Article citation info:
Lijewski P, Fuć P, Brydziński A, Zygmanowski M. Analysis of energy consumption of electric two-wheeled vehicles based on road cycle simulation. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-215450

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Analysis of the energy consumption of electric two-wheeled vehicles based on the road cycle simulation

ARTICLE INFO

Received: 15 June 2025
Revised: 25 November 2025
Accepted: 10 December 2025
Available online: 26 January 2026

The paper focuses on the development and validation of a simulation model that allows the assessment of the influence of the design and operating parameters on the maximum range of an urban electric two-wheeler. The performed research included real-world tests under urban conditions, covering a distance of 5.2 km, while monitoring the electrical parameters of an electric scooter. The sampling resolution was 0.1 seconds. The results of the measurements allowed for estimating the range of the vehicle under real-world conditions to be 60.053 km, corresponding to an energy consumption of 2.15 kWh/100 km. Based on the experimental data, the authors developed an advanced simulation model in the MATLAB environment. The model included dynamic acceleration/deceleration cycles, aerodynamic drag, rolling resistance and battery characteristics. The simulation of the driving cycle has shown the vehicle range of 60.778 km with the energy consumption of 2.12 kWh/100 km. The simulation results are characterized by a very high convergence with the results obtained in the road cycles. The simulation model enables the analysis of vehicle range variability in relation to various design and operating parameters, including gross vehicle weight, aerodynamic drag, drivetrain efficiency, and battery characteristics. The investigations described in the paper support the advancement of electromobility, thus, adding to the improvement of urban transport.

Key words: *electric vehicle, electric scooter, energy-consumption rate*

1. Introduction

Currently manufactured electric urban two-wheelers can be divided into three categories: traditional scooters, bicycles and ekick-scooters. Table 1 presents the technical data of different electric scooter models fitted with Li-ion batteries and compares their parameters and functionalities. Vehicles fitted with Li-ion batteries are characterized by higher energy capacity, which directly translates into improved range and better ride dynamics. Models such as the Iamelectric IML NCE-S or the Iamelectric T-REX, fitted with high-capacity batteries (4896 Wh and 5040 Wh, respectively), have a greater range and higher maximum speeds. It can be assumed that the electric vehicle market will develop, this applies not only to two-wheelers, but also to other categories of vehicles [4, 5].

Table 1. Technical data of selected electric scooters

Model	Battery capacity [V, Ah]	Battery energy [Wh]	Motor power [W]	Maximum speed [km/h]	Declared maximum range [km]
Iamelectric Eagle Lithium	60, 20	1200	1200	45	50
Iamelectric Hawk Lithium	72, 20	1440	1800	45	65
Iamelectric IML NCF-S	2 × 60, 34	4080	4310	80	80
Iamelectric IML NCE-S	2 × 72, 34	4896	6600	90	130
Iamelectric T-REX	72, 70	5040	6000	110	100

Energy consumption is a crucial parameter that significantly influences the performance and functionality of electric vehicles (EVs). The energy consumption parameter describes the amount of energy (expressed in kilowatt-hours – kWh) required to cover a certain distance, typically 100 kilometers (kWh/100 km). Siemionek [13] defines the energy consumption of a vehicle in motion, allowing for energy loss throughout the entire drivetrain, the vehicle's technical condition, and the weight of the passengers. Similar studies were presented in [7], where the investigation objective was to examine the dynamic and energy consumption of an electric scooter by varying key input parameters, including rider mass, electric scooter mass, wind speed, wheel radius, and slope grade. A simulation model of an electric scooter was developed in MATLAB-Simulink to simulate the scooter's velocity, required power, battery voltage, and powertrain torque. In [3], the authors presented the role of battery condition in electric vehicles as a main parameter affecting vehicle distance. Boumediene et al. [2] developed a control algorithm for energy management to maintain the scooter battery and supercapacitor at their optimal states of charge. An electric scooter's powertrain performance under varying loads is simulated in MATLAB and Simulink to verify the effectiveness of the EMS. The simulation results validate the effectiveness of the proposed approach and demonstrate the novel EMS as a suitable solution for energy management.

Yuan et al. [15] emphasize the significance of energy consumption. "In order to assure standardization, the ECR indicator (ECR – Energy-Consumption Rate) is determined under certain test conditions – a standard cycle that is deemed to be the most representative driving profile." The ECR is the fundamental parameter that allows for an accurate analysis of the energy performance of electric vehicles under standard test conditions, ensuring consistency and comparability of the results.

To sum up, the energy consumption of electric vehicles is defined as the amount of energy consumed per unit of covered distance. The value of this parameter is influenced by the vehicle's design (weight, drivetrain efficiency, and aerodynamics) and the operating parameters, which include the driving style and route profile. Standardized measurement methods, such as driving cycles, allow for comparable results and parameter analysis under different scenarios.

Two-wheeled electric vehicle energy consumption modeling is not widely discussed in the literature. In [12], the authors focused on modeling the energy performance and energy consumption of an e-scooter using the AUTONOMIE simulation tool [1]. Literature also describes a methodology based on assessing energy consumption derived from the scooter motor's power output and road data [9]. In [8], the authors propose a model that utilizes the MATLAB environment; however, its application requires very detailed engine and drivetrain data. A similar solution was proposed in [10], where the developed model uses MATLAB/Simulink. In [14], a dynamic simulation model was proposed that was experimentally validated on a chassis dynamometer. In [16], the authors presented a method for developing an electric scooter model to simulate its performance, especially its range estimation. The modeling method was the use of an electric scooter model developed in MATLAB/Simulink. Based on the dimensions and targeted performance, the authors simulated the device to determine its power and energy requirements. The research results of the simulation were validated in an experimental test on a dynamometer and in on-road conditions.

Selecting the correct battery technology is of vital importance. The technical parameters, such as capacity, weight, number of charging cycles, and performance under varying operating conditions, have a direct influence on the vehicle's range, performance, and useful life. Based on the analysis of different types of vehicles (Table 2), we can infer that Li-ion (lithium-ion) and Li-Po (lithium polymer) batteries are characterized by the highest specific energy and energy density, making them the best choice for electric scooters.

Table 2. Comparison of the battery parameters

Parameter	NiCd	NiZn	NiMH	Li-ion/Li-Po
Specific energy [Wh/kg]	40–60	100	60–120	100–265
Energy density [Wh/l]	50–150	280	140–300	250–730
Specific power [W/kg]	150	> 900	250–1000	250–340
Charge/discharge efficiency [%]	70–90	80	66	80–90
Self-discharge indicator [%]	10	13	30	8–5
Cycle durability [cycle]	2000	400–1000	500–1000	400–1200
Cell voltage [V]	1.2	1.65	1.2	NMC 3.6/3.7; LiFePo4 3.2

2. Research methodology

The research object has been presented in Fig. 1. It is an electric scooter. It is an urban two-wheeled electric vehicle, known as the Eagle Lithium, made by Iamelectric. The basic parameters of the object have been shown in Table 3. The vehicle is driven by a 1200 W electric motor that allows a maximum speed of 45 km/h. The unit is powered by a 70 V 20 Ah lithium-ion battery.

Fig. 1. Iamelectric Eagle Lithium scooter used for test [11]

Table 3. Basic parameters of the tested object [11]

Parameter	Data
Homologation	Yes
Equivalent of petrol scooter	50cc
Battery	Lithium-ion
Battery capacity	70V 20Ah
Battery charging time	4–6 hours
Battery weight	10 kg
Battery lifespan	1000 cycles
Electric motor power	1200 W
Maximum range	Up to 45 km (1 person, 70 kg)
Maximum speed	45 km/h
Tire size (front/rear)	3.50–10"
Curb weight	63 kg
Max. Permissible payload	188 kg
Gross vehicle weight	263 kg
Dimensions	1810 × 710 × 1100 mm

The planned experiment aimed to determine the energy characteristics of the tested object's operation under real-world operating conditions. The tests were carried out on a route of 5.2 km in length (Fig. 2), which the object covered in 10 minutes. The tests included recording the variations in voltage (V) and current (mA) in the power supply circuit of the electric motor. The tests were conducted using real-time measurement equipment. The recorded data were also transmitted in real-time to the computing unit located at Poznan University of Technology. The data transmission was completed through a computer installed in the scooter rear trunk (wireless communication, Internet access).

The Fluke i30s, utilizing the Hall effect, was used to measure the current and voltage at the input to the electric motor. Using the Advantech Elmatica UNO 137, the data were processed in real-time. The Advantech CR 1601W recorded and forwarded data to the Internet. Prior to commencing the tests, the sensors were calibrated to ensure measurement accuracy. The measurement equipment recorded the voltage and current values continuously at a sampling frequency of 10 Hz. The data collected during the tests enabled a detailed analysis of the voltage (V) and current (mA) variations as a function of time. The data were used to develop a detailed mathematical model, which constitutes the basis for the simulation.

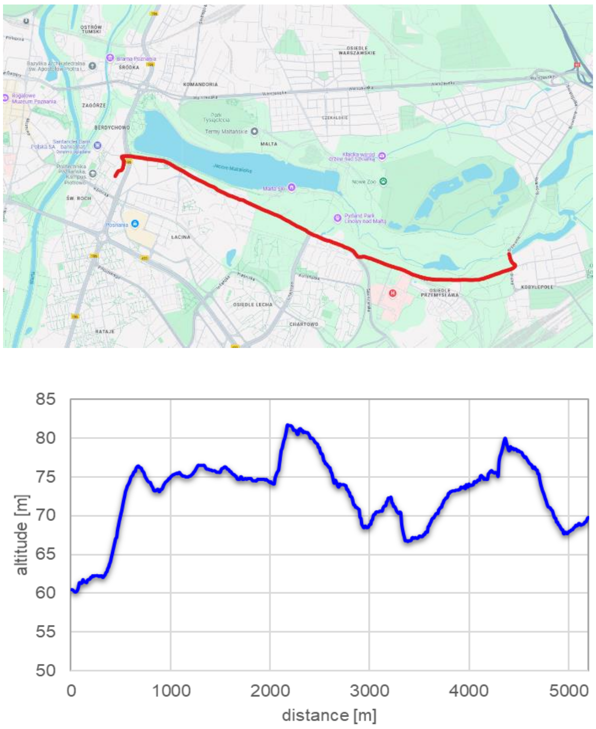

Fig. 2. Test route [google.com/maps]

3. Results

Based on the recorded data, the authors calculated the instantaneous energy consumption (P) as per the relation:

$$P = \frac{U \cdot I}{1000} \text{ [kW]} \quad (1)$$

The results of the calculations showing the instantaneous energy consumption were used to generate a graph, as shown in Fig. 3. From the analysis of the graph, it is evident that the instantaneous energy consumption is characterized by visible fluctuations that reflect the driving dynamics. The maximum values of energy consumption, reaching 1.4 kW, occur during vehicle acceleration. The total energy consumption by the motor of the tested object was calculated as the sum of the instantaneous energy for all recorded samples. The calculations were made according to the equation as shown below:

$$E = \frac{(P \cdot \Delta t)}{3600} \text{ [kWh]} \quad (2)$$

The results of the calculations show that the accumulated amount of energy used during the test was the value calculated from equation (2):

$$E \approx 0.112 \text{ kWh}$$

The obtained results also show that the energy consumption was clearly dependent on the driving dynamics. The highest energy consumption occurred in the acceleration phase.

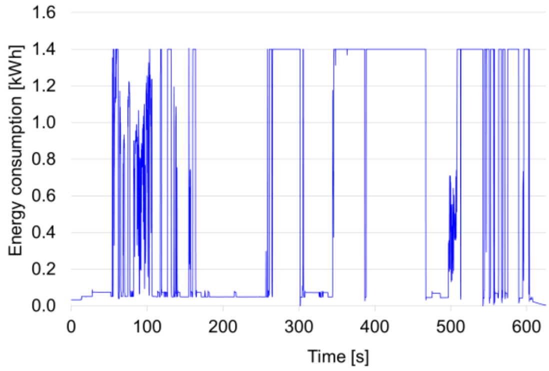

Fig. 3. Instantaneous energy consumption as a function of time

The voltage values during the test varied in the range from approx. 62 V to the nominal value of 70 V (Fig. 4). Instantaneous voltage drops to approx. 60 V occurred during heavy battery load, particularly during acceleration. This phenomenon is characteristic of the operation of lithium-ion battery cells, where the voltage drops in response to high energy demand.

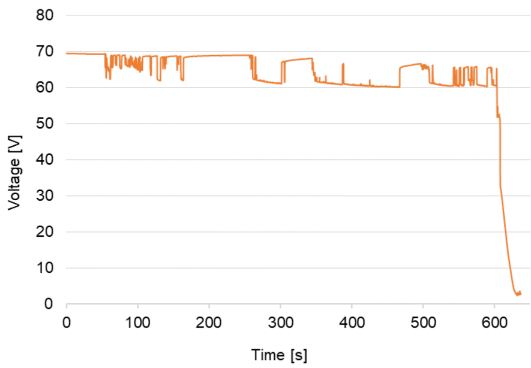

Fig. 4. Voltage changes as a function of time

During the tests, the current reached its maximum value of 25 A during heavy acceleration (Fig. 5). Low current values, close to 0 A, were recorded when the vehicle was stationary or when coasting and the electric motor was not engaged.

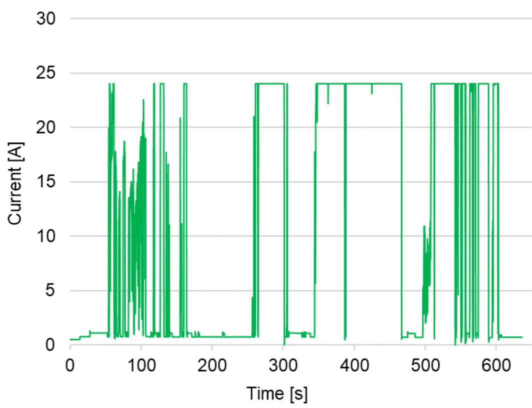

Fig. 5. Change in the current as a function of time

Figure 6 presents the cumulative value of energy consumption, reflecting the total amount of energy drawn from the battery during the tests. The greatest increase in energy consumption was observed during the acceleration phase, indicating a significant load on the battery resulting from high power demand.

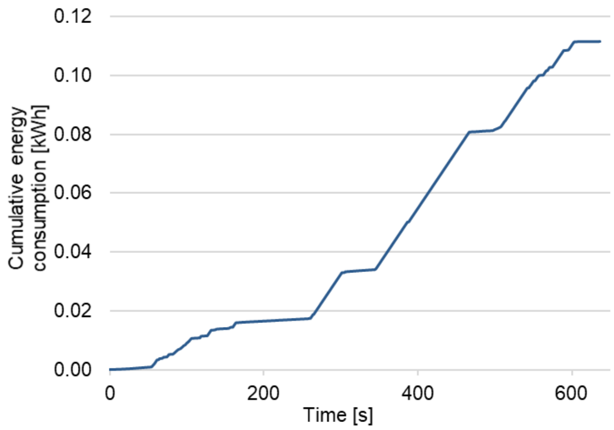

Fig. 6. Cumulative energy consumption as a function of time

Based on the collected data related to energy consumption and battery parameters, the authors performed an analysis aimed at assessing the projected range of the tested object. The results of the calculations have been presented in Table 4.

Table 4. Assessment of the projected range of the tested object

Description	Value
Total energy consumed [kWh] = (Samples · delta t)/3600	0.112
Remaining energy [Wh]	1288.472
Remaining charge percentage [%]	92.034
Used charge percentage [%]	7.966
Estimated range at 100% battery efficiency [km]	65.275
Estimated range at 92% battery efficiency [km]	60.053

4. Simulation of the scooter range

The simulation of the driving cycle, based on real-world data collected during tests, aimed to reproduce the actual driving profile of the test object and estimate its range, allowing for dynamic speed changes, accelerations, and decelerations. Based on the analysis of the real-time data collected during the tests, the authors observed that within a 10-minute experiment, 40 acceleration cycles were identified.

The simulation served as a tool to validate the compliance of the calculated results with those obtained under real-world conditions. Gołębiewski and Prajwowski have presented the mathematical formulas used as the basis for the simulation in [11]. The input data necessary to carry out the simulation were those modeled from the data obtained under real-world driving conditions. The input data necessary to carry out the simulation are shown in Table 5.

In the first step of the simulation, the authors entered the most fundamental parameters of the vehicle (Fig. 7). The input data may vary, as it is possible to use factory data related to specific models of electric scooters.

Table 5. Simulation input data

Parameter	Value
Maximum motor power output (Pmax)	1200 W (1.2 kW)
Maximum speed (Vmax)	45 km/h (12.5 m/s)
Vehicle weight (m)	160 kg
Air density (rho)	1.225 kg/m^3
Aerodynamic drag coefficient (Cd)	0.6
Frontal area of the vehicle (A)	0.6 m^2
Rolling resistance coefficient (f_r)	0.015
Gravitational acceleration (g)	9.81 m/s^2
Battery capacity (capacity Ah)	20 Ah
Battery voltage (V_battery)	70 V
Nominal battery energy (E_battery)	1400 Wh (5.040.000 J)
Battery efficiency (eta_battery)	92% (0.92)
Drivetrain efficiency (eta_drive)	95% (0.95)
Acceleration/deceleration cycles (n_cycles)	40 cycles
Acceleration (a_acc)	1.5 m/s^2
Deceleration (a_dec)	–1.5 m/s^2
Total test time (t_test)	600 s (10 min)

```
% Scooter range Iamelectric Eagle Lithium

% Vehicle data
P_max = 1.2 * 1000; % Max engine power W (1.2 kW)
V_max = 45 / 3.6;  % Max velocity m/s (45 km/h)
m = 160;           % Vehicle duty (kg)
rho = 1.225;       % Air density (kg/m^3)
C_d = 0.6;         % Aerodynamic drag coefficient
A = 0.6;           % Frontal area (m^2)
f_r = 0.015;       % Rolling resistance coefficient
g = 9.81;          % Gravitational acceleration (m/s^2)
```

Fig. 7. Parameters of the vehicle

where:
P_max – maximum motor power output; P_max = 1200 W
V_max – maximum speed of the vehicle; V_max = 45/3.6 m/s
m – vehicle weight including the driver, the vehicle equipment and measurement devices m = 160 kg
rho – air density under standard conditions, used to calculate aerodynamic drag rho = 1.225 kg/m^3
C_d – drag coefficient, determining the aerodynamic performance of the vehicle C_d = 0.6
A – frontal area influencing the aerodynamic drag; A = 0.6 m^2
f_r – rolling resistance coefficient, allowing for loss resulting from the contact of the tires with the road; f_r = 0.015
(g) – gravitational acceleration, used for calculating the mass forces g = 9.81 m/s^2.

The input data presented in Fig. 8 describe the parameters of the battery that were vital for the correct performance of the vehicle range simulation.

```
% Battery data
capacity_Ah = 20;  % Capacity (Ah)
voltage_V = 70;    % Battery voltage (V)
E_battery_Wh = 1400; % Battery energy (Wh)
E_battery_J = E_battery_Wh * 3600; % Battery energy (J)
battery_efficiency = 0.92; % Battery efficiency (92%)
E_battery_J = E_battery_J * battery_efficiency; % Battery effective energy
```

Fig. 8. Parameters of the battery

where:
capacity_Ah – battery capacity capacity_Ah = 20 Ah
voltage_V – rated battery voltage voltage_V = 70 V
E_battery_Wh – nominal energy of the battery expressed in watt-hours E_battery_Wh = 1400 Wh

E_battery_J – nominal energy of the battery converted into joules
E_battery_J = 1400 × 3600 = 5040000 J
battery_efficiency – battery efficiency; battery_efficiency = 92% = 0.92
E_battery_Jr – effective energy available at the battery terminals, calculated as the product of nominal energy and battery efficiency; E_battery_Jr = 5040000 × 0.92 = 4636800 J.

The formulas presented in Fig. 9 describe the efficiency of the drivetrain and calculations of the motion resistance.

```
% Powertrain efficiency
drive_train_efficiency = 0.95; % Powertrain efficiency (95%)

% Motion resistance efficiency calculation
% Air drag: F_drag = 0.5 * rho * C_d * A * V^2
% Rolling resistance: F_roll = m * g * f_r
```

Fig. 9. Efficiency of the drivetrain and calculations of the motion resistance

where:
drivetrain_efficiency – drive_train_efficiency = 95% = 0.95
F_drag – aerodynamic drag, described as F_drag = 0.5 × rho × C_d × A × V^2 [N]
rho – air density [kg/m^3], (C_d) – drag coefficient [-]
A – vehicle frontal area [m^2]
V – vehicle speed squared [m/s]
F_roll – rolling resistance force described with the formula F_roll = m × g × f_r [N]
m –vehicle weight including the weight of the driver and the equipment [kg], (g) – gravitational constant [m/s^2]
f_r – rolling resistance coefficient [-].

The parameters presented in Fig. 10 define the acceleration/deceleration cycles.

```
% Acceleration and deceleration parameters
n_cycles = 40;        % Number of acceleration mode in 10 minute
a_acc = 1.5;          % Acceleration (m/s^2)
a_dec = -1.5;         % Deceleration (m/s^2)
time_acc = V_max / a_acc; % Acceleration time to max velocity (s)
time_dec = V_max / abs(a_dec); % Deceleration time to stop (s)
time_test = 10 * 60;   % Total cycle time (s)
|
```

Fig. 10. Parameters of the acceleration/deceleration cycles

where:
n_cycles – number of full cycles of acceleration and deceleration per each 10 minutes of test n_cycles = 40
a_acc – vehicle acceleration a_acc = 1.5 m/s^2
a_dec – vehicle deceleration a_dec = –1.5 m/s^2
time_acc – acceleration time, calculated as the quotient of the maximum speed and acceleration; time_acc = V_max / a_acc [s]
time_dec – deceleration time calculated as the quotient of the maximum speed and the absolute value of deceleration time_dec = V_max / abs(a_dec) [s]
t_test – total time of the simulation covering all driving cycles, t_test = 600 [s].

The fragment of code presented in Fig. 11 pertains to the analysis of vehicle operating conditions at a constant maximum speed.

```
% Motion and idle time calculation
active_time = time_test; % active motion time (s)

% Assumation constant vehicle velocity
V = V_max;
F_drag = 0.5 * rho * C_d * A * V^2;
F_roll = m * g * f_r;
F_total = F_drag + F_roll; % Drag force

% Required power constant velocity
P_required = F_total * V / drive_train_efficiency; % Power (W) (with powertrain efficiency)

% Verification max vehicle velocity
if P_required > P_max
    disp('Vehicle is not able to going with constant velocity.');
    return;
end
```

Fig. 11. Calculating the active time of the vehicle and when stationary

where:
active_time – active time equal to the total time of the test active_time = 600 s
V – vehicle speed assumed as constant and equal to the maximum vehicle speed V = V_max [m/s]
F_drag – aerodynamic drag calculated as F_drag = 0.5 × rho × C_d × A × V^2 [N]
F_roll – rolling resistance determined from the formula F_roll = m × g × f_r [N]
F_total – total resistance force being the sum of aerodynamic drag and rolling resistance; F_total = F_drag + F_roll [N]
P_required – power required to overcome the total resistance at a constant speed, calculated as P_required = F_total × V/drive_train_efficiency [W]
P_max – maximum power output of the motor used to verify the possibility of the vehicle to maintain the maximum speed [W].

The fragment of a code presented in Fig. 12 pertains to the simulation of 40 cycles of acceleration and deceleration that were recorded during a 10-minute test under real-world conditions.

```
% Simulation 40 cycle acceleration and deceleration in 10 minute
E_total_J = 0; % Total Energy consumption (J)
for i = 1:n_cycles
    % Acceleration mode
    F_acc = m * a_acc + F_total; % Acceleration force
    P_acc = min(P_max, F_acc * V_max / drive_train_efficiency); % Acceleration power
    E_acc = P_acc * time_acc; % Energy consumption during acceleration (J)

    % Deceleration mode
    F_dec = m * abs(a_dec); % Deceleration force (only deceleration, without drag)
    P_dec = F_dec * (V_max / 2) / drive_train_efficiency; % Approximately power (deceleration)
    E_dec = P_dec * time_dec; % Deceleration energy consumption (J)

    %
    E_total_J = E_total_J + E_acc + E_dec;
end
```

Fig. 12. Simulation of 40 cycles of acceleration/deceleration per each 10-minute portion of the test

where:
E_total_J – total energy used by the vehicle during the simulation, initially 0 and updated after each cycle [J]
i – index of an iterative loop, in which subsequent acceleration/deceleration cycles are carried out i=: n_cycles [-]
F_acc – acceleration force F_acc = m × a_acc + F_total [N]
P_acc – power used during acceleration P_acc = min(F_acc × V_max, P_max) [W]
E_acc – energy used during acceleration E_acc = P_acc × time_acc [J]
F_dec – deceleration force F_dec = m · abs(a_dec) [N],
P_dec – power used during deceleration P_dec = F_dec × (V_max / 2)/drive_train_efficiency [W],
E_dec – energy used during deceleration E_dec = P_dec × time_dec [J].

The fragment of code presented in Fig. 13 pertains to the analysis of the energy remaining in the battery, taking into account the energy used during the 40 acceleration/deceleration cycles.

```
% Summing cycle energy with constant velocity
E_battery_remaining_J = E_battery_J - E_total_J;

% Verification energy level
if E_battery_remaining_J <= 0
    disp('Discharged battery after acceleration mode and deceleration mode.');
    return;
end
```

Fig. 13. Summing up the energy used during the cycles

where:

E_battery_remaining_J – remaining battery energy after completion of the cycles E_battery_remaining_J = E_battery_J – E_total_J [J]

E_total_J – total energy used during vehicle operation in cycles [J]

if E_battery_remaining_J <= 0 – logical condition validating if the battery is discharged, which would result in ending of the simulation,

return – a command to stop the software operation if the battery is discharged

E_battery_remaining_J > 0 – condition indicating that the vehicle still has energy resources and the simulation can be continued.

The fragment of code presented in Fig. 14 pertains to calculations of the battery operation time and the projected vehicle range, making allowances for energy use during acceleration and deceleration cycles.

The results of the simulations related to the vehicle's maximum range and battery energy consumption indicate compliance with the results obtained during tests performed under real-world conditions. The obtained results confirm the correctness of the simulation model and its compatibility with real-world operating conditions.

Under actual operating conditions, with the assumed battery efficiency of 92%, the projected vehicle range (as declared by the manufacturer) reaches 60.053 km. In the MATLAB simulation, the vehicle's range is estimated to be 60.778 km. The difference between these results is merely 0.725 km, which corresponds to a relative error of 1.2%. It should be acknowledged that such a difference is miniscule and the simulation model successfully reproduces the real-world operating conditions of the vehicle.

```
% Calculation battery operation time  with constant velocity
% Required energy for time unit (W) P_required (W)
% Battery operation time: t = E_battery_remaining / P_required

t_max_sec = E_battery_remaining_J / P_required; % Operation time (s)
t_max_h = t_max_sec / 3600; % Operation time (h)

% calculation vehicle range after acceleration mode and deceleration mode
range_km = (V * t_max_sec) / 1000; % Range km (for activity time)
```

Fig. 14. Calculation of the battery operating time

where:

t_max_sec – battery operating time after finishing the acceleration and deceleration cycles t_max_sec = E_battery_remaining_J / P_required [s]

t_max_h – battery operating time expressed in hours t_max_h = t_max_sec / 3600 [h]

range_km – vehicle range after the cycles range_km = (V × t_max_sec) / 1000 [km].

5. Conclusions

The results of the investigations indicate that the developed simulation tool can be used to estimate energy consumption by two-wheeled electric vehicles. The accuracy of the tool is fully satisfactory, as confirmed by experimental investigations conducted under real-world operating conditions in urban traffic. The proposed model can be used to assess the influence of design parameters, such as vehicle weight, rolling resistance coefficient, and aerodynamic drag, on the vehicle's energy performance and range. Another potential application of the model is assessing energy consumption based on traffic conditions. In further stages of the research, the authors plan to expand the simulation tool to other applications, such as two-wheeled vehicles with higher power output, operated in conditions other than urban. Additionally, the authors consider adapting the tool to simulate the energy consumption of other road vehicles, particularly passenger cars (PCs).

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