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Regenerative braking process for the urban traffic conditions in Gdańsk and Bremen

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ABSTRACT

This study examines the regenerative braking process under urban traffic conditions observed in Gdańsk and Bremen. Data on the potential energy recovery along specific routes should be considered when planning the paths of hybrid and electric vehicles. Integrating this functionality into mobile car navigation systems is recommended, as continuous updates are essential for high system efficiency. This paper introduces a novel method for evaluation of the regenerative braking efficiency in urban traffic conditions. Average values of efficiency of regenerative braking were determined for three electric vehicles. The results obtained are similar for all vehicles. The highest efficiency of regenerative braking is 69.6% and this applies to the lightest vehicle. For other two vehicles of larger masses, the results are clearly lower. In addition, the method was verified, which showed acceptable accuracy for urban traffic conditions, especially for the lighter vehicle (average error is 5.6%), while for rural traffic conditions the relative error increases to 9.8%.

Keywords: electric vehicle, urban conditions, regenerative braking, energetic efficiency.

INTRODUCTION

Vehicles with ability for reuse the energy from braking process have revolutionized the automotive industry. In traditional vehicles, braking dissipates kinetic energy as heat, leading to energy loss. In contrast, regenerative braking systems equipped electric and hybrid vehicles utilize the drive motor as a generator during braking events, capturing energy that would otherwise be wasted [1]. This process not only enhances energy efficiency but also extends the vehicle's driving range. The implementation of regenerative braking offers additional advantage. Since regenerative braking reduces reliance on mechanical braking systems, there is less wear and tear on brake components, leading to lower maintenance costs and extended component lifespan. Despite its benefits, energy regeneration faces certain challenges. The efficiency of energy recovery is constrained by the battery's state of charge (SOC) and its capacity to accept rapid charging during regenerative events. High SOC levels can limit the amount of regenerative energy the battery can accept, reducing the effectiveness of regenerative braking systems. The amount of energy that can be regenerated is highly dependent on driving patterns. Urban driving with more brakes allows for more regeneration opportunities compared to highway driving with fewer braking events. Integrating regenerative braking with traditional friction braking systems requires sophisticated control strategies to ensure seamless operation and maintain vehicle safety and comfort. In contemporary electric vehicles, battery longevity is a key area of focus. This criterion is strongly dependent on an accurate assessment of the state of charge and health. The battery charge status is most often monitored by the vehicle control system based on the instantaneous battery voltage [2, 3]. Using this parameter, it is also possible to model the battery operation for the purposes of developing an efficient drive system operation strategy [2].

When planning routes for such vehicles, the potential for regenerative braking should be taken into account, as this feature is not currently integrated into modern car navigation systems. A model of the regenerative braking process can be useful for this application. It can provide insights into how traffic conditions influence the amount of energy lost as heat, while also aiding in optimizing routes for vehicles equipped with regenerative braking systems. Various studies have been carried out to address this issue [4, 5], with existing methods for predicting electricity consumption differing significantly [6]. In the work [7] the authors optimized regenerative braking energy recovery system of pure electric vehicle based on driving style. The tests carried out for two types of drivers showed that for the lowest cruising speeds (semi constant), in the range of 10–15 km/h, the consumption of electric energy was the lowest. It should be emphasized that the cruising speed, used to determine the traffic conditions, cannot be identified with the average speed for the complex driving cycle, because in this case a low value of the average speed may be the result of long and frequent stops. At higher cruising speeds the energy consumption gradually increased. In the work [8] very similar results were obtained, and the authors conducted simulation studies for traffic conditions corresponding to driving at constant speed. In the case of cars with conventional drives, fuel consumption, which is an equivalent of energy consumption, reaches a minimum at much higher speeds, in the range of 40–55 km/h [9, 10].

The efficiency of regenerative braking is most often used to determine how much energy can be reused to drive a vehicle, i.e. for traction purposes, from the mechanical energy that has been transferred to the vehicle's drive system from the wheels. In a traditional drive system, this energy is irreversibly lost through conversion to heat in the braking system [11]. Depending on the local traffic conditions, driver behaviour and the energy management system used in the vehicle, the achieved efficiencies may differ significantly [12, 13]. Different control strategies will be used in hybrid and electric vehicles. In hybrid vehicles, the state of fully charged batteries is most often avoided. Thanks to this, it is almost always possible to redirect the surplus energy to the batteries. In electric vehicles, just after charging is completed, receiving a large amount of regenerative energy is not always possible. This situation most often occurs when the vehicle's route begins with a long downhill drive. Example values for electric vehicles indicate that the achieved efficiencies of this process are at the level of 31–42% [14]. Such results were recorded for the China Typical City Regenerative Driving Cycle. Other authors, taking into account the isolated braking process, showed that it is possible to achieve a regenerative braking efficiency of 86% [15]. Assuming that the energy from the braking process must be processed twice by the drive system and batteries, the above result seems to be too optimistic. Above test assumed braking from a speed of 80 km/h, which is already associated with relatively large losses in air and rolling resistance. Only after covering them is it possible to transfer energy from braking to the drive system. Other studies, conducted on a large number of tests in city traffic, indicate an efficiency of the regenerative braking process at the level of 50% [16]. The efficiency of the electric generator is also of great importance and depending on the technical solution used [3]. The maximum of efficiency is typically located around the maximum power, which is not a good solution for city cars. A better solution is to obtain maximum efficiency near minimum torque, which is economically advantageous [17]. In addition, the efficiency characteristics of older type electric generators, especially Brushed DC, are characterized by very rapidly decreasing efficiency with reduced load.

This study examines the regenerative braking process under urban traffic conditions observed in Gdańsk and Bremen using initially defined parameters, which identify the vehicle traffic conditions. The next section of the paper presents an original method for evaluation for the efficiency of the drive system in the drive mode as well as in the regeneration mode. The last section presents the results of verification of the determined efficiencies based on data obtained from real trips of electric vehicles in the area of Gdańsk and Bremen.

TRAFFIC CONDITIONS

The main parameters characterizing the traffic conditions are defined below. The amount of energy expended to drive the vehicle will depend on the maximum speeds achieved, the number of acceleration cycles, their intensity, but also the vehicle mass and the distance travelled. In order to use the data in the analysis of the operation of drive systems of various vehicles, with different masses and covering different distances, it was decided to use specific energy consumption (SEC), in which the amount of energy expended is related to the vehicle mass and the distance travelled [9]:

$$SEC = \frac{E}{m \cdot L} \tag{1}$$

where: E – mechanical energy delivered to the wheels, L – distance covered, m –vehicle mass.

Mechanical energy delivered to the wheels can be calculated based on the following relationship:

$$E = \int_{t=0}^{t=t_c} \left(k_p \cdot M \cdot \omega \cdot \eta_t\right) dt \tag{2}$$

where: M – engine torque, t_c – time of the cycle, ω – engine angular velocity, η_t – transmission system efficiency, k_p – positive tractive force factor:

$$k_p = \begin{cases} 1 \; for\; powered\; wheels \\ 0 \; for\; idlling\; or\; braking \end{cases} \tag{3}$$

Alternatively the mechanical energy delivered to the wheels can be calculated as follows:

$$E = \int_{t=0}^{t=t_c} \left(k_p \cdot F_t \cdot V\right) dt \tag{4}$$

where: F_t – tractive force, V – vehicle velocity.

There are four types of driving resistances, which must be covered by the tractive force: aerodynamic drag, rolling resistance, gradient resistance, and acceleration resistance.

With a constant time step for measuring vehicle motion parameters, the following relationship can be used:

$$E = \Delta t \cdot \sum_{i=1}^{N} \left(k_{p_i} \cdot F_{t_i} \cdot V_i\right) \tag{5}$$

where: Δt – constant time step.

For the regeneration process, the regenerative braking energy can be calculated:

$$E_{reg} = \Delta t \cdot \sum_{i=1}^{N} \left(k_{reg_i} \cdot F_{t_i} \cdot V_i\right) \tag{6}$$

where: k_{reg} – negative tractive force factor:

$$k_{reg} = \begin{cases} -1 \; for\; idlling\; or\; braking \\ \;\;0 \; for\; powered\; wheels \end{cases} \tag{7}$$

Using negative tractive force factor when calculating regenerative braking energy, which is available for recovery system may cause some ambiguity in the research results, because the amount of available energy from the regeneration process depends not only on the speed profile and changes in height but also on the degree of aerodynamic perfection and quality of the driving wheels capable of generating lower or higher rolling resistance. In other words, a vehicle with low rolling and air resistance will have more energy available for the regeneration process than a vehicle of the same mass that generates higher rolling and air resistance.

Regenerative braking specific energy (RBSE) has been defined as follows:

$$RBSE = \frac{E_{reg}}{m \cdot L} \tag{8}$$

Absolute electric energy delivered by the battery can be calculated as follows:

$$E_{battery} = m \cdot L \cdot \left(SEC \cdot \frac{1}{\eta_{el}} - RBSE \cdot \eta_{reg}\right) + P_{aux} \cdot t_c \tag{9}$$

where: η_{el} – efficiency of electric drive system (including: battery, inverter, motor and transmission), η_{reg} – efficiency of regenerative braking system (including: transmission, generator, inverter, battery), x – auxiliary devices power consumption.

In an electric vehicle, energy consumption is measured by considering both the electric energy drawn from the battery and the energy supplied by the generator. This measurement also includes the energy used by all auxiliary systems in the vehicle. Therefore, the energy consumption data provided by the vehicle's original on-board system can be used for accurate analysis, as long as the power consumption of auxiliary devices is accounted for. As a result, there is no need to separately track the electricity usage of each individual component. Electric energy consumption can be calculated as follows:

$$EEC = m \cdot \left(SEC \cdot \frac{1}{\eta_{el}} - RBSE \cdot \eta_{reg}\right) + \\ + \frac{P_{aux} \cdot t_c}{L} \quad (10)$$

THE REGENERATIVE BRAKING SPECIFIC ENERGY PREDICTION CAPABILITIES

Identification studies were conducted in two cities: Gdańsk and Bremen. Both cities have over 0.5 million inhabitants. Both, electric and conventional vehicles were used in the studies. Vehicle operating conditions were recorded using the GPS system. The obtained results show the amount of mechanical energy (not electrical) necessary to cover the resistance to vehicle motion or potentially delivered to the wheels as a result of regenerative braking. Calculations based on Equations 1–8. The results include tests of cars with conventional, hybrid and electric drives. Results of SEC as well as regenerative braking specific energy (RBSE) are given in kWh/(t·100 km) units. The use of relative units made it possible to compare the test results of different cars, with different masses and for different route lengths. The use of the one-tonne unit is intended to facilitate the calculation of energy consumption by vehicles of a specific mass. The results can also be interpreted as being appropriate for a one-tonne car. The routes were located mainly in the city centre, a small number of routes, with the highest travel speeds, were located on peripheral roads.

In Figure 1 it can be observed that there is no clear relation between average speed and specific energy consumption. At higher average driving speeds, e.g. rural driving, there are fewer acceleration and braking processes, which influences positively on the final energy consumption. At the same time, it can be observed that drivers using electric drives try to drive more economically and they limit the intensity of acceleration and braking, which statistically affects the reduction of specific energy consumption.

The increase in average driving speed is usually associated with free flow traffic (no congestions), which means fewer accelerations and braking (Figure 2). This in turn translates into less energy recovered from the braking process.

Figures 3–6 show the dependence of regenerative braking specific energy share, defined as RBSE divided by SEC, on various parameters. Due to the same unit used for RBSE and SEC, the result has a dimensionless unit.

It has been noticed that a lower average speed is associated with a share of regenerative braking energy, reaching up to 71% (Figure 3). It should be emphasized that the recorded values, despite the units used kWh/(t·100 km), do not constitute electrical energy, but only mechanical energy calculated “from wheels point of view”. This is typical of city center traffic conditions, where frequent stops and braking phases occur. Additionally, a significant variation in values (ranging from 16% to 71%) can be seen for the same average speed. In urban environments, the same average speed can result from either a combination of high maximum speeds with long idling periods or from a consistently low cruising speed. At higher average speeds, the share of regenerative braking

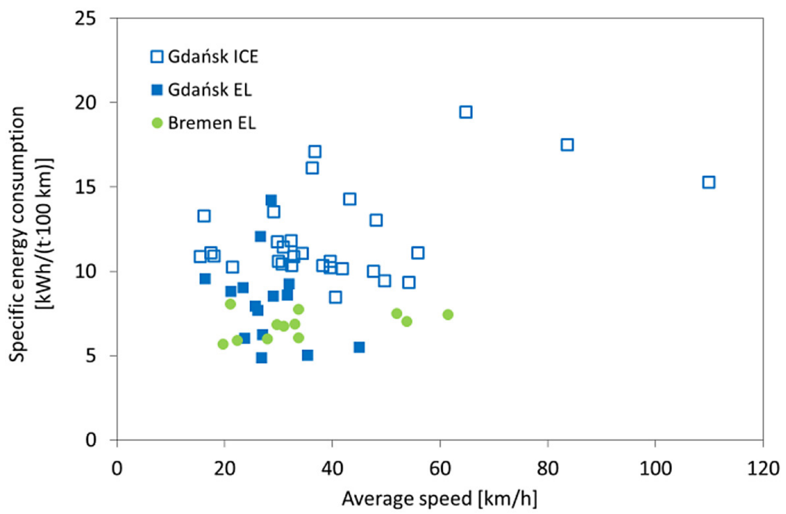


Figure 1. Specific energy consumption vs. average speed

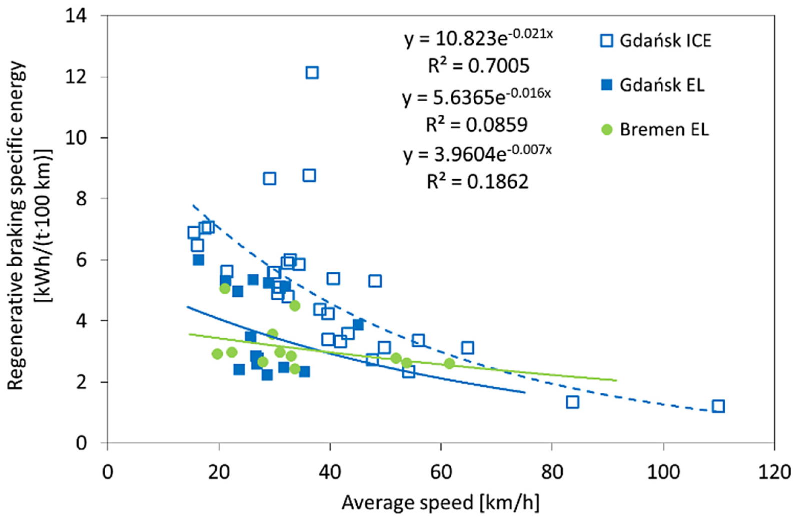


Figure 2. Regenerative braking specific energy vs. average speed

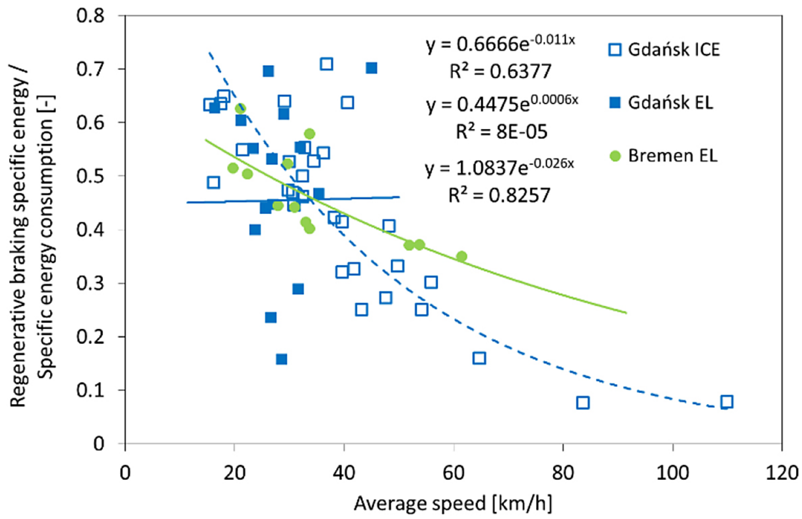


Figure 3. Regenerative braking specific energy share vs. average speed

energy stabilizes at around 8%, likely due to the absence of traffic congestion on suburban roads and a reduced number of braking phases.

The braking distance share can be potentially useful for further analysis:

$$\frac{L_b}{L} = \frac{1}{L} \cdot \sum_{i=1}^{N} \left(-k_{reg_i} \cdot L_i\right) \tag{11}$$

Alternatively it can be defined as follows:

$$\frac{L_b}{L} = 1 - \frac{L_p}{L} = = 1 - \frac{1}{L} \cdot \sum_{i=1}^{N} \left(k_{p_i} \cdot L_i\right) \tag{12}$$

A good correlation has been observed between in the Figure 4. The slope coefficients of the approximating functions are nearly identical for electric vehicles in both cities analysed.

The idling time share can be defined as follows:

$$\frac{t_i}{T} = \frac{1}{T} \cdot \sum_{j=1}^{N} \left(t_{i_j}\right) \tag{13}$$

In Figure 5, we can observe the lack of correlation between idling time share and regenerative braking specific energy share. In particular, a very large scatter of measurement points can be observed at very small idling time share. Lack of correlation between specific energy

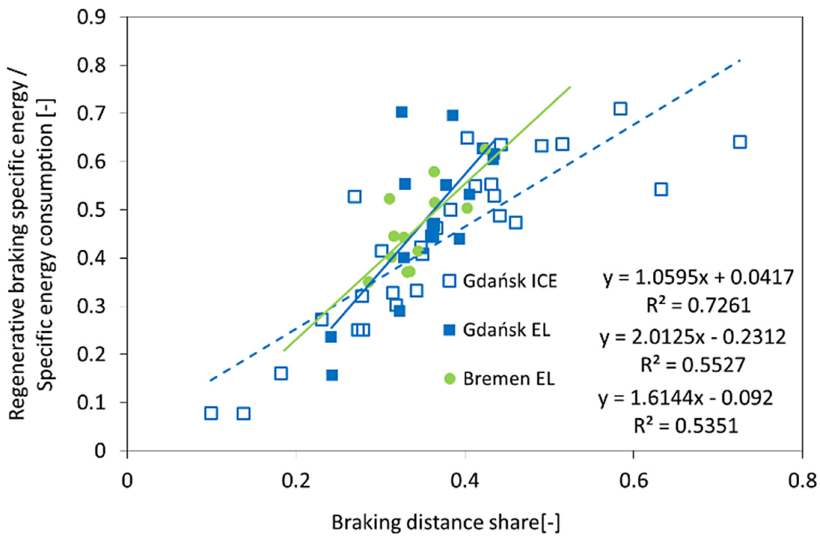


Figure 4. Regenerative braking specific energy share vs. braking distance share

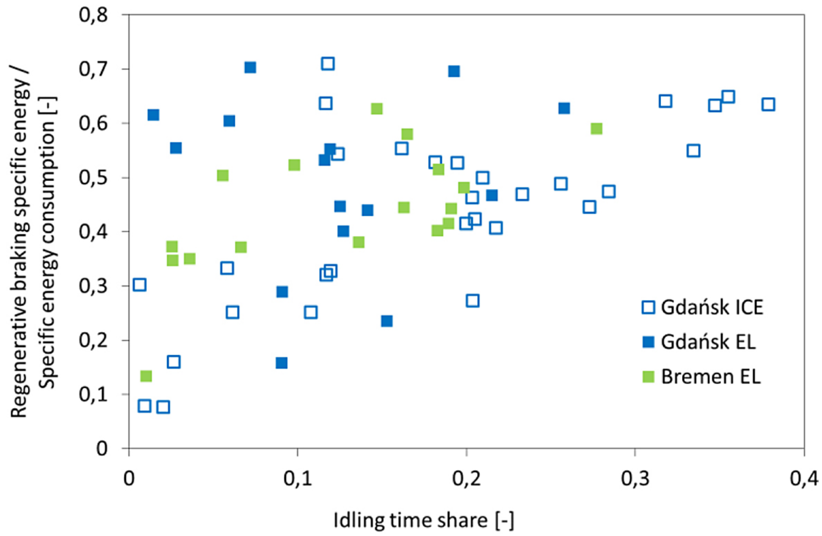


Figure 5. Regenerative braking specific energy share vs. idling time share

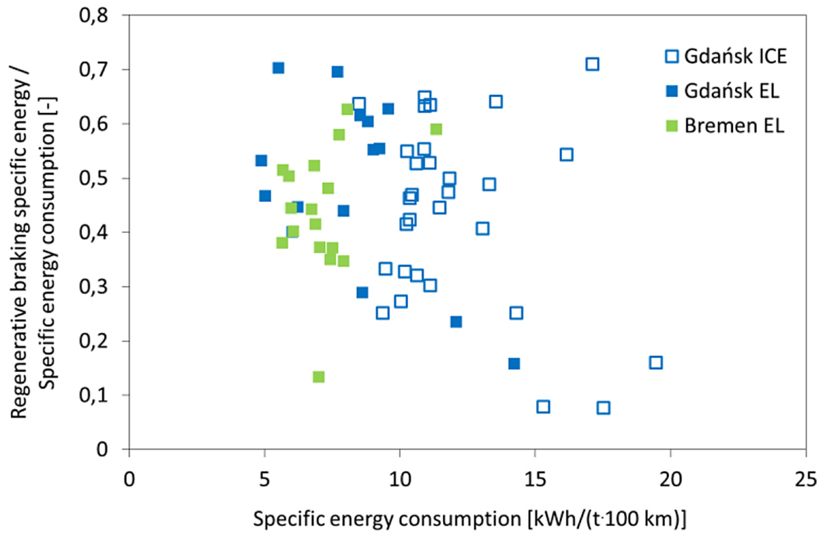


Figure 6. Regenerative braking specific energy share vs. specific energy consumption

consumption and regenerative braking specific energy share can be noticed (Figure 6).

In summary, it can be stated that there are no parameters describing the vehicle traffic conditions that would allow for unambiguous and accurate prediction of specific energy consumption or regenerative braking specific energy. For this reason, in the further part of the work, direct methods of measuring specific energy consumption and regenerative braking specific energy were used, which, in combination with measurements of vehicle traffic conditions: position, speed, acceleration, height, allowed for experimental evaluation of regenerative braking efficiency and then quantitative verification of this method.

EVALUATION OF THE EFFICIENCY OF REGENERATIVE BRAKING SYSTEM

Evaluation of the efficiency of a regenerative braking system requires determining the amount of energy that is supplied by the vehicle's drive wheels during the braking process to the drive transmission system. For this purpose Equation 6 was used. This energy is then transformed twice in the drive system: drive wheels - power generator – controller – battery. Once for the energy storage and then for driving the vehicle purpose. The energy from the braking process can therefore be reused for the drive, which can be defined as energy reused for tractive purpose:

$$E_{reused} = E_{reg} \cdot \eta_{gen} \cdot \eta_{el} \quad (14)$$

where: η_{gen} – efficiency of electric power generation system (including: transmission, generator, inverter and battery).

Efficiency of regenerative braking can be consequently defined:

$$\eta_{reg} = \frac{E_{reused}}{E_{reg}} \quad (15)$$

or

$$\eta_{reg} = \eta_{gen} \cdot \eta_{el} \quad (16)$$

In order to simplify the method of determining the efficiency of regenerative braking, based on operational data, it can be assumed that:

$$\eta_{gen} = \eta_{el} \quad (17)$$

Then we get:

$$\eta_{reg} = {\eta_{el}}^2 \quad (18)$$

Equation 10 defining electric energy consumption will then have only one unknown and can be used for evaluation of the efficiency of regenerative braking based on measurement data from driving cycles:

$$EEC = m \cdot \left(SEC \cdot \frac{1}{\sqrt{\eta_{reg}}} - RBSE \cdot \eta_{reg} \right) + + \frac{P_{aux} \cdot t_c}{L} \quad (19)$$

During the tests, the energy consumption for self consumption was minimized by turning off the radio, air conditioning and setting the ventilation system to minimum capacity. In such a situation, based on the research results presented in the work [18], it can be assumed that power consumed by auxiliary systems is constant. In the calculations, it was assumed that the power of auxiliary systems is 200 W. The analysis was carried out for three selected electric vehicles (Table 1).

The vehicles were equipped with a GPS positioning system, tests have been carried out using a correction of the height signal based on phenomenological correction [19] due to low original accuracy of the system. Typical urban traffic conditions as well as bypass roads in proximity of city centre have been selected in Gdańsk and Bremen. The method of recording data for further evaluation of the efficiency of regenerative braking is presented in Figures 7–9. The presented results are only examples of data recording, evaluation and they concern one type of vehicle only. The route has been divided into 100-m-long sections (Figure 7). The example route shows runs through the very centre of Bremen. Recorded average speeds

Table 1. Drive system parameters of the tested vehicles

No.	Vehicle	Mass [kg]	Power [kW]	Battery capacity [kWh]	City of operation
1	eGolf	1790	100	35.8	Bremen
2	EQE 500	2475	375	90.6	Gdańsk
3	EQB 300	2175	167	66.5	Gdańsk

Figure 7. The average speed (V) [km/h] distribution over the specified route for 100-m-long sections

Figure 8. SEC [kWh/(t·100 km)] distribution over the specified route for 100-m-long sections

for 100-m-long sections range from 8 to 41 km/h, which is typical for urban driving conditions. Figures 8 and 9 show the distribution of SEC [kWh/(t·100 km)] and RBSE [kWh/(t·100 km)] on a specific route, respectively. High SEC values occur just behind intersections, when the vehicle is accelerating, while low values occur when the vehicle is traveling at a constant speed. In braking mode, SEC is zero. Analogically, RBSE reaches its highest values in braking mode and zero values, when the vehicle is accelerating.

The first vehicle was tested on three different routes, the speed profile, height change, as well as SEC and RBSE were presented in Figure 10. The route 1.1 is characterized by a relatively small change in speed and no stops, except for the final section of the route. The route also runs in flat terrain. This translates into small SEC and RBSE values. In the route 1.2, the changes in height are also small, while during the trip there are several stops at intersections. This results in the higher SEC values corresponding to the acceleration of the vehicle and higher RBSE values corresponding to the braking before intersections. The route 1.3 is similar to 1.2, but in the second part of this route the road slopes down, which is accompanied by a rapid drop in height and causes a decrease in SEC in the acceleration phases.

Figure 9. RBSE [kWh/(t·100 km)] distribution over the specified route for 100-m-long sections

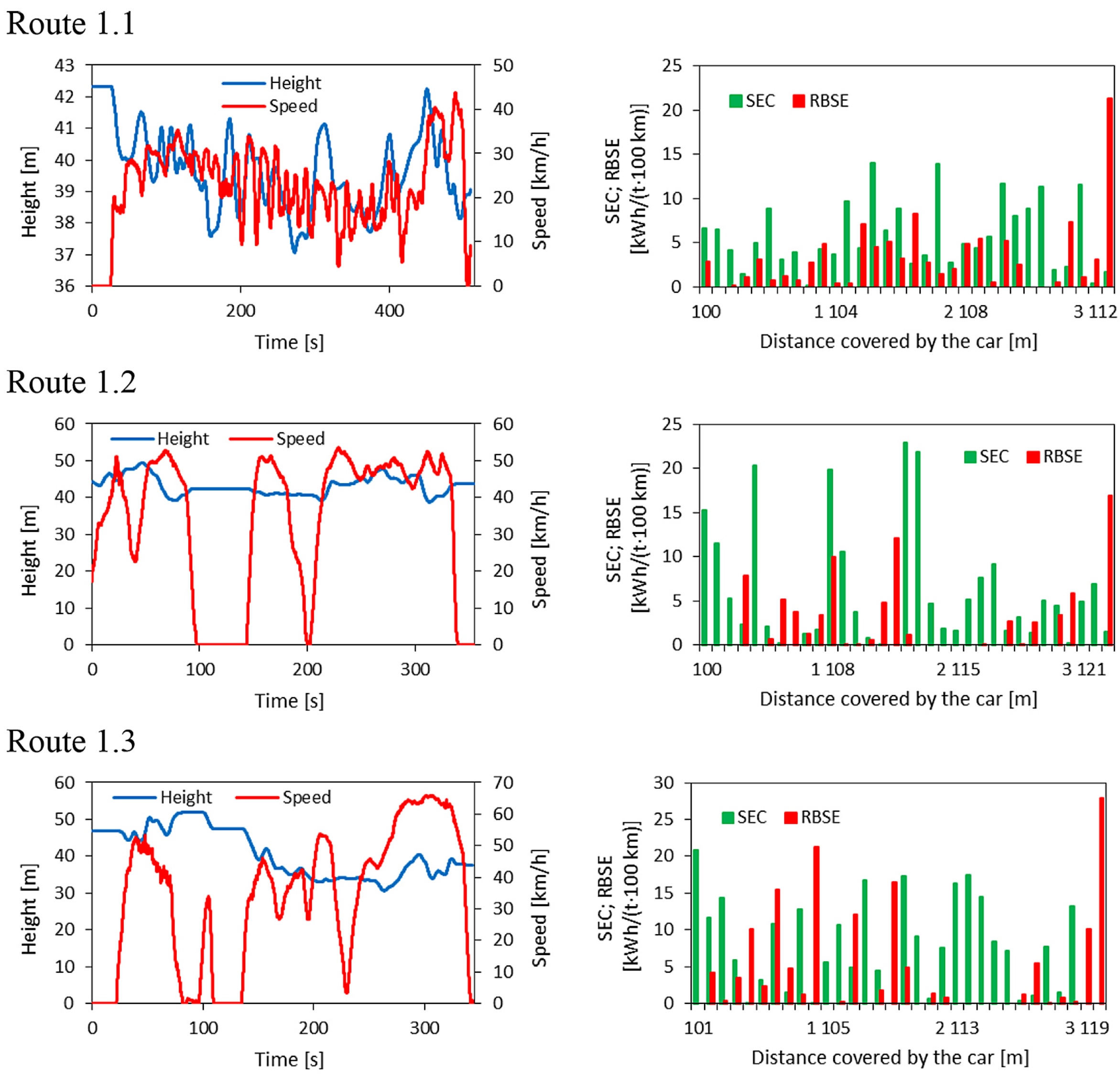


Figure 10. Routes used for evaluation of the efficiency of regenerative braking of vehicle No. 1

In route 2.1, for vehicle No. 2, large changes in height can be found in the initial phase of the route, which in combination with acceleration gives high SEC values. Further acceleration processes occur with low intensity or take place during the downhill drive, which results in low SEC values. In route 2.2, large changes in speed and height can be seen, which results in high average SEC values, as well as RBSE. The last route 2.3 is characterized by a small number of accelerations, while in the middle part of the route it is combined with uphill drive, giving a very high SEC value (Figure 11).

Route 3.1, for vehicle No. 3, has intensive braking sections combined with a downhill drive, which translate into high RBSE values. Route 3.2, on the other hand, has numerous changes in height, which causes, depending on the direction of the road, an increase in RBSE, in the first phase of the route, and an increase in SEC in the final phase of the route. In route 3.3, similarly to the previous one, one can observe large changes in height, which alternately cause a decrease in SEC, when going downhill, and a decrease in RBSE when going uphill (Figure 12).

Based on the Equation 19, the efficiency of regenerative braking of three vehicles was evaluated. The measurement of electric energy consumption was conducted using the vehicle's original on-board system. This measurement accounts for the energy used by the drive system, all auxiliary systems, and the energy recovered through regeneration by the electric generator. Due to the model used to assess the efficiency of the regeneration process, it was necessary to define the power consumption of auxiliary devices. Based on findings from studies [18], this auxiliary power consumption was assumed to be constant at 200 W. Table 2 presents the results of

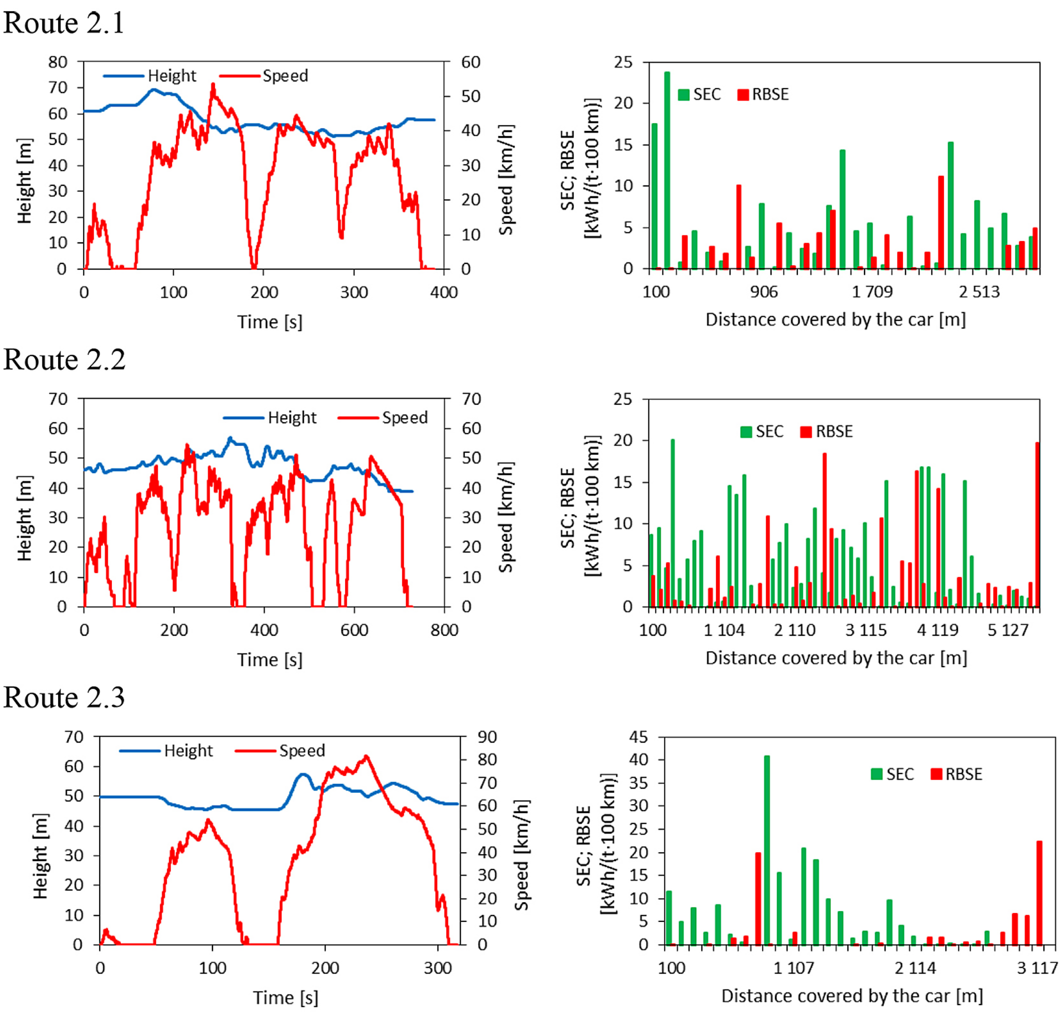
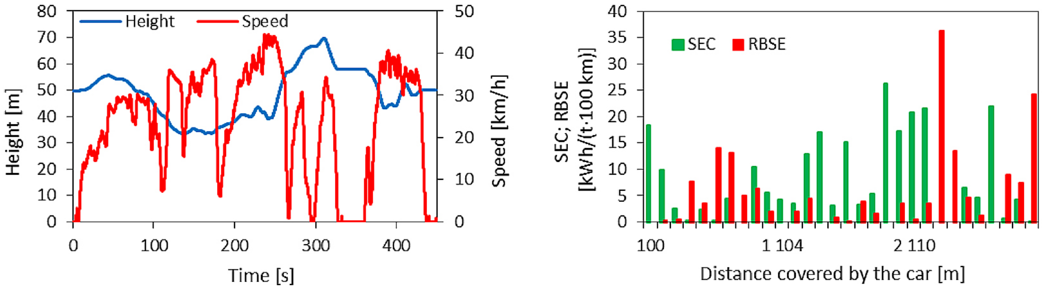
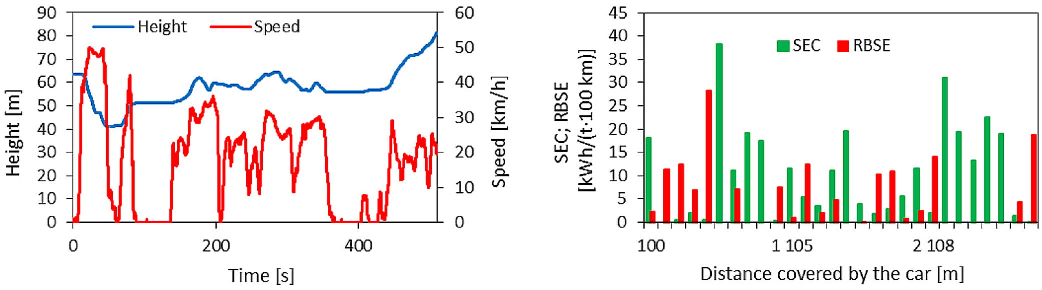


Figure 11. Routes used for evaluation of the efficiency of regenerative braking of vehicle No. 2

Route 3.1



Route 3.2



Route 3.3

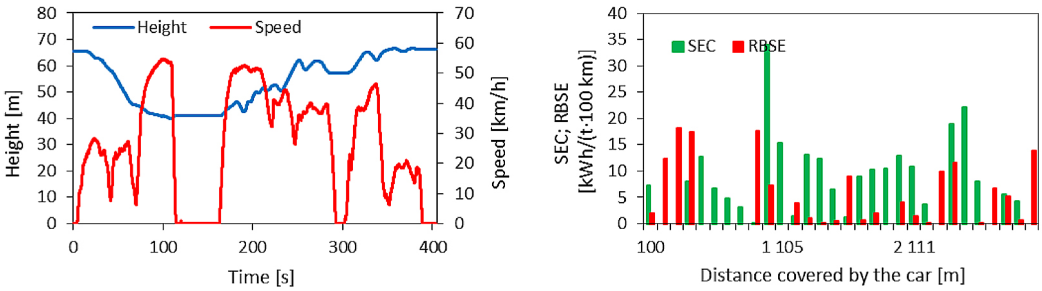


Figure 12. Routes used for evaluation of the efficiency of regenerative braking of vehicle No. 3

Table 2. Results of the evaluation of the efficiency of regenerative braking

Vehicle No.	Model	Route No.	Mean speed [km/h]	EEC [kWh/100 km] (Equation 19)	η_{el} [%]	η_{reg} [%]	Mean η_{el} [%]	Mean η_{reg} [%]
1	eGolf	1.1	22	10.5	80.6	65.0		
1	eGolf	1.2	34	10.4	84.0	70.6	83.4	69.6
1	eGolf	1.3	34	10.9	85.6	73.3		
2	EQE 500	2.1	27	13.0	77.4	59.9		
2	EQE 500	2.2	27	16.8	78.2	61.2	76.9	59.2
2	EQE 500	2.3	35	14.3	75.2	56.6		
3	EQB 300	3.1	23	22.3	74.2	55.1		
3	EQB 300	3.2	16	24.2	72.2	52.1	74.9	61.2
3	EQB 300	3.3	26	15.7	78.2	61.2		

the evaluation of the efficiency of regenerative braking of the three tested vehicles.

The results obtained in Table 2, due to the approximate conditions of urban operation, are similar for all vehicles. The highest efficiency of regenerative braking is noted for vehicle No. 1, which is on average 69.6%, for the three tested routes. On the other hand, the lowest result was achieved by vehicle No. 2, which is also the vehicle with the highest mass. It can therefore be assumed that the greater mass of the vehicle allows for the recovery of a greater amount of kinetic energy, but on the other hand, a greater part of it is used to cover rolling resistance and does not flowing into the energy recovery system. For urban traffic conditions (lower maximum speeds), this proportion of energy accumulated in the vehicle mass (related to the square of the speed) and necessary to cover rolling resistance (linear dependence on speed) may be to the advantage of cars with a smaller mass. Another problem is the possibility of accepting the full power from the regenerative braking process by the electric generator, controller and battery. When it happens, part of the regenerative energy is absorbed by the traditional braking system, thus reducing the efficiency of regenerative braking.

VERIFICATION OF THE METHOD FOR EVALUATION THE EFFICIENCY OF REGENERATIVE BRAKING

In order to verify the method, tests of the vehicles were carried out in urban conditions using routes other than those used during the evaluation of the efficiency of regenerative braking. It was assumed that the calculated efficiencies of regenerative braking are constant for urban traffic conditions, regardless of differences in the routes and local traffic conditions. Using the relationship (19), for the recorded traffic conditions, the electric energy consumption (EEC) was calculated, which was named as the result of the model operation. Then, this value was compared with the directly measured electric energy consumption in the vehicle drive system during the test, this value was named as the experimental value. Figures 13–15 show the verification results for the tested vehicles.

In order to learn about the universality of the method and the possibility of applying the evaluated efficiency of regenerative braking values for rural conditions, additional tests of vehicle No. 1 were carried out. Results are presented in Figure 16. The results of the verification tests are presented in Table 3.

Based on the obtained results, it can be stated that the average EEC relative error using a constant efficiency of regenerative braking, evaluated for urban conditions ranges from 5.6 to 8.4%, with the smallest relative error occurring for the lightest vehicle No. 1. For vehicles No. 2 and No. 3, this error is significantly greater. It can also be observed that for lighter traffic conditions (smaller EEC), the EEC value is underestimated and, analogically, for more difficult traffic conditions, it is overestimated. For rural traffic conditions, for vehicle No. 1, the EEC relative error increases practically twice, when using the efficiency of regenerative braking evaluated for urban conditions.

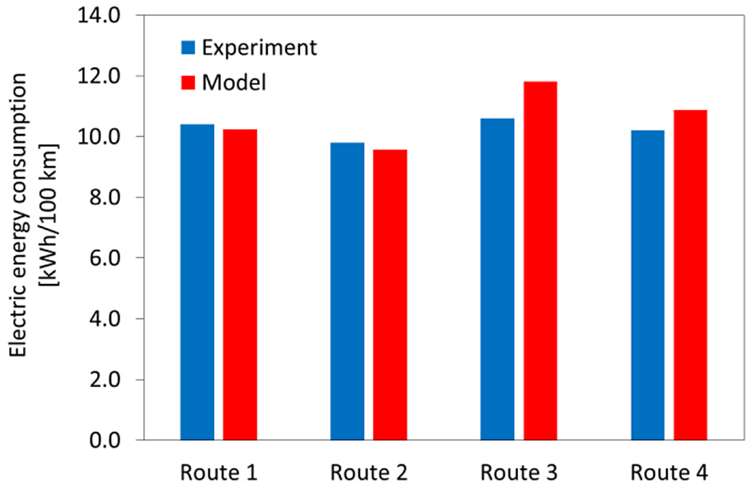


Figure 13. Experimental vs. modelled electric energy consumption for vehicle No. 1 (city traffic)

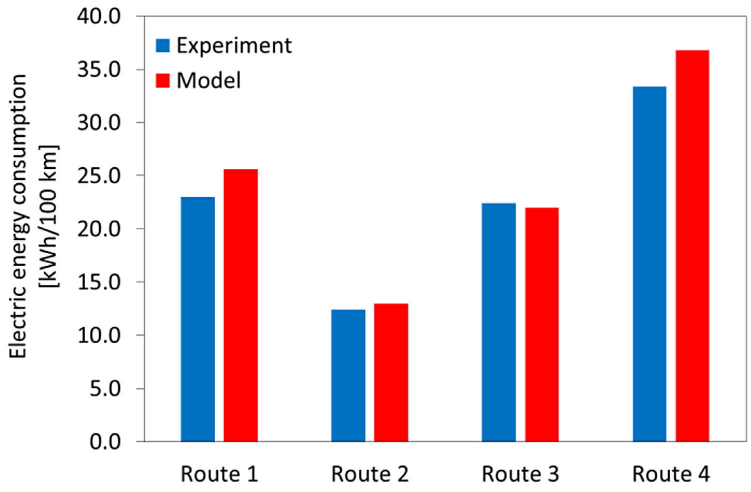


Figure 14. Experimental vs. modelled electric energy consumption for vehicle No. 2 (city traffic)

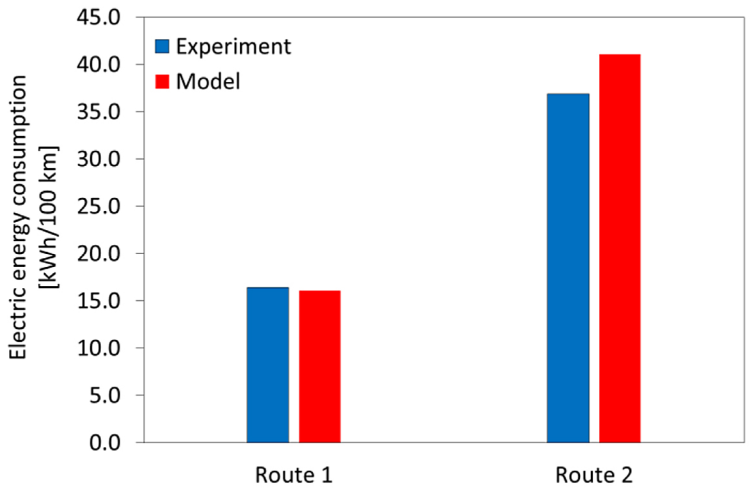


Figure 15. Experimental vs. modelled electric energy consumption for vehicle No. 3 (city traffic)

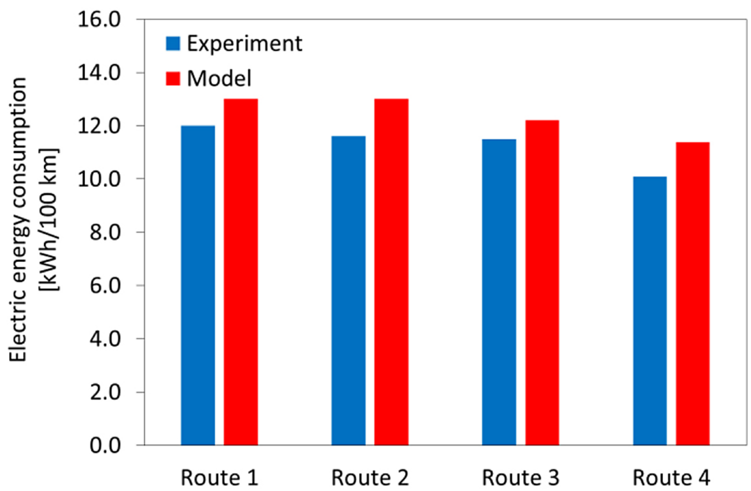


Figure 16. Experimental vs. modelled electric energy consumption for vehicle No. 1 (rural traffic)

Table 3. Verification of the method for evaluation the efficiency of regenerative braking

Vehicle	Route No.	Route location	Mean speed [km/h]	EEC experiment [kWh/100 km]	EEC model [kWh/100 km] (Equation 19)	Relative error [%]	Mean rel. error [%]
eGolf	1	City center	28	10.4	10.2	-1.6	5.6
eGolf	2	City center	20	9.8	9.6	-2.4	
eGolf	3	City center	33	10.6	11.8	11.5	
eGolf	4	City center	30	10.2	10.9	6.7	
eGolf	1	Rural	61	12.0	13.0	8.4	9.8
eGolf	2	Rural	52	11.6	13.0	12.2	
eGolf	3	Rural	54	11.5	12.2	6.2	
eGolf	4	Rural	31	10.1	11.4	12.7	
EQE 500	1	City center	32	23.0	25.6	11.5	7.8
EQE 500	2	City center	45	12.4	13.0	4.3	
EQE 500	3	City center	26	22.4	22.0	-2.0	
EQE 500	4	City center	27	33.4	36.8	10.3	
EQB 300	1	City center	24	16.4	16.1	-2.2	8.4
EQB 300	2	City center	29	36.9	41.0	11.2	

CONCLUSIONS

This study examines the regenerative braking process under urban traffic conditions observed in Gdańsk and Bremen. Data on the potential energy recovery along specific routes should be considered when planning the paths of hybrid and electric vehicles. The most successful results were obtained for the tested relationship between the braking distance ratio and the share of regenerative braking specific energy. The slope coefficients of the approximating functions are practically the same for electric cars for both considered cities: Gdańsk and Bremen. Anyway, for further calculative purposes, it can be stated that there are no parameters describing the vehicle traffic conditions that would allow for unambiguous and accurate prediction of specific energy consumption or regenerative braking specific energy. For this reason, in the further part of the work, direct methods of measuring specific energy consumption and regenerative braking specific energy were used.

An original method of evaluation of efficiency of regenerative braking for traffic condition has been presented and tested in this work. Based on the Equation 19, the efficiency of regenerative braking of three vehicles was evaluated. The electric energy consumption was carried out with the use of the on-board system. In accordance with the previously made assumption, it was assumed that the vehicle's own electricity consumption is constant and amounts to 200 W. The highest efficiency of regenerative braking is noted for vehicle No. 1, which is on average 69.6%, for the three tested routes. On the other hand, the lowest result was achieved by vehicle No. 2, which is also the vehicle with the highest mass. It can therefore be assumed that the greater mass of the vehicle allows for the recovery of a greater amount of kinetic energy, but on the other hand, a greater part of it is used to cover rolling resistance and does not flowing into the energy recovery system. For urban traffic conditions (lower maximum speeds), this proportion of energy accumulated in the vehicle mass (related to the square of the speed) and necessary to cover rolling resistance (linear dependence on speed) may be to the advantage of cars with a smaller mass.

In order to verify the method, tests of the vehicles were carried out in urban conditions using routes other than those used during the evaluation of the efficiency of regenerative braking. It was assumed that the calculated efficiencies of regenerative braking are constant for urban traffic conditions, regardless of differences in the routes and local traffic conditions. Based on the obtained results, it can be stated that the average EEC relative error using a constant efficiency of regenerative braking, evaluated for urban conditions ranges from 5.6 to 8.4%, with the smallest relative error occurring for the lightest vehicle No. 1. For rural traffic conditions, for vehicle No. 1, the EEC relative error increases practically twice, when using the efficiency of regenerative braking evaluated for urban traffic conditions.

To sum up, it can be stated that the efficiency of regenerative braking evaluated for urban traffic conditions, used as a constant value, has limited application. Traffic conditions that differ from evaluation process, make it difficult to accurately calculate the EEC. In particular, the EEC relative error increases significantly under rural traffic conditions, which indicates the need to evaluate the efficiency of regenerative braking separately for those traffic conditions.

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