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A study on the electric energy consumption of a lightweight four-wheeled vehicle powered by the hub-mounted brushless direct-current hub motors designed for disabled people

Bartłomiej Romowicz[1*], Magdalena Machno[1], Krzysztof Weigel-Milleret[2]

[1] Department of Rail Vehicles and Transport, Faculty of Mechanical Engineering, Cracow University of Technology, Poland
[2] Department of Motor Vehicles, Faculty of Mechanical Engineering, Cracow University of Technology, Poland
* Corresponding author's e-mail: bartlomiej.romowicz@pk.edu.pl

ABSTRACT

Electric vehicles (EVs) play a key role in sustainable transport, offering high efficiency, lower emissions and reduced operating costs. The aim of the tests was to determine the electric power consumption of a lightweight quadricycle class L6e-BP, designed for people with disabilities, and then to check its energy consumption in an urban cycle. The vehicle uses hub-mounted brushless direct-current (BLDC) motors and lithium iron phosphate (LFP) batteries. Tests were conducted at constant speeds (13, 25, 35 km/h) and simulated city driving. Optimum efficiency was achieved at a speed of 25 km/h, with a consumption of 3.7 kWh/100 km. In urban conditions, energy consumption increased to 8.24 kWh/100 km due to frequent acceleration and braking. The maximum system efficiency reached 95% at 500 rpm. Using quadratic regression, the energy demand was modeled over the range of 6–50 km/h, confirming a minimum of around 20–25 km/h. The results highlight the influence of real-world conditions on EV performance and confirm the need to develop tailored drive systems and control strategies for urban mobility-oriented vehicles.

Keywords: electric vehicle, BLDC motor, low-emission vehicles, urban mobility, energy consumption.

INTRODUCTION

Currently, electric vehicles (EVs) play a key role in the implementation of global sustainable development strategies and the reduction of greenhouse gas emissions. Their dynamic development is an important element of actions aimed at achieving climate neutrality by 2050. As part of the European Union's climate policy, an intermediate target has been set, assuming a reduction of greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. As a consequence, electric vehicles are becoming the foundation of the transformation of the transport sector towards low emissions. These vehicles are a response to global challenges related to climate protection and the need to reduce dependence on fossil fuels [1, 2]. In addition, these vehicles allow for lower operating costs. The costs of charging an electric vehicle are lower compared to purchasing fuel for a diesel vehicle, as shown by the analysis in [3].

According to the International Energy Agency (IEA), in 2023, electric car sales reached almost 14 million units, which accounted for 18% of global new car sales. In 2024, this trend continued, with predicted sales of around 17 million electric vehicles. This corresponds to over 20% of the global automotive market share [4]. Data from the Edison Electric Institute report show that the number of electric cars on U.S. roads is expected to increase to almost 80 million in 2035 (see Figure 1) [5]. This shows that the share of electric cars in the automotive market is a still growing, and they are becoming a more significant means of transport every year.

An important aspect of electromobility is the technological advancement of electric vehicles. These vehicles are characterized by high energy efficiency, effectiveness and low level of local pollutant emissions. Engines powered by electricity differ fundamentally from conventional combustion engines – both in terms of design and operating principle. The basic element of an electric drive is an electric motor, which converts electrical energy directly into mechanical energy, transferred to the vehicle's wheels. This form of energy conversion is characterized by greater efficiency, especially in comparison to combustion engines. In combustion engines, the chemical energy of the fuel undergoes a multi-stage transformation, associated with significant energy losses [6, 7].

However, the efficiency of electric vehicle drive systems and their actual energy consumption remain the subject of intensive research. These studies focus particularly on the analysis of the impact of variable operating and environmental conditions. As shown in the studies [8], ambient temperature, route characteristics, driving style and vehicle load have a significant impact on electricity consumption. In low temperature conditions, increased energy consumption is noted, related to, among others, the operation of heating systems and a decrease in battery efficiency. In the work [9], the energy flow through electric vehicle systems was analyzed in order to estimate their energy consumption. The results of these tests showed that the vehicle energy consumption is strongly dependent on the type of test used. The energy consumption values in the New European Driving Cycle and Worldwide Harmonized Light Vehicles Test Cycle tests are lower by about 20 % and 10%, respectively, in relation to the Real Driving Conditions test. In addition, the increase in vehicle weight causes an increase in energy consumption (an increase of 100 kg in vehicle weight increases energy consumption by 0.34 kWh/100 km).

Compared to combustion engine vehicles, EVs are characterized by higher energy efficiency, which translates into lower primary energy consumption. However, it is worth paying attention to the entire energy chain - from energy generation, through its processing, transmission, to final use in the electric motor. Although electric motor themselves achieve very high efficiency (even above 90%), the efficiency of the entire system also depends on the source of energy. In countries where renewable energy sources or nuclear power plants dominate, the ecological balance of electric vehicles is favorable. In Poland, however, a significant part of electricity still comes from burning coal, which weakens the potential environmental benefits of electromobility. According to data published by Yale Climate Connections [10], electric cars consume on average half as much energy as their counterparts with combustion engines. Thus, they are not only an ecological, but also energy-efficient alternative to traditional solutions.

Considering the diverse operating conditions of electric vehicles, it is important to carry out accurate measurements of energy consumption in real driving conditions. Comparative studies have

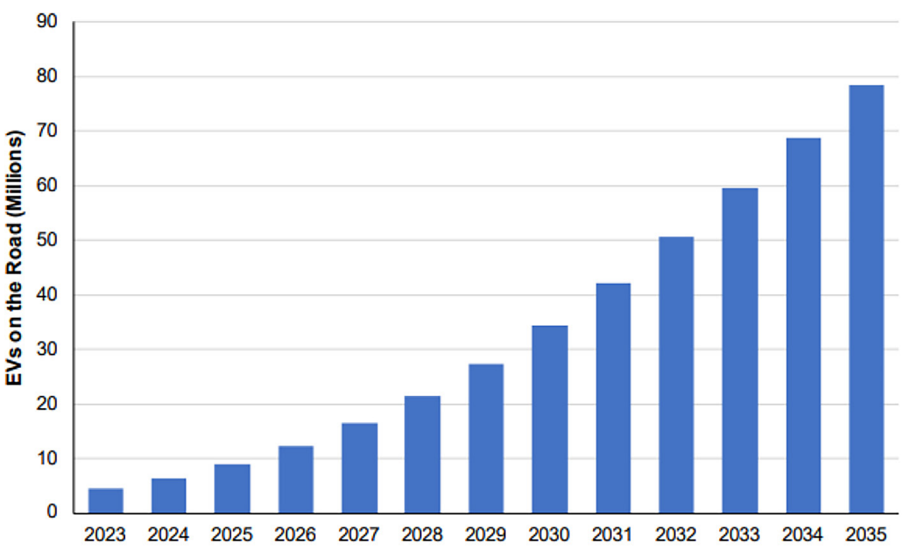

Figure 1. EEI Forecast of EV Stock: 78.5 Million EVs on U.S. Roads in 2035 [5]

shown that the brushless direct-current (BLDC) motors are characterized by higher efficiency compared to commutator and induction motors, especially in the low and medium speed range. Azizi et al. [11] compared the energy consumption of BLDC and DC (direct current) motors in electric motorcycles, showing significant differences in their energy efficiency. In turn, Malarselvam and Carunaiselvane [12] analyzed the effect of different driving cycles (including the New European Driving Cycle) on the energy efficiency of motors used in electric vehicles, showing the advantage of BLDC motors over other types of drives, especially in typical operating conditions. This is also confirmed by the results of Nandhini and Devapriya [13], who analyzed the efficiency of electric motors of EVs depending on different driving cycles, confirming the advantage of BLDC motors in terms of overall efficiency.

Urban electric vehicles

For current efforts towards sustainable development and reducing greenhouse gas emissions, urban electric vehicles (UEVs) play a key role in the transformation of transport systems. Their analysis in terms of energy consumption is important for several reasons. One reason is the specificity of urban traffic – including numerous stops, starts and low speeds – favors the efficient use of electric vehicles. In such conditions, they demonstrate higher energy efficiency than combustion vehicles. This is due, among other things, to the possibility of regenerating braking energy and better adaptation of the drive to variable loads, which makes them a particularly adequate means of transport in the urban environment.

Studies show that electric vehicles in urban conditions can achieve higher energy efficiency compared to combustion vehicles, which is related to the possibility of recovering energy during braking and better adaptation to the characteristics of urban driving [14].

Secondly, urban electric vehicles contribute to improving air quality in urban agglomerations by eliminating local exhaust emissions. Replacing combustion vehicles with electric vehicles in urban areas therefore has a direct impact on reducing air pollution, which has been confirmed in studies conducted in various cities around the world [15].

Prepared analyses indicate that electric vehicles can be up to four times more energy efficient than vehicles with internal combustion engines [16]. This study compared the actual energy consumption of two types of vehicles: electrical energy drawn from the battery in an electric car and the amount of chemical energy contained in the fuel burned by a vehicle with an internal combustion engine, calculated on the basis of the calorific value of the fuel used. The results showed that despite losses at the stage of charging and energy conversion, electric vehicles use a much larger percentage of the supplied energy for propulsion. While in the case of internal combustion engines, a significant part of the energy is lost in the form of heat. In addition, a simpler mechanical design and fewer moving parts in electric motors reduce the risk of failure and lower maintenance costs.

Among the light electric quadricycles (category L6e-BP) intended for the disabled, the market offers a limited number of models adapted to the specific needs of these users. One of the few examples is Elbee – an innovative vehicle designed specifically for people using wheelchairs. Elbee allows the driver to enter the interior directly from the street level through the front, lifting doors, which eliminates the need to transfer from the wheelchair to the driver's seat. This design provides the user with full independence in terms of mobility. Another solution is Kenguru – a compact electric vehicle that also allows driving directly from the wheelchair. Thanks to the rear doors and a ramp, the user can enter the vehicle and drive it using the handlebars resembling those of a motorcycle. Kenguru reaches a maximum speed of about 45 km/h and is intended for moving in urban areas.

It is a worth emphasizing that the number of electric vehicles available on the market dedicated to disabled people is very limited. Many of the projects designed so far, although innovative, remain in the prototype phase, have been withdrawn from production or are only available in selected markets. This indicates a significant gap in the automotive market in the offer of vehicles adapted to the needs of people with limited mobility.

Electric motors used in vehicles

Electric motors have been developed since the 19th century. During these years, many types of motors have been created, some of them, such as unipolar motors, are not useful for driving vehicles due to their construction. Currently, in various types of vehicles, you can find motors divided into groups:

- alternating current (AC), inductive motor (asynchronous) (IM). In these motors, alternating current in the usually multi-phase stator winding creates an alternating magnetic field rotating around the motor rotor. Electromagnetic induction creates currents in the rotor winding itself, and these create a magnetic field. The interaction of the rotating magnetic fields creates useful rotor torque. They require simple control.
- direct current (DC), brush motors. These motors contain a commutator that supplies direct current to individual rotor windings. The interaction of the rotor and stator magnetic fields generates the motor's useful torque. The stator magnetic field can be generated by permanent magnets (PM) or by windings connected to the rotor (in series, parallel) or not – a separately excited motor. They do not require advanced control.

BLDC permanent magnet synchronous motor (PMSM). This motor is constructed in such a way that the rotor contains permanent magnets. The stator usually contains a three-phase winding. The rotating magnetic field generates a useful driving torque. The magnetic field is synchronized with the rotor magnetic field, which means that these are structures that require advanced control and precise rotor positioning. The controller electronically commutates the current to the appropriate windings. Most often, a system of three Hall sensors or sensors that provide a sin/cos signal of the rotor position angle are used for control. Sensorless control is also possible, where measurements of the electromotive force and winding currents are used to collect information to estimate the rotor position.

reluctance motors (RM), synchronous reluctance motors (SynRM). In this motor, the stator windings are constructed in a similar way to induction motors. The motor rotor is made of soft ferromagnetic material so that the reluctance of the magnetic circuit depends on the rotor position. The torque is generated due to the rotor asymmetry. The reluctance torque tends to minimize the magnetic reluctance in the motor rotor. Similarly to BLDC and PMSM motors, they require advanced control systems. A serious problem of these designs is a greater tendency to generate noise and vibrations [17, 18].

The electric motors currently used in selected vehicles are presented in Table 1.

Despite numerous works on the energy efficiency of electric motors and their comparison with combustion drives, there is still a research gap regarding the actual energy consumption in electric vehicles. It seems reasonable to conduct further tests aimed at assessing the energy efficiency and efficiency of electric motors in real operating conditions. Analyses to date have focused mainly on conventional vehicles or motorcycles, omitting specific designs of light four-wheelers with direct drive based on BLDC motors placed in wheel hubs. Tests of energy efficiency and efficiency of electric motors can be used to improve the reliability of operation of these vehicles.

In response to this need, a new design of a lightweight electric vehicle was developed, enabling it to be driven directly from a wheelchair. The project uses modern technical solutions, such as brushless DC motors integrated with the rear wheel hubs. This solution allows for simplifying the drive system and increasing energy efficiency. Additionally, the vehicle presented in this paper is equipped with a suspension clearance adjustment system, which allows for smooth and comfortable entry into its interior without the need to use ramps or lifts. This vehicle can be lowered down to the road level (0 mm), which significantly facilitates access for people using wheelchairs and increases its functionality in urban conditions.

MATERIALS AND METHODS

Research object

The subject of this research is a light road quadricycle powered by electricity, meeting simplified homologation requirements of class

Table 1. Motor technologies applied by EVs companies [19–23]

Car model	Year of production	Motor type
BMW iX	2022	PMSM
Tesla Model X	2021	SynRM
Tesla Model Y	2021	SynRM
Volvo XC60	2021	PMSM
Renault ZOE	2020	PMSM
Porshe Taycan	2020	PMSM
Hyundai Kona E	2020	PMSM
Mercedes Benz EQ	2020	IM
Audi E-Tron Q	2019	IM

L6e-BP, designed with users with disabilities in mind. Figure 2 shows the analyzed vehicle from the front and rear. The vehicle was developed as a means of individual urban transport, enabling driving directly from a wheelchair. Modern technical solutions were used in the design. These solutions include direct drive implemented by brushless DC motors (BLDC) integrated with rear wheel hubs and height-adjustable suspension. This suspension facilitates access to the interior of the vehicle. The source of the vehicle's energy are four lithium iron phosphate (LFP) batteries. These batteries are characterized by high cyclic durability, temperature stability and an increased level of operational safety compared to other types of lithium cells [24].

The vehicle built for the purposes of this work was equipped with a drive system adapted to urban conditions. Figure 3 shows the layout of the test vehicle, showing the drive system, batteries, and suspension. However, Table 2 presents the basic technical parameters of the BLDC motors used.

Motor of this type have little detailed technical documentation. Motor parameters are usually provided not by the manufacturer, but by the supplier and differ from each other up to several dozen percent, due to the fact, that motors are

Figure 2. Tested light quadricycle for disabled people

paired with different controllers during the conducted tests. The architecture of the controller can significantly change the motor output despite similar values of basic parameters such as maximum phase current or maximum battery current. The most popular characteristics are trapezoidal, sinusoidal, FOC. In order to verify the motors parameters and check how they work with specific controllers, it was decided to collect speed characteristics of the entire drive system.

In the analyzed vehicle, the control of the electric motors is carried out using a Kelly KLS-N series controller. This device is designed to operate brushless DC motors with permanent magnets and operating in sinusoidal mode. This controller enables precise control of torque and speed, ensuring smooth and efficient operation of the drive system. The nominal operating voltage is 48 V. The controller is equipped with advanced security functions, such as protection against overheating, overload and short circuit, as well as Hall sensors and rotor position errors detection. Thanks to the programming interface (communication via USB or Bluetooth), it is possible to individually configure the operating parameters, adapted to the specifics of the vehicle and its operating conditions.

The power source for the drive system is a set of four LFP batteries connected in series. This system provides a safe nominal voltage of 48 V and a capacity of 100 Ah, which allows for obtaining an appropriate energy resource while maintaining temperature stability, high cyclic durability and an increased level of operational safety. The batteries are equipped with a battery management system (BMS) that protects the cells against overcharging, excessive discharge and overheating. Table 3 contains a summary of the catalog parameters of the LFP batteries used.

Description of measured values

In this work, dynamometer tests were carried out to determine the characteristics of the motors used in the vehicle. Then, an analysis of electric energy consumption was made in quasistatic operating conditions, i.e. while driving at a constant speed, which allowed for measuring the actual energy consumption in controlled conditions. Next, energy consumption measurements were carried out in urban conditions, taking into account the effect of driving parameters and load on the energy profile of the drive system.

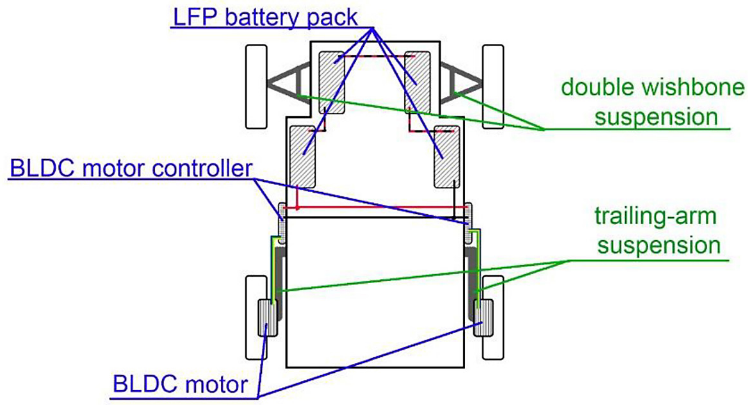

Figure 3. Diagram of the test vehicle layout

Table 2. The catalog data of the brushless direct-current motor from QS Motor

Motor type	Brushless DC motor
Continuous power	3.000 W
Maximum power	6.000 W
Voltage range	48–96V
Magnet height	50 mm
Maximum rotation speed	700 rpm
Maximum torque	181 Nm
Motor efficiency	85–90%
Hall sensors	2 sets (1 for use, 2 in case of failure)
Maximum operating temperature	70 °C (peak 120 °C in 5–10 seconds)
Net weight of the motor	16 kg

During tests on the chassis dynamometer, the following electrical parameters were measured:
- current drawn from the battery by the motor controllers (I_total, A),
- voltage at the battery terminals (U_batt, V),
- and mechanical:
- driving torque (M_total, Nm),
- motor rotational speed (rpm).

The parameter *U_batt* was used to calculate the power *N_batt* based on the following formula (1):

$$N\_batt = U\_batt \cdot I\_total \qquad (1)$$

After determining the losses in the drive system by means of a coasting test, it was possible to calculate the values of electrical and mechanical power, drive torque on the motor shaft. The measured electrical parameters allowed the calculation of the electrical power drawn from the battery, and then the efficiency of the motors.

In this paper, the analysis of electric energy consumption will allow to obtain data and results that will provide important information for improving vehicle reliability and minimizing its operational faults.

Description of the measuring station

The station-based tests were carried out on the SuperFlow AutoDyn 30 SF-832 chassis dynamometer, which is the equipment of the laboratory of the Department of Automotive Vehicles of the Cracow University of Technology. It is a single-axis inertial-load braking dynamometer. The contact with the wheel was ensured by one roller with a diameter of 30”, which is why the deformation of the vehicle tires is much smaller than in the case of a dynamometer with a two-roller contact. The measuring track consisted of two LEM HAIS 100 current sensors, a voltage divider on the battery terminals connected to the Spider 8 measuring amplifier and an archiving computer with HBM Catman software (Figure 4). The remaining parameters were recorded using the WinDyn 5 chassis dynamometer software.

Table 3. Catalog data of lithium-iron-phosphate battery

Data	Value
Nominal voltage	12.8 V
Nominal capacity	100 Ah
Voltage range	10.8 V~14.4 V
Cut-off voltage	9.4 V
Maximum charging current	100 A
Maximum continuous discharge current	100 A
Durability	6.000 cycles (0–100%)
BMS system	yes
Temperature at discharge	-20 °C to 55 °C
Height	215 mm
Width	171 mm
Length	330 mm
Weight	10 kg+/-3%

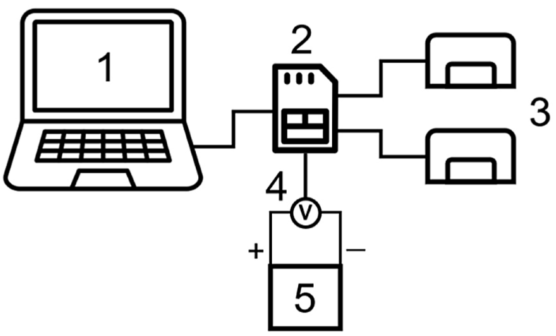

Figure 4. Measurement diagram:
1 – archiving computer with Catman software,
2 – Spider 8 measurement card,
3 – LEM HAIS 100 A current sensors,
4 – voltmeter, 5 – accumulator

Measuring equipment

The Racelogic PerformanceBox device (Figure 5) was used to record data during road tests of the tested vehicle. It is an advanced motion parameter recorder based on high-precision GPS technology, enabling the measurement of such values as instantaneous speed, acceleration and other important dynamic parameters of the vehicle.

In order to measure the electrical parameters of the drive system, LEM HAIS 100 A current sensors were used (Figure 6), connected via the Micro Input Module to the archiving device. This solution enabled the current values of the currents supplying the motors to be recorded on an ongoing basis. Additionally, the voltage at the battery terminals was recorded during the measurements, which allowed for determining the instantaneous power drawn by the drive system and the energy efficiency of the entire system. Thanks to this, it was possible to simultaneously monitor the current drawn by the motors from the batteries and the voltage in the power supply system.

The obtained measurement data were preprocessed using the Circuit Tools software and then exported to a Microsoft Excel spreadsheet. After preliminary analysis of the results, a data set of over 13 thousand measurement records was obtained, which were then subjected to detailed analysis in the MATLAB StatisticToolbox environment.

Vehicle testing

The aim of the conducted research was to determine the electric energy consumption in a light quadricycle of the L6e-BP class, intended for people with disabilities, and then to evaluate its energy use under simulated urban driving conditions. To achieve this, an assessment of the vehicle's energy efficiency was carried out, and the effect of speed on energy consumption was determined.

Experimental tests were conducted in real operating conditions and included energy consumption measurements at three constant driving speeds (13, 25, 35 km/h) and during a simulation of an urban driving cycle. All measurements were performed on a flat section of a paved road, without significant elevation differences. Weather conditions during testing were stable: sunny weather, ambient temperature of 17 °C, and wind speed below 5 km/h, ensuring high repeatability and minimal environmental interference.

The urban cycle was designed to reflect typical stop-and-go city driving. It included multiple phases of acceleration, cruising, deceleration, and full stops. The test route was 1.2 km long and consisted of four complete cycles, each lasting approximately 3 minutes. Each cycle included:
- 4 full acceleration starts and stops,
- sections of driving at 15–30 km/h,
- two full braking events from speeds above 25 km/h.

To improve accuracy and reproducibility, the entire urban test sequence was repeated three times on the same day, with full battery recharge between repetitions. This approach ensured the consistency

Figure 5. Racelogic PerformanceBox device mounted on the vehicle during testing

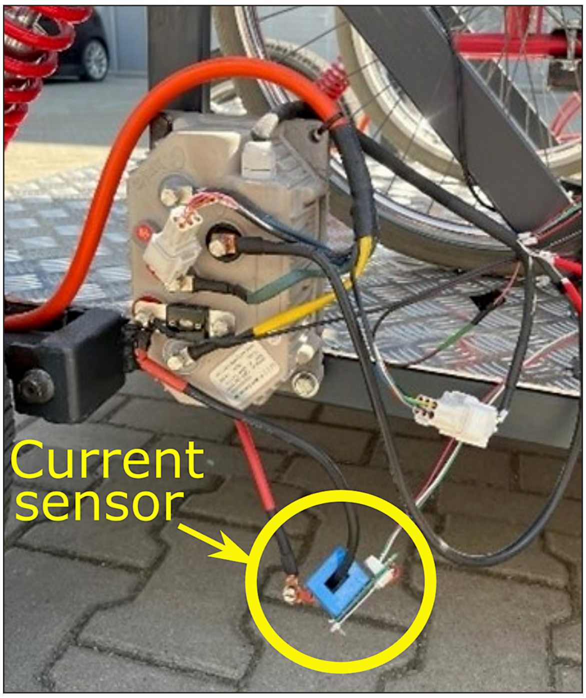

Figure 6. LEM HAIS 100-P current sensor installed in the test vehicle

of initial conditions and allowed the calculation of average energy consumption under urban-like dynamics. All test runs were recorded using onboard data logging systems with 0.1-second resolution for voltage, current, and speed readings.

This expanded urban test protocol enabled a more reliable estimation of real-world energy use by simulating realistic, low-speed traffic conditions with frequent changes in driving dynamics.

RESULTS AND DISCUSSION

Analysis of results for constant speed conditions

Testing the vehicle on the dynamometer provided data for developing the motor speed characteristics, which are presented in Figure 7.

During the tests on the dynamometer, the maximum driving torque of the engines exceeding 380 Nm was recorded, which remains almost unchanged up to a rotational speed of approx. 300 rpm. Above this rotational speed, the driving torque decreases in a manner close to linear. Such a torque curve translates into a linear curve of the mechanical power line of the engines in the initial range, the peak value of which reaches approx. 16 kW. The calculated peak electrical power drawn from the battery exceeds 17 kW.

Engine efficiency was calculated for several dozen measurement points (Figure 8). In the range of low engine speeds (below 100 rpm), engine efficiency does not exceed 50%. The results indicate that the maximum efficiency of the drive system (approximately 95%) occurs at a speed of approximately 500 rpm. In the test object, due to the use of wheels with tire size 135/80 R13, this occurs at a driving speed of approximately 52 km/h, which exceeds the maximum permitted homologation speed of 45 km/h.

Then, the vehicle's electric energy consumption was analyzed while driving at a constant speed. Measurements were taken for three selected speed values such as: 13 km/h, 25 km/h and 35 km/h. The aim of this analysis was to determine the effect of driving speed on the value of power drawn from the batteries and the electric energy consumption expressed in (kWh/100 km).

Figure 9 shows the average values of the dependence of the power drawn from the battery on the vehicle speed. The graph shows that as the speed increases, the energy demand increases non-linearly. For a speed of 13 km/h, the average power drawn was about 500 W, while for 25 km/h it was already 44.5% more, and at 35 km/h 70.5% more. The values of standard deviations indicate greater measurement variability at higher speeds (during the measurement at a speed of 35 km/h, the maximum power value of 2174.49 W and the minimum power value of 1453.71 W were obtained), which may be related to variable air resistance, road unevenness and a short measurement section, which did not allow for appropriate averaging of the results.

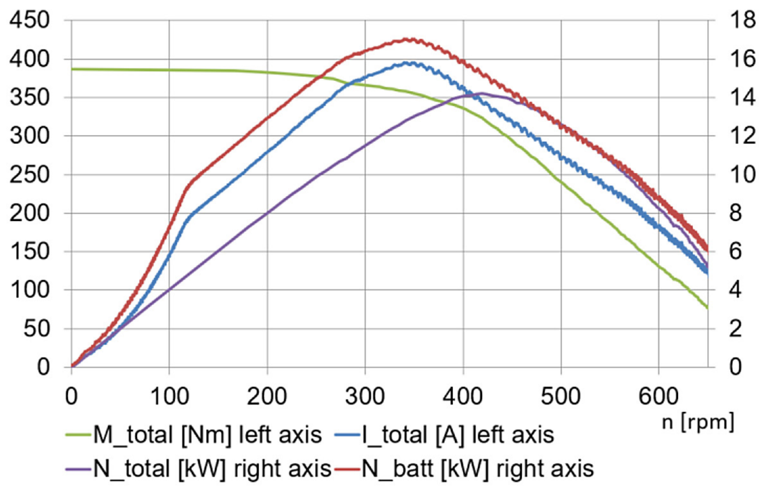

Figure 7. Speed characteristics of the BLDC motor set used in the vehicle; M_total -total drive torque [Nm], I_total -total current drawn from the battery [A], N_total -total mechanical power at the motor shafts [kW], N_batt - electrical power drawn from the battery [kW]

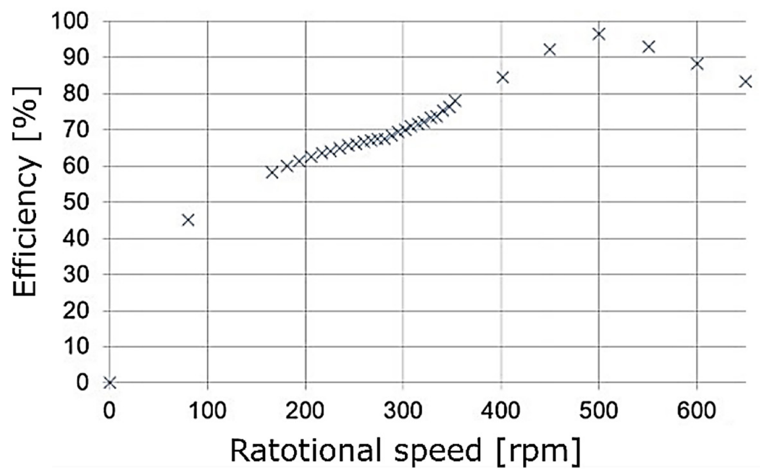

Figure 8. Efficiency characteristics of a BLDC motor set as a function of rotational speed

Figure 10 shows the energy consumption expressed in kWh/100 km as a function of driving speed. The lowest energy consumption was recorded at a speed of 25 km/h (average value of approx. 3.7 kWh/100 km), a similar value was also obtained for 13 km/h, while a significant increase was obtained at a speed of 35 km/h (average value of approx. 5.2 kWh/100 km). This is due to the fact that at the lowest speed, a significant share of the energy balance is made up of losses resulting from the constant energy consumption for powering the vehicle's on-board systems. At higher speeds, however, aerodynamic drag dominates.

Although the power drawn from the battery increases with increasing speed, the consumption has a minimum for a certain driving speed. The engine efficiency increases with increasing driving speed. The aerodynamic drag force increases with the square of the speed, and the aerodynamic drag power with the third power. The rolling resistance force is practically constant in this speed range (car tires adapted to greater loads), which causes the rolling resistance power to increase linearly with increasing speed. The most energy-efficient operating range of the vehicle was recorded at a moderate driving speed of 25 km/h. Both driving too slowly and too fast lead to increased demand for electrical energy.

Energy efficiency can be improved by matching the motor speed to the driving speed. In the case of a drive system, where the wheel is mounted in the hub, the possibilities of introducing an additional gear ratio are limited. The use of a planetary gear can be considered. However,

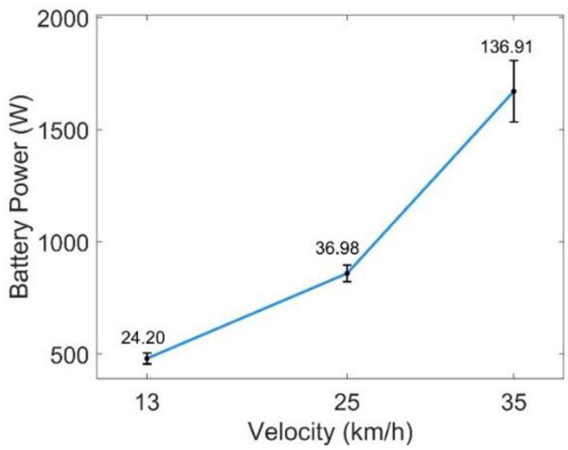

Figure 9. Relationship between battery power and vehicle velocity with the standard deviation values

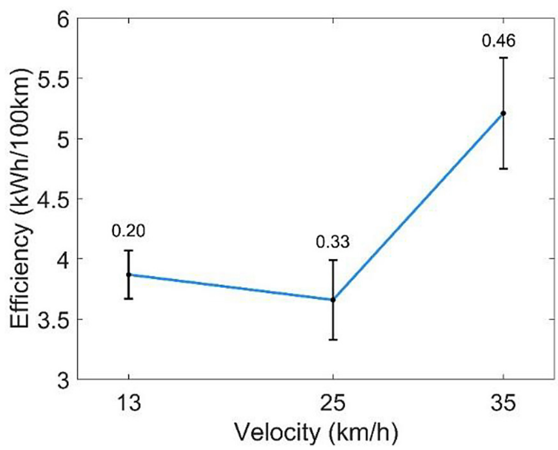

Figure 10. Relationship between efficiency and vehicle velocity with the standard deviation values

this could significantly increase the cost of such a drive system. In further analyses of the efficiency of such a vehicle, the efficiency of the gear itself should be taken into account. Another way to change the gear ratio is to change the dynamic radius of the wheel by changing the tires. However, this has an impact on the vehicle's design – it can disturb the proportions between the wheel and the body, worsen the comfort of driving on minor unevenness and is limited by the diameter of the motor itself.

Extrapolation of data to determine vehicle energy consumption at driving speeds up to 50 km/h. Based on the data obtained from the vehicle test runs at three set speeds (13, 25, 35 km/h), the results were approximated. The aim was to estimate the power drawn from the battery and energy consumption over a wider speed range. Function models were developed describing the dependence of power and energy efficiency on vehicle speed in the range of 6 to 50 km/h. The Matlab Software was used to approximate the data. Regression Diagnostics (Regstats) was used to obtain the models. Regstats uses a linear additive model with a constant term. In this case, a second-degree polynomial 'purequadratic' (with constant, linear, and square terms) was used as the function. The approximation results are presented as quadratic functions (Equation 2, Equation 3):

- For battery power:

$$Battery\ Power = 802.12 - 54.07 \cdot Velocity + \\ + 2.25 \cdot Velocity^2 \quad (1)$$

- For efficiency:

$$Efficiency = 6.65 - 0.32 \cdot Velocity + \\ + 0.0078 \cdot Velocity^2 \quad (2)$$

The values of the coefficient R^2 (R—square Statistic) were 1, which may confirm that the fitted square models are statistically significant for the analyzed relationships. This result for the R^2 coefficient results from a properly selected function. The data for acronymization included the results of battery power and efficiency for the three tested vehicle speeds. The results obtained from the tests had a clear trend. Therefore, the function determined using Regstats is well-fitted and the R^2 value was a high fit result.

Figure 11 shows the estimated value of the power drawn from the battery as a function of speed. The curve shows a non-linear character: for low speeds, a small decrease in power demand is observed, followed by a strong increase above approx. 20 km/h. This trend results from the increase in aerodynamic drag, which dominates at higher driving speeds.

Figure 12 shows the expected energy consumption expressed in kWh/100 km. The vehicle reaches its highest energy efficiency value at a speed of about 20 km/h, which is confirmed by earlier observations. The increase in energy consumption for higher speeds reflects the non-linear nature of motion resistance.

In summary, the obtained results confirm the existence of an optimal speed range from the point of view of the vehicle's energy efficiency. Driving at speeds higher than 30 km/h causes a sharp increase in power demand and energy consumption, which can significantly affect the vehicle's range in urban conditions.

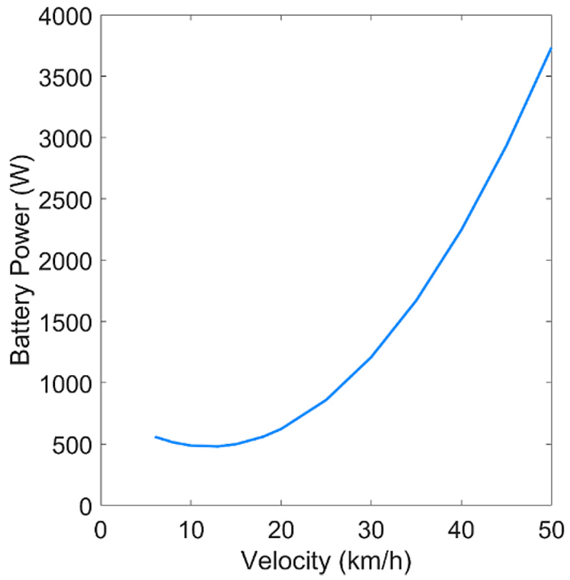

Figure 11. Relationship between battery power and vehicle velocity with the standard deviation values

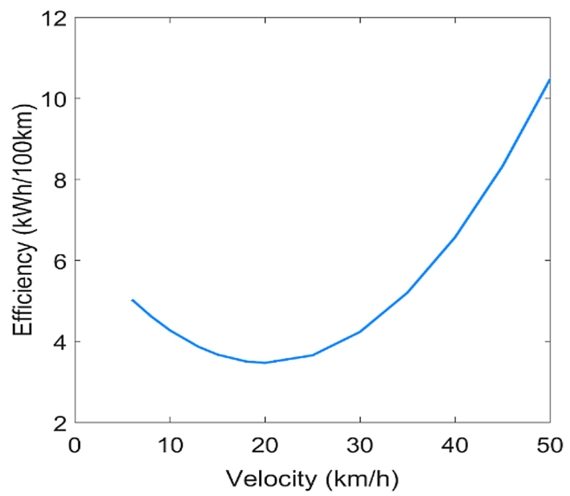

Figure 12. Relationship between efficiency and vehicle velocity with the standard deviation values

Road simulation of the urban operating cycle

In order to model the real conditions of use of a light electric vehicle in an urban environment, road tests were conducted. The tests simulated a typical vehicle operating cycle. The test process included numerous stops, accelerations, braking and driving at variable speeds, which allowed for the assessment of the dynamic profile of the drive system and energy consumption in conditions corresponding to everyday use.

Figure 13 shows a graph of the relationship between driving speed and distance as a function of time. The total distance traveled during the test was approximately 16 km. The speed graph shows an irregular character, typical of city traffic – with numerous acceleration sections, braking phases and many stops. The observed profile indicates significant variable loads of the drive system and cyclical fluctuations in power demand.

Figure 14 shows the route on which the test was carried out. The route included the area around the urban development, and its configuration allowed for the introduction of elements typical of urban vehicle traffic - such as turning maneuvers, U-turns, sections with limited maneuvering space and stopping zones.

Detailed measurement data recorded during the test are presented in Table 4. They include, among others, the values of the minimum and maximum battery voltage, the maximum current and power drawn from the power supply system, the total energy drawn during the test, and the values of the average energy consumption, maximum speed, distance and test duration.

In summary, the results obtained in both static and dynamic tests constitute a coherent set of data that allows for drawing clear and unambiguous conclusions regarding the operation of the drive system.

High variability of driving conditions directly affects increased energy consumption. During the test simulating the urban operating cycle, the average energy consumption was 8.24 kWh/100 km, the average vehicle speed was about 22 km/h. This confirms the increase in energy demand in dynamic conditions, typical of urban traffic.

Comparison of tests under 3 constant driving speeds to simulate the urban vehicle operation cycle

Analyzing the results obtained during tests conducted under steady speed conditions (13, 25 and 35 km/h) and simulations of the urban operating cycle, significant differences in energy consumption characteristics are observed. Driving at a constant speed allows for an accurate assessment of the drive system efficiency with minimal influence of variable factors, which is reflected in the clear power and energy consumption curves presented in the graphs (Figure 9, Figure 10). The lowest energy consumption was recorded at a speed of 25 km/h and amounted to approx. 3.7 kWh/100 km, which indicates optimal operating conditions of the drive system.

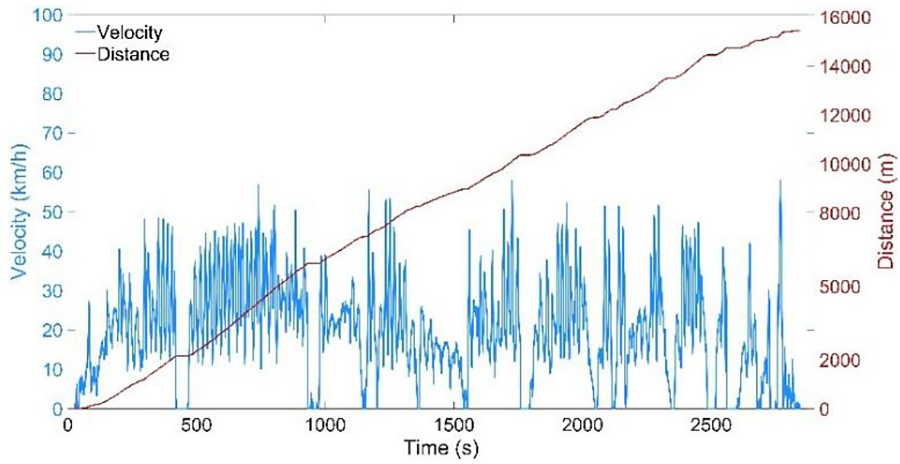

Figure 13. Velocity and distance relationship as a function of time

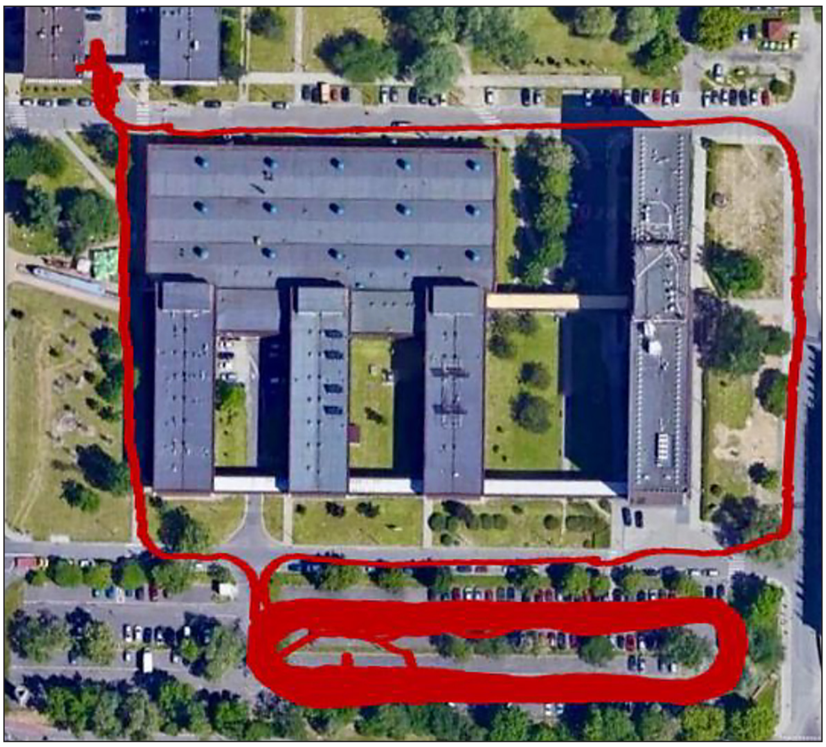

Figure 14. Measuring track to simulate the urban vehicle operating cycle

In the case of the test simulating the urban operating cycle (Figure 11, Figure 12), a much greater variability of the drive system operating conditions was observed than when driving at a constant speed – this cycle is characterized by high dynamics of speed changes, frequent acceleration and braking phases and numerous stops.

This type of variability generates significant momentary loads on the drive system, which translates into higher values of momentary power and average energy consumption. During this test, energy consumption of 8.24 kWh/100 km was recorded, which is more than twice the value of the most efficient constant speed test.

The values obtained are also influenced by specific vehicle design conditions. During the tests, the regenerative braking function was intentionally switched off. This was done because the amount of energy recovered during braking strongly depends on the individual driver's behavior, and regenerative braking itself cannot be implemented in every vehicle design and every electric drive system: e.g. traction battery pack must be adapted for high current charging, the

Table 4. Summary of recorded parameters during the simulation of the urban vehicle operation cycle

Parameter	Value
Minimum voltage at battery terminals	43.76 V
Maximum voltage at battery terminals	54.40 V
Maximum current drawn from the battery	431.17 A
Maximum power drawn from batteries	19.31 kW
Energy drawn from batteries	25.54 Ah
Energy drawn from batteries	1.27 kWh
Energy consumption	8.24 kWh/100 km
Maximum velocity	58.06 km/h
Test time	47.5 min
Distance covered during the test	15.43 km

normal load on the drive axle cannot decrease significantly during braking, the tests could not start with fully charged batteries because during initial braking the permissible charging voltage could be exceeded and the battery could be disconnected by the BMS (battery management system). To prevent this, resistors are installed in some road vehicles to dissipate excess energy. The tested vehicle is still under development and in order to limit the number of variables, the regenerative braking function was disabled. Further tests with various regenerative braking characteristics are planned.

The possibility of recovering energy during braking would certainly reduce the average energy consumption, the exact impact of which will be analyzed in further studies.

When comparing both types of tests, it should be clearly noted that urban driving conditions – despite the same average speed (22 km/h) – lead to more than twice the energy consumption compared to driving at a constant speed. While in steady traffic the consumption was around 4 kWh. In the urban cycle, due to the numerous acceleration and braking phases, this value increased to over 8 kWh. Such a significant difference should be taken into account in particular when designing vehicles for the urban environment, both in terms of battery selection and energy management strategy.

Additionally, the research results carry important practical implications for future design work.

The high energy consumption observed in the urban cycle (8.24 kWh/100 km) compared to steady-speed conditions confirms that battery capacity should be selected based on the dynamic driving profile rather than solely on nominal range. For instance, to ensure a 100 km range in urban traffic, a minimum of 10 kWh of usable energy is recommended.

The findings also highlight the relevance of implementing a regenerative braking system, especially in urban conditions where frequent deceleration significantly affects the vehicle's energy balance.

Furthermore, optimizing the drive control strategy – for example, by limiting the vehicle's speed in urban mode to around 25 km/h, where efficiency is highest – may positively influence performance and driving range. Finally, the wheel size and any torque transmission ratio (even in hub motor configurations) should be selected so that the motor reaches its peak efficiency at the most common speed encountered in urban operation, allowing for more efficient energy use under real-world conditions.

CONCLUSIONS

Based on the conducted experimental tests and analysis of data on the electricity consumption in a light quadricycle of the L6e-BP class, equipped with an in-wheel direct drive (BLDC) and powered by LFP batteries, the following conclusions were concluded:

a) Impact of speed on energy consumption:
- tests carried out at three set speeds (13, 25, 35 km/h) showed the existence of an optimal operating range in terms of energy efficiency. The lowest energy consumption was recorded for a speed of 25 km/h and amounted to about 3.7 kWh/100 km. Both lower and higher speeds resulted in an increase in specific energy consumption.

b) Dynamic characteristics of the urban cycle:
- simulation of the urban operating cycle showed a significant increase in the vehicle's energy demand. Despite the lower average speed, the variability of driving conditions (frequent stops, accelerations and braking) caused an increase in energy consumption to the level of 8.24 kWh/100 km. This indicates a significant impact of dynamic conditions on the efficiency of the drive system.

c) Application of approximation:
- extrapolation of data using quadratic functions made it possible to estimate energy consumption and power demand values for speeds in a wider range of values (6–50 km/h).

The conducted research and analysis of the results confirm that the actual operating conditions of electric vehicles – especially those intended for urban traffic and use by people with disabilities – have a significant impact on the energy efficiency of the entire drive system. The obtained results can be the basis for the design of power supply systems and control strategies that optimize energy consumption in light electric vehicles of the L6e-BP class. In addition, in future tests, it would be worthwhile to test the vehicle under various operating conditions, such as ambient temperature, payload variation, terrain incline. As part of future work, it would be worthwhile to perform a detailed analysis of other electric vehicles for disabled people (Elbee, Kenguru) in order to demonstrate greater capabilities and innovativeness of the analyzed vehicle.

Although this study focused primarily on energy consumption and drive system parameters, the tested vehicle is also equipped with several accessibility-enhancing features, such as adjustable suspension and the ability for direct wheelchair access. Preliminary user feedback indicates that these solutions significantly improve comfort and independence. As part of future development work, a comprehensive ergonomic assessment is planned, involving a broader group of users with diverse mobility needs.

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