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# Evaluation of the energy efficiency of electric vehicle drivetrains under urban operating conditions

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*In electric vehicles, as in hybrids vehicles, a very important factor affecting the energy efficiency of the powertrain is the ability to use the regenerative braking energy. Depending on the settings available in electric vehicles, the driver can choose different modes of operation: switch off the regenerative braking mode altogether, select the intensity of regenerative braking, or leave the control system in automatic mode. The last mode is often the only one available on eclectic vehicles, so the driver cannot decide whether to switch off or increase intensity of the regenerative braking. This paper presents a new method for evaluating the energy efficiency of electric vehicle powertrains under urban operating conditions. The presented method uses a procedure for mapping the operating conditions allowing to determine the reference level of energy consumption in relation to those recorded during the identification tests. Identification tests were carried out in the Tri-City area using electric vehicles of different purposes and operating parameters. Performed tests allowed to evaluate the regenerative braking efficiency of tested vehicle, which varies over a relatively wide range, for vehicle A from 33 to 77%, for vehicle B from 27 to 55% and for vehicle C from 36 to 58%. It can be concluded that one of the main factors determining the regenerative braking efficiency is the level of state of charge of the accumulator and the management algorithm used by the vehicle for controlling this parameter.*

Key words: *electric vehicle, urban conditions, regenerative braking, energetic efficiency, drivetrains*



## 1. Introduction

Electric drive systems have the potential to be much more efficient than conventional ones [6, 19], influenced by the very high efficiency of the electric motor itself, but also by its low variability over the range of typical operating conditions [6, 18]. Taking into account typical urban operating conditions, the efficiency of an eclectic motor can be expected to reach values ranging from 70% for very low loads up to 90% for maximum loads [14].

A very important factor in reducing the energy consumption of electric vehicles in urban conditions is the possibility of using regenerative braking to recharge the battery while driving [16, 21]. The efficiency of the process itself of generating electricity by the generator reaches a very similar level to that obtained in driving mode, but the process of reusing the electricity to drive the vehicle includes converting the energy twice, on the way from the wheels to the battery and back to the drive wheels. This means that the efficiency of the regenerative braking process can reach at most the square of the efficiency of the electric drive system. Control strategies for hybrid and electric vehicles are relatively complex [14, 16, 19] and depend on the state of charge of the batteries [9, 10, 20]. Typically, the efficiency of a regenerative braking process [1, 3, 4] is defined as a regenerative braking energy delivered to the battery and back to a drive system divided by the energy achievable from the braking process [5, 7]. Performed research show varying results, depending on the type of test, the vehicle and the strategy used by the manufacturer: 86% [14], 50% [15] and 31–42% [21].

Evaluation of the efficiency of an electric vehicle's drive system can be carried out under laboratory conditions for strictly defined operating conditions with the assumed repeatability of the tests. However, from a practical point of view, for the users of such vehicles, the results of tests and perform evaluations, which are created on the basis of real operating conditions [2, 8, 17], will be of greater value. It is necessary to use a testing method, which, on the one hand, allows for a simple and quick determination of the expected energy indicators, while on the other hand, the results obtained should be comparable regardless of the types of vehicles tested and the place of operation.

This paper presents a description of an original method of evaluation of the energy efficiency of electric vehicle drivetrains under urban operating conditions. The study uses measurements carried out in regular urban traffic. The presented method uses a procedure for mapping the operating conditions allowing to determine the reference level of energy consumption and compare it to the recorded during the identification tests.

In the first stage of energy efficiency evaluation, the drive system efficiency in a driving mode is determined, and in the second stage in a regenerative braking mode. The method is demonstrated using operating examples of three electric vehicles.

The work supports the evaluation of guidelines for controlling traffic in city centers using mobile applications and on-board navigation systems to reduce the energy consumption of vehicles equipped with regenerative braking systems.

## 2. Drive system description and parameters defining energy efficiency

Mapping the operating conditions depends on recording position, speed and elevation of the tested vehicles and evaluation of parameters, which map the operating condition for covered route. The first parameter mapping operating condition is a specific energy consumption (SEC) [12, 13]:

$$\mathrm{SEC} = \frac{E_t}{m \cdot L} \quad (1)$$

where SEC is the specific energy consumption, $E_t$ is the mechanical energy delivered by drive system to the wheels, L is the distance covered by the car and m is the gross vehicle mass.

Mechanical energy transmitted to the drive wheels (traction energy), can be calculated using the following equation:

$$E_t = \int_{t=0}^{t=t_c} \left(k_p \cdot F_t \cdot V\right) dt \quad (2)$$

where $k_p$ is the positive traction force factor:

$$k_p = \begin{cases} 1 & \text{for powered wheels} \\ 0 & \text{for idlling or braking} \end{cases} \quad (3)$$

$F_t$ is the traction force, calculated for recorded speed and altitude change,

$$F_t = m \cdot a \cdot \delta + m \cdot g \cdot \sin(\alpha) + \rho_{air} \cdot A_f \cdot C_D \cdot \frac{V^2}{2} + m \cdot g \cdot C_r \cdot \cos(\alpha) \quad (4)$$

where a is the vehicle acceleration, δ is the rotating mass factor, g is the acceleration due to gravity, α is the road grade, $\rho_{air}$ is the air density, $A_f$ is the vehicle frontal area, $C_D$ is the vehicle aerodynamic drag coefficient, $C_r$ is the vehicle rolling drag coefficient and V is the vehicle speed.

Alternatively, for the data recorded at the uniform time step, traction energy transmitted to the drive wheels may be calculated using the following equation:

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

where $\Delta t$ is the time step.

Total energy that can potentially be delivered to the regenerative braking system (regeneration energy) can be calculated using the following equation:

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

where $k_{reg}$ is the negative traction force factor:

$$k_{reg} = \begin{cases} -1 & \text{for idlling or braking} \\ 0 & \text{for powered wheels} \end{cases} \quad (7)$$

The second parameter mapping operating condition is regenerative braking specific energy (RBSE) for the covered distance can be calculated using the following equation:

$$\mathrm{RBSE} = \frac{E_{reg}}{m \cdot L} \quad (8)$$

Some part of the electrical energy is consumed by auxiliary devices. This energy consumption is defined by the parameter $P_{AD}$, which is electrical power delivered to the auxiliary devices (non traction electricity consumption).

The third parameter mapping operating condition is auxiliary devices specific energy (ADSE).

$$\mathrm{ADSE} = \frac{\Delta t \cdot \sum_{i=1}^{N}\left(P_{AD_i}\right)}{L \cdot m} \quad (9)$$

where $P_{AD}$ is electrical power delivered to the auxiliary devices (non traction electricity consumption).

Figure 1 shows a diagram of the energy flow in the drive system of an electric vehicle with a regenerative braking system and auxiliary devices.

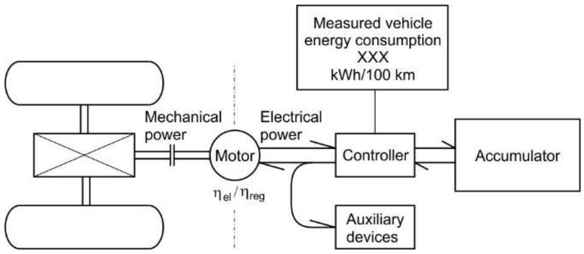


Fig. 1. Diagram of the energy flow in the drive system of an electric vehicle with a regenerative braking system and auxiliary devices

According to the diagram shown in Fig. 1, two operating modes of the drive system can be considered:

a) driving mode, when the electrical energy from the battery is supplied via the controller to the electric motor and then via the driveline to the wheels
b) regenerative braking mode, when the mechanical energy from the wheels is transferred by the driveline to the electric motor, which in this situation acts as an electricity generator and is then transferred to the battery via the controller.

A drive system efficiency is corresponding to the electric energy delivered by the accumulator to the controller and transformed into mechanical energy in the electric motor, then conversed by the drive line into form consumed for traction purposes. It can be defined as follows:

$$\eta_{el} = \frac{E_t}{E_{el}} \cdot 100\% \quad (10)$$

where $E_{el}$ – is the electric energy delivered to the electric motor by the accumulator (used for traction)

$$E_{el} = \Delta t \cdot \sum_{i=1}^{N} \left(P_{el_i}\right) \quad (11)$$

$P_{el}$ is the electrical power delivered by the accumulator to the electric motor. The power of the electric motor did not need to be measured directly in the proposed algorithm. According to eq. (10), electrical energy taken from the battery was measured using the on-board system of the vehicle.

A regenerative braking efficiency is corresponding to mechanical energy delivered to the driveline, next to the electric generator and by the controller to the accumulator, then back to the controller, electric motor, and the drive line. It can be defined as follows:

$$\eta_{reg} = \frac{E_{t_{reg}}}{E_{reg}} \cdot 100\% \quad (12)$$

where $E_{t_{reg}}$ – is the traction energy reused from regeneration energy.

The regenerative braking efficiency determines how much of the recoverable energy from the regenerative braking process will be reused to drive the vehicle. The amount of usable energy is determined by mapping the operating conditions.

Calculation of the electric energy consumption, which corresponding to energy measured by the on-board system of the vehicle, can be performed using the following equation:

$$\mathrm{EEC} = \mathrm{SEC} \cdot \mathrm{m} \cdot \frac{1}{\eta_{\mathrm{el}}} - \mathrm{RBSE} \cdot \mathrm{m} \cdot \eta_{\mathrm{reg}} + \mathrm{ADSE} \cdot \mathrm{m} \tag{13}$$

where EEC is the electric energy consumption; SEC is the specific energy consumption; RBSE is the regenerative braking specific energy; ADSE is auxiliary devices specific energy; $\eta_{el}$ is the drive system efficiency; $\eta_{reg}$ is the regenerative braking efficiency; m is the mass of the vehicle.

## 3. Evaluation of the energy efficiency of electric vehicle drivetrains

### 3.1. Evaluation of the drive system efficiency in driving mode

Performed evaluation of the drive system efficiency in driving mode depended on making drive tests in regular city traffic in the Tri-City area. Global Positioning System (GPS) was used for recording position, speed and altitude of the car with phenomenological correction of the altitude signal [11] at a frequency of 10 Hz using a VBOX GPS Racelogic recorder.

All tests were performed with the cooling or heating system turned off, and the energy consumption of other comfort systems (radio, displays, and ventilation) was reduced to a minimum. It was assumed that electrical power delivered to the auxiliary devices is constant and equal to 0.3 kW, which is a typical value for electric cars with cooling and heating systems switched off [14]. Electric energy consumption was measured using the on-board system of the vehicle, according to the layout shown in Fig. 1. The reading was taken once, at the end of the test. During the tests, 3 vehicles were tested of different purposes and operating parameters. Drive system parameters of the tested vehicles have been shown in Table 1.

Table 1. Drive system parameters of the tested vehicles

| No. | Vehicle | Mass [kg] | Power [kW] | Battery capacity [kWh] |
|---|---|---|---|---|
| A | Mercedes EQE 500 | 2575 | 375 | 90.6 |
| B | Mercedes EQB 300 | 2275 | 168 | 66.5 |
| C | Mazda MX-30 | 1745 | 107 | 35.0 |

In the first stage of energy efficiency evaluation, the drive system efficiency is determined. For this purpose, the best way is make test, when the regeneration system is switched off. Unfortunately most of electric cars have this function unachievable, in several models driver can regulate the intensity of regenerative braking, which enable to achieve similar effect.

The evaluation tests of the drive system efficiency were performed for all three tested vehicles. Formula (13) was used to determine the drive system efficiency. For vehicle A and B, it was not possible to disable regenerative braking entirely, but to minimise the impact of the error in the estimation of the regenerative braking efficiency, tests with the highest possible ratio of traction energy (5) to regenerative braking energy (6) were used. In this case, the efficiency of regenerative braking system was assumed to be equal to the square of the drive system efficiency. For vehicle C, it was possible to disable regenerative braking entirely. Figures 2–4 show the courses of speed, altitude and power delivered to the driveline (positive) or potentially useful for regenerative braking (negative) vs. time. When determining the drive system efficiency of vehicle A and B, a route with gradually increasing altitude was used, allowing high traction energy to be achieved during the test, with relatively low level of regenerative braking energy (Fig. 2 and 3). For vehicle C test, the relation of traction energy to regenerative braking energy was not relevant, as it was technically possible to switch off regenerative braking entirely.

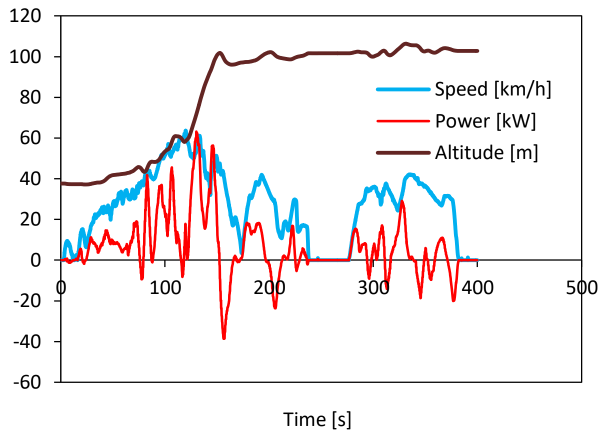


Fig. 2. Speed, power and altitude while evaluating the drive system efficiency of vehicle A

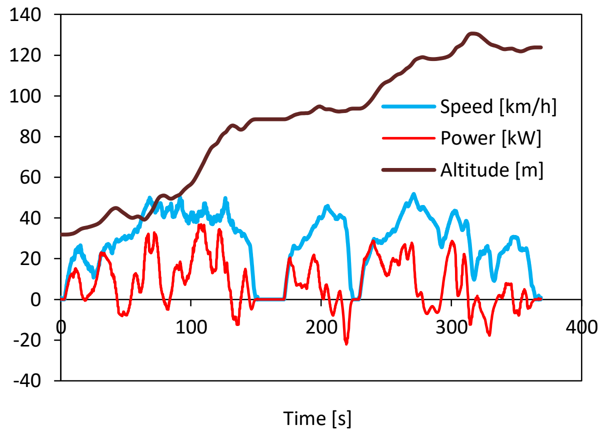


Fig. 3. Speed, power and altitude while evaluating the drive system efficiency of vehicle B

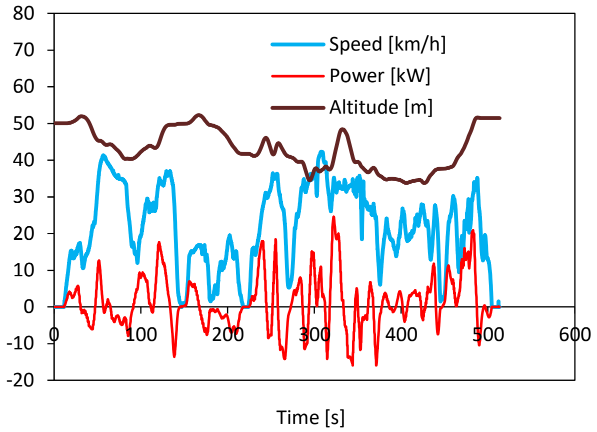


Fig. 4. Speed, power and altitude while evaluating the drive system efficiency of vehicle C

Table 2 shows the test results of the evaluated drive system efficiency and the assumed regenerative braking efficiency.

Table 2. Results of the evaluation tests of the drive system efficiency

| Vehicle | $E_t/E_{reg}$ | $\eta_{reg}$ | $\eta_{el}$ |
|---|---|---|---|
| A | 4.24 | $\eta_{reg} = (\eta_{el})^2$ | 83% |
| B | 6.35 | $\eta_{reg} = (\eta_{el})^2$ | 82% |
| C | 1.66 | 0% | 85% |

The drive system efficiency for the vehicles analysed reaches a similar level of 82–85%, and the results are in line with literature data [14, 15, 21]. The values obtained will be used when testing the regenerative braking efficiency.

### 3.2. Evaluation of the regenerative braking efficiency

Evaluation of the regenerative braking efficiency was carried out using the vehicles whose data are shown in Table 1. On the basis of the test performed, the values of traction energy, regenerative braking energy were calculated. It was assumed that electrical power delivered to the auxiliary devices is constant and equal 0.3 kW. Using the previously determined values of the drive system efficiency, the regenerative braking efficiency for analysed vehicles was determined based on equation (13). The results of the evaluation are shown in Fig. 5.

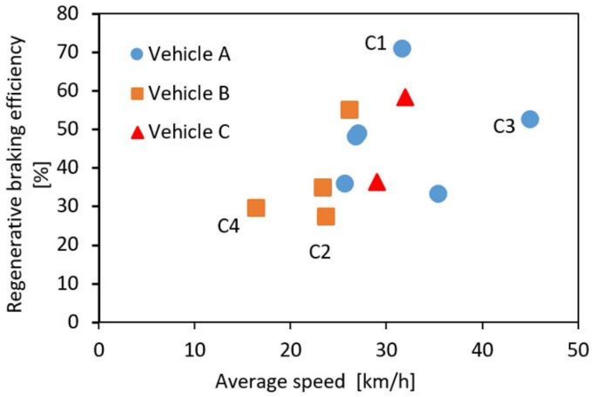


Fig. 5. Influence of average speed on regenerative braking efficiency

It can be conclude that the regenerative braking efficiency varies over a relatively wide range, for vehicle A from 33% to 77%, for vehicle B from 27% to 55% and for vehicle C (2 tests only) from 36% to 58%. In order to identify more closely the factors influencing the observed distribution of the regenerative braking efficiency, four case studies were selected, which are analysed below:

C1 – maximum regenerative braking efficiency
C2 – minimum regenerative braking efficiency
C3 – maximum average speed
C4 – minimum average speed.

The coordinates of the case studies are shown in Fig. 5. In Fig. 6–9 courses of speed, power and altitude of tested vehicles for analysed case studies C1-C4 have been presented. Those courses enable to evaluate the parameters mapping operating condition (SEC and RBSE), the third mapping operating parameter, related to the auxiliary devices (ADSE), must be evaluated separately. In Table 3 parameters mapping operating conditions for analysed case studies have been presented. The results shown in Table 3 are averages for the entire test, without distinguishing between acceleration, braking and constant-speed driving phases. The results obtained are consistent with the data of the manufacturers of these vehicles, but it should be noted that the results given in Table 3 are related to the weight of the vehicle expressed in Mg (1000 kg), hence a direct comparison is possible after multiplying the result by the weight of the vehicle.

Table 3. Parameters mapping operating conditions for case studies C1–C4

| Case study | SEC [kWh/(Mg·100 km] | RBSE [kWh/(Mg·100 km)] | ADSE [kWh/(Mg·100 km)] | Average speed [km/h] | $\eta_{reg}$ |
|---|---|---|---|---|---|
| C1 | 8.60 | 2.49 | 0.37 | 32 | 71% |
| C2 | 6.02 | 2.41 | 0.56 | 24 | 27% |
| C3 | 5.51 | 3.87 | 0.26 | 45 | 53% |
| C4 | 9.56 | 6.00 | 0.80 | 16 | 30% |

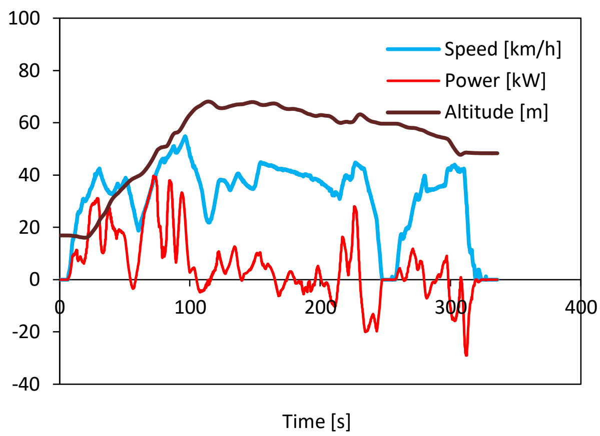


Fig. 6. Speed, power and altitude for case study C1 (maximum regenerative braking efficiency)

Case study C1 corresponds to uphill driving, with relatively small share of regenerative braking. It can be assumed that state of charge (SOC) of the accumulator, just after intensive driving mode is at an adequate level to absorb all regenerative braking energy. Additionally, higher initial speed of the braking process corresponds to higher speed of the electric generator, which also corresponds to higher efficiency of the regenerative braking process.

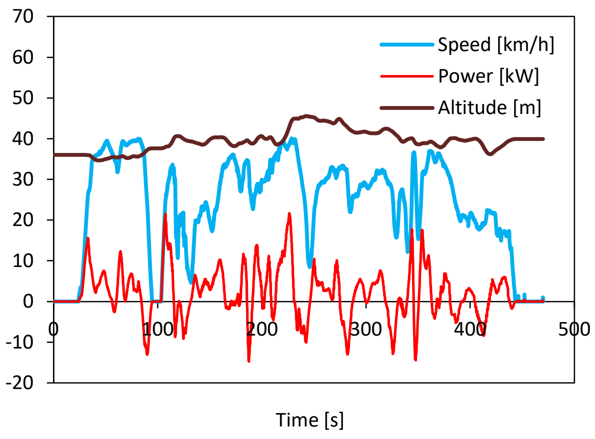


Fig. 7. Speed, power and altitude for case study C2 (minimum regenerative braking efficiency)

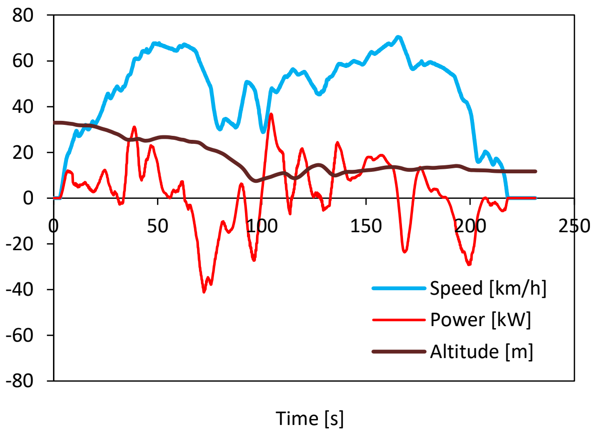


Fig. 8. Speed, power and altitude for case study C3 (maximum average speed)

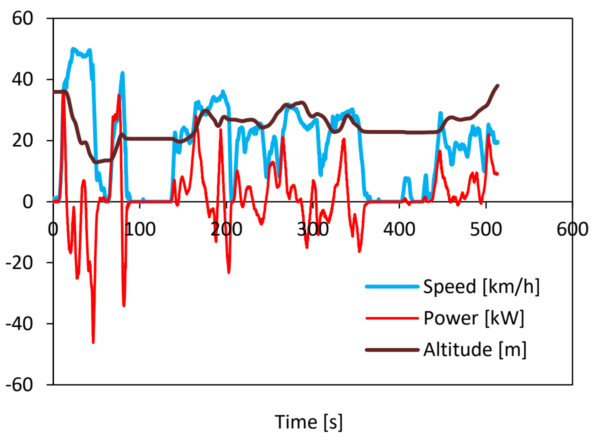


Fig. 9. Speed, power and altitude for case study C4 (minimum average speed)

Case study C2 corresponds to low average speed route, with relatively small elevation change and non-intensive regenerative braking. I can be assumed that SOC of the accumulator is all the time in relatively high lever, which limits absorption of the achievable regenerative braking energy. Additionally, the lower initial speed of the braking process corresponds to a lower speed of the electric generator, which also corresponds to the lower efficiency of the regenerative braking process.

Case study C3 corresponds to high average speed route, with down-hill driving and long-time intensive regenerative braking. It can be assumed that high level of state of charge (SOC) of accumulator is reached relatively quickly during intensive regenerative braking, after that energy cannot be used any longer. The energy recovery process, when applicable is performed with high efficiency due to the relatively high rotational speed of the generator during the initial braking phase, which corresponds to high efficiency of the regenerative braking process.

Case study C4 corresponds to low average speed route, with small elevation change and long-time regenerative braking. It can be assumed that SOC of the accumulator is all the time at high level, which limits absorption of the achievable regenerative braking energy. Additionally, lower initial speed of the braking process corresponds to a lower speed of the electric generator, which corresponds to lower efficiency of the regenerative braking process.

## 4. Conclusions

This paper presents a description of an original method of evaluation of the energy efficiency of electric vehicle drivetrains under urban operating conditions. The method uses universal measuring devices to collect the data for the following analyses. The method can be widely used and results can be implemented in applications that support drivers in energy-efficient driving. A novelty of this method is the use of a procedure for mapping the operating conditions allowing to determine the reference level of energy consumption and compare it to the electric energy consumption recorded during the identification tests. In the paper, the full calculation algorithm was presented using equations (1)–(10), for example, traction energy was evaluated using eq. (5), traction force was calculated based on the vehicle's resistance to motion (4) using design data provided by vehicle manufacturers. The power of the electric motor did not need to be measured directly in the proposed algorithm. According to eq. (10), electrical energy taken from the battery was measured using the on-board system of the vehicle.

In the first stage of the electric vehicle drivetrain efficiency evaluation, the drive system efficiency (in driving mode) is determined, and in the second stage in the regenerative braking mode. In this study, a new method of mapping operating conditions was used, based on recorded vehicle speed, position and latitude. Performed tests enabled to determine the drive system efficiency. In vehicles, where regenerative braking cannot be switched off, this evaluation stage requires a special approach. It has been proposed to use testing routes with a sufficiently high ratio of the specific energy consumption to the regenerative braking specific energy. This minimise the impact of the unknown value of the regenerative braking efficiency. At the same time, it was necessary to assume a certain value for this efficiency, which was defined as the square of the drive system efficiency. Based on the known value of the electric energy consumption (on-board recording system) and the other components of equation (13), the drive system efficiency was determined.

The drive system efficiency for the vehicles analysed reaches a similar level of 82–85%, and the results are in line with literature data [15, 16]. The values obtained were then used to test the regenerative braking efficiency. The parameters mapping operating conditions and the equation (13) were consequently used for this purpose.

To conclude, the regenerative braking efficiency varies over a relatively wide range, for vehicle A from 33% to 77%, for vehicle B from 27% to 55% and for vehicle C (2 tests only) from 36% to 58%, which is in line with literature data [14, 21]. To identify more closely the factors influencing the observed distribution of the regenerative braking efficiency, four case studies were analysed (C1–C4). Based on the case studies, it can be concluded that one of the main factors determining the regenerative braking efficiency is the level of state of charge (SOC) of the accumulator and the management algorithm used by the vehicle for controlling this parameter. If the regenerative braking distances are long then the controller managing the SOC is limiting absorption of energy from regenerative braking process. On the other hand, low driving speeds at the start of the regenerative braking process, i.e. typical for urban conditions, corresponds to low generator speeds, which does not guarantee high operating efficiency of the generator.

## Nomenclature

| | |
|---|---|
| a | vehicle acceleration |
| ADSE | auxiliary devices specific energy |
| $A_f$ | vehicle frontal area |
| $C_D$ | vehicle aerodynamic drag coefficient |
| $C_r$ | vehicle rolling drag coefficient |
| EEC | electric energy consumption |
| $E_{el}$ | electric energy delivered to the electric motor by the accumulator |
| $E_t$ | mechanical energy delivered by drive system to the wheels |
| $E_{t_{reg}}$ | traction energy reused from regeneration energy |
| g | acceleration due to gravity |
| GPS | Global Positioning System |
| $k_p$ | positive traction force factor |
| $k_{reg}$ | negative traction force factor |
| L | distance covered by the vehicle |
| m | gross vehicle mass |
| $P_{AD}$ | electrical power delivered to the auxiliary devices |
| RBSE | regenerative braking specific energy |
| SEC | specific energy consumption |
| V | vehicle speed |
| $\alpha$ | road grade |
| $\delta$ | rotating mass factor |
| $\eta_{el}$ | drive system efficiency |
| $\eta_{reg}$ | regenerative braking efficiency |
| $\rho_{air}$ | air density |
| $\Delta t$ | time step |

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