it was 9% lower. An analysis of the percentages by gear reveals that the effect can be 0.7% higher in the second gear at the 60% setting than in the third gear at 100% setting. Therefore, for the given electric vehicle in urban driving, it is useful to select the second gear and regenerative braking setting in the range of 60-80%, depending on the driver’s experience and the sensitivity of the braking system.

Simulation studies available in the literature found that a Nissan Leaf could recover up to 31% energy during a NEDC driving cycle. When road testing the Renault Clio electric vehicle, the maximum energy regeneration efficiency of up to 35.1% was identified, while in real urban driving the efficiency is lower.

Conclusions

1. An original methodology for identifying the maximum regenerative effect if braking only by means of the motor and not using the main braking system has been designed and tested.
2. Regenerative braking cycle studies have found that at low regenerative braking settings, e.g. at 20-40%, the braking time is 2-3 times longer than at higher settings. For this reason, the proportion of braking force due to rolling resistance increases, and only a part of the potential kinetic energy is charged into the batteries.

3. The maximum values of instantaneous regenerative current might reach 151.8 A and 247.6 A in second gear and 97.1 A and 168.8 A in third gear at the settings of 80% and 100%, respectively.
4. At the regenerative braking settings in the range of 20 to 40%, the amount of energy charged into the batteries during braking was small and did not exceed 12.43 Wh in second gear and 7.48 Wh in third gear.
5. The maximum amount of energy charged into the batteries was reached at the 100% setting: 29.18 Wh in second gear and 22.07 Wh in third gear. The amount of energy regenerated did not decrease significantly even at the 80% setting, decreasing by only 7.8% in second gear and 9.0% in third gear.
6. In the experiment, in second gear it was possible to regenerate 26.1-35.1% of the energy at the regenerative braking settings of the controller in the range of 60-80%, while in third gear it was 18.5-25.4%.
7. The maximum regeneration percentages are lower in real urban driving, as the driving cycle does not consist only of acceleration to maximum speed and the braking process, as well as due to the kinetic energy dissipated by the main braking system.
8. For the converted electric vehicle, according to preliminary studies in a city, it is useful to choose regenerative braking setting of the inverter for the second gear in a range of 67-77%, depending on the "feel" of the brake pedal of the driver and comfort during smooth braking.
9. For the converted electric vehicle, it would be useful to introduce variable regenerative braking setting, depending on the pedal position, which would improve comfort during braking.

Author contributions

Dainis Berjoza: conceptualization; methodology; experimental research; data processing; visualization, analysis of results. Inara Jurgena: literature analysis; experimental research; writing – review and editing; visualization, investigation. All authors have read and agreed to the published version of the manuscript.

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