DOI 10.2478/ama-2023-0035 acta mechanica et automatica, vol.17 no.2 (2023)
Special Issue "Modeling and experimental investigations of thermo-hydraulic, hydrogen, manufacturing and mechanical systems"

ESTIMATION OF THE REGENERATIVE BRAKING PROCESS EFFICIENCY IN ELECTRIC VEHICLES

Jacek KROPIWNICKI*, Tomasz GAWŁAS**

*Faculty of Mechanical Engineering and Ocean Technology, Gdańsk University of Technology,
ul. Gabriela Narutowicza 11/12, 80-233, Gdańsk, Poland
**BMG Goworowski Gdynia, ul. Łużycka 9, 81-537, Gdynia, Poland

jkropiwn@pg.gda.pl, tomasz.gawlas@mazdagdynia.pl

received 2 September 2022, revised 3 February 2023, accepted 18 February 2023

Abstract: In electric and hybrid vehicles, it is possible to recover energy from the braking process and reuse it to drive the vehicle using the batteries installed on-board. In the conditions of city traffic, the energy dissipated in the braking process constitutes a very large share of the total resistance to vehicle motion. Efficient use of the energy from the braking process enables a significant reduction of fuel and electricity consumption for hybrid and electric vehicles, respectively. This document presents an original method used to estimate the efficiency of the regenerative braking process for real traffic conditions. In the method, the potential amount of energy available in the braking process was determined on the basis of recorded real traffic conditions of the analysed vehicle. The balance of energy entering and leaving the battery was determined using the on-board electric energy flow recorder. Based on the adopted model of the drive system, the efficiency of the regenerative braking process was determined. The paper presents the results of road tests of three electric vehicles, operated in the same traffic conditions, for whom the regenerative braking efficiency was determined in accordance with the proposed model. During the identification of the operating conditions of the vehicles, a global positioning system (GPS) measuring system supported by the original method of phenomenological signal correction was used to reduce the error of the measured vehicle's altitude. In the paper, the efficiency of the recuperation process was defined as the ratio of the accumulated energy to the energy available from the braking process and determined for the registered route of the tested vehicle. The obtained results allowed to determine the efficiency of the recuperation process for real traffic conditions. They show that the recuperation system efficiency achieves relatively low values for vehicle No. 1, just 21%, while the highest value was achieved for vehicle No. 3, 77%. Distribution of the results can be directly related to the power of electric motors and battery capacities of the analysed vehicles.

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

1. INTRODUCTION

Electricity delivered by the grid or range extenders [21] to an electric car is used by the propulsion system with various efficiencies, depending on the performance of the charging process [26], energy storage process in battery [28], electric engine control system, drive motor [10] and driveline system [23, 27]. It is estimated that the efficiency of all the above-mentioned processes is approximately 77%. Nowadays, electric drive systems of vehicles additionally enable the recovery of energy during braking and its reuse while driving the vehicle [11, 15]. Recently developed technical solutions that use recuperative braking energy allow the conversion of mechanical energy into electricity with high efficiency, even for very high power [7, 29, 31]. Control strategies for hybrid and electric vehicles in the field of regenerative braking energy are relatively complex [15, 17, 22] and depend strongly on the state of charge of the batteries. In modern electric cars, battery durability is a very important point of interest. This criterion is heavily impacted by the accurate estimation of the state of charge and state of health. In order to improve the accuracy of state of charge or state of health estimation, new researches are provided [24]. However, as a rule, manufacturers are trying to use the regenerative braking energy for charging batteries to the highest extent possible. Tests performed on a Toyota C-HR in urban conditions showed that the share of energy recovery from regenerative braking is over 50% of all energy supplied to the battery while driving [25].

It is necessary to consider the possibility of regenerative braking when planning the route of such vehicles, which is not implemented with the use of today's car navigation systems. A model of a regenerative braking process may be helpful for this purpose. On one hand, it will enable providing information on how traffic conditions affect the amount of energy dissipated (wasted) into the atmosphere, while on the other hand, it will help to optimize the route of vehicles with regenerative braking systems. A number of studies have been carried out to achieve this objective, while the methods used to predict electricity consumption are characterized by a very diverse level of complexity and accuracy [9, 19, 22].

Typically, the efficiency of a regenerative braking process is defined as a regenerative braking energy delivered to battery and back to a drive system, for an assumed driving cycle, divided by the energy achievable from braking process, which in conventional drive system is consumed by a hydraulic brake system. The achieved efficiency depends on the configuration of the drive system, applied control strategy and the driving cycle. For example, for a China Typical City Regenerative Driving Cycle (CTCRDC) driving cycle, one vehicle was tested and different strategies were applied; the calculated efficiency of a regenerative braking process

DOI 10.2478/ama-2023-0035

was 31%–42% [25]. According to the results of simulations performed in work [15], for pure braking process, starting from the vehicle's initial speed of 80 km/h, the efficiency of a regenerative braking process for the tested control strategy was calculated at the level of 86%. Another study [16] shows that up to 50% of the total brake energy can be recycled in the urban driving cycle.

One of the most important factors directly affecting the aforementioned complexity and accuracy is the method used to identify car operating conditions [4, 10, 20]. Using the car operating conditions and model connecting the operating conditions with electricity consumption, it is possible to predict electricity consumption for the selected vehicle and route [5, 8, 9]. Due to the constantly increasing number of roads in city centres, in particular building new express roads within an agglomeration, drivers usually have more than one route to choose from. Their choice is most often determined by the travel time, but from an ecological point of view, more attention should be paid to the energy consumption or the emission of toxic compounds.

Currently, there are several platforms for the effective collection of data on the instantaneous traffic; however, as a rule, they determine the fastest or the shortest route. The development of a tool for determining the route due to the energy consumption is a primary need. This, in turn, requires the construction of a universal model, which enables the parametric description of traffic conditions to be linked with the amount of energy used to drive the vehicle [1, 2, 18]. This work focuses on the initial stage of building such a model. The paper presents a comprehensive method of identifying vehicle traffic conditions, and the method of estimation of the efficiency of the regenerative braking process using an on-board energy consumption measurement system for electric vehicles. Vehicle tests have been carried out in regular traffic for urban, rural and motorway conditions, following the operating conditions specified in the Real Driving Emissions (RDE) test [3, 6, 30]. Such a test represents the real operating conditions of vehicles as opposed to the previously used synthetic tests performed on a chassis dynamometer.

2. ENERGY CALCULATION OF THE REGENERATIVE BRAKING PROCESS

Vehicle operating conditions are identified in this work with the use of the specific energy consumption (SEC) that takes into account both an influence of external conditions and a driver's style of driving [13, 14]. The factors mentioned above affect the amount of mechanical energy transmitted to the drive wheels, which is one of the parameters constituting the SEC. Information on SEC for the considered road section can be directly used to calculate electricity consumption in the case of battery-powered vehicles. The value of the parameter for assumed cycle duration may be calculated using the following equation:

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

where *SEC* is the specific energy consumption, *E* 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 can be calculated using the following equation:

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

where k_p is the positive traction force factor:

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

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

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

where a is the vehicle acceleration, δ is the rotating mass factor, g is the acceleration due to gravity, α is the road grade, ρ_{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, mechanical energy transmitted to the drive wheels may be calculated using the following equation:

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

where Δt is the time step.

As far as the usage of electric motor supporting conventional drive system is concerned, the regenerative braking energy must be taken into consideration. According to Eq. (4), the traction force is negative when the balance between acceleration component, road grade component, rolling resistance and air drag resistance is negative. This negative traction force in a conventional drive system is balanced by the brake system, while in hybrid or electric cars, it can be used for powering regenerative braking system. In the general case, however, the total energy that can potentially be delivered to the regenerative braking system can be calculated using the following equation:

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

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

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

Regenerative braking specific energy (RBSE) for the covered distance can be calculated using the following equation:

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

Power reception from the vehicle's drive system during braking is limited by specific restrictions and cannot be completed 100%. Typical restrictions come from the maximum power of the generator, its minimum operational speed or capacity of the battery. The part of energy that cannot be used for regenerative braking is transferred to the regular braking system. Distribution of this energy and efficiency of regenerative braking process are strongly influenced by the strategy applied by the system controller [17].

In electric cars, the electricity consumed by the drive system is measured at the input to the motor. Similarly, the electricity recovered from the braking process is measured at the generator output. The recorded result is the difference between the energy taken

DOI 10.2478/ama-2023-0035
acta mechanica et automatica, vol.17 no.2 (2023)
Special Issue "Modeling and experimental investigations of thermo-hydraulic, hydrogen, manufacturing and mechanical systems"

from the battery and that supplied to it from the braking process. Therefore, if we want to compare the results from the vehicle on-board system with the results of the traffic analyses, we should refer to the measuring points indicated above. Fig. 1 shows a diagram of the energy flow in the drive system of an electric vehicle with a regenerative braking system.

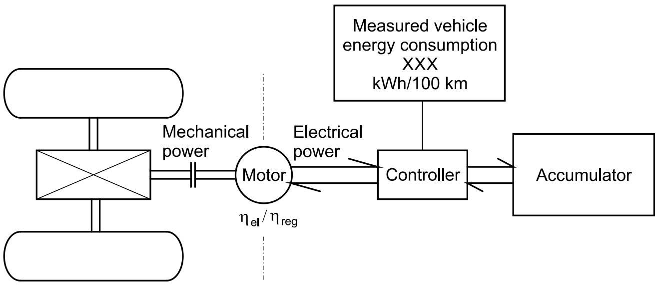

Fig. 1. Diagram of the energy flow in the drive system of an electric vehicle with a regenerative braking system

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

$$EEC = SEC \cdot m \cdot \frac{1}{\eta_{el}} - RBSE \cdot m \cdot \eta_{reg} \tag{9}$$

where η_{el} is the efficiency of electric drive system including electric motor and driveline and η_{reg} is the efficiency of regenerative braking system including electric generator and driveline.

The study did not consider the energy self-consumption of the vehicle, all tests were performed with the cooling or heating system turned off, and the energy consumption of other comfort systems (radio, displays, ventilation) was reduced to a minimum.

3. EFFICIENCY OF THE REGENERATIVE BRAKING PROCESS OF AN ELECTRIC VEHICLE

The analysis was carried out for three selected electric vehicles whose characteristics are presented in Tab. 1. The first two vehicles were designed for operation in typical urban conditions, and the third vehicle was equipped with a bigger battery, allowing its usage in extra-urban conditions also. The specified vehicle mass includes, in addition to the curb weight, the driver's weight. Due to the operating parameters, all vehicles can reach the speed of 120 km/h required in the test.

Tab. 1. Drive system parameters of the tested vehicles

No.	Vehicle	Mass [kg]	Power [kW]	Battery capacity [kWh]
1	Smart EQ	1175	60	17
2	Mazda MX-30	1725	107	35
3	Hyundai IoniQ 5	2100	224	72.6

To determine the efficiency of the electric drive and the regeneration process, a route taking into account typical urban conditions and bypass roads within the city has been selected in Gdańsk. The route is presented in Fig. 2 with the average speed (V) distribution. The road has been divided into 100-m-long sections, to which the average speed has been assigned. Fig. 3 shows the powered distance share (Lp/L) in indicated road sections. It has been assumed that the indicated road section can be covered by the vehicle in two states: powering and regenerative braking.

(a)

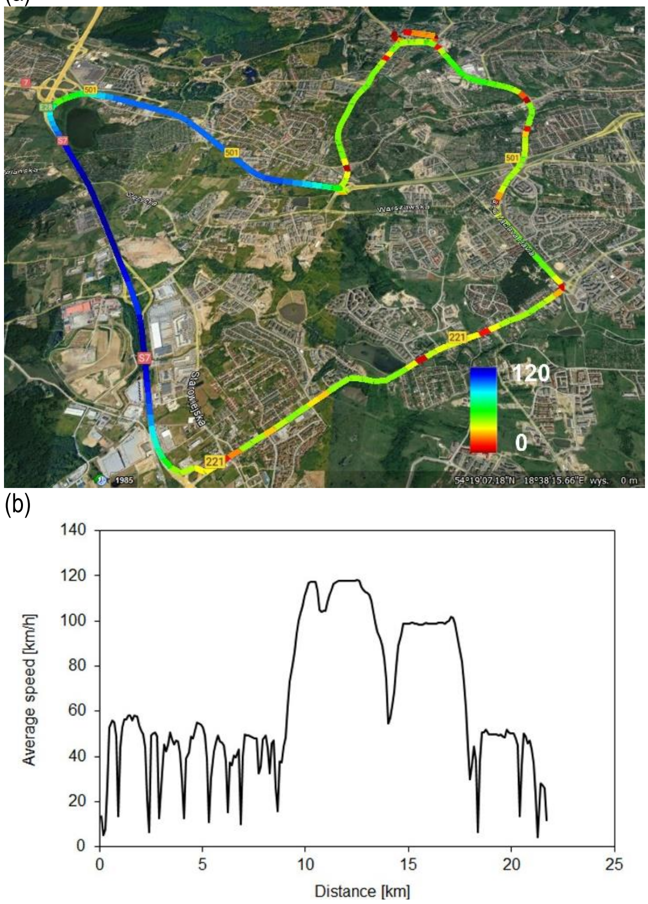

Fig. 2. The average speed (V) [km/h]: (a) distribution over the specified route and (b) distribution over the travelled distance

To determine the energy consumption and the energy that can potentially be used in regenerative braking process, the vehicle motion parameters (geographical coordinates, speed and altitude) have been determined on the basis of the recorded Global Positioning System (GPS) parameters. The traction force on the vehicle wheels has been calculated according to Eq. (4).

The road grade has been calculated using GPS coordinates. The altitude provided by the GPS receiver (Fig. 4) is not very accurate for terrestrial applications. The simple geometry of the system's satellite components means that the accuracy of the altitude measurement is about 10 times worse than the horizontal position measurement [12]. Typical vertical position error in signals for civilian use is about 5 m. However, the basic problem with the use of these receivers in road tests is the formation of reflections of the signal coming from satellite transmitters or its temporary disappearance. In urban conditions, this phenomenon is mainly caused by the proximity of buildings and the presence of tall buildings in the immediate vicinity of the road, as well as the presence of viaducts and tunnels.

DOI 10.2478/ama-2023-0035

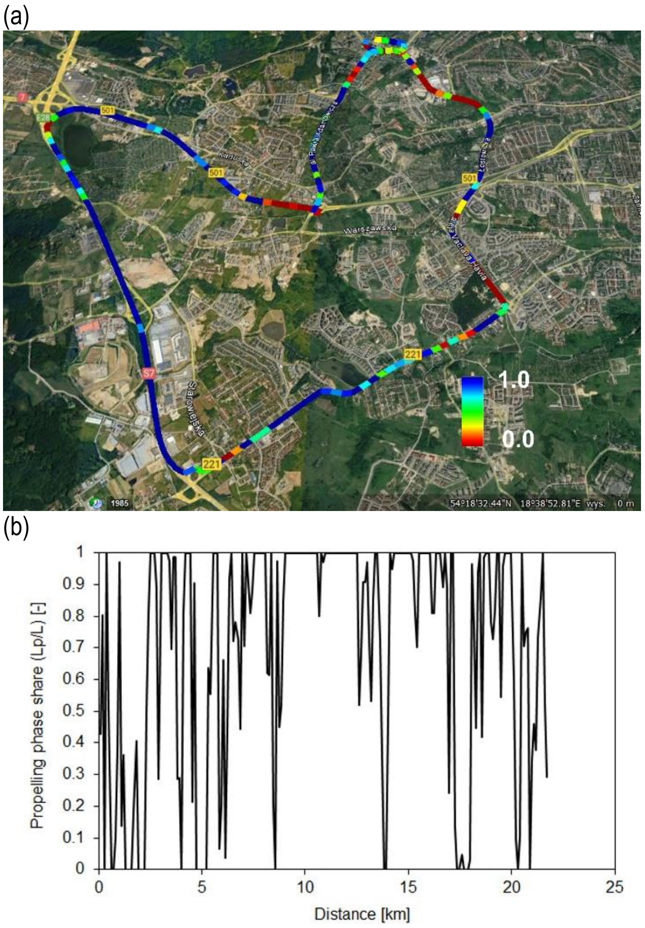

Fig. 3. The powered distance share (Lp/L) [-]: (a) distribution over the specified route and (b) distribution over the travelled distance

Fig. 4. GPS receiver used to determine the position of the vehicle and its altitude. GPS, Global Positioning System

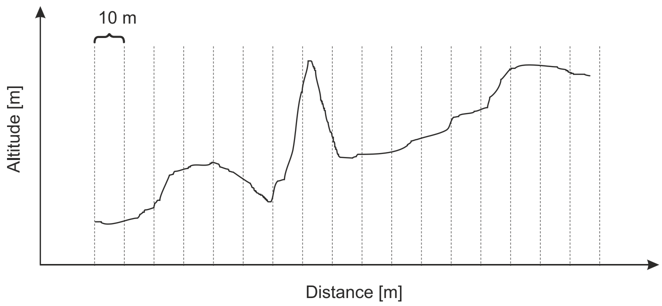

Fig. 5. Diagram of the division of the travel route in the horizontal direction into equal sections

Due to the above, the test has been carried out using a correction of the altitude signal based on phenomenological correction. The usage of the correction of the altitude signal depended on the exclusion of points giving greater road grade than allowed by the regulations. This method makes it possible to eliminate the influence of incorrect indications of the GPS regarding the measurement of altitude, as opposed to commonly used digital filtering methods, which only reduce this influence. The analysed route in the horizontal plane was divided into intervals of equal length of 10 m, and then the average value of the altitude in each interval indicated by the GPS was calculated (Fig. 5). The only exception is the last interval, the length of which results from the difference in the length of the entire route and values accumulated in the previous intervals.

Then, the first recorded altitude was connected with the average value in the middle of each section with straight lines. This way, a road profile was generated and mapped with straight sections with a constant horizontal component (except for the first and last sections). According to Polish regulations, the permissible absolute road grade for national roads should not exceed 3.7°. It was assumed that road grades smaller than 4° correspond to the actual course of the road profile and are marked with a bold line (Fig. 6), while the road grades which do not correspond to the given condition are marked with a dotted line. The condition of maintaining the permissible road grade can then be formulated as follows:

$$\alpha < \alpha_{perm} \tag{10}$$

where α is the road grade and α_{perm} is the permissible road grade, assumed to be 4°.

From the point where the incorrectly routed section begins, alternative road grade is starting, omitting the original altitude and the initial section is joined to the next one corresponding to the new road grade (Fig. 6).

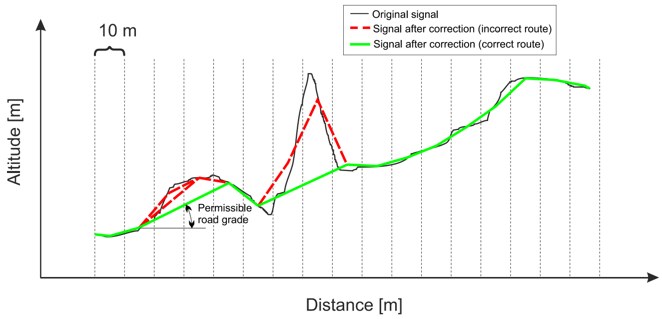

Fig. 6. Schematic drawing of phenomenological road profile correction: thin line – original route, dashed line – incorrect route, bold line – correct route meeting the condition (10)

In the event that the alternative road grade also fails to meet the condition of the permissible road grade (dotted line), the procedure is repeated. This procedure may also be performed in the opposite direction, if the first road grade, determined on the basis of the recorded original signal, does not meet the condition (10). In such a situation, the starting point for mapping the road profile can also be the first section fulfilling the condition (10), and the procedure of determining road grade will be carried out both in the forward and in the reverse directions. Fig. 7 shows an example of the road profile calculation with the use of phenomenological correction. Details of the mathematical basis of the method have been presented in Appendix A.

After calculating the road grade, speed and acceleration of the vehicle, it was possible to determine the power used to drive the vehicle and the power that can be used in the regenerative braking process. Fig. 8 presents the speed of the vehicle and the power calculated for vehicle No. 2.

DOI 10.2478/ama-2023-0035
acta mechanica et automatica, vol.17 no.2 (2023)
Special Issue "Modeling and experimental investigations of thermo-hydraulic, hydrogen, manufacturing and mechanical systems"

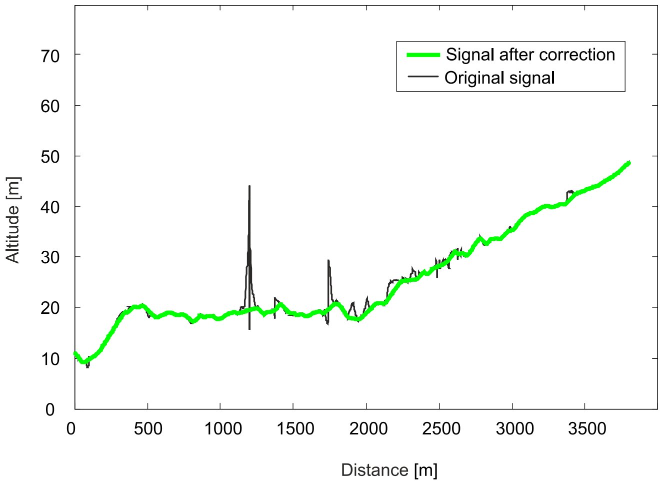

Fig. 7. Example of the road profile calculation with the use of phenomenological correction

Based on the relationships (1)–(8), SEC and RBSE have been determined. The calculations were performed for 100-m-long road sections. According to Eq. (1), high values of SEC correspond to a large amount of energy per distance travelled, which technically corresponds to intensive acceleration of the vehicle, climbing up a hill or driving at a very high speed. The results of this analysis have been presented in Figs. 9 and 10. Tab. 2 presents the parametric description of the route. This route was used in each analysed case.

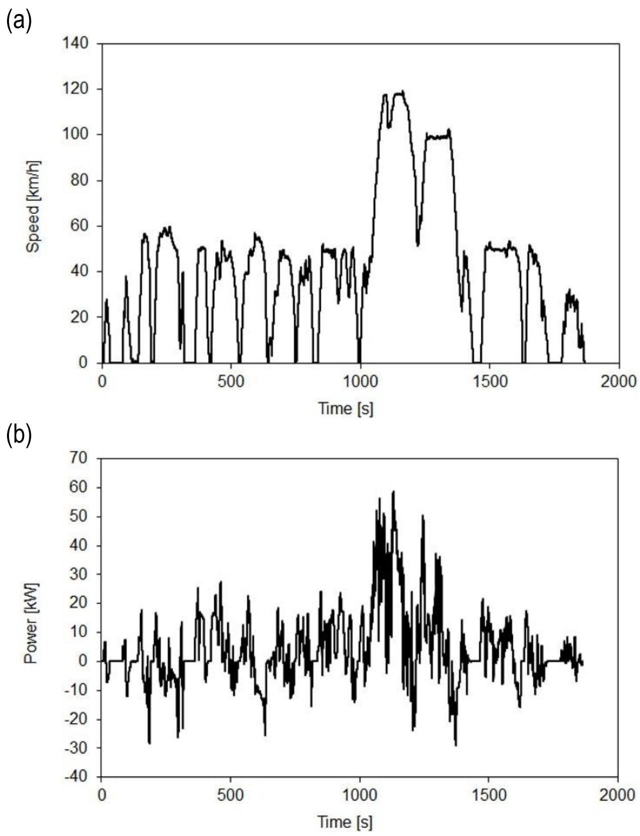

Fig. 8. The speed (a) of the vehicle and the power (b) calculated for vehicle No. 2

Tab. 2. Parametric description of the route used in tests (calculations processed for vehicle No. 2)

Distance	21.7 km
Average speed	41.9 km/h
SEC	9.11 J/(Mg*100 km)
RBSE	2.86 J/(Mg*100 km)
Idling time share	14.7%
Propelling phase share (Lp/L)	70.0%
Average power in propelling mode	10.3 kW
Average power in braking mode	5.1 kW

RBSE, Regenerative braking specific energy; SEC, specific energy consumption.

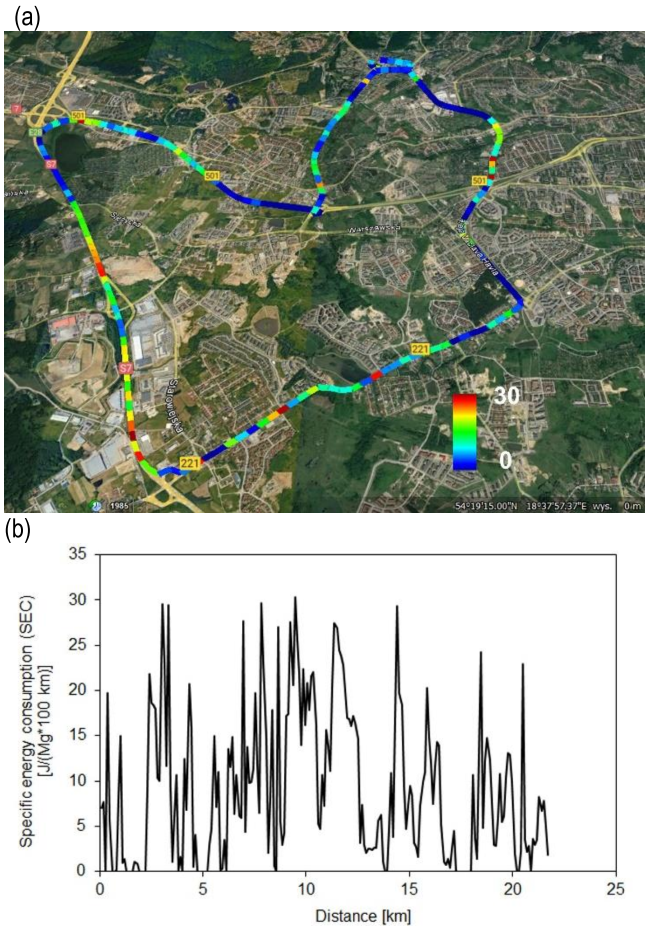

Fig. 9. The SEC [J/(Mg*100 km)]: (a) distribution over the specified route and (b) distribution over the travelled distance. SEC, specific energy consumption

In the first stage of determining the efficiency of regenerative braking system, it was necessary to determine the efficiency of the electric drive system. For this purpose, the energy consumption of vehicle No. 2 with the regenerative braking system turned off has been measured. The obtained result is presented in Tab. 3. Due to the lack of technical possibilities to turn off the regenerative braking system in the other two vehicles, in further analysis, it was assumed that the drive system efficiency is the same in each of the tested vehicles.

DOI 10.2478/ama-2023-0035

Tab. 3. Energy consumption of vehicle No. 2 with the regenerative braking system turned off

Vehicle	Vehicle energy consumption [kWh/100 km]	Drive system efficiency [%]
Mazda MX-30	18.1	87

For the assumed route (Fig. 2), tests were conducted with selected cars. The electric energy consumption measurements in these tests, carried out with the use of the on-board systems, are presented in Tab. 4. The regenerative braking system was turned on in all the vehicles used in this test. In the tests, the control algorithms of the regenerative braking system were not influenced in any way. The strategies applied to control them were not the subject of the research and the original strategies implemented by vehicle manufacturers were used. Regenerative braking system efficiency was calculated using Eq. (9), where the SEC along with the RBSE was calculated for the registered route of the vehicle. The calculated regenerative braking system efficiency refers to the energy potentially available in a braking process, not to the total energy consumed by the drive system during operation.

(a)

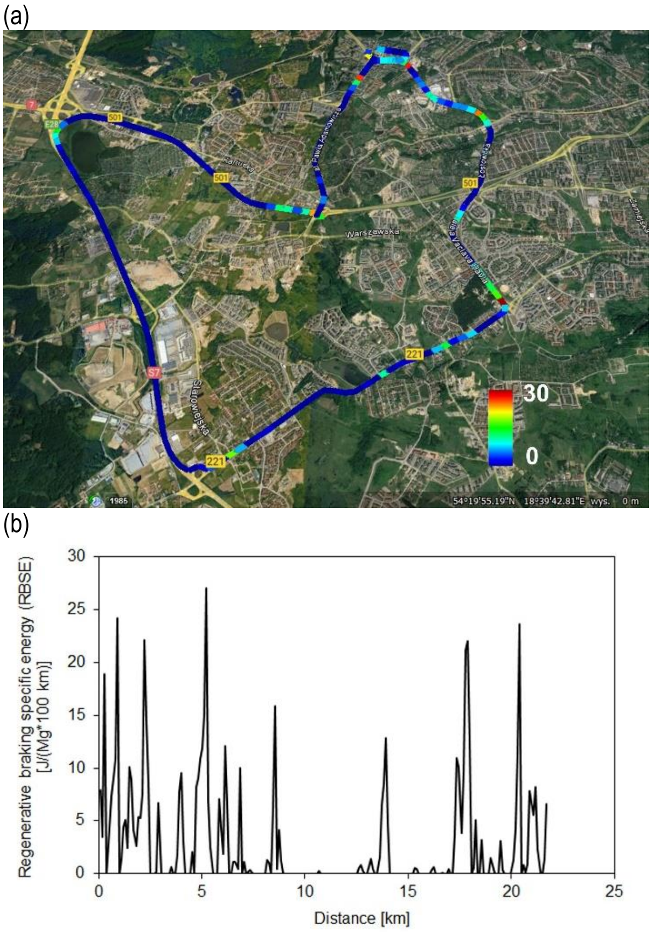

Fig. 10. The RBSE [J/(Mg*100 km)]: (a) distribution over the specified route and (b) distribution over the travelled distance. RBSE, regenerative braking specific energy

Tab. 4. Electric energy consumption of the tested vehicles with the regenerative braking system turned on

Vehicle	Vehicle energy consumption [kWh/100 km]	Drive system efficiency [%]	Regenerative braking system efficiency [%]
Smart EQ	13.6	87	21
Mazda MX-30	16.0	87	43
Hyundai IoniQ 5	15.5	87	77

4. CONCLUSIONS

The presented method of determining the efficiency of regenerative braking process requires relatively simple measuring devices, i.e. a GPS and an on-board energy consumption recording system. The procedure has been adapted for using the on-board energy consumption recording system of electric vehicles, which essentially simplifies the measurement procedure. Thus, the energy supplied from an external power source for charging the battery is not measured directly. Instead, the result of the electricity consumption balance recorded by the vehicle controller is taken into account.

Technically, the input and output energy can hardly be measured with sensors mounted on wheels, which enable taking into account the dual-direction energy flow considering the regenerative brake [25]. In this work, the applied calculation model was not verified due to the lack of technical possibility of interfering with the drive systems of the tested vehicles.

The obtained results enabled the formulation of the following conclusions:

- The adopted method of identifying vehicle operating conditions and its usage in the form of distribution of SEC (Fig. 9) and RBSE parameters (Fig. 10) over the specified route, for defined 100 m long sections, significantly facilitates the calculations of regenerative braking system efficiency.
- The applied original method consisting in using the on-board energy consumption recording system for measuring the electric energy consumption enabled a non-intrusive measurement of the parameters required to determine the regenerative braking system efficiency.
- A new phenomenological correction method was used to eliminate the influence of the incorrect indications of the GPS on the measured altitude.
- Road tests conducted for three electric vehicles enabled the measurement and comparison of the braking system efficiency (9) in real operating conditions.
- The obtained results show that the recuperation system efficiency achieves relatively low values for vehicle No. 1, merely 21%, which corresponds to the lowest electric motor power to mass relation (51 W/kg), as well as the lowest battery capacity to mass relation (14 Wh/kg). Vehicle No. 2 achieved 43% efficiency, which corresponds to the electric motor power to mass relation (62 W/kg) and the battery capacity to mass relation (20 Wh/kg). Vehicle No. 3 achieved the best efficiency amounting to 77%, which corresponds to the electric motor power to mass relation (107 W/kg) and the battery capacity to mass relation (35 Wh/kg). The factor that had a considerable impact on the results consisted of the wide range of altitude change, which has a particularly strong influence during long-term braking combined with going downhill, taking place at the end of the route section with a registered speed of 100 km/h.

DOI 10.2478/ama-2023-0035 acta mechanica et automatica, vol.17 no.2 (2023)
Special Issue "Modeling and experimental investigations of thermo-hydraulic, hydrogen, manufacturing and mechanical systems"

NOMENCLATURE

a – vehicle acceleration,
A_f – vehicle frontal area,
C_D – vehicle aerodynamic drag coefficient,
C_r – vehicle rolling drag coefficient,
E – mechanical energy delivered by drive system to the wheels,
F_t – traction force,
g – acceleration due to gravity,
k_p – positive traction force factor,
k_{reg} – negative traction force factor,
L – distance covered by the car,
m – gross vehicle mass,
RBSE – regenerative braking specific energy,
SEC – specific energy consumption,
V – vehicle speed,
α – road grade,
α_{perm} – permissible road grade,
δ – rotating mass factor,
Δt – time step,
η_{el} – efficiency of electric drive system including electric motor and driveline,
η_{reg} – efficiency of regenerative braking system including electric generator and driveline,
ρ_{air} – air density,
CTCRDC – China Typical City Regenerative Driving Cycle
GPS – Global Positioning System,
RDE – Real Driving Emissions.

REFERENCES

1. Abdurazzokov U, Sattivaldiev B, Khikmatov R, Ziyaeva S. Method for assessing the energy efficiency of a vehicle taking into account the load under operating conditions. In: E3S Web of Conferences 264 (8). 2021.
2. Alves J, Baptista PC, Gonçalves GA, Duarte GO. Indirect methodologies to estimate energy use in vehicles: Application to battery electric vehicles. Energy Convers Manag. 2016;124:116–29.
3. Andrych-Zalewska M, Chłopek Z, Merkisz J, Pielecha J. Analysis of the operation states of internal combustion engine in the Real Driving Emissions test. Arch Transp. 2022;61(1): 71–88.
4. Berzi L, Delogu M, Pierini M. Development of driving cycles for electric vehicles in the context of the city of Florence. Transp Res Part D Transp Environ. 2016;47:299–322.
5. Brady J, O'Mahony M. Development of a driving cycle to evaluate the energy economy of electric vehicles in urban areas. Appl Energy. 2016;177:165–78.
6. Cieslik W, Zawartowski J, Fuc P. The Impact of the Drive Mode of a Hybrid Drive System on the Share of Electric Mode in the RDC Test. In: SAE Technical Papers. 2020. p. 1–8.
7. Damiani L, Repetto M, Prato AP. Improvement of powertrain efficiency through energy breakdown analysis. Appl Energy. 2014;121:252–63.
8. Fiori C, Ahn K, Rakha HA. Power-based electric vehicle energy consumption model: Model development and validation. Appl Energy. 2016;168:257–68.
9. Fiori C, Arcidiacono V, Fontaras G, Makridis M, Mattas K, Marzano V, et al. The effect of electrified mobility on the relationship between traffic conditions and energy consumption. Transp Res Part D Transp Environ. 2019; 275–90.
10. Galvin R. Energy consumption effects of speed and acceleration in electric vehicles: Laboratory case studies and implications for drivers and policymakers. Transp Res Part D Transp Environ. 2017;53:234–48.
11. Huang J, Qin D, Peng Z. Effect of energy-regenerative braking on electric vehicle battery thermal management and control method based on simulation investigation. Energy Convers Manag. 2015;105:1157–65.
12. Krasuski K, Ćwiklak J. Accuracy Analysis of Aircraft Position at Departure Phase Using DGPS Method. Acta Mech Autom. 2020;14(1):36–43.
13. Kropiwnicki J, Kneba Z, Ziółkowski M. Test for assessing the energy efficiency of vehicles with internal combustion engines. Int J Automot Technol. 2013;14(3).
14. Kropiwnicki J. A unified approach to the analysis of electric energy and fuel consumption of cars in city traffic. Energy. 2019;182.
15. Li L, Li X, Wang X, Song J, He K, Li C. Analysis of downshift's improvement to energy efficiency of an electric vehicle during regenerative braking. Appl Energy. 2016;176:125–37.
16. Li L, You S, Yang C, Yan B, Song J, Chen Z. Driving- behavior-aware stochastic model predictive control for plug-in hybrid electric buses. Appl Energy. 2016;162:868–79.
17. Liu W, Qi H, Liu X, Wang Y. Evaluation of regenerative braking based on single-pedal control for electric vehicles. Front Mech Eng. 2020;15(1):166–79.
18. Mamala J, Graba M, Bieniek A, Prażnowski K, Augustynowicz A, Śmieja M. Study of energy consumption of a hybrid vehicle in real-world conditions. Maint Reliab. 2021;23(4):636–45.
19. Mamala J, Śmieja Michałand Prażnowski K. Analysis of the total unit energy consumption of a car with a hybrid drive system in real operating conditions. Energies. 2021;14(3966).
20. Orofino, Luifi; Cilimingras, Luis; Morello E. Ecodrive: Driver Behaviour Evaluation System To Reduce CO2 Emissions. FISITA World Automot Congr. 2010;1(E3-1: Intelligent Transportation Systems):261–76.
21. Pielecha I, Cieślik W, Fluder K. Analysis of energy management strategies for hybrid electric vehicles in urban driving conditions. Combust Engines. 2018;173:14–8.
22. Pielecha I, Cieślik W, Szałek A. The use of electric drive in urban driving conditions using a hydrogen powered vehicle – Toyota Mirai. Combust Engines. 2018;172:51–8.
23. Pielecha I. Control algorithms for a Range Extender vehicle with an combustion engine. Combust Engines. 2020;183(4): 3–10.
24. Qian KF, Liu XT. Hybrid optimization strategy for lithium-ion battery's State of Charge/Health using joint of dual Kalman filter and Modified Sine-cosine Algorithm. J Energy Storage. 2021;44.
25. Qiu C, Wang G. New evaluation methodology of regenerative braking contribution to energy efficiency improvement of electric vehicles. Energy Convers Manag. 2016;119:389–98.
26. Racewicz S, Kazimierczuk P. Light Two-Wheeled Electric Vehicle Energy Balance Investigation Using Chassis Dynamometer. Acta Mech Autom. 2020;14(4):175–9.
27. Rakha HA, Ahn K, Moran K, Saerens B, den Bulck E Van. Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Model development and testing. Transp Res Part D Transp Environ. 2011;16:492–503.
28. Rydh CJ, Sandén BA. Energy analysis of batteries in photovoltaic systems. Part I: Performance and energy requirements. Energy Convers Manag. 2005;46:1957–79.
29. Smith R, Shahidinejad S, Blair D, Bibeau EL. Characterization of urban commuter driving profiles to optimize battery size in light-duty plug-in electric vehicles. Transp Res Part D Transp Environ. 2011;16:218–24.
30. Triantafyllopoulos G, Kontses A, Tsokolis D, Ntziachristos L, Samaras Z. Potential of energy efficiency technologies in reducing vehicle consumption under type approval and real world conditions. Energy. 2017;140:365–73.
31. Zhang R, Yao E. Electric vehicles' energy consumption estimation with real driving condition data. Transp Res Part D Transp Environ. 2015;41:177–87.

Jacek Kropiwnicki: https://orcid.org/0000-0001-7412-7424

Tomasz Gawłas: https://orcid.org/0009-0005-1699-6193

DOI 10.2478/ama-2023-0035

Appendix A
Mathematical basis of the phenomenological correction of the road profile