Pomiary Automatyka Robotyka, ISSN 1427-9126, R. 27, Nr 1/2023, 85–92, DOI: 10.14313/PAR_247/85

The Effect of Driving Style on Battery Electric Vehicle Range

Piotr Błaszczyk, Michał Kopeć
Lodz University of Technology, Institute of Electrical Power Engineering, 20 Stefanowskiego Street, 90-537 Lodz, Poland

Abstract: The demand for electric vehicles is high due to the fact of their low travel costs. Meanwhile, an increase in the car driving range is expected. Hence, this paper examines different concepts related to driving a battery electric vehicle. The driving scenarios were divided into two parts. The first part consisted of four stages: driving in a mixed cycle, charging the battery, driving a very short distance, and driving distances that were within the maximum theoretical range of the batteries. The second part involved driving a distance until the range extender system was activated. The outcomes of these experimental investigations are described and the key findings are presented in the discussion.

Keywords: battery electric vehicle, driving style, driving range, energy consumption

1. Introduction

The operating principle of a battery electric vehicle (BEV) may differ from those of an internal combustion engine (ICE). A driver who uses an ICE is not necessarily involved in an economic drive for a variety of reasons [1, 2]. One of the reasons is the difference between BEVs and ICEs in the consumption of fuel. An aggressive driving style has an impact on the operating costs of a vehicle and the emission of environmental air pollutants [3]. The results of a study [4] demonstrated that the average fuel consumption under an aggressive style of driving in an urban area was up to 30 % higher than that during a calm style of driving. In motorway tests, the average fuel consumption increased by 4 %. This is different for BEVs, where unskilled driving significantly increases the energy requirement [5]. Therefore, many studies have been conducted on energy requirements, determining that the driving style is crucial [6–8]. In Poland, the topic of BEV is up to date. Poland is a leading manufacturer of batteries for BEV, and the production of Izera BEV was scheduled for two years. Scientists from i.a. Kielce, Warszawa, and Lublin are conducting research on electric cars. Scientists at the Warsaw University of Technology are conducting research on a new generation of batteries without substances such as fluoride, nickel, and cobalt [9, 10]. The specified chemical composition allowed for an increase in battery life. In turn, researchers from the Kielce University of Technology are focusing on the issue of introducing BEVs as an alternative to ICEs [11–13]. Such actions are very important due to reducing environmental pollution and improving air quality. These requirements relate to zero-emissions standards. The feeling of range connected with access to suitable EV charging outlets is very important [14]. Therefore, a minimum number of electric vehicle charging outlets has been determined [12], and even innovative charging stations were developed by scientists from Lublin, who are working on improving the methods of charging BEVs [15, 16].

Autor korespondujący:
Michał Kopeć, michal.kopec@p.lodz.pl

Artykuł recenzowany
nadesłany 10.10.2022 r., przyjęty do druku 10.01.2023 r.

Abbreviations used in article

Nomenclature	Description
BEV	battery electric vehicle
DtE	distance to empty
EC	energy consumption
ICE	internal combustion engine
SoC	state of charge
BR	battery's range
BR_{init}	initial battery range
E	energy
O	overestimation
S	distance
V	velocity

Energy consumption (EC) in BEVs should be considered in terms of the manner of EC in these vehicles and the type of driving range estimation algorithm. One of the research companies is the BMW brand, which has attempted to improve its I3 model. Studies focused on improving an electric vehicle's distance to empty (DtE) estimation. Studies [17–19] confirm that estimating the theoretical range of electric vehicles is inaccurate. Factors, such as driving style or heat pump operation in the heating mode, are not included in the estimation algorithm. Conventional DtE algorithms estimate the vehicle's future EC and the estimation results are displayed on the vehicle's dashboard as a theoretical range. Firstly, as long as the estimated error rate of the DtE is greater, there will be more changes from its past use to its future use, i.e., the more EC factors that occur (heating, defrosting, etc.), the more difficult it is to predict future EC. Accurate results will be displayed when the future use is similar to its past use or applicable information about its future use is known beforehand [19]. Secondly, energy measurements can be made in strictly defined locations. One may experience some problems while measuring energy as when energy is measured at the input of the motor, the motor controller and battery losses are not included [18].

Energy consumption models can be also found in the literature [20, 21]. However, these models do not include driving style parameters. In [20], a comprehensive model to measure an electric vehicle's EC and carbon emissions was developed. This model consisted of velocity, load, and distance parameters. In another work [21], vehicle mass, velocity, and gradient of the terrain were included. There were also models that assumed a linear dependence of the EC on the traveled distance [22, 23]. Real-life EC is not a linear function of traveled distance [21] as assumed in [22, 23]. Even more realistic models do not take into account driving styles. Although the above-mentioned papers analyzed the EC problem, they did not consider the case of driving styles. This is why the impact of driving style on the EC in BEVs is of great importance, as demonstrated in the conducted research. Therefore, the extendibility of the theoretical driving range considered in the driving style problem may be another promising research direction.

Due to the inaccuracies of the range estimation algorithm [17–19] and simulation models [20–23], an upgrade of the driving technique and DtE experiments should be considered. Moreover, the results of DtE experiments are not presented in the literature [24–29].

2. Materials and Methods

The main goal of the manuscript was to conduct the DtE tests and to show the impact of driving style on the range of BEVs. The tests were performed on a BEV with a REx System (i.e., BMW I3 REx from 2017). The tested car had the 0.65 dm^3 in-line two-cylinder engine with a 21.6 kW generator, a 125 · kW permanent magnet synchronous AC motor, and an 18.8 kWh lithium-ion battery (60 Ah BMW i3 REx). The REx System automatically recharges the battery using a combustion engine when its level is low [30]. The REx System's activation is loud, making it uncomfortable for everyday usage or onward travel [31]. The obtained data were read from the hidden service menu to avoid energy measurement problems described in [18]. In this case, each test was repeated at a full state of charge (SoC). To ensure accuracy, all used batteries were in warranty and free of any mechanical damage. The tests simulated driving on a daily basis. During the trials we assumed the following:

- The season was common to all tests;
- The air cooling was always turned off [17–19];
- The vehicle followed traffic regulations;
- The vehicle accelerated adequately according to the traffic conditions and driving style of the other drivers;
- The vehicle did not move while idling.

3. Results

The following results relate to the selected concepts of electric vehicle driving, which were different compared to the cataloged data considered in [45]. The presented results came from different stages of the research and were divided into two modules, which are described in Sections 3.1 and 3.2. For both modules, test drives of an electric vehicle powered by a battery were performed.

3.1. First test

The first stage of the test was a test drive in a mixed cycle. The obtained results are shown in Figure. 1, where the data were available in Polish. Subsequently, the English language equivalents are provided in Figure. 1. The first stage of the driving test was conducted for the distance (S) = 117 km, and the travel time was 176 min. The average EC for the S = 100 km was 11.2 kWh, and the average velocity (V) was 11.3 m/s.

During the second stage of the test, the battery was charged with an external charger powered by a 400 V network. We used the EC meter, LE-03MW [46], as it complies with the standard EN50470-1/3. After charging the battery, the theoretical driving range for the battery was 161 km, and the theoretical driving range for the REx System was 122 km (Fig. 2).

The aim of the third stage of the test was to verify the information shown on the on-board computer. The third stage consisted of driving of S = 100 m with a constant V equal to 0.67 m/s. When finished driving, the theoretical driving range for the battery was 140 km and the theoretical driving range for the REx System was 106 km (Fig. 3).

The fourth stage of the test related to a test distance that was within the maximum theoretical range of the battery. The fourth scenario was to drive distances of different lengths and consumptions of a part of the battery's energy (Table 1). One of the cases was performed for the S = 115 km, with the initial range of the battery being 161 km and the initial range for the fuel being 122 km. Having completed the distance S = 115.2 km,

10:07 RADIO
22:15 Start
2:56 h Czas
117 km Odcinek
11.2 kWh/100 km Zużycie
41.5 km/h Prędkość
Zresetuj
☐ Zresetuj automatycz.

Travel time
Distance
Energy consumption
Velocity

Fig. 1. Data from the on-board computer from the first stage of the first test
Rys. 1. Dane z komputera pokładowego; pierwszy etap pierwszego testu

Fig. 2. The theoretical ranges calculated by the on-board computer from the second stage of the first test
Rys. 2. Wskazanie zasięgu teoretycznego obliczone przez komputer pokładowy; drugi etap pierwszego testu

Fig. 3. The theoretical ranges after driving the test distance S = 100 m from the third stage of the first test
Rys. 3. Wskazanie zasięgu teoretycznego obliczone przez komputer pokładowy po przejechaniu odcinka S = 100 m; trzeci etap pierwszego testu

Tab. 2. Overestimations of the range
Tab. 2. Wartości przeszacowań zasięgu

Energy source	Battery Range, km	Distance, km	Overestimation, km
Battery	161	0	–
	140	0.1	20.9
	136	0.2	24.8
	80	43.6	37.4
	63	60.2	37.8
	21	100.3	39.7
	20	102.8	38.2
	16	111.4	33.6
Range Extender System	8	115.2	37.8

the battery's remaining range was 8 km, and the REx's range was 106 km. This leads to the conclusion that the discrepancies between the battery's range and the REx's range between the initial and final values were 37.8 km and 16 km, respectively. One can determine that the battery's range was overestimated by 37.8 km, which is inadequate according to the initial information. Another overestimation of the battery's range (Table 2) for other lengths of the test distances can be also calculated (1) in a similar manner. For example, at a distance of 100.3 km, the overestimation was 39.7 km, while at a distance of 200 m, the overestimation was 24.8 km. The overestimation was calculated as the difference between the initial range of the battery (161 km), the battery's range, and the distance of a given length. A detailed analysis of the results is described in Section 4.

$$O = BR_{init} - BR - S \qquad (1)$$

Here:
- O stands for overestimation of the range;
- BR_{init} is the initial battery range, a constant = 161 km;
- BR is the battery's range;
- S represents distance.

For the displayed battery range, statistical parameters such as mean $\overline{BR}$, median M_e, quartiles Q_1, Q_2, Q_3 and standard deviation σ were calculated. $\overline{BR}$ value was 72, M_e value was 63, Q_1 was 20, Q_2 was 63, Q_3 was 136, and σ value was 61. If the two longest distances i.e. 111.4 km and 115.2 km were not taken into account, the $\overline{BR}$ value would be 89, and σ value would be 58. This proves that the battery range value was incorrectly estimated by the on-board computer even after driving more than 100 km where the theoretical range should be predicted with high precision after recognizing factors such as ambient temperature or traffic conditions. Even dividing data using quartiles Q_1, Q_2, and Q_3, the distances do not match the on-board computer estimation.

The obtained results were also presented in Fig. 4. Figure. 4 shows the dependence of the distance in the function of the

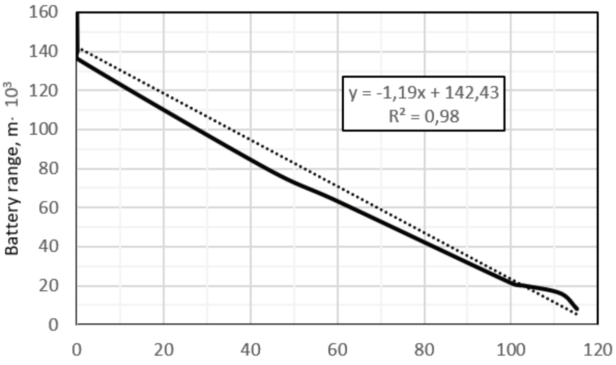

Fig. 4 Distance graph in the function of the battery range
Rys. 4. Wykres przejechanego dystansu w funkcji wyświetlanego zasięgu na pakiecie bateryjnym

Tab. 1. Energy (E) for a charging battery (E = 18.75 kWh) – cumulative data from the first test
Tab. 1. Zużycie energii do naładowania pakietu bateryjnego (E = 18,75 kWh) – zbiorcza tabela danych dla pierwszego testu

Energy source	Total Theoretical Range, km	Displayed Fuel Range, km	Displayed Battery Range, km	SoC, %	Ambient Temperature, K	Distance, km
Battery	283	122	161	100	299.65	0
	246	106	140	–	299.65	0.1
	240	104	136	–	299.65	0.2
	177	97	80	–	299.65	43.6
	161	98	63	52.5	300.15	60.2
	120	99	21	–	300.15	100.3
	121	101	20	16.0	300.15	102.8
	122	106	16	11.0	300.15	111.4
Range Extender System	114	106	8	6.5	300.15	115.2

Tab. 3. Energy (E) for a charging battery (E = 18.94 kWh) cumulative data from the second test
Tab. 3. Zużycie energii do naładowania pakietu bateryjnego (E = 18,94 kWh) – zbiorcza tabela danych dla drugiego testu

Energy source	Total Theoretical Range, km	Displayed Fuel Range, km	Displayed Battery Range, km	SoC, %	Ambient Temperature, K	Distance, km
Battery	258	106	152	100	293.15	0
	232	97	135	–	293.15	6.6
	271	147	124	–	293.15	6.8
	265	145	120	–	292.15	8.6
	259	143	116	–	290.15	8.9
	243	135	108	86.0	290.15	13.7
	167	125	42	39.0	288.15	52.2
	150	123	27	26.0	288.15	72.7
	146	129	17	16.5	289.65	84.9
Range Extender System	146	139	8	7.5	290.15	96.9
	155	146	9	8.0	291.65	104.9
	153	146	9	6.0	291.15	113.1

displayed battery range. It should be noted that the displayed battery range decreased linearly with the distance. Linear regression was obtained with a high correlation coefficient of 0.98. The results differ from linear dependence referring to the moment after starting and before REx System activation.

3.2. Second test

The second test started with charging the battery. The theoretical range for the battery was 135 km and the theoretical range for REx System was 151 km (Fig. 5).

In this scenario, the considered distance was 96.9 km. The distance was understood as driving until the REx System was activated. The example results are as follows: the displayed battery range changed from 152 km to 8 km (Table 3); thus, it decreased by 144 km. By contrast, the reverse was true for the displayed fuel range, where the theoretical distance increased by 33 km, from 106 km to 139 km. The information displayed on the monitor was optimistic, though imprecise. For the battery, the effective range was 33 % less than the theoretical range. The difference may be explained by the analysis of the power management solutions. One can easily observe that the report from the on-board computer confirms that the accumulated energy for a full SoC was 17.7 kWh (Fig. 6); however, all of the accumulated energy in the battery cannot be used. At an 8 % battery SoC, the REx System was automatically activated [47].

Fig. 5. The theoretical ranges calculated by the on-board computer from the first stage of the second test
Rys. 5. Wskazanie zasięgu teoretycznego obliczone przez komputer pokładowy; pierwszy etap drugiego testu

Fig. 6. Information regarding the full SoC
Rys. 6. Wskazanie na wyświetlaczu po naładowaniu pakietu bateryjnego

This solution is imposed by BMW, and it is not possible to interfere with the REx System's activation. By comparison, in [32], a 6 % battery SoC for the REx System was modeled for the 2014 BMW i3. The 8 % level corresponded to 1.42 kWh of remaining energy; hence, the usable energy was 16.28 kWh.

One of the declared parameters (Table 4) was the theoretical range that equaled 120 km with a 14.75 kWh/100 km EC. The declared parameters are impossible to reach for a 17.7 kWh battery capacity. The performed research confirmed that a 15 kWh/100 km EC is necessary to achieve 118 km of the theoretical range (Table 4). Based on the results of the investigations, it was proven that the catalog data strongly depended on the efficiency of the battery, which changed over time. If the efficiency of the battery changes, the catalog data should also change. After charging a battery several times, the efficiency decreased by 5.8 % in our studies. It is worth mentioning that the efficiency of the battery is due to the method of charging the battery [33, 34]. Decreasing the battery efficiency mainly affects the car's performance, and the catalog data cannot be achieved. Therefore, decreasing the battery capacity will discredit the achievement of the catalog data.

The battery efficiency was estimated at 94.2 %. This implies that its efficiency decreased by 5.8 % relative to the nominal rate. In addition, there was no problem with the power or its transfer to the traction system during the charging and discharging processes. Thus, it can be concluded that the battery was not worn out (which was confirmed by the battery management system (BMS) and the charger analysis system); thus, the energy was distributed evenly among the battery cells [35].

4. Discussion

Taking into account the main objectives of this paper, as formulated in the last paragraph of Section 1, one should address the given test suites as correct. However, there was a discrepancy between the obtained results and the catalog data. Therefore, it was essential to verify the information regarding the tested electric car. The main problem arises from the small transfer of experience from the use of an ICE to the use of a BEV [17, 36]. An inexperienced driver will have concerns about limited range in the middle of the trip [37]. This anxiety is reduced with experience, as the driver learns about his car during the trip [38]. However, the most experienced the car's capabilities, the greater concerns about the displayed range [38]. Range information changes because of factors not known or understood by drivers (silence while driving) [36], and the information is therefore deemed unreliable. The authors of [39] rightly concluded that "the most perfect device, in the hands of a person unprepared to handle it, becomes a useless device". This follows from the fact the use of a BEV is more difficult than the use of an engine vehicle or electric traction vehicle, resulting in energy efficiency. BEVs do not move along strictly defined routes and do not have scheduled places to stop in comparison to electric traction vehicles, where the traffic is planned ahead [40, 41]. The experience with the use of electric vehicles and implementation of the selected driving techniques allow for high energy efficiency. For clarity, the discussion was also divided into two parts. The first part describes the first test, and the second part describes the second test.

Testing began with a test drive and charging a battery (first and second stage of the first test). Based on the performed research, it was shown that the on-board computer calculated an instantaneous range [42]; thus, the theoretical range after charging (161 km) was higher than the traveled distance (117 km). An analysis of the theoretical ranges confirmed the thesis regarding the strong impact of the average EC. The theoretical distance changed when the motor started. Itself, the driver model in the used electric car is a moot point and can shorten the theoretical range. This problem is related to the small capacity of the battery; therefore, the range changes very dynamically depending mainly on the driving style. One solution to this problem could be limiting the vehicle's power, which reduces the EC. The reduction in EC could cause better management of the energy and, above all, a more realistic calculation of the range. A short $S = 100$ m with a constant V was also performed in the third stage of the first test. One may wonder why the overestimations of the theoretical ranges were so large, even for short distances (Table 2). Short distances shall be understood as 100 m and 200 m. For longer distances, one could assume that the causes of the overestimations were uphill driving and a strong wind blowing in the opposite direction of the travel [43]. However, in such cases, the overestimations for short distances should not be so drastic (up to 24.8 km). This confirms the analysis was intended to prove the calculation of the averaged EC with respect to the last drive.

In the second test, the first attempt at driving was made until the REx System was activated. The first attempt was performed for the $S = 96.9$ km, where the change in the displayed battery range decreased by 144 km, and for the displayed fuel range it increased by 33 km (Table 3). The changes in the displayed ranges concern the effective range. Longer distances (after REx activation), (i.e., 104.90 km and 113.10 km) were also characterized by a similar relationship. In addition, the fuel range did not change for longer distances, as it had a constant value of 146 km. The REx System generated power for the battery from the ICE; thus, the fuel range value should decrease. This is what should be considered a wrong algorithm. In the catalog data [34], one can find notice of the REx System's activation. The system is activated when the battery

Tab. 4. Comparison of the tests and catalog data
Tab. 4. Zestawienie uzyskanych wyników i danych katalogowych

Parameter	Battery Capacity, kWh	Power taken from the Grid, km	Distance, km	Energy Consumption kWh/100 km	Energy Consumption by the I3REx, kWh/100 km	Theoretical Range of the I3REx, km	Distance Discrepancy, %	Energy Consumption Discrepancy, %
First test	16.55	18.75	115.2	14.36	14.00	116.3	1	3
Second test	16.37	18.99	96.9	16.89	15.10	107.8	11	12
Catalog data (averaged minimum energy consumption)	17.7	Catalog data			15	118	–	–
Catalog data (averaged maximum energy consumption)	17.7	Catalog data			18	98	–	–
Catalog data (minimum battery range)	17.7	Catalog data			14.75	120	–	–
Catalog data (maximum battery range)	17.7	Catalog data			11.80	150	–	–
Catalog data (NEDC[1])	17.7	Catalog data			13.50	131	–	–

[1] NEDC – New European Driving Cycle

level is below 8 %. This internal control system is not generally available, and it is not possible to interfere with it. Only the on-board computer determines the REx System's activation. However, despite this, the 8 % level is a debatable value. The precise determinations of the SoC at the time of the REx System's activation were from 6.5 % to 7.5 %, which corresponded to 1.15 kWh and 1.33 kWh.

The battery's efficiency as well as the influence of different factors on its efficiency are also subjects worth discussing. The reliability of batteries requires an efficient battery management system. Charging/discharging rates and temperature affect the battery's efficiency. In [44], two main factors were taken into account: charging/discharging rates and temperature. The main factors that affected the battery's efficiency were technological and consumable. The technological factor depended on the final quality of the battery cells, the choice of voltage correctness in every cell, and the technological quality of battery balancing for the charging and discharging processes. Firstly, the energy is stored in the battery, and then there is the balancing process. The balancing process begins when the energy in the battery is at an 80 % level, and it is necessary to stabilize the voltage in each cell. It is important not to disconnect a charger and perform the balancing process. The consumable factor depended on the driver's experience and the way that the battery was used.

A discussion regarding the discrepancy between the obtained results of the test drives was also established. Let's compare the fourth stage of the first test (S = 115.2 km) and the second test (S = 96.9 km). One should notice that the test drives were made for different pre-programmed modes. The following two pre-programmed modes were considered: eco and comfort. The arrangement of these driving modes characterizes different driving strategies. The eco mode is designed for maximum ranges where driving comfort is not important, for example, the air conditioning is turned off. The comfort mode, by contrast, is designed for maximum driving comfort where ranges are not so important. When the comfort mode is selected, the driver expects better conditions inside the cabin and is able to increase travel costs by increasing comfort. Here, the energy is used up on electrical devices. The obtained results are incompatible with the idea of the manufacturer. The distance in the comfort mode should be shorter than in the eco mode and reach 115.2 km for comfort mode and 96.9 km for eco mode. These results do not deny the manufacturer's technology; it only shows how important is the driver's role in the electric car. An experienced driver with technical knowledge regarding an electric car can achieve a better result in the comfort mode with a proper driving style. An inexperienced driver will obtain a shorter distance, even in the eco mode.

Experimental observations of BEVs are important and help to understand their EC characteristics. This article can be considered as a source of data for the development of a new EC model taking into account driving styles. The results of the research presented in this paper are encouraging, especially on urban routes where traffic conditions change rapidly and are unstable (i.e., stop-and-go). Urban routes are understood as the flow of traffic with a large number of crossroads, devices that break off traffic, and the presence of pedestrians and cyclists. Driving on extra-urban routes is more stable (i.e., a constant V). The scenarios adopted in the research process can be useful for battery electric producers or consumers. If the manufacturers provide cars for testing before buying and keep statistics, then it will be possible to choose the appropriate drive train. The drive train would be personalized to the individual person, which would decrease operational costs by reducing the battery capacity and its weight. All of this results in energy savings.

In conclusion, the conducted research showed the importance of driving styles. Even when driving according to the regulations, one may observe an increase in EC. As a result, the theoretical range was significantly lower than the vehicle's specifications or those displayed on the on-board monitor. This exposes drivers to low psychological comfort and more frequent charging. The measurements show that the driving style reduced the theoretical range of BEVs. In particular:

- The DtE value was different from the prediction of the on-board computer. The on-board computer calculated an instantaneous range;
- The battery range was lowered by 21 km after only 100 meters of driving. The reason is averaging EC with respect to the last drive;
- The precisely determined SoCs were from 6.5 % to 7.5 % at the time of the REx System's activation;
- An experienced driver with technical knowledge regarding an electric car can achieve a better result in the comfort mode with a proper driving style;
- The used battery efficiency was estimated at 94.8 % and therefore the catalog data cannot be achieved (Table 4);

The presented results concern the BMW I3 REx from 2017, but it should be noted that the manufacturer introduced significant changes to the next model in 2018. The changes relate to the battery's energy management system, and this was because of the environmental requirements and the assumption that a BEV should have zero emissivity. Thus, eco-friendly vehicles cannot be supported by an ICE, as a BMW with a REx system.

References

1. Sehil K., Alamri B., Alqarni M., Sallama A., Darwish M., *Empirical Analysis of High Voltage Battery Pack Cells for Electric Racing Vehicles.* "Energies", Vol. 14, No. 6, 2021, DOI: 10.3390/en14061556.
2. Ehsani M., Gao Y., Gay S.E., Emadi A., *Modern Electric Hybrid Electric and Fuel Cell Vehicles*; CRC Press: Boca Raton, FL, USA, 2005.
3. Türler D., Hopkins D., Goudey H., *Reducing Vehicle Auxiliary Loads Using Advanced Thermal Insulation and Window Technologies.* SAE International, 2003.
4. Helmers E., Dietz J., Weiss M., *Sensitivity Analysis in the Life-Cycle Assessment of Electric vs. Combustion Engine Cars under Approximate Real-World Conditions.* "Sustainability", Vol. 12, No. 3, 2020, DOI: 10.3390/su12031241.
5. Szumska E., Jurecki R., *The Effect of Aggressive Driving on Vehicle Parameters.* "Energies", Vol. 13, No. 24, 2020, DOI: 10.3390/en13246675.
6. Xian T.F., Soon C.M., Rajoo S., Romagnoli A., *A Parametric Study: The impact of Components Sizing on Range Extended Electric Vehicle's Driving Range.* Asian Conference on Energy, Power and Transportation Electrification (ACEPT), Singapore, 25-27 October 2016, DOI: 10.1109/ACEPT.2016.7811511.
7. Jurecki R.S., Stańczyk T.L., *A Methodology for Evaluating Driving Styles in Various Road Conditions.* "Energies", Vol. 14, No. No. 12, 2021, DOI: 10.3390/en14123570.
8. Benderius O., Markkula G., Wolff K., Wahde M., *Driver behaviour in unexpected critical events and in repeated exposures – a comparison.* "European Transport Research Review", Vol. 6, 2014, 51–60, DOI: 10.1007/s12544-013-0108-y.
9. Bitner-Michalska A., Nolis G.N., Żukowska G., Zalewska A., Poterała M., Trzeciak T., Dranka M., Kalita M., Jankowski P., Niedziecki L., Zachara J., Marcinek M., Wieczo-

rek W., *Fluorine-free electrolytes for all-solid sodium-ion batteries based on percyano-substituted organic salts.* "Scientific Reports, Vol. 7, 2017, DOI: 10.1038/srep40036.

10. Marcinek M., Syzdek J., Marczewski M., Piszcz M., Niedziecki L., Kalita M., Plewa-Marczewska A., Bitner A., Wieczorek P., Trzeciak T., Kasprzyk M., Łężak P., Żukowska Z., Zalewska A., Wieczorek W., *Electrolytes for Li-ion transport – Review.* „Solid State Ionics", Vol. 276, 2015, 107–126, DOI: 10.1016/j.ssi.2015.02.006.
11. Sendek-Matysiak E., Grysa K., *Assessment of the Total Cost of Ownership of Electric Vehicles in Poland.* "Energies", Vol. 14, No. 16, 2021, DOI: 10.3390/en14164806.
12. Sendek-Matysiak E., Pyza D., *Prospects for the development of electric vehicle charging infrastructure in Poland in the light of the regulations in force.* "Archives of Transport", Vol. 57, No. 1, 2021, 43–58.
13. Sendek-Matysiak E., *Multi-criteria analysis and expert assessment of vehicles with different drive types regarding their functionality and environmental.* "Scientific Journal of Silesian University of Technology", Vol. 102, 2019, 185–195, DOI: 10.20858/sjsutst.2019.102.15.
14. Szumska E.M., Jurecki R.S., *Parameters influencing on electric vehicle range.* "Energies", Vol. 14, No. 16, 2021, DOI: 10.3390/en14164821.
15. Yadav A.K., Gopakumar K., Krishna R., Umanand L., Bhattacharya S., Jarzyna W., *A Hybrid 7-Level Inverter Using Low-Voltage Devices and Operation With Single DC--Link.* "IEEE Transactions on Power Electronics", Vol. 34, No. 10, 2019, 9844–9853, DOI: 10.1109/TPEL.2018.2890371.
16. Majumder M.G., Rakesh R., Gopakumar K., Al-Haddad K., Jarzyna W., *A Fault-Tolerant Five-Level Inverter Topology With Reduced Component Count for OEIM Drives.* "IEEE Journal of Emerging and Selected Topics", Vol. 9, No. 1, 2021, 961–969, DOI: 10.1109/JESTPE.2020.2972056.
17. Qi J., Lu D.D.-C., *Review of battery cell balancing techniques.* Australasian Universities Power Engineering Conference (AUPEC), 2014, DOI: 10.1109/AUPEC.2014.6966514.
18. Rodgers L., Zoepf S., Prenninger J., *Analysis the energy consumption of the BMW ActiveE field trial vehicles with application to distance to empty algorithms.* "Transportation Research Procedia". Vol. 4, 2014, 42–54, DOI: 10.1016/j.trpro.2014.11.004.
19. Rodgers L., *Estimating an Electric Vehicle's "Distance to Empty" Using Both Past and Future Route Information.* Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Oregano, 2013.
20. Li J., Wang F., He Y., *Electric Vehicle Routing Problem with Battery Swapping Considering Energy Consumption and Carbon Emissions.* "Sustainability", Vol. 12, No. 14, 2020, DOI: 10.3390/su122410537.
21. Goeke D., Schneider M., *Routing a mixed fleet of electric and conventional vehicles.* "European Journal of Operational Research", Vol. 245, No. 1, 2015, 81–99, DOI: 10.1016/j.ejor.2015.01.049.
22. Schneider M., Stenger A., Goeke D., *The Electric Vehicle--Routing Problem with Time Windows and Recharging Stations.* "Transportation Science", Vol. 48, No. 14, 2014, 500–520, DOI: 10.1287/trsc.2013.0490.
23. Erdogan S., Miller-Hooks E., *A Green Vehicle Routing Problem.* "Transportation Research Part E. Logistics and Transportation Review", Vol. 48, No. 1, 2012, 100–114, DOI: 10.1016/j.tre.2011.08.001.
24. Hayes J., de Oliveira R., Vaughan S., Egan M., *Simplified Electric Vehicle Power Train Models and Range Estimation.* Vehicle Power and Propulsion Conference (VPPC), Chicago, 2011, DOI: 10.1109/VPPC.2011.6043163.
25. Karbowski D., Pagerit S., Calikns A., *Energy Consumption Prediction of a Vehicle along a User-Specified Real-World Trip.* "World Electric Vehicle Journal", Vol. 5, No. 4, 2012, 1109–1120, DOI: 10.3390/wevj5041109.
26. Minett C., Salomons M., Daamen W., van Arem B., Kuijpers S., *Eco-routing: Comparing the fuel consumption of different routes between an origin and destination using field test speed profiles and synthetic speed profiles.* IEEE Forum on Integrated and Sustainable Transportation System, Vienna, 2011, DOI: 10.1109/FISTS.2011.5973621.
27. Zhang Y., Wang W., Kobayashi Y., Shirai K., *Remaining Driving Range Estimation of Electric Vehicle.* IEEE International Electric Vehicle Conference, Greenville, USA, 2012, DOI: 10.1109/IEVC.2012.6183172.
28. Ferreira J., Monteiro V., Afonso J., *Data Mining Approach for Range Prediction of Electric Vehicle.* Conference on Future Automotive Technology – Focus Electromobility, Germany, 2012.
29. Yu H., Tseng F., McGee R., *Driving Pattern Identification for EV Range Estimation.* IEEE International Electric Vehicle Conference, Greenville, USA, 2012, DOI: 10.1109/IEVC.2012.6183207.
30. Kopczyński A., Krawczyk P., Lasocki J., *Parameters selection of extended-range electric vehicle supplied with alternative fuel.* E3S Web of Conference, Vol. 44, 2018, DOI: 10.1051/e3sconf/20184400073.
31. Styler A., Sauer A., Rottengruber H., *Learned Optimal Control of a Range Extender in a Series Hybrid Vehicle.* IEEE 18th International Conference on Intelligent Transportation System, Gran Canaria, Spain, 2018, 2612–2618, DOI: 10.1109/ITSC.2015.420.
32. Miri I., Fotouhi A., Ewin N., *Electric vehicle energy modelling and estimation – A case study,* "International Journal of Energy Research", Vol. 45, No. 1, 2020, 501–520, DOI: 10.1002/er.5700.
33. Chiasserini C.F., Rao R.R., *Routing protocols to maximize battery efficiency.* MILCOM 2000 Proceedings. 21st Century Military Communications. Architectures and Technologies for Information Superiority (Cat. No.00CH37155), Los Angeles, CA, USA, 2000, DOI: 10.1109/MILCOM.2000.905002.
34. Jeong K.S., Lee W.Y., Kim C.S., *Energy management strategies of a fuel cell/battery hybrid system using fuzzy logics.* "Journal of Power Sources", Vol. 145, No. 2, 2005, 319–326, DOI: 10.1016/j.jpowsour.2005.01.076.
35. Franke T., Neumann I., Bühler F., Cocron P., Krems J.F., *Experiencing Range in an Electric Vehicle: Understanding Psychological Barriers.* "Applied Psychology", Vol. 61, No. 3, 2012, 368–391, DOI: 10.1111/j.1464-0597.2011.00474.x.
36. Strömberg H., Andersson P., Almgren S., Ericsson J., Karlsson M., Nåbo A., *Driver interfaces for electric vehicles.* AUI2011 Proceedings of the 3rd International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Salzburg, Austria, 2011, 177–184, DOI: 10.1145/2381416.2381445.
37. Cocron J., *Expectations and experiences of drivers using an EV: Findings from a German field study.* Abstacts of the 27th International Congress of Applied Psychology, Melbourne, Australia, 11–16 July 2010.
38. Hoffman J., *Does use of battery of battery electric vehicles change attitudes and behaviour?* Abstacts of the 27th International Congress of Applied Psychology, Melbourne, Australia, 11–16 July 2010.
39. Kubik A., Turoń K., Stanik Z., *Car-sharing systems vehicles versus taxis in urban transport system – legal requirements, technical service, operation.* International Conference on Traffic and Transport Engineering. ICTTE, Belgrade, Serbia, 27–28 September 2018, 923–930.

40. Hansen I., Pachl J., *Railway Timetabling and Operations*, 2nd ed.; Eurailpress: Hamburg, Germany, 2014.
41. Croce A.I., Musolino G., Rindone C., Vitetta A., *Traffic and Energy Consumption Modelling of Electric Vehicles: Parameter Updating from Floating and Probe Vehicle Data*. "Energies", Vol. 15, No. 1, 2022, DOI: 10.3390/en15010082.
42. Ondruska P., Posner I., *Probabilistic Attainability Maps: Efficiently Predicting Driver-Specific Electric Vehicle Range*. IEEE Intelligent Vehicles Symposium (IV), 2014, DOI: :10.1109/IVS.2014.6856572.
43. Liu K., Yamamoto T., Morikawa T., *Impact of road gradient on energy consumption of electric vehicles*. "Transportation Research Part D. Transport and Environment", Vol. 54, 2017, 74-81, DOI: 10.1016/j.trd.2017.05.005.
44. Lu L., Han X., Li J., Hua J., Ouyang M., *A review on the key issues for lithium-ion battery management in electric vehicles*. "Journal of Power Sources", Vol. 226, 2013, 272–288, DOI: 10.1016/j.jpowsour.2012.10.060.

Other sources

45. BMW i3. www.bmw.pl/i3 (accessed on 25 February 2022).
46. LE-03MW F&F. www.tme.com/ca/en/details/le-03mw/energy-meters/f-f/ (accessed on 25 February 2022).
47. BMW. BMW i3 Contents A-Z; Poland, 2008; pp. 1–257.

Wpływ stylu jazdy na zasięg samochodu elektrycznego

Streszczenie: Popyt na pojazdy elektryczne jest duży ze względu na niskie koszty podróży. Jednocześnie spodziewany jest wzrost zasięgu. Dlatego w niniejszym artykule przeanalizowano różne koncepcje związane z prowadzeniem pojazdu elektrycznego. Scenariusze jazdy zostały podzielone na dwie części. Pierwsza część składała się z czterech etapów: jazdy w cyklu mieszanym, ładowania pakietu bateryjnego, przejazdu bardzo krótkiego odcinka oraz przejazdu odcinków o różnej długości, mniejszej niż maksymalny zasięg teoretyczny. Druga część polegała na przejechaniu odcinka do momentu aktywacji systemu REx. Wyniki przeprowadzonych badań zostały zaprezentowane, a kluczowe ustalenia przedstawiono w sekcji dyskusji.

Słowa kluczowe: samochód elektryczny, styl jazdy, zasięg pojazdu, zużycie energii

Piotr Błaszczyk, PhD

piotr.blaszczyk@p.lodz.pl
ORCID: 0000-0002-0397-3313

He is currently an Assistant Professor with the Institute of Power Engineering, Lodz University of Technology. His research interests include problems of designing drivetrains, power supply and control in battery electric vehicles, and control of electric machines and drivetrains.

Michał Kopeć, PhD

michal.kopec@p.lodz.pl
ORCID: 0000-0003-1431-6201

He was born in Zgierz, Poland. He received the PhD degree in electronic engineering in 2021 from Lodz University of Technology, Lodz, Poland. He is currently an Assistant Professor with the Institute of Power Engineering, Lodz University of Technology. His research interests include nondestructive testing using infrared cameras and heat transfer problems.