Article citation info:
PIELECHA I, PIELECHA J. Simulation analysis of electric vehicles energy consumption in driving tests. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2020; 22 (1): 130–137, http://dx.doi.org/10.17531/ein.2020.1.15.

Ireneusz PIELECHA
Jacek PIELECHA

SIMULATION ANALYSIS OF ELECTRIC VEHICLES ENERGY CONSUMPTION IN DRIVING TESTS

SYMULACYJNA ANALIZA ENERGOCHŁONNOŚCI POJAZDÓW ELEKTRYCZNYCH W TESTACH BADAWCZYCH*

The assessment of energy flow through electric vehicle systems makes estimating their energy consumption possible. The article presents analyzes of the energy consumption of electric vehicles in selected driving tests (NEDC, WLTC and in real traffic conditions – RDC test) in relation to the vehicles different curb weight. The use of electric motors was also analyzed, providing their operating ranges, data of the energy flow in batteries and the change in their charge level. Simulation tests and analyzes were carried out using the AVL Cruise software. It was found that despite similar vehicle energy consumption values in NEDC and RDC testing, there are significant differences in energy flow in vehicle subsystems. The changes in the battery charge level per 100 km of test drive are similar in both the WLTC and RDC tests (6% difference); for the NEDC test, this difference is the greatest at 25% (compared to the previous tests). The energy consumption of electric vehicles depends significantly on the test itself; the values obtained in the tests are in the ranges of 10.1–13.5 kWh/100 km (NEDC test); 13–15 kWh/100 km (WLTC test) and 12.5–16.2 kWh/100 km in the RDC test. The energy consumption values in the NEDC and WLTC tests, compared to the RDC test, are approximately 20% and 10% lower, respectively. Increasing the vehicle mass increases the energy consumption (increasing the vehicle mass by 100 kg was found to increase the energy consumption by 0.34 kWh/100 km).

Keywords: *automotive vehicles, electric drive, high voltage batteries, energy flow, driving tests.*

Ocena przepływu energii przez układy pojazdów elektrycznych umożliwia oszacowanie ich energochłonności. W artykule przedstawiono analizy dotyczące zużycia energii pojazdów elektrycznych w wybranych testach jezdnych (NEDC, WLTC oraz w rzeczywistych warunkach ruchu – test RDC) w odniesieniu do zróżnicowanej masy pojazdów. Analizie poddano również wykorzystanie silników elektrycznych, przedstawiając mapy ich pracy, wielkości przepływu energii w akumulatorach oraz stopień zmiany ich naładowania. Badania i analizy symulacyjne wykonano z wykorzystaniem oprogramowania AVL Cruise. Stwierdzono, że mimo podobnych wartości energochłonności pojazdów w testach badawczych NEDC oraz RDC, to występują znaczące różnice przepływu energii w układach akumulacji pojazdów. Zmiany stopnia naładowania akumulatora odniesione do 100 km testu są zbliżone w testach WLTC oraz RDC (różnica 6%); dla testu NEDC różnica ta wynosi maksymalnie 25% (w odniesieniu do poprzednich testów). Energochłonność pojazdów elektrycznych jest silnie zależne od testu badawczego; wartości uzyskane w testach kształtują się na poziomie 10,1–13,5 kWh/100 km (test NEDC); 13–15 kWh/100 km (test WLTC) oraz 12,5–16,2 kWh/100 km w teście RDC. Wartości energochłonności w testach NEDC oraz WLTC są odpowiednio mniejsze o około 20% i 10% w odniesieniu do testu RDC. Zwiększenie masy pojazdu zwiększa zużycie energii (zwiększenie o 100 kg masy pojazdu zwiększa zużycie energii o 0,34 kWh/100 km).

Słowa kluczowe: *pojazdy samochodowe, napęd elektryczny, akumulatory wysokonapięciowe, przepływ energii, testy jezdne.*

1. Introduction

The push towards the reduction of fuel consumption of motor vehicles equipped with internal combustion engines (and hybrid drives) also drives an increase in the production of vehicles with electric propulsion systems, which leads to an increase in their share in the total number of vehicles in use. Changes to the requirements for reducing fuel consumption from the vehicle fleet by 2030 should be expected to contribute significantly to the development of electromobility [3] while also reducing greenhouse gas emissions.

Sales of electric vehicles (BEV – battery electric vehicle) on the global markets are increasing, however, their share in the overall car market is still not very large. The average European market share of EVs (electric vehicles) is about 2.5%, despite 200,000 units being sold in 2018 (Fig. 1). The most dynamic market is currently the Chinese market, with more than 800,000 new electric vehicle registrations in 2018. Despite this, the share of BEVs there is about 3.5%. In Europe, Norway is at the forefront with 45,000 new registrations in 2018 (the market share of BEVs there currently stands at 29%). In Poland, the share of BEVs is set at a low point of 0.4% [10]; at the end of July 2019, only 4009 electric vehicles were registered [14].

The last few years have seen a large increase in electric vehicle models in a whole range of segments (Fig. 2). The largest increase in models could be observed in the Chinese market – in all segments, where about 120 EV models are available. Compared to that there are only about 20 models on the European market – and half that on the American market [5]. Of the total vehicle sales in 2018 on the Chinese market, 90% were small cars. The development of electric crossovers and SUVs is, however, observed on the European market.

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

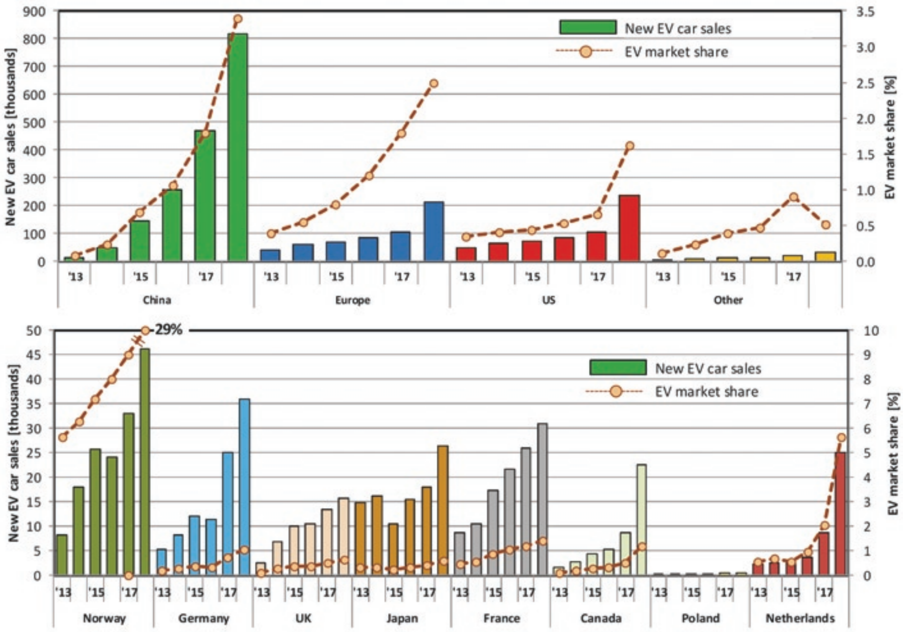


Fig. 1. Worldwide sales of electric vehicles and their share in the markets of selected countries and regions [5]

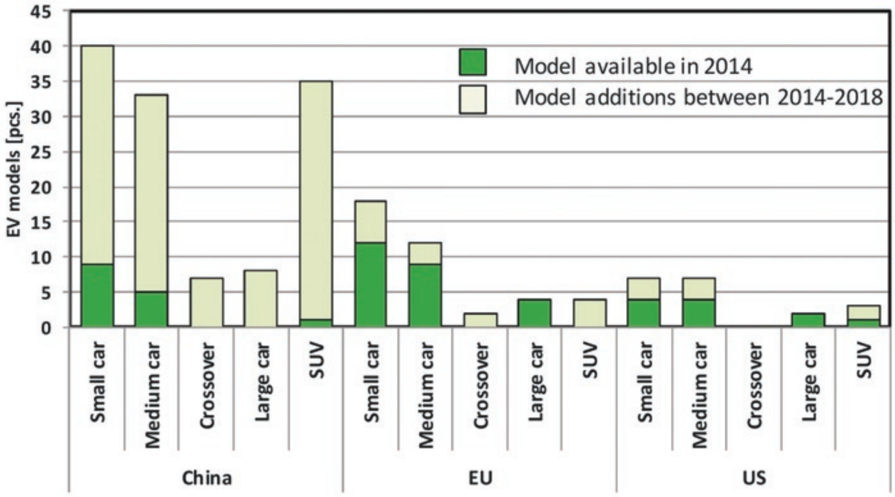


Fig. 2. Electric vehicle models divided into categories available on the markets of selected regions [5]

There are 20 BEV models officially available on the Polish market (including vans) [14]. Their range is quite diverse and is between 100 km to 540 km (in the NEDC test – New European Driving Cycle), this range is provided by batteries with capacities between 6.1 kWh and 90 kWh, respectively. The list does not include Tesla vehicles, as their official sales (on-line) only began at the end of August 2019.

The Transport & Environment [10] estimates that the share of electric vehicles in 2025 will reach around 8% of total sales and nearly 17% by 2030.

The analysis of energy consumption in conventional drive systems is based on the fuel consumption values or the carbon dioxide emissions. However, exhaust emission tests of motor vehicle drives indicate large discrepancies (between 30–40%) in fuel consumption and CO_2 emissions between type approval tests and the real driving conditions [4].

The carbon dioxide emission values are also influenced by the vehicle operating conditions as well as any equipment designed to reduce fuel consumption at a standstill. The impact of various test routes and the use of the start-stop system were the subject of research conducted during real-world traffic tests for passenger cars [8]. It was stated there that the non-repeatable nature of the vehicle operating conditions on the same test route may cause a difference in the value of carbon dioxide emissions of about 26%. Additionally, the use of the start stop system makes it possible to reduce this emission by a further 11–15%.

The impact of dynamic conditions in road tests on carbon dioxide emissions was also assessed [6]. These tests, known as RDC (Real Driving Conditions), have been required since 2018 as a part of the vehicle type approval process. The authors concluded that there is a strong relationship between carbon dioxide road emissions and dynamic driving conditions. It has been shown that doubling the value of relative positive acceleration results in a 3-fold increase in carbon dioxide road emissions.

According to Pavlovic et al. [11] CO_2 emissions in the WLTC test are approximately 10% higher than those in the NEDC test (for vehicles with SI engines with a curb weight of approximately 1500 kg), while energy consumption is increased by approximately 40% (for vehicles with SI engines).

Simulation tests of fuel consumption and CO_2 emissions using AVL Cruise conducted by Tsokolis et al. [16] indicate differences in values obtained from NEDC and WLTC tests. These differences were observed for over 63% of tested vehicles with SI engines and for 81% of vehicles with CI engines. CO_2 emissions were on average 11% higher for all vehicles in the WLTC test compared to the NEDC test. The average efficiency values were higher in the WLTC test (than in NEDC) and they amounted to: engine efficiency – 31% (compared to 25%) and vehicle efficiency – 26% (compared to 21%).

Electric vehicle propulsion analysis is currently considered in two forms. The first concerns vehicle tests, the other – simulation tests. Both test variants can be combined to determine the energy consumption of an electric vehicle.

Analyzes conducted by Wu et al. [18] indicate a higher efficiency of electric drive system in urban traffic than in the conditions of highway traffic. This is due to the greater potential for energy recovery in urban driving conditions.

The analysis of energy flow in hybrid vehicles in real traffic had been carried out for several years now [12, 13, 17]. The analysis of such drive systems is based primarily on the analysis of electrical energy use by vehicles while excluding fuel consumption. This is due to the fact that the internal combustion engine works in part as an electric power generator, which allows increasing the energy capacity of the vehicle's battery.

Current research on the electric vehicle energy consumption reduction relates to analyzes towards the optimization of the electric motors torque [19], limiting the losses generated by electric motors [15], the vehicles speed profile [1], the problem of route selection in the aspect of charging stations [7, 20], and optimization of the charging infrastructure [2, 9].

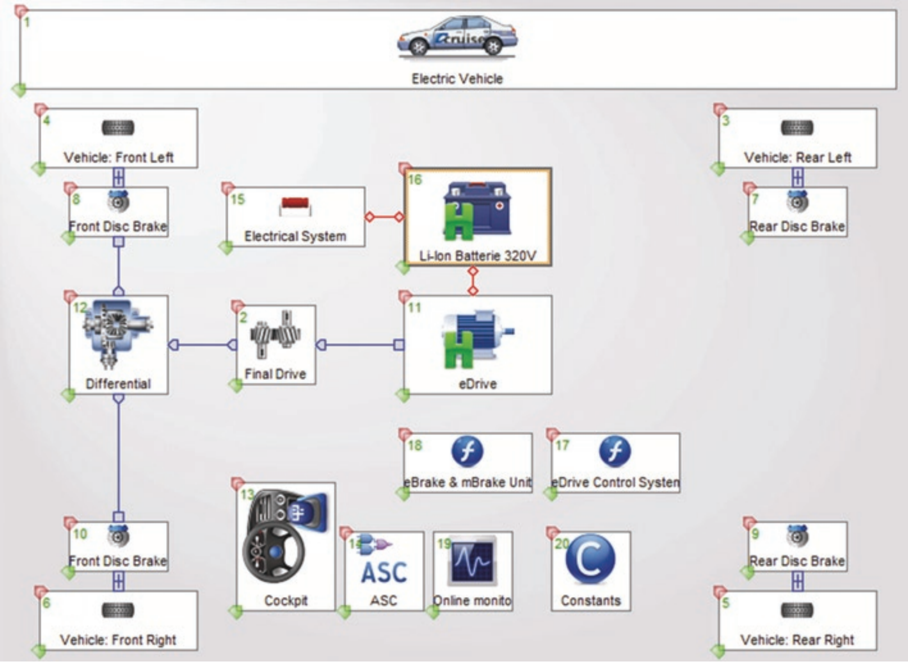
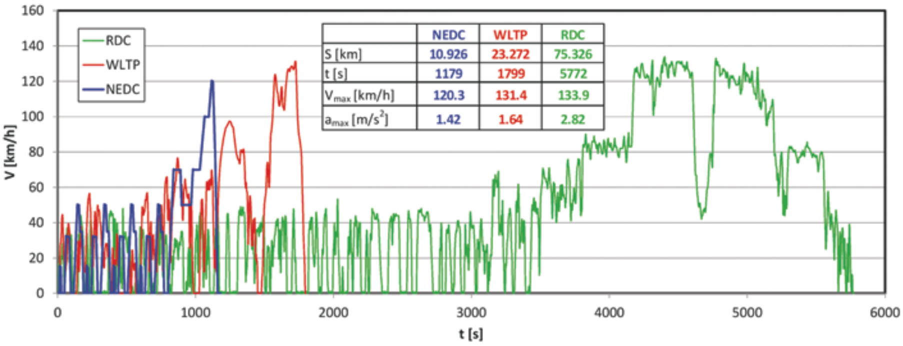


Fig. 3. Diagram of the electric vehicle drive system (AVL Cruise)



	NEDC	WLTP	RDC
S [km]	10.926	23.272	75.326
t [s]	1179	1799	5772
V_{max} [km/h]	120.3	131.4	133.9
a_{max} [m/s^2]	1.42	1.64	2.82

Fig. 4. Driving tests used in the research and their characteristics

The main aim of the research is to determine the differences in specific electricity consumption of motor vehicles in driving tests. It is therefore necessary to answer the question: to what extent different tests influence the estimation of specific energy consumption and whether it is possible to use such tests interchangeably. An additional factor taken into account in the tests was the variable vehicle mass.

2. Testing method

The research was carried out using AVL Cruise simulation software. It is a system enabling the simulation of a drive system (BEV, HEV or conventional), whose special features include: (1) the division of the drive system into functional elements with predefined characteristics of individual components; (2) the model structure and solution algorithm being independent; (3) generation of equations based on full system definition and (4) multi-threaded data models integrity.

An electric vehicle with variable curb weight was modeled, the structural model of which was shown in Fig. 3. The technical characteristics of the vehicle were shown in Table 1.

Table 1. Technical data of the simulated vehicle and drive system

Vehicle		
Curb weight	1000; 1500; 2000	kg
Wheelbase	2467	mm
Electric circuit		
Battery	Li-Ion, 25 kWh	
Nominal voltage	360	V
Cell capacity × number of cells	36 × 2	Ah
Electric motor		
Type	asynchronous	
Torque	240 @ 0–3000	Nm@rpm
Transmission		
Gear ratio	6.058	

Energy consumption tests were carried out in relation to various driving tests (NEDC, WLTC and RDC) and for a vehicle with different curb weights (1000; 1500 and 2000 kg). The characteristics of the driving tests are shown in Fig. 4. The tests included the current NEDC driving test, the modern WLTC driving test and the RDC road test. These are characterized by a varied driving profile, different test route lengths and similar maximum driving speeds. Due to the different acceleration curves, different total energy consumption is expected.

3. Vehicle electric drive characteristics

The electric drive tests were carried out at a constant initial value of the battery charge level (SOC = 95%). Because recharging was only possible during regenerative braking, this value has not been changed. It was found that the type of driving test used significantly affects the final battery state of charge (Fig. 5). The shortest test (NEDC) causes a few percent change in the battery SOC. Increasing the length and intensity of the test results in lower final SOC values. Taking into account the length of the driving test, the final SOC value per 100 km of the test distance was determined. The final value ΔSOC/100 km in the NEDC test (taking into account the initial battery charge of 95%) was 53%, while in the WLTC test it was 42%, and in the RDC test – 45%. This means that the SOC final values were not the smallest in most aggressive RDC driving test. The maximum ΔSOC variations between the tests were 11% (NEDC and WLTC) and the values were small when comparing the ΔSOC of the WLTC and RDC tests – 3%.

In addition, an increase in vehicle curb weight causes a 5% change in SOC (NEDC test), and a 12% change for the WLTC test. During the RDC test, the vehicle weight results in the most significant changes the final SOC values. An increase in weight of 100 kg reduces battery state of charge by approximately 4% on average. This value is very important,

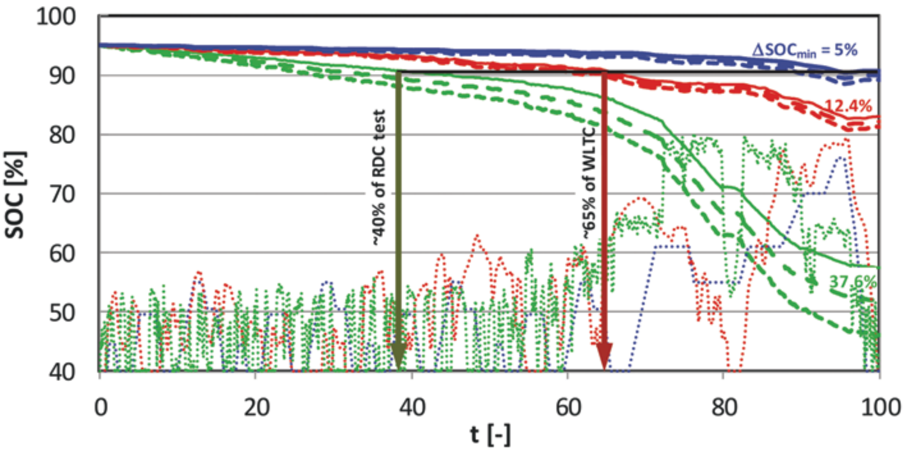


Fig. 5. Analysis of changes in the battery state of charge for different vehicle curb weights (1000 kg – solid line, 1500 kg – long dashed line, 2000 kg – short dashed line) and various driving tests)

because with a minimum vehicle weight (1000 kg) the change in the SOC value in this test was already as high as 95 – 57 = 38%. Considering that the total energy of the battery is 25 kWh and its operating capacity lies in the real SOC range of 20–80%, the change in the battery's SOC was already 63% of its entire usable energy. This means that 1/3 of the SOC changes were responsible for 2/3 of the effective energy of a Li-Ion battery.

In addition, it was found that the maximum change in SOC obtained in the NEDC test occurs after just 40% of the RDC test length and 65% of the WLTC test duration. This means that the driving test selection greatly influences the final SOC value of the battery.

To assess the range of used operating parameters of the electric motors, a fixed matrix was used in the coordinates Mo = f(n) under the following assumptions (a simplified diagram is shown in Fig. 6a):

- n = 250 rpm – resulting in 30 intervals (in the range of 0–7000 rpm),
- Mo = 20 Nm – resulting in 25 intervals (in the range of –250–250 Nm).

An example map of the electric motor operating points in the RDC test for a vehicle mass m = 2000 kg is shown in Fig. 6b.

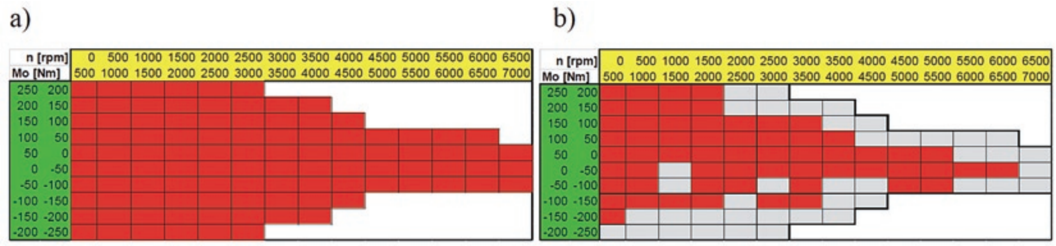


Fig. 6. Example methodology for determining the useful parameter ranges of the electric motor operation: a) full operating area, b) actual operating area of the electric motor in the RDC test

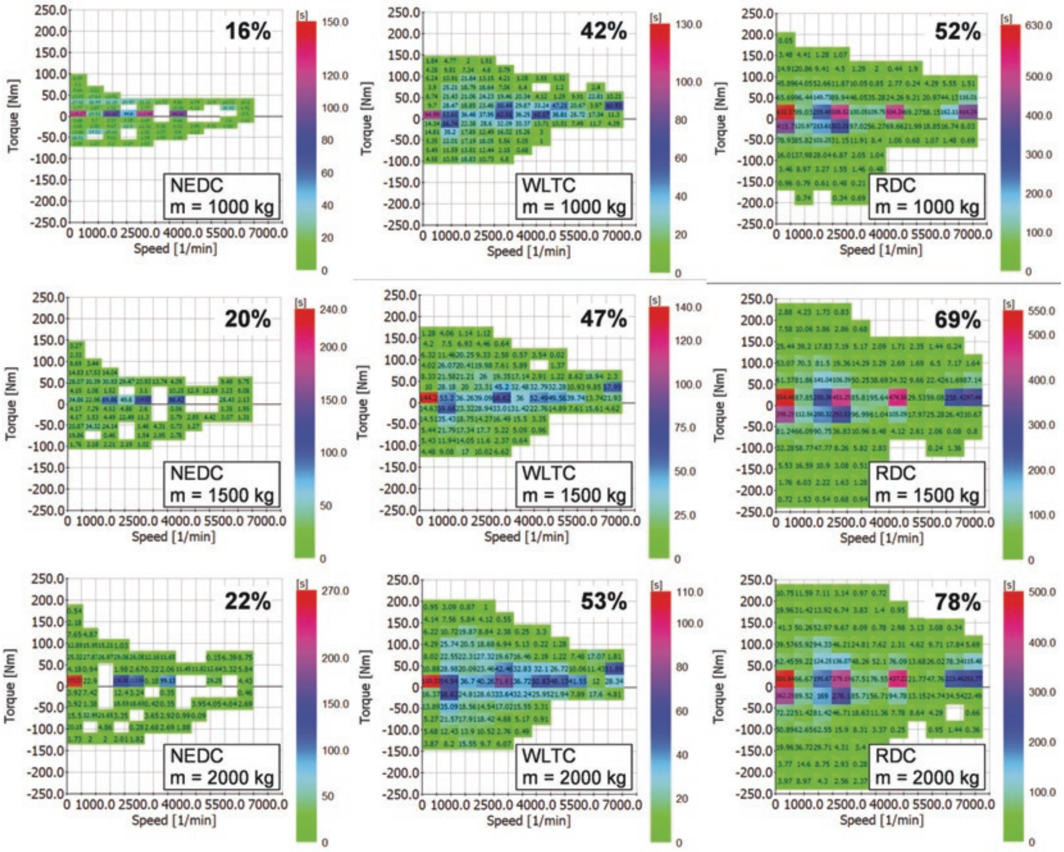


Fig. 7. Electric motor performance characteristics in various driving tests and for different vehicle curb weights

A high density of maximum torque at low speeds can be observed, as well as unused operating ranges with high engine efficiency. Regenerative braking also allows the use of a large operating range (two-quadrant operation of the electric motor), while the maximum values are limited especially in the middle range of the rotational speed of this motor.

The degree to which the full characteristic of the electric motor's operating range was used was determined for such maps. The values for the operating intervals usage were given in Fig. 7. Each operating interval contains information on the amount of time that a given interval, described by the values Mo and n, was used. At the same time, these values were in line with the legend presented for each characteristic. The main percentage values on the top right indicate the percentage of the total available range of the electric motor operating parameters that was used in any given test. An increase in the use of the electric motor's full range of operation for different drive tests can be observed. For the NEDC test, the range of motor operating parameters used was at most 22% of the total range available for the electric motor, while for the RDC test – 78% (at vehicle mass m = 2000 kg). Increasing the torque of the electric motor is most important when increasing the weight of the vehicle in a test simulating real driving conditions (RDC test).

4. Analysis of energy flow through the battery

The high-voltage battery with a nominal voltage of 360 V was simulated as a system consisting of two rows of cells with an electrical capacity of 36 Ah. This arrangement results in the total value of accumulated energy being about 25 kWh.

Energy flow simulation of was made for all test routes, with an example of battery charging and discharging process given in Fig. 8. Due to the high values of SOC changes (Fig. 5), the presented results are for the RDC test. The data shows that it is possible to recover only a dozen or so percent of the battery charge while travelling the test route.

Although the RDC test generates the largest SOC changes, it does not result in the recovery of large amounts of electric energy. Relative to NEDC and WLTC tests, the average share of battery energy from charging were only about 3–4 percentage points higher for each vehicle mass tested.

Detailed data regarding the energy flow was shown in Fig. 9. The conditions for charging and discharging the batteries as well as their total energy change were determined. The data provided shows that the increase in vehicle mass, despite the increase in the amount of energy recovered, reduces its share in the total energy balance. This result indicates the need to optimize the vehicle's mass in the context of the energy flow in the electric vehicle's drive system. Larger energy flows during the RDC test also point to the need to provide large energy capacities for BEV batteries and large initial SOC values. The total energy change values were the largest for the RDC test and were 3–4 times the energy change amount observed in the WLTC test. The differences between the energy changes in the NEDC and RDC tests were about 8 times (in favor of the NEDC test). An increase in vehicle weight (by 1/3) resulted in approximately 12% increase of the overall energy cosumed, regardless of the test used. The smallest effect of mass on energy consumption was obtained in the NEDC test (about 6%), the largest in the RDC test – 17%.

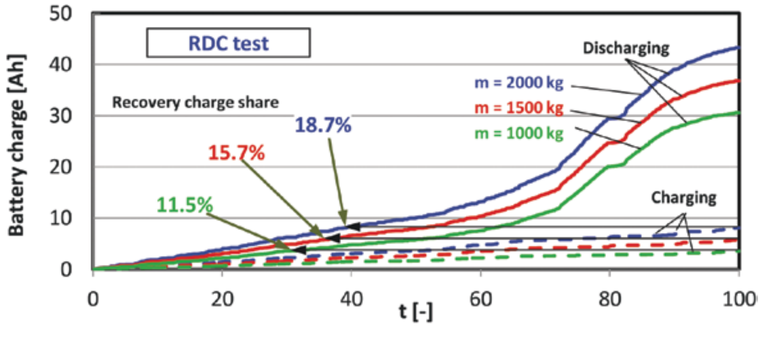


Fig. 8. Changes in the battery charge during the RDC test for different vehicle weights, and the characteristics of its charging and discharging

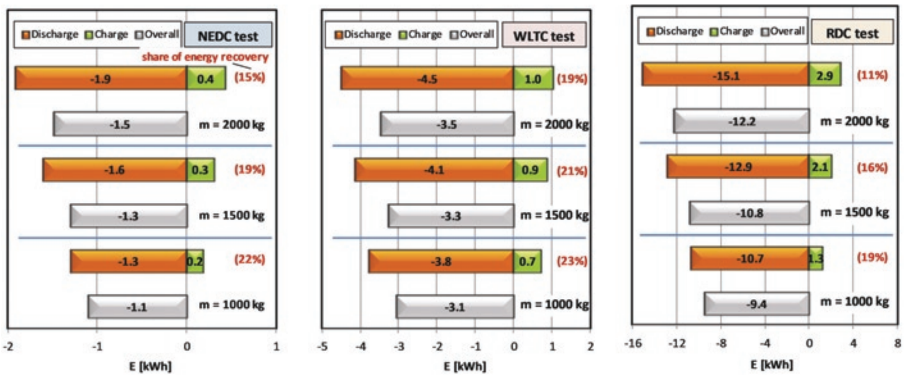


Fig. 9. Battery operating conditions and energy flow in driving tests

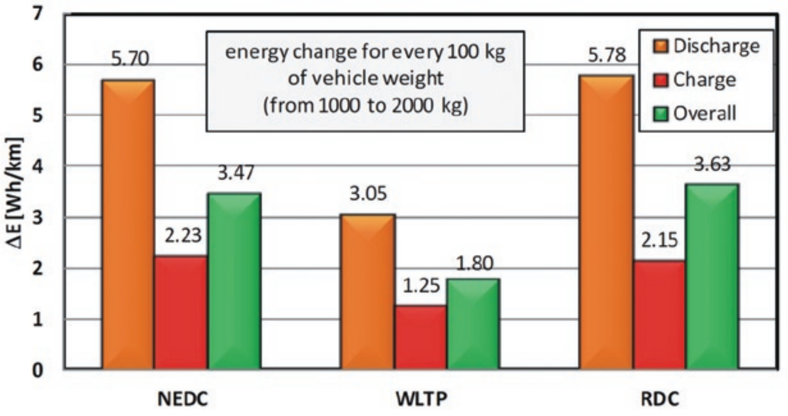


Fig. 10. Analysis of changes in energy flow through the battery, taking into account the change in vehicle mass by Δm = 100 kg

The assessment of energy demand in the form of energy per 100 kg of vehicle mass and to the driving test distance was determined using the equation:

$$\Delta E = \frac{E_{i,m_2} - E_{i,m_1}}{n \cdot S_{test,j}} \tag{1}$$

where: E – battery energy value [Wh]; i – driving phases taking into account discharge, charging and total energy flow; j – driving tests carried out: NEDC, WLTC, RDC, S – driving test distance [km]; m_2 = 2000 kg, m_1 = 1000 kg; n = 10 – means the energy per 100 kg of vehicle weight.

The results of these calculations were shown in Fig. 10. The analysis shows that similar energy expenditure per 100 kg of vehicle mass and per unit test length occur for NEDC and RDC tests. Although the NEDC test is less dynamic compared to WLTC, the specific energy expenditure is much higher (by about 50%) according to equation (2). It should be noted that such parallels are similar in NEDC and RDC tests; these similarities occur both when discharging and charging the batteries.

5. Analysis of the vehicle's specific energy consumption

Vehicle energy consumption was determined in the form of specific energy for each of the driving tests and taking into account the weight of the vehicle in the range from 1000 kg to 2000 kg. Specific energy consumption [kWh/100 km] was defined as the amount of energy consumed to perform a test drive length of 100 km:

$$E_j = \frac{\int_{t=0}^{t} E dt}{S} \cdot 100 \tag{2}$$

where: t_0 – is the start of the test, t_{max} – test duration, S – test drive distance E – the amount of energy used in the test at a given time.

This energy was determined in two ways: in the whole test (E_{end}) and as a function of time during the test – E_j (Fig. 11). The initial phase of each test generates large E_j values (due to the short duration of the test), this value stabilizes in further test phases. The amount of time it takes for the final energy consumption value in the test to stabilize depends on the dynamics of the driving test. The specificity of driving tests means that even during the static NEDC test, the final energy consumption value was obtained after 98% of its duration. It was assumed that the energy consumption value will have reached its final value when it falls within the range of 5% from the value observed by the end of the test:

$$t_{\%} = \pm 5\% \text{ of } E_{end} \tag{3}$$

where: $t_{\%}$ – relative stabilization time (within ±5% of the final determined total energy consumption value – E_{end}).

During the analysis of the more dynamic WLTC and RDC tests, $t_{\%}$ values were reached at 98% and 90% of the total test duration, respectively (Fig. 11a). This means that for the most dynamic RDC test, the time to determine the final value of total energy consumption was the shortest (Fig. 11c). It should be noted that the modification of the test phases (urban, extra-urban, highway driving) may contribute to earlier determination of the final value (assuming that the order of the driving phases does not change).

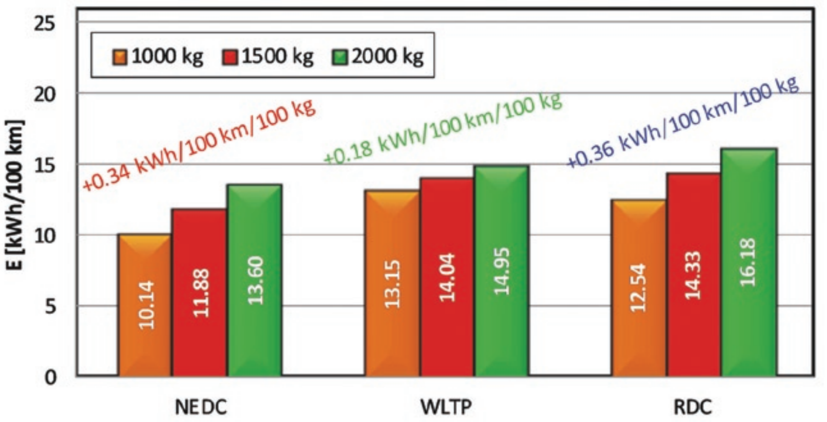


Fig. 12. Vehicle energy consumption values in driving tests, taking into account the changes in vehicle mass

The shortest energy consumption value stabilization time was obtained in the RDC test. In this (most dynamic) test, the final energy consumption value was also the highest. The lowest values of energy consumption occurred in the NEDC test. A proportional effect of the vehicle mass on the final energy consumption values of each test should be stated.

The total energy consumption analysis results were shown in Fig. 12. The highest values of this consumption were obtained in the RDC test. They were measured to be about 20% higher than the energy consumption value in the NEDC test. The specific increases in this energy consumption also related to the increase in vehicle weight by 100 kg were also indicated there. It was found that the increases in energy consumption were the same for NEDC and RDC tests and they were about 0.34 kWh/100 km for each additional 100 kg of vehicle weight. The energy consumption change depending on the weight of vehicles recorded for the WLTC test increased by only half the value for the other two tests.

Such estimation of the energy consumption increase value allows to determine this consumption without the need to perform simulations or real tests of the vehicle with its own weight changed.

6. Conclusions

Based on the simulation tests (using AVL Cruise software) the operating conditions of EV motors and the energy consumption of the vehicle with different curb weight values were determined in various driving tests. Based on them, the following conclusions were formulated:

1. Regarding the level of battery charge:
   - The dynamic character of the RDC test resulted in the largest changes in battery state of charge (ΔSOC). These changes are three times higher than in the WLTC test and 7 times higher than in the NEDC test.

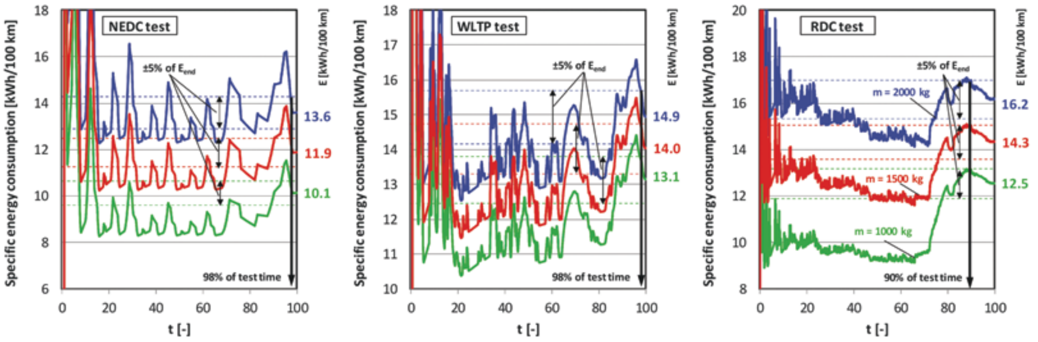


Fig. 11. Conditions for determining the final energy consumption value of the driving tests

  - ◦ Taking into account the test length means that the ratio of changes in ΔSOC per 100 km of the tests RDC; WLTC; and NEDC were: 1.06; 1; 1.25 respectively. This means a change in ΔSOC/100 km in percentage values of: 53%: 42%: 45% respectively. The smallest differences were recorded in the WLTC and RDC tests – up to only 6%.
2. Regarding the energy flow through the battery:
   - ◦ The values for the total change in battery charge and discharge energy were highest in the RDC test; they were 3–4 times greater than the energy changes measured in the WLTC test. The energy changes in the NEDC and RDC tests differed by about 8 times (in favor of the NEDC test).
   - ◦ An increase in vehicle weight (by 1/3) results in an approximately 12% increase in the overall energy consumption, regardless of the test used. The smallest effect of mass on the total energy flow through the battery was obtained in the NEDC test (about 6%), the largest in the RDC test – 17%.
3. Regarding the energy consumption in the test:
   - ◦ The highest energy consumption values were obtained during the RDC test. They were about 20% greater than the energy consumption value in the NEDC test. During the WLTC test, the energy consumption values were 30 to 10% greater than the energy consumption in the NEDC test (corresponding to increasing the weight of the vehicle).
   - ◦ The increase in energy consumption in the NEDC and RDC tests was the same and amounts to approximately 0.34 kWh/100 km for each additional 100 kg of vehicle weight. The increases in energy consumption depending from increased weight for the WLTC test were recorded to be only half that value.

The obtained tests and analyzes results of electric vehicles energy consumption indicate the need for further simulation works and tests in real driving conditions. The energy consumption of such vehicles was strongly dependent on the test type; values obtained in driving tests were at the level of 10.1–13.5 kWh/100 km (NEDC test); 13–15 kWh/100 km (WLTC test) and 12.5–16.2 kWh/100 km in the RDC test. The differences in controled driving tests (NEDC and WLTC) reached up to 25% (larger in the WLTC test for vehicles with a lower curb weight). Tests conducted in real conditions show similar values of energy consumption (for light vehicles – about 1000 kg) and an increase of this consumption by another 10% when vehicles with a mass of about 2000 kg were tested.

Acknowledgements

The research was conducted using the AVL Cruise software thanks to the AVL University Partnership Program.

References

1. Basso R, Kulcsár B, Egardt B, Lindroth P, Sanchez-Diaz I. Energy consumption estimation integrated into the Electric Vehicle Routing Problem. Transportation Research Part D: Transport and Environment 2019; 69: 141–167, https://doi.org/10.1016/j.trd.2019.01.006.
2. Davidov S, Pantoš M. Planning of electric vehicle infrastructure based on charging reliability and quality of service. Energy 2017; 118: 1156–1167, https://doi.org/10.1016/j.energy.2016.10.142.
3. European Commission. Proposal for a regulation of the European Parliament and of the Council setting emission performance standards for new passenger cars and for new light-commercial vehicles as part of the Union's integrated approach to reduce CO2 emissions from LDVs. Brussels, 8.11.2017, SWD(2017) 650 final. ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/swd_2017_650_p1_en.pdf.
4. Fontaras G, Zacharof N-G, Ciuffo B. Fuel consumption and CO2 emissions from passenger cars in Europe – Laboratory versus real-world emissions. Progress in Energy and Combustion Science 2017; 60: 97–131, https://doi.org/10.1016/j.pecs.2016.12.004.
5. IEA, Global EV Outlook 2019. IEA, Paris, www.iea.org/publications/reports/globalevoutlook2019.
6. Kurtyka K, Pielecha J. The evaluation of exhaust emission in RDE tests including dynamic driving conditions. Transportation Research Procedia 2019; 40: 338–345, https://doi.org/10.1016/j.trpro.2019.07.050.
7. Langbroek J H M, Cebecauer M, Malmsten J, Franklin J P, Susilo Y O, Georén P. Electric vehicle rental and electric vehicle adoption. Research in Transportation Economics 2019; 73: 72–82, https://doi.org/10.1016/j.retrec.2019.02.002.
8. Merkisz J, Pielecha J, Radzimirski S. New trends in emission control in the European Union. Springer Tracts on Transportation and Traffic 2014; 4: 170, https://doi.org/10.1007/978-3-319-02705-0.
9. Micari S, Polimeni A, Napoli G, Andaloro L, Antonucci V. Electric vehicle charging infrastructure planning in a road network. Renewable and Sustainable Energy Reviews 2017; 80: 98–108, https://doi.org/10.1016/j.rser.2017.05.022.
10. Muzi N. New car CO2 standards: Is the job of securing electric cars in Europe done? Transport & Environment 2019. www.transportenvironment.org.
11. Pavlovic J, Marotta A, Ciuffo B. CO2 emissions and energy demands of vehicles tested under the NEDC and the new WLTP type approval test procedures. Applied Energy 2016; 177: 661–670, https://doi.org/10.1016/j.apenergy.2016.05.110.
12. Pielecha I, Cieslik W, Szalek A. Operation of electric hybrid drive systems in varied driving conditions. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2018; 20 (1): 16–23, https://doi.org/10.17531/ein.2018.1.3.
13. Pielecha I, Cieslik W, Szalek A. Operation of hybrid propulsion systems in conditions of increased supply voltage. International Journal of Precision Engineering and Manufacturing 2017; 18: 1633–1639, https://doi.org/10.1007/s12541-017-0192-3.
14. PSPA, 2019. Licznik elektromobilności. Polskie Stowarzyszenie Paliw Alternatywnych. pspa.com.pl
15. Sun B, Zhang T, Ge W, Tan C, Gao S. Driving energy management of front-and-rear-motor-drive electric vehicle based on hybrid radial basis function. Archives of Transport 2019; 49 (1): 47–58, https://doi.org/10.5604/01.3001.0013.2775.
16. Tsokolis D, Tsiakmakis S, Dimaratos A, Fontaras G, Pistikopoulos P, Ciuffo B, Samaras Z. Fuel consumption and CO2 emissions of passenger cars over the New Worldwide Harmonized Test Protocol. Applied Energy 2016; 179: 1152–1165, https://doi.org/10.1016/j.apenergy.2016.07.091.
17. Wei Z, Xu Z, Halim D. Study of HEV power management control strategy based on driving pattern recognition. Energy Procedia 2016; 88: 847–853. https://doi.org/10.1016/j.egypro.2016.06.062.
18. Wu W, Freese D, Cabrera A, Kitch W A. Electric vehicles' energy consumption measurement and estimation. Transportation Research Part D: Transport and Environment 2015; 34: 52–67, https://doi.org/10.1016/j.trd.2014.10.007.
19. Xie L, Luo Y, Zhang D, Chen R, Li K. Intelligent energy-saving control strategy for electric vehicle based on preceding vehicle movement. Mechanical Systems and Signal Processing 2019; 130: 484–501. https://doi.org/10.1016/j.ymssp.2019.05.027.

20. Zhang S, Gajpal Y, Appadoo S S, Abdulkader M M S. Electric vehicle routing problem with recharging stations for minimizing energy consumption. International Journal of Production Economics 2018; 203: 404–413, https://doi.org/10.1016/j.ijpe.2018.07.016.

Ireneusz PIELECHA
Jacek PIELECHA
Institute of Combustion Engines and Transport
Poznan University of Technology
ul. Piotrowo 3, 60-965 Poznań, Poland

E-mail: Ireneusz.Pielecha@put.poznan.pl,
Jacek.Pielecha@put.poznan.pl