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DESIGN AND TESTING OF THE PROPULSION SYSTEM OF A PROTOTYPE ELECTRIC VEHICLE INTENDED FOR PEOPLE WITH DISABILITIES

Summary. The paper describes the design and testing of the first lightweight electric vehicle designed for people with disabilities, which was developed at the Faculty of Mechanical Engineering of the Cracow University of Technology. The tests included bench tests on a dynamometer and urban driving simulations to evaluate parameters such as torque, engine power, top speed, and energy consumption. The vehicle was equipped with BLDC motors mounted directly in the rear wheel hubs and lithium-iron-phosphate batteries. The results showed good vehicle dynamics and efficiency with low energy consumption in the urban cycle. The analysis confirmed the vehicle's satisfactory range on a single charge. Based on the results, further improvements were suggested, such as implementing regenerative braking and reducing aerodynamic drag through body design. This allowed for increased energy efficiency and functionality of the vehicle in everyday use.

1. INTRODUCTION

An analysis of the European market for vehicles for wheelchair users with disabilities has shown that currently available means of transportation still do not fully meet their specific needs, resulting in serious social and occupational consequences. The lack of appropriate technological solutions that would enable active participation of people with disabilities in social life translates into their exclusion from many spheres of life, limiting their mobility, independence, and ability to travel longer distances independently. This situation leads to social isolation, reduces the availability of jobs, makes it difficult to continue education, and significantly limits recreational opportunities [1].

A mobility disability should not be synonymous with limited access to basic social or vocational activities. In this context, the development of modern vehicles that meet the unique requirements of users with mobility limitations is key to overcoming these barriers [2, 3]. There is now a growing interest in developing propulsion systems tailored to the needs of this segment of the population - powertrains that will not only increase their mobility but also provide a high level of safety and comfort. What's more, innovative electric-powered projects align with the global trend of sustainability and the drive to minimize emissions, thus fitting in with the idea of green transportation solutions [4, 5, 25]. In specialist literature, authors increasingly often present the results of analysis, road and laboratory tests of energy consumption and CO_2 emissions by electric vehicles, comparing them to vehicles with classic combustion engines. The results confirm that, especially when using renewable energy sources to charge batteries, electric vehicles are more energy-efficient and environmentally friendly (CO_2 emissions, noise) compared to their combustion counterparts [22-24]. Designing various types of electric vehicles, especially city cars and light special-purpose cars, which this work concerns, is a very interesting area of development of the automotive industry in the near future.

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This introduction lays the foundation for further analysis of powertrain technologies and design parameters that can significantly impact the development of the disability vehicle sector [6]. This work focuses on developing an efficient propulsion system for a lightweight four-wheeler, taking into account the requirements of users and the specifics of their needs.

The drivetrain in motor vehicles is a set of mechanisms and devices used to transmit mechanical energy from the engine to the drive wheels, allowing the vehicle to move. It mainly includes the engine, clutch, transmission, driveshaft, differential and drive wheels. The most important task of the drivetrain is to ensure the proper transmission of drive torque in order to adjust the speed and driving force according to the current driving needs, both in terms of acceleration and overcoming off-road obstacles or maintaining a stable speed [7]. Over the years, drivetrains have evolved, undergoing revolutionary changes that have affected the performance, economics and environmental impact of vehicles. In recent years, we have seen the rapid development and popularity of electric drive systems, including fully electric vehicles (EV) and hybrid vehicles. These systems significantly reduce emissions and, in the case of electric cars, eliminate them altogether. Today's electric drivetrains use advanced battery technology, braking energy recovery systems, and innovative energy management solutions. Hybrids, which combine internal combustion engines with electric motors, reduce fuel consumption and emissions, especially in urban traffic. In addition, the development of plug-in electric vehicle (PHEV) systems offers users the possibility of short journeys using only electric power, while at the same time using the combustion engine for longer journeys [8].

2. LITERATURE REVIEW ON THE DESIGN OF ELECTRIC DRIVE SYSTEMS

Electric-powered propulsion systems differ significantly from traditional combustion solutions in many respects, both in terms of design and operation. The main component of an electric vehicle's propulsion system is the electric motor, which converts electrical energy into mechanical energy, driving the vehicle's wheels. This direct energy conversion is much more efficient than in the case of internal combustion engines, which must first convert the chemical energy of the fuel into indirect energy, which involves greater energy losses [9]. Electric drives can be divided into two main classes (Fig. 1):

- central drive,
- direct drive in wheel hubs.

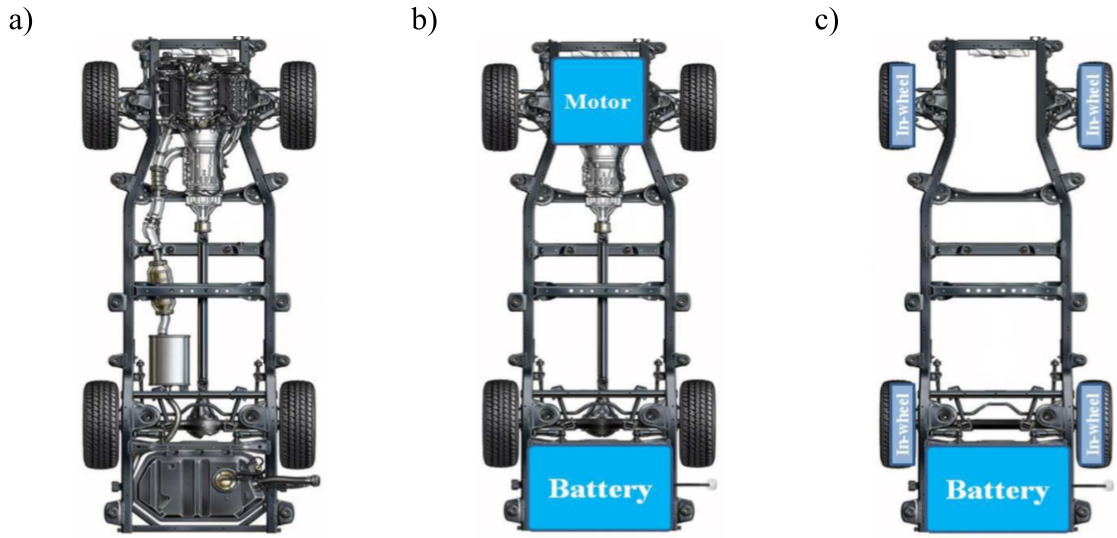

Fig. 1. a) classic combustion drive, b) central hybrid drive, c) direct electric drive (based on [10])

The development and research related to the drive motor placed directly in the wheels of motor vehicles are due to the disadvantages of centrally placed electric motors, i.e.:

- a lot of space needed to mount an electric motor,

– major design limitations of the vehicle dictated by the centrally located electric engine,
– the need for half-shafts or other solutions to transmit drive to the wheels.

These disadvantages have led to a growing worldwide interest in direct drives, which are characterized by mounting drive motors directly in the wheels of the vehicle (Fig. 2b) [11]. This solution is most often used in the rear wheels, less often in the case of four-wheel drive. Modern and advanced technologies in this type of drive combine not only the electric drive motor, but also integrate the braking system and the electric suspension system. The use of a drive located directly in the vehicle's wheel hubs brings a number of benefits, including eliminating the need for a complex transmission system such as half-shafts or gears. In addition, the space gained due to the lack of traditional drive components can be used to mount additional batteries, which will increase the range and power of the vehicle [12].

a) b)

Fig. 2. a) Centrally located electric motor [26], b) Engine placed directly in the vehicle wheel [27]

In electric vehicles and hybrid vehicles, batteries with varying characteristics are the energy source:

– Lithium-ion (Li-ion) cells: Most commonly used in modern electric vehicles, they have a high energy density, allowing for longer range and lighter batteries. They offer a good power-to-weight ratio, which improves vehicle efficiency and long life due to good charge retention and resistance to multiple charge and discharge cycles [13].
– Nickel-metal-hydride (NiMH) cells: Known for their longer lifespan and lower environmental impact, they were previously popular in hybrid vehicles. However, they have a lower energy density and are heavier than lithium-ion batteries, making them less common in full electric vehicles [14].
– Lead-acid cells: Common in older and smaller electric vehicles, mainly due to low cost. Often used also in electrical auxiliary systems, they offer reliability and a well-developed recycling process, but have a lower energy density and shorter lifespan [15].
– Lithium-iron-phosphate (LFP) cells: These batteries are distinguished by their high thermal and chemical stability, which reduces the risk of overheating and ignition, and their long durability thanks to a large number of charging cycles. The use of iron phosphate as a cathode material reduces production costs and increases the environmental performance of these batteries, eliminating the need to use cobalt. This makes LFP batteries environmentally friendly. This is of great importance in striving for sustainable development and minimizing the negative impact on our planet [16].

The rise in popularity of electric vehicles has made the Battery Management System (BMS) an indispensable component for ensuring efficiency and safe operation in electric vehicles and other devices using battery technology. Its task is to monitor the battery's charge level, temperature, and general condition. As a result, the BMS can optimize battery performance through several key functions:

– monitoring the charge status,
– temperature management,
– cell balancing,

- diagnostics and protection,
- charge and discharge optimization.

The operation of the BMS system is intended to extend the battery life and thus increase the vehicle's energy efficiency [17].

Another important component of the electric drive system is the inverter. It plays a significant role in electric vehicles by converting direct current (DC) from the battery into alternating current (AC) needed to drive electric motors. Its use enables precise control of engine speed and torque, which translates into vehicle performance and responsiveness.

Electric systems are also characterized by a greater simplicity of construction than internal combustion vehicle powertrains. They do not require complex transmissions, exhaust systems, turbochargers, or engine cooling systems in the traditional sense. This reduction in mechanical parts not only lowers the risk of failure but also reduces vehicle maintenance costs.

Electric vehicles use a variety of motor types designed to meet specific requirements and maximize performance and energy efficiency depending on the nature of operation.

- Induction motors: Robust and ideal for heavy-duty vehicles such as buses due to their ability to withstand high loads and reliability [18].
- Permanent magnet motors: Highly efficient at low speeds, used in passenger cars; limited by cost and dependence on scarce raw materials [19].
- BLDC motors: They have a long life and high efficiency, are suitable for light vehicles such as scooters and electric bicycles, and offer low maintenance costs [20].
- Switched Reluctance Motors (SRMs): Simple design and low manufacturing cost, but they require advanced control and emit noise and torque pulsations [21].

The main part of the work is a study of an electric vehicle drivetrain and an analysis of the energy requirements of a lightweight four-wheeler for people with disabilities. This section details the vehicle's technical parameters and evaluation criteria, as well as the measurement methodology and apparatus used. Based on the tests carried out, an analysis of the four-wheeler's drivetrain was made, also discussing the test conditions under which the measurements were made. The obtained test results are presented, which were used to evaluate the efficiency of the drive and determine the energy requirements of the vehicle.

However, despite the high efficiency of the electric drivetrain itself, the overall environmental impact depends on the origin of the electricity used. In this study, electricity from the Polish national grid was used, which includes both renewable and non-renewable energy sources. Designing various types of electric vehicles, especially city cars and light special-purpose vehicles — such as the one discussed in this paper — remains a promising area of automotive development.

3. DESCRIPTION OF THE TEST OBJECT - ELECTRIC DRIVE SYSTEM

The vehicle under study is a prototype lightweight four-wheeler designed for people with disabilities. Its unique features include the use of BLDC motors mounted directly in the rear wheels, lithium-iron-phosphate (LFP) batteries, and a semi-active suspension system that allows the vehicle to be lowered close to ground level. The vehicle is equipped with four lithium-iron-phosphate batteries with a total voltage of 48 V and a capacity of 100 Ah, providing an adequate power supply.

3.1. Parameters and data collection methods

Due to its nature and purpose, the vehicle must meet high standards of safety, comfort, and performance. To ensure these requirements, it was necessary to carry out detailed research and tests that would allow for the assessment of the vehicle's technical and operational parameters. This section discusses the key parameters recorded during testing and the assessment criteria adopted. Fig. 3 shows batteries installed in the tested vehicle.

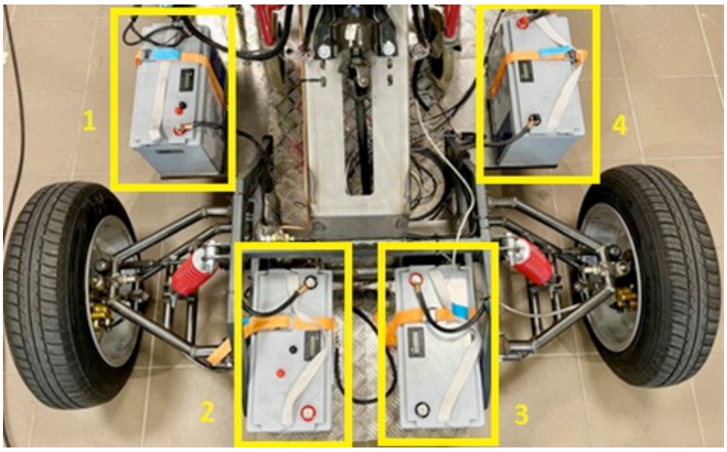

Fig. 3. Batteries installed in the tested vehicle. Numbers 1–4 indicate individual 12 V battery modules connected in series to form a 48 V system

Table 1
Catalog data of lithium-iron-phosphate battery

Nominal voltage	12.8V
Nominal capacity	100Ah
Voltage range	10.8V~14.4V
Cut-off voltage	9.4V
Maximum charging current	100A
Maximum continuous	100A
Durability	6,000 cycles (0% -
BMS system	yes
Temperature at discharge	-20°C to 55°C
Height	215mm
Width	171mm
Length	330mm
Weight	10 kg+/-3%

The propulsion system consists of two brushless direct current motors with 6 kW of continuous power, mounted directly in the rear wheel hubs to optimize power transmission and improve energy efficiency (Fig. 4). The analyses and results presented in the article are based on real-life experimental tests conducted with the prototype vehicle on a controlled route under repeatable conditions.


Fig. 4. BLDC motor mounted directly on the test vehicle

Table 2 lists the technical parameters of the BLDC motor that was installed in the test vehicle.

The following parameters were recorded during the four-wheeler tests:

- Vehicle position: Crucial for assessing maneuverability and movement in various terrain conditions. Tracking the route also makes it possible to analyze the vehicle's energy efficiency.

- Vehicle speed: Speed measurement provides information on vehicle dynamics, covering top speed, acceleration time and stability under various driving conditions. This is important for a full assessment of its behavior and acceleration.
- Current drawn from the batteries by the BLDC motors: This parameter reflects engine load and energy consumption, which makes it possible to estimate the vehicle's range on a single charge and identify potential overloading problems. The evaluation criteria include average and maximum current values, its dependence on driving conditions, and energy efficiency in various modes of operation.
- Battery voltage: Voltage monitoring allows for assessing the state of charge and stability of electrical system operation. Among other things, voltage drops under load are analyzed, as well as the batteries' ability to maintain sufficient voltage for the drivetrain. The evaluation criteria include voltage stability, changes during discharge, and the ability of the batteries to power the vehicle.

Table 2

Catalog data of brushless direct current (BLDC) motor from QS Motor

Engine type	Brushless DC motor
Continuous power	3,000 W
Maximum power	6,000 W
Voltage range	48V - 96V
Magnet height	50 mm
Maximum rotation speed	700 rpm
Maximum torque	181 Nm
Engine 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

In summary, the analysis of parameters such as position, speed, current consumption, and battery voltage allows for a detailed assessment of the technical characteristics of the four-wheeler and the determination of its energy characteristics.

A variety of data collection methods, including road tests and bench tests on a chassis dynamometer, were used in the study of a lightweight four-wheeler for people with disabilities.

a) Data collection during road tests

Road test data was collected using Racelogic's PerformanceBox (Fig. 5), along with LEM HAIS 100-P current sensors (Fig. 6) designed to measure the current drawn by the motors. PerformanceBox is an advanced device that enables precise monitoring and recording of vehicle parameters while driving, using GPS technology to accurately measure speed, acceleration and other key vehicle dynamic parameters.

LEM HAIS 100-A current sensors, along with a micro input module, allow analog signals to be recorded during road tests. The current drawn by the motors from the batteries and the voltage of the batteries were recorded. The collected data was processed in Circuit Tools and exported to MS Excel for further analysis.

b) Data collection during bench tests on a chassis dynamometer

Fig. 7 shows a simplified measurement scheme. During bench tests conducted on an AutoDyn 30 chassis dynamometer, data was also collected using LEM HAIS 100A current sensors. The signal from these sensors went to a Spider 8 measurement card, then to an archiving computer with Catman software. The collected data was preprocessed and exported to MS Excel, where it was further analyzed. Additionally, a voltage divider with resistances matched to the capabilities of the measurement card was installed in the measurement system. This allowed the input signals to be accurately matched to the requirements of the measurement equipment, thus ensuring the reliability and credibility of the collected data.

Fig. 5. Racelogic device mounted on the vehicle during testing

Fig. 6. LEM HAIS 100-A current sensor installed in the test vehicle

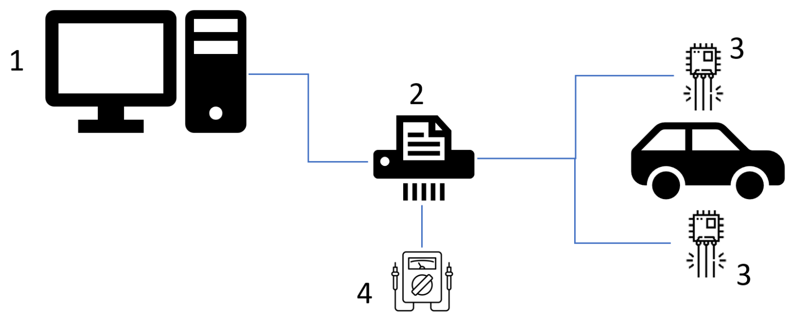

Fig. 7. Measurement scheme: 1 – archiving computer with Catman software, 2 – Spider 8 measurement card, 3 – LEM HAIS 100 A current sensors, 4 – voltmeter

By using the described methods, high-quality data were obtained, which served as the basis for a comprehensive analysis of the technical parameters and energy efficiency of the vehicle under study. Testing the vehicle on the AutoDyn 30 chassis dynamometer is shown in Fig. 8.

3.2. Test conditions during vehicle road tests

Road tests of the vehicle were conducted on asphalt pavement in good condition, ensuring stability and safety. The driving track was in the form of a loop, allowing for repeatable maneuvers and consistency of the results, and the flat terrain eliminated the impact of the slope. The tests took place on May 5, 2024, in favorable weather conditions: a temperature of 20°C, light wind (10 km/h), and dry asphalt, which minimized the risk of slipping.

Fig. 8. Testing the four-wheeler on an AutoDyn 30 chassis dynamometer

The vehicle was tested with a load of the driver and a standard wheelchair, whose combined weight was about 85 kg. This load corresponds to the average load with which the vehicle will be used on a daily basis, so the results obtained are authoritative. The pressure in all wheels was 2.3 bar, which is adequate for optimal grip and driving comfort. The batteries in the vehicle were fully charged before the tests began, ensuring maximum battery performance and eliminating the effect of charge level on test results. Moreover, it allowed determining the approximate range of the vehicle on a single charge.

The road tests were designed to simulate the urban operating environment of the vehicle in order to represent as closely as possible the conditions in which the four-wheeler will be used on a daily basis. The test route was laid out to include typical elements of urban driving, such as frequent stops, starts, speed changes and turning maneuvers. This provided data on the vehicle's behavior in real urban traffic conditions, which included analysis of energy consumption, driving dynamics and comfort.

4. TEST RESULTS

4.1. Testing the four-wheeler on an AutoDyn 30 chassis dynamometer

The data exported to MS Excel was presented in tabular form. After filtering the results and verifying the curves by means of comparison with the current drawn by the motors, the speed characteristics were obtained. Fig. 9 shows the relationship of torque (Msym) and power (Nsym) as a function of engine speed. The torque (green line) initially remains constant at around 400 Nm, and then begins to gradually decrease after exceeding about 400 rpm. Motor power (purple line) increases linearly from zero, reaching a maximum value of about 14 kW at about 415 rpm, after which it begins to decline.

The key conclusions from the conducted bench tests are as follows:

– The engine generates high torque at low rpm, which is beneficial for acceleration from a standstill and in difficult road conditions,
– Maximum power is achieved at about 400 rpm, suggesting an optimal engine operating point for maximum efficiency,
– Beyond 400 rpm, both torque and horsepower begin to drop, meaning that the engine's efficiency decreases at higher speeds.

The most important data from the conducted analysis are summarized in Table 3.

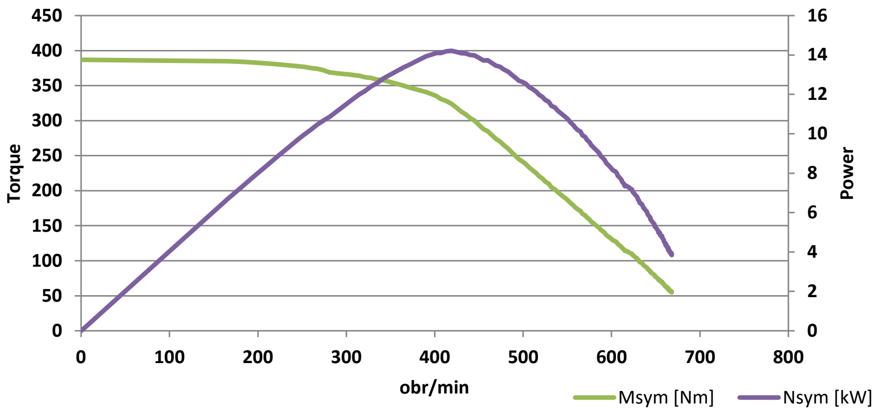

Fig. 9. Diagram of torque (Msym) and power (Nsym) dependence as a function of engine speed

Table 3

Summary of data collected during the test on the chassis dynamometer

Parameter		Value	Unit
Maximum power	N_N	14.22	kW
Maximum drive torque	M_M	400	Nm
Maximum rotation speed	n_{max}	668	rpm
Speed at which there is maximum drive torque	n_M	0	rpm
Maximum speed	V_{max}	53.72	km/h

4.2. Road tests of the vehicle - an attempt to determine the energy consumption of the vehicle in the urban cycle

Fig. 10 shows the route on the campus of the Cracow University of Technology in Czyżyny, Krakow, along which the tested vehicle was driven, simulating operation in urban cycle conditions. The route was determined based on the GPS signal from the Racelogic device, which ensured precise mapping of driving parameters.

Graph (Fig. 11) shows the dependence of speed and distance on time, illustrating how the vehicle moved in a simulated urban cycle. Initially, the vehicle's speed is low, gradually increasing, with many noticeable accelerations and braking. The highest accelerations occur repeatedly throughout the test run, reaching speeds approaching 60 km/h, followed by a drop in speed. The distance covered (red line) increases over time, reaching about 16 kilometers at the end of the trial. The graph shows regular changes in speed, which is characteristic of driving in urban conditions, where the vehicle frequently accelerates and stops.

Graph (Fig. 12) shows the battery voltage as a function of time during a test simulating an urban cycle. Initially, the voltage remains constant at about 55 V. During the test, small voltage fluctuations are visible, remaining close to the initial value. The largest voltage drops are noticeable at several points on the graph, reaching values close to 0 volts. This is caused by the BMS disconnecting the battery after the maximum permissible current is exceeded. To prevent this, adjustment of controller settings is required so that the maximum current is limited to about 400 A. The voltage of the batteries shows high stability with only occasional short dips, indicating their good condition and ability to maintain a constant voltage during varying loads.

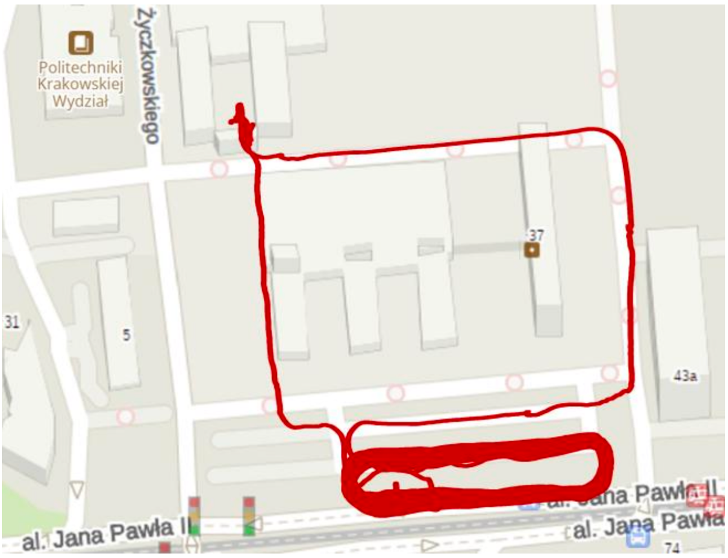

Fig. 10. The track on which urban driving was simulated with the tested vehicle

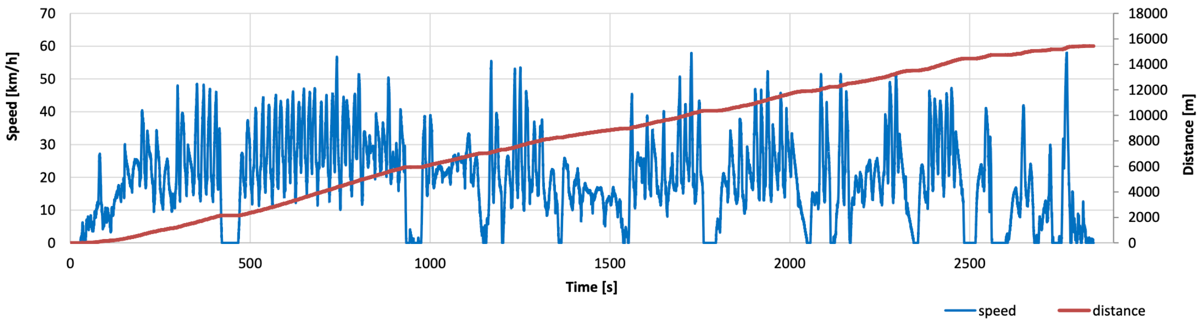

Fig. 11. Graph of speed and distance as a function of time

Graph (Fig. 13) shows the course of battery current as a function of time during a test simulating an urban cycle. At the beginning of the test, the current is low, except for a few small peaks. As the test continues, the current shows numerous increases, reaching values as high as 400 A at many points on the graph. Significant increases in current occur repeatedly throughout the test run, indicating moments of intense load on the batteries during vehicle acceleration. After each peak, the current usually drops quickly to lower values, which may suggest that the vehicle is moving to more stable operation or slowing down. Further, smaller increases in current can be observed throughout the test, reaching maximum values of around 200-300 A. Current intensity remains at a variable level most of the time, suggesting a variable battery load typical of an urban duty cycle.

The graph illustrates that the batteries are repeatedly subjected to different load levels, which is characteristic of actual vehicle use in urban conditions, where acceleration, braking and stopping are frequent. Graph (Fig. 14) shows battery power versus time during a test simulating an urban cycle of vehicle operation. At the beginning of the test, power is low, except for a few small peaks. As the test continues, battery power shows numerous increases, reaching values as high as 20 kW. Graph 16 shows battery power versus time during a test simulating an urban cycle of vehicle operation. After each peak, power usually drops quickly to lower values. Further, smaller increases in power can be observed throughout the test period, reaching maximum values of about 10-15 kW. Battery power remains at a variable level most of the time, suggesting the varying battery loads resulting from simulated urban cycles.

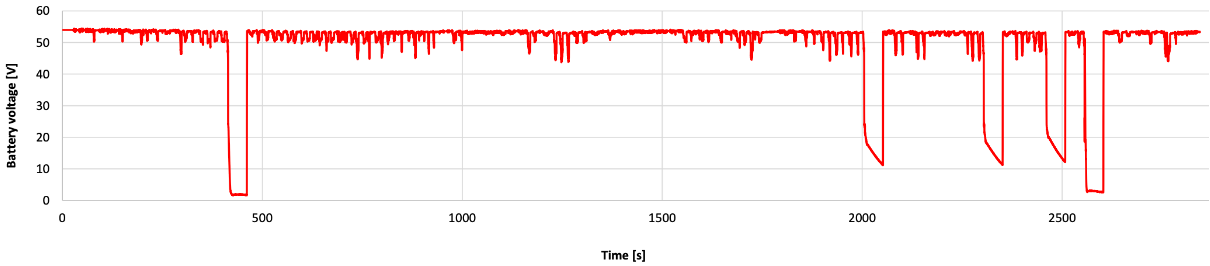

Fig. 12. Graph of battery voltage as a function of time

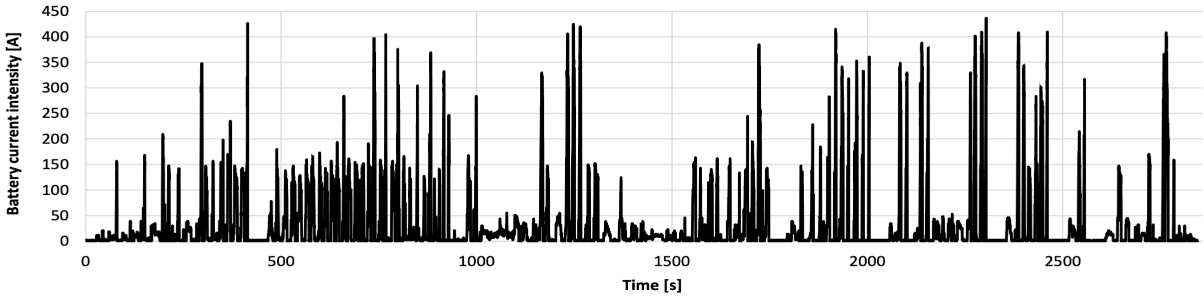

Fig. 13. Graph of battery current as a function of time

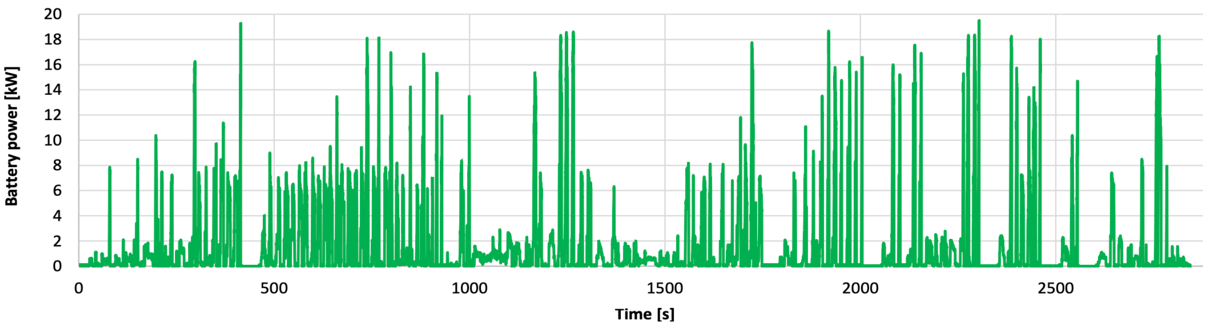

Fig. 14. Graph of battery power as a function of time

The table below summarises the most important parameters recorded when trying to determine the vehicle's energy consumption.

Table 4

Summary of the most important parameters recorded

Parameter		Value	Unit
Minimum voltage at battery terminals	U_{bat_min}	1.71	V
Maximum voltage at battery terminals	U_{bat_max}	54.40	V
Maximum current drawn from batteries	U_{bat_max}	431.17	A
Maximum power drawn from batteries	P_{bat_max}	19.31	kW
Battery power	q_{bat}	25.54	Ah
Battery power	E_{bat}	1.27	kWh
Average energy consumption	e	8.24	kWh/100 km
Maximum speed	V_{max}	58.06	km/h
Duration of the test performed	t	47.5	min
The distance covered during the test	s	15.43	km

5. CONSLUSIONS

The purpose of the study was to determine the energy and performance characteristics of a light four-wheeler designed for people with disabilities. The tests and research carried out provided key information on the vehicle's technical parameters and its behavior in real-world conditions. The following conclusions have been formulated on the basis of the conducted tests and analyses:

– The vehicle equipped with 5 kWh batteries can cover about 63 km on a single charge in the urban cycle, which was confirmed during the simulation of energy consumption in the urban cycle, where consumption was 8.24 kWh/100 km. It should be noted that during testing of the four-wheeler, braking energy recovery (so-called recuperative braking) was disabled in the controls, which has a direct impact on increased energy consumption and reduced vehicle range. Additionally, the vehicle has no body, resulting in high aerodynamic drag and and a high air drag coefficient C x , which has a significant impact on energy consumption and thus on the vehicle's range.
– The maximum recorded current drawn from the batteries by the BLDC motors was 431.17 A during a simulation of the urban use cycle in an attempt to determine the vehicle's energy consumption.
– During the tests, the battery voltage was around 54.40 volts. There were momentary drops in voltage during heavy engine loading, but the voltage quickly returned to the initial value. This proves that the batteries used meet the requirements, withstand operation in various conditions and maintain safety standards.
– The maximum power of the engines is 14.22 kW at 415 rpm, and the maximum driving torque registered on the chassis dynamometer is 400 Nm. These parameters ensure adequate vehicle dynamics and smooth acceleration from a standstill, regardless of operating conditions.

In conclusion, the assumed goal has been achieved. The study provided detailed data on the key technical parameters of the four-wheeler. These parameters include the power of the motors, the driving torque generated by the motors and the maximum speed, which made it possible to determine the mechanical characteristics of the electric motors installed in the vehicle. In addition, the voltage and current drawn from the batteries during the tests were analyzed, and the range the vehicle can cover on a single charge was determined. The performed analysis provided comprehensive information on the energy efficiency and technical characteristics of the vehicle. In further stages of the project's development, solutions that will significantly improve the energy efficiency and functionality of the vehicle are planned to be introduced. These include braking energy recovery and body design to maximize the reduction of aerodynamic drag on the vehicle.

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