

ORIGINAL ARTICLE

Energy Minimization in City Electric Vehicle using Optimized Multi-Speed Transmission

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ABSTRACT – This article discusses a set of solutions for creating a city electric car with a low-voltage power supply system for a DC motor. Based on a constructed city vehicle with a low voltage electric drive system, a simulation model was prepared and verified. An energy flow analysis was performed, and the developed simulation model was described. Then, the optimization method was focused on minimizing the energy consumption of the vehicle in the driving cycles under consideration. To mirror the actual road conditions as much as possible, the real traffic cycle registered over an actual route was used in the process of optimization, with the cycle's velocity profile and recording of the road slope angle used in the simulation program. Established optimality quantitative dependence of the design and control parameters of the gearbox on the operational characteristics of the electric vehicle, which allowed for the determination of parametric and functional limitations during optimization. As a result of employing the described design solutions and optimization of drivetrain parameters, an over 40% reduction in the vehicle's energy consumption in a real driving cycle test was obtained.

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INTRODUCTION

As noted in the annual report of the International Energy Agency [1], electric mobility will be a major trend in the field of transportation development in the coming decades. For the leading car manufacturers, the priority is the improvement of electric transportation, which meets local environmental requirements. This primarily concerns the perspective of full-electric mobility in populated areas [2, 3, 4, 5], while inter-city communication may be secured with more sustainable transportation means and energy systems [6]. Therefore, electric vehicles should replace combustion vehicles, mainly in urban areas. Due to the short distances travelled every day, this would reduce the range concerns [7, 8], while the construction of charging points [9] and vehicle servicing infrastructure would involve the modernization of the existing network [10]. An analysis of the proposed solutions related to the development of electromobility in urban agglomerations shows that the most viable concept is to reduce the size of the car and then downsize the electric drive. The use of a low voltage power supply is also possible in this concept. This concept requires a new synergistic approach when designing a city car.

Currently, advanced optimization methods are used to search for new construction solutions and control algorithms for electric vehicle researchers. Researchers are using advanced optimization methods, both at the stage of constructing electric vehicles as well as during their operation in real conditions. Coronado et al. [11] present the use of a genetic algorithm to find the optimal value of gear ratios, while in [12], the same algorithm was used to optimize the electric speed profile of the minibus along the route to reduce energy consumption. Optimization is also used in electric drive control systems in vehicles. In [13], various optimization methods are assessed regarding the issue of gear shifting in the gearbox to minimize energy consumption as well as maximize energy recovery during recuperative braking.

However, the effectiveness of these methods depends primarily on the selected quality criteria. For EV, the main criteria can be defined as reducing the energy consumption of traffic, increase the amount of energy recovered during regenerative braking, and thus, increase the range of the vehicle on one charge. In this way, the efficiency of the optimization process depends on the assumed operational conditions for an object. There are research results in which an EV's travel velocity [14, 15, 16, 17] and other restrictions [18] are used for the evaluation of energy consumption. At the same time, it must be stressed that the average velocity is not the only parameter required to predict energy consumption [19]. When using normalized algorithms of distance measurements, implemented (among others) in the New European Driving Cycle (NEDC), World Harmonized Light-Duty Vehicles Test Procedure (WLTP) cycles, it is possible to compare results between various vehicles, as well as against actual performance. At the same time, it is cumbersome to consider many additional factors which influence the energy balance of an EV. Therefore, any work based on a comparative analysis of vehicle parameters obtained in real and experimental operating conditions is relevant.

The original approach to EV downsizing involves the use of a hybrid low-voltage power supply to a DC electric motor. This paper is one of the first to show how the choice of a driving cycle affects the results of optimizing electric

vehicle parameters. The tested vehicle, due to the relatively low power of the electric motor, was equipped with a gearbox, which allowed for more effective use of the engine's characteristics. This solution is relatively rarely used in electric vehicles produced. Using such a structure of the drive system, it is also shown that it is advisable to distinguish between a change in the gear ratio with increasing and decreasing revolutions of the electric motor.

The outline of this article is as follows. Section 2 presents the concept of electric drive for a small city vehicle, which uses a gearbox and a small set of batteries to ensure a range corresponding to the daily mileage of city vehicles. Section 3 presents the characteristics of the considered EV and its drive system. An energy flow analysis was performed and the developed simulation model was described in the AMESim program. Then, the optimization method was focused on minimizing the energy consumption of the vehicle in the driving cycles under consideration. Section 4 presents and discusses the research results, while Section 5 presents conclusions and final comments. The scientific novelty of the work is:

- i. the proposed methodology for selecting the parameters of the electric vehicle transmission with hybrid energy storage and recovery unit, which consists of the method of gearbox optimization and the gear shift algorithm based on energy consumption criteria in real operating conditions,
- ii. established quantitative dependence of the design and control parameters of the gearbox on the operational characteristics of the electric vehicle, which allowed for the determination of parametric and functional limitations during optimization.

JUSTIFICATION OF THE CONCEPT OF A CITY ELECTRIC CAR

The design and construction of electric vehicles require finding solutions for numerous issues — on the one hand, taking into account the minimization of energy losses in drive systems, and on the other, providing for the right functional parameters of a vehicle. Undoubtedly, an important issue is providing optimum gear ratios in a drive system [11, 13]. The majority of EVs constructed nowadays feature no gearboxes and only a transmission gear with a gear ratio selected to provide the right characteristics of the drive system. However, an EV construction may feature a gearbox, which provides for adjusting gear ratios in a drive system and thus allows for adjusting the ratios to actual load conditions without the need to use a high-power electric motor. Such an approach makes it possible to obtain satisfactory characteristics of the drive system with motor downsizing and a set of batteries so that the combination caters for a typical usable range of a vehicle in a city while allowing for fast recharging in charging points located around the city. The issue of electric energy sources in a vehicle mentioned here also requires careful consideration and thorough analysis since, in a city EV, small capacity batteries may be used, which provide for ranges typical for city usage, although the user expects (as much as possible) maintenance-free operation, with mileages comparable with similar vehicles with conventional drive systems. However, the employment of sets of batteries with large capacities generates problems connected with charging times and recuperation.

OBJECT AND METHODS OF INVESTIGATION

The City Electric Vehicle

Earlier studies [20] were conducted based on the construction of a city EV operated at the University of Warmia and Mazury in Olsztyn (Poland). To implement the given concept of adapting the vehicle's design to operational conditions of city traffic, it was proposed to use a minimized drive system and the vehicle's energy storage system. There was also a need to conduct a series of optimization tests to adjust the project vehicle's conversion into an EV adapted to city operational conditions, as well as to perform drive and energy storage system downsizing.

In the study, a vehicle was used that had been a subject of prior conversion from an internal combustion engine to an electric motor drive system. Since the requirement was to use a vehicle designed mainly for city traffic, the priority included small external dimensions and the low mass of the vehicle subjected to conversion. It was assumed that the range of the city vehicle per one charging should reach approx. 100 km, and the maximum velocity should be within speed limits in an urbanized area. To this end, a city class vehicle was used, factory-equipped with a 1,050 ccm (cm³) internal combustion (petrol) engine with spark-ignition, with a maximum power of 30 kW at 5,300 rpm. The vehicle's technical specifications after conversion to electric motor drive are presented in Table 1.

When altering the drive system of the vehicle, a factory-installed gearbox was left to better adjust gear ratios to the motor's power and momentary value of motion resistance forces. The vehicle was driven by a permanent magnet (brush type), DC motor with neodymium iron boron magnets (in Figure 1), powered by a set of four traction batteries with a capacity of 150 Ah and a total voltage of 48 V. The motor manufacturer has provided the possibility of supplying also with a higher voltage, but the voltage recommended in the documentation is 48 V. For such a voltage, the manufacturer also presented all the characteristics of the motor. The voltage of 48V was justified by the characteristic of changes in the torque in the working range of engine rotational speeds (Figure 1). A pulse controller was used in the control system. This configuration of the drive system meant that the ready-to-ride vehicle weighs less than 900 kg.

The presented results were obtained using the vehicle's hybrid electric energy storage system. It is known that it is possible to increase the energy recovery process efficiency through the use of super-capacitors in the system [21, 22]. However, modern super-capacitors are not capable of replacing chemical batteries for electrical energy storage. Even under favourable conditions, the specific energy of super-capacitors is several times lower than in modern EV batteries

[21, 22]. Moreover, it is a challenge to store an electrical charge in super-capacitors since they are currently capable of storing energy for only approximately 24 hours. In connection with the listed flaws, such a solution is impossible to be used as a main energy storage means, but their capacity to accept large electric charges within short periods of time makes them suitable for the use of energy recovered in the recuperation process.

Table 1. EV’s technical specifications.

No.	Parameter	Value
1	Maximum velocity	20 m/s
2	Vehicle’s range	47 km/ one charging
3	Drag factor, C_x	0.37
4	Vehicle's width	1.505 m
5	Vehicle’s height	1.44 m
6	Wheelbase	2.02 m
7	Filling factor	0.8
8	Vehicle's gross weight	873 kg
9	Maximum power	11 kW

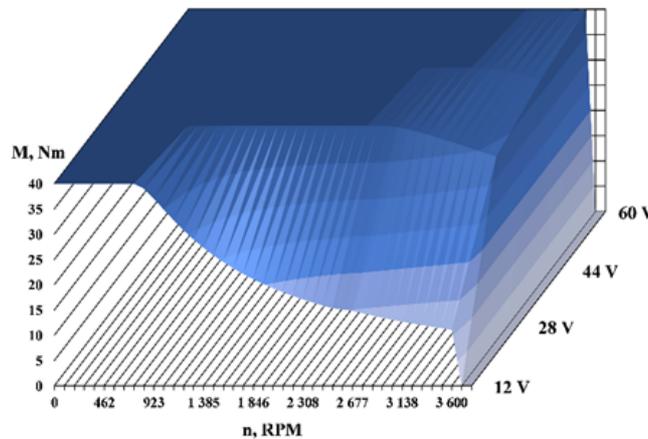


Figure 1. Characteristics of the EV’s Motor (motor torque, rotate speed, voltage) (based on data from the engine manufacturer Briggs & Stratton)

In this paper, a hybrid energy storage solution is proposed, allowing the storage of a large amount of energy in a short period of time during acceleration that can be later reused for driving the vehicle. At the same time, the system features a battery as the main energy storage and this provides for the capacity of the entire system and ensuring the vehicle’s range. In such a system, a super-capacitor is responsible for the short-time storage of energy and thus increases the amount of energy recovered in the process of energy recuperation. Such a concept may reduce the unavoidable losses in the process of converting mechanical to electrical energy and vice-versa, and thus increases the efficiency of the energy recovery process during braking [21, 22].

In order to eliminate any disturbances in the energy balance, this paper focuses solely on the consumption of electricity intended for the vehicle movement without taking into account other electricity consumers, such as air conditioning, heating, lighting, etc. Therefore, the electric drive is not affected by current consumers because they do not consume energy from traction batteries.

Simulation Model and Energy Flow Analysis

Energy consumption per unit of distance travelled is defined in kJ/km, and this may also be used to evaluate the efficiency of the used drive system. For the evaluation of an electric drive system, the definition of a course per one charging of a set of batteries (defined as range per one charging, the efficiency of the energy recuperation process) and evaluation of the level of charging or discharging of batteries is also very useful. The energy demand of the travelling vehicle in Eq. (1) may be represented as:

$$E = \int_0^{t_c} F_{op}(t)V(t) dt, \tag{1}$$

where t_c is driving cycle time; F_{op} is the sum of resistance forces influencing the travelling vehicle (air resistance, inertia resistance, resistance to climbing hills, rolling resistance, internal resistance of the powertrain); V is the vehicle’s linear velocity. For an EV, energy balance may be represented as [23]:

$$\Delta E = E_f + E_{pow} + \Delta E_k + \Delta E_p + \Delta E_l, \tag{2}$$

$$E_0 - E_1 = f \cdot Q_i \cdot \int_0^T V(t)dt + 0,5 \cdot c_x \cdot \rho_a \cdot A \cdot \int_0^T V(t)^3 dt + 0,5 \cdot I \cdot \int_0^T \varepsilon(t)dt + 0,5 \cdot m \cdot \int_0^T a(t)dt + m \cdot g \cdot \int_0^T \sin\alpha \cdot V(t)dt + \Delta E_l, \tag{3}$$

where f is the rolling resistance factor; m is the vehicle’s mass with driver and luggage; α is the slope angle of an elevation; Q_i is the ground reaction force influencing a wheel; c_x is the drag factor; ρ_a is the air density; A is the area of vehicle’s front face; V is the vehicle’s linear velocity; E_0 is the energy level in batteries at the beginning of the considered section of a road; E_1 is the energy level in batteries at the end of the section of a road; E_f is the energy consumed to overcome the rolling resistance; E_{pow} is the energy consumed to overcome the aerodynamic resistance; ΔE_k is the changes in kinetic energy of the vehicle’s motion; ΔE_p is the changes in vehicle’s potential energy; ΔE_l is the energy losses; I is the rotating elements’ moment of inertia; ε is angular acceleration. The energy supplied from batteries may be represented as:

$$E = \int_0^T U(i, SoC)i(t)dt, \tag{4}$$

where $U(i, SoC)$ is the voltage at the battery clamps, being a function of discharge current i and State-of-Charge SoC ; then, the EV energy balance can be represented as:

$$\int_0^T U(i, SOC)i(t)dt = f \cdot Q_i \cdot \int_0^T V(t)dt + 0,5 \cdot c_x \cdot \rho_a \cdot A \cdot \int_0^T V(t)^3 dt + 0,5 \cdot I \cdot \int_0^T \varepsilon(t)dt + 0,5 \cdot m \cdot \int_0^T a(t)dt + m \cdot g \cdot \int_0^T \sin\alpha \cdot V(t)dt + \Delta E_l \tag{5}$$

The value of driving force generated by the motor at the driving wheel (F_t), as well as the value of the vehicle’s velocity (V), may be represented by Eq. (6) and Eq. (7), respectively:

$$F_t = \frac{M \cdot i_g \cdot i_o \cdot \eta_t}{r_d} \tag{6}$$

$$V = \frac{\pi \cdot n \cdot r_d}{30 \cdot i_g \cdot i_o} \tag{7}$$

where M, n are, respectively, the torque and the rotary velocity of a motor shaft; η_t is transmission efficiency; i_g, i_o are, respectively, transmission gear ratio at a given gear and main gearbox gear ratio; and r_d is the dynamic radius of a wheel.

To conduct the optimization of an EV’s design, a simulation model of the vehicle’s operation has been elaborated in the AMESim environment of Figure 2). The model was based on the constructed EV, which, in turn, served as the basis for measurements to verify the model. The hybrid energy storage system was implemented in a simulation model of the EV. In this system, a set of super-capacitors consisted of six serial cells (2.7 V 3,500 F×1 pcs) with a specific energy of 5.17 Wh/kg. In a subsequent part of the work determining the optimal solution for parameters of the EV drive system, a hybrid electric energy storage system was employed.

The battery and capacitor parameters were determined using the Battery Assistant application, which is a virtual test bench with a dynamic battery model which uses an identification tool. Real-time measurements of the processes of charging and discharging cells were used to identify the model. The ultracapacitor model is based on the approach developed by Rafik et al. [24] and adapted by Prada et al. [25]. Describes the electrothermal behaviour of an ultracapacitor using an equivalent approach to modelling electrical circuits. The cells used in the simulation model were tested on a 500 A / 500 V test stand. The test consisted of charging with 200A pulses for 30 seconds, followed by a 10-minute rest period, and then discharging with 200 A for 30 seconds at an ambient temperature of 23°C. The dynamic model of the ultracapacitor was built and validated using experimental data provided by the IFP Energies Nouvelles test stands [25]. The convective exchange coefficient between the cell core and the cell shell was assumed to be 130 W/m²/K.

In the presented research, two travel cycles were used in the process of the vehicle’s design optimization. The first cycle was the WLTP cycle (in Figure 3), whose course was adapted to the object of research (Table 1). The second cycle was the real traffic conditions (RTC), registered during an actual run in city traffic conditions (Figure 3(b)) and used for verification of the vehicle’s mathematical model (Figure 3(a)). To provide for the comparability of optimization results, based on each of the discussed cycles, the RTC cycle’s distance was set to 7.144 km, just like in the WLTP cycle, adapted to the tested vehicle. The average velocity in the WLTP cycle was 7.6664 m/s, and 7.738 m/s for the RTC cycle. The maximum velocity in the WLTP cycle was 21.72 m/s, and 14.98 m/s for the RTC cycle. The basis for using the elaborated RTC cycle in the optimization process was the need to consider changes in potential and kinetic energy when passing through various elevations. This is particularly important for energy recovery during de-acceleration or braking at various road elevations. This greatly influences the efficiency of the recuperation process and, in turn, influences the specific

usage of energy. It should be noted that assumptions for the WLTP cycle require that the vehicle is following a flat route (with a zero slope road profile). Alves et al. provide evidence of the need to consider the road profile when evaluating a vehicle's energy consumption [26], as well as when conducting the evaluation process of the drive system [2]. For the RTC, the changes in amplitude of road elevation level reached 21.32 m (Figure 4), and the average slope was 0.20909 %. These conditions led to an increase in the vehicle's energy consumption from 170.92 kJ/km (Table 2) to 252.92 kJ/km (more 48 %).

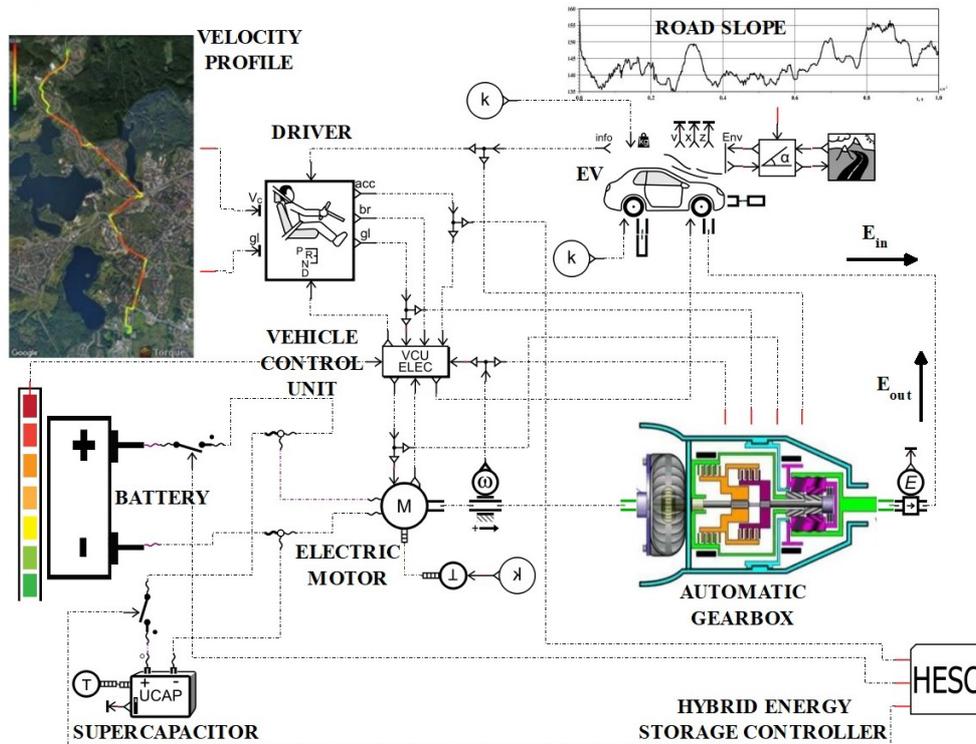


Figure 2. Diagram of the EV Model AMESim©, where k1 - additional load on the vehicle, k2 - the braking force of the rear axle, k3 - electric motor temperature (map in this picture was created using Google Maps and Torque Pro).

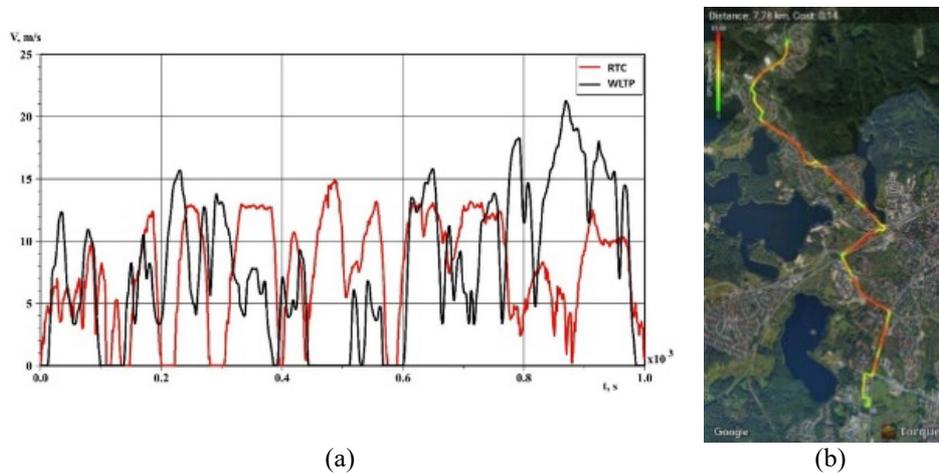


Figure 3. (a) Driving cycles of the EV in city traffic (red line – RTC; black line – WLTP) and (b) the RTC route view in a city with a population of approximately 175,000 (map in this picture was created using Google Maps and Torque Pro) (creation of the authors)

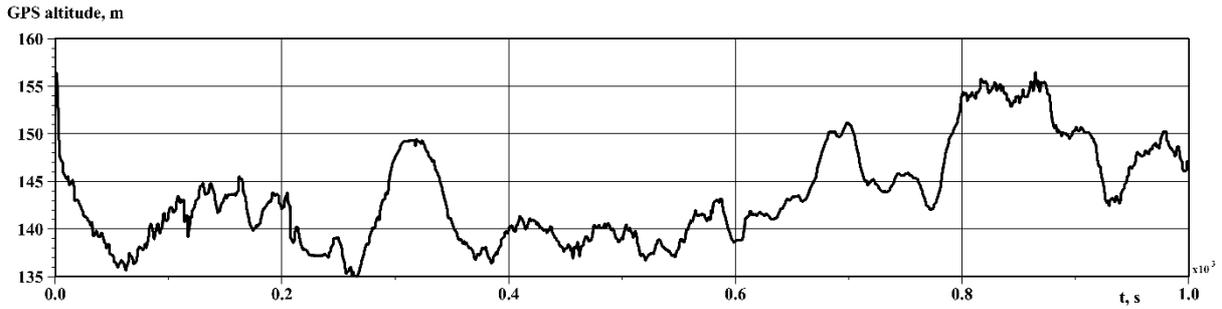


Figure 4. Route profile in RTC.

Optimization Method

The conducted research was aimed at collecting data, which then allowed for the verification of the EV simulation model developed in the AMESim program. In order to secure reproducible ambient conditions during the research, the tests were conducted on a double-axis MAHA LPS 3000 chassis dynamometer in motion simulation mode (Figure 5). The data was used to calculate the factors necessary for the simulation of motion resistance forces (in Table 1).



Figure 5. Traction tests of the EV on a MAHA LPS 3000 Chassis Dynamometer.

The test included the acceleration of the vehicle from a stop-start in the first three gear ratios of the gearbox with the highest possible acceleration rate to the maximum velocity at a given gear ratio. To have the operating conditions of the electric drive system be as close as possible to the actual conditions, the initial level of battery charging was assumed at SoC = 60%. Charts for the vehicle’s velocity changes over time at each gear ratio and the results of the simulation of a test run are presented in Figure 6. It may be noted that the acceleration of the vehicle in first gear one was characterized by the highest dynamics and average vehicle acceleration value of $a_I = 0.743 \text{ m/s}^2$. The longest was the acceleration in third gear, where the maximum velocity $V_{III \text{ max}} = 11.25 \text{ m/s}$ was reached with an average acceleration of $a_{III} = 0.388 \text{ m/s}^2$.

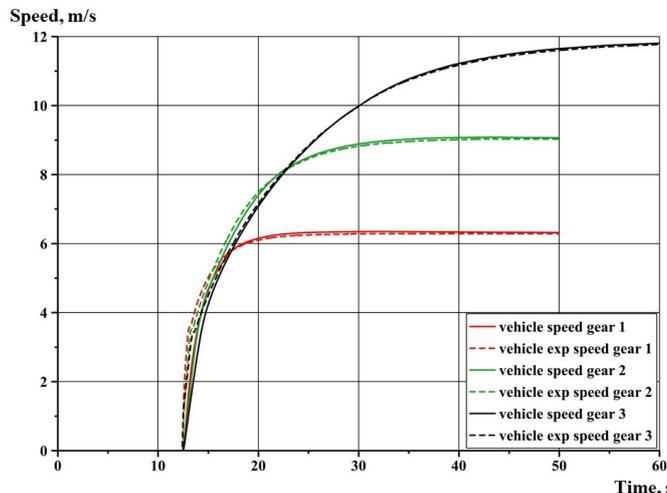


Figure 6. Velocity change during acceleration with gear ratios of $i_I = 13.87$, $i_{II} = 8.76$, $i_{III} = 5.73$; exp – experimental.

The obtained traction parameters of the constructed EV (Table 2) indicate the possibility of implementing the proposed conversion concept. It was noted that the EV energy transfer efficiency (presented as E_{out}/E_{bat} factor) remains at the level of 0.7–0.75 for all modes. But the presented results do not reflect fully the functioning of the vehicle in the conditions of actual city traffic. Simulation using the conditions of the vehicle’s operation with the velocity profile (Figure 7) allowed for collecting the data necessary to analyze the energy balance components (Figure 8, Table 2) and to validate the EV’s calculation model. Based on the obtained results, several solutions were analyzed to increase the vehicle’s range, which reached 47 km for the tested object. The most efficient among these solutions included an improvement in the energy storage system in a vehicle, as well as the optimization of the gearbox and improving recuperation process efficiency.

Table 2. Results of calculated (calc) and empirical (exp – experimental) determination of selected components of energy balance.

Parameter		E_{out} , kJ	distance, km	E_{bat} , kJ	e_{out} , kJ/km
$i_I = 13.87$	calc	36.343	0.2228	50.848	163.12
	exp	35.401	0.219	49.066	161.65
$i_{II} = 8.76$	calc	59.390	0.299	80.487	198.63
	exp	61.626	0.302	86.797	204.06
$i_{III} = 5.73$	calc	97.934	0.461	132.643	212.44
	exp	97.392	0.463	138.738	210.35
Test in the chassis dynamo-meter	calc	476.925	2.767	651.900	172.36
	exp	473.790	2.772	653.400	170.92

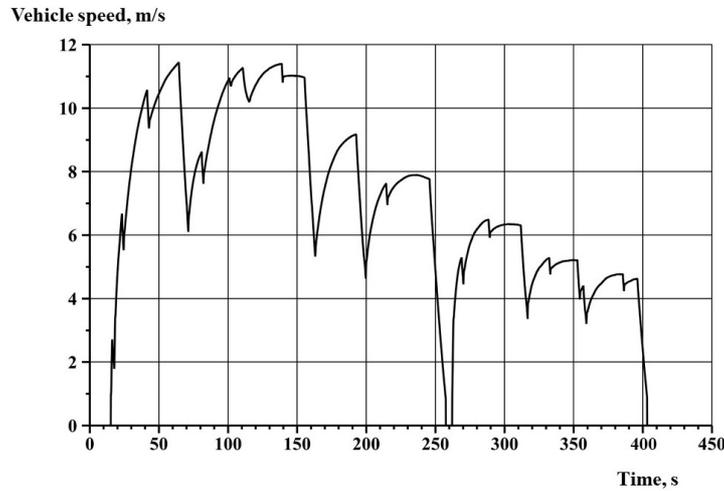


Figure 7. Velocity profile obtained during a trial run with the chassis dynamometer.

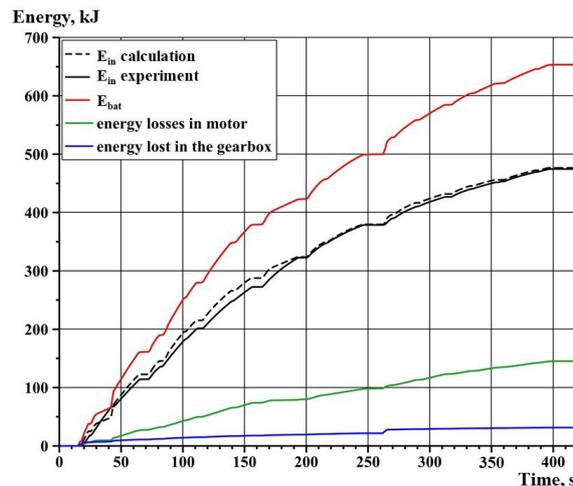
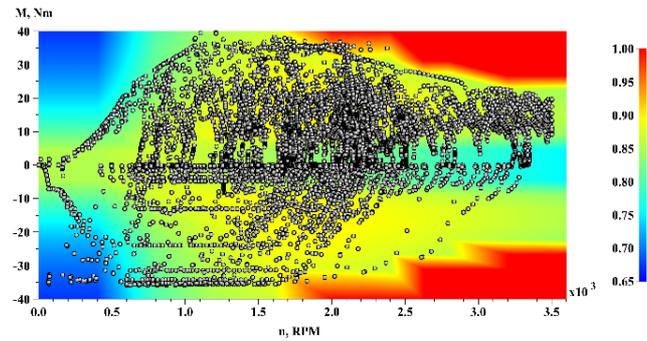


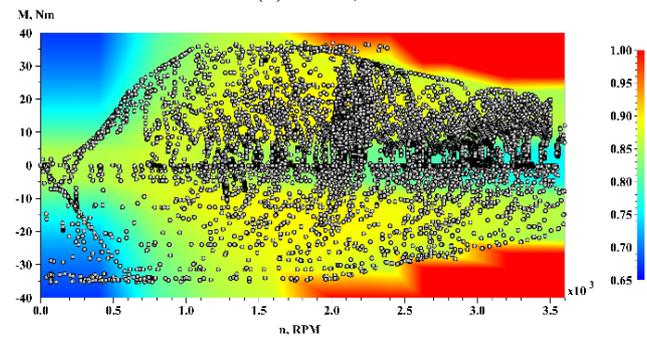
Figure 8. Energy consumption at the output of the drive system, E_{out} ; the battery, E_{bat} ; and energy losses in the EV’s motor and gearbox.

The vehicle acceleration test attempts were used for verification (Figure 6, 8) of the EV’s simulation model (Figure 2), developed in the AMESim environment. In the process of verification of the 1D EV model, the output data were empirical velocity profiles (Figure 6). The obtained calculated velocity profile is compared with the empirical profile. The mismatch of the profiles does not exceed 0.003 m/s (Figure 6). This is the basis for determining the plausibility of the simulation results.

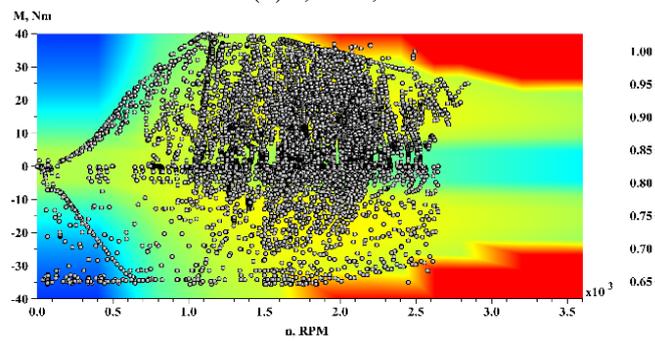
Contrary to the constructions of transmissions in EVs [23, 27] as they are known, in this paper, a gearbox is proposed that provides for the possibility of changing the value of the gear ratio in the drive system depending on the actual road conditions. The change of the gear value can be performed with the use of an automatic gearbox or continuous variable transmission (CVT) [28, 29]. A key role in such a system is played by the gear shifting control algorithm. When a vehicle is driven, gears are shifted at higher rotary velocities of the motor shaft, but when a vehicle de-accelerates, when the energy recovery system is used, the gear is downshifted to force higher rotary velocity of the motor shaft, increasing the recuperation process efficiency and the braking momentum of the motor. With such a gearbox, the algorithm that controls the gear shifts defines the rotary velocity of a gear upshift (nominal upshift engine rotary velocity) n_u and motor's RPM, at which gear is downshifted (nominal downshift engine rotary velocity) n_d .



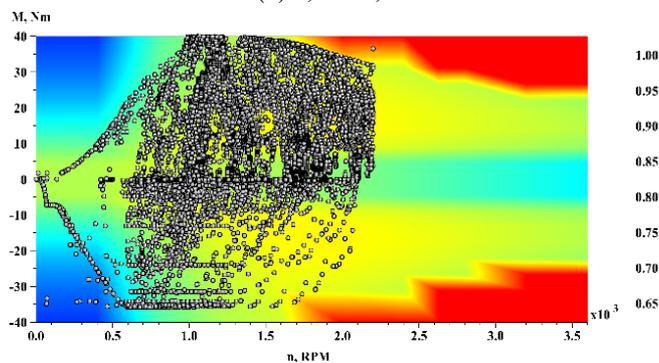
(a) 600/3,500



(b) 2,500/3,500



(c) 1,500/2,200



(d) 600/2,200

Figure 9. Characteristics of motor loads in efficiency function for four (a-d) ratio values (n_d/n_u). The coloured background shows a map of the efficiency of the electric motor.

A comparison of the location of work points within the velocity characteristics of torque $M = f(n)$ for four ratio values n_d/n_u (Figure 9) shows a shift of the functional operation area of an electric machine in generator mode to an area in which higher values of braking torque are reached, and thus, higher efficiency of energy recuperation process is obtained. Further attempts to find a solution to the optimization issue indicated the possibility of increasing the recovery energy share, also through the proper n_d/n_u ratio selection. When optimizing the gearbox, the decisive parameters should be their ratio values. In correlation with values of n_d and n_u , they define the tested parameter space and allow for obtaining the best energy recovery results and minimizing energy consumption during the vehicle's motion [30].

The exact mirroring of the set travel cycle constitutes a functional limitation of optimization. This is mostly due to momentary deviations in velocity obtained through the vehicle's simulation model with respect to the value set at a given moment. The simplest and, at the same time, the most efficient means of imposing such a functional limitation may be to define the deviation of the distance reached at the end of a cycle. It may be expected that with the minimum value of difference $C - dyst$, where $dyst$ is the distance covered, and C is any given value meeting the requirement $C > dyst$, the deviation of the calculated velocity will be minimal.

The analysis of the energy flow rate that drives the EV shows that, during optimization, the specific energy delivered to the driven wheels may be considered a quality criterion when referenced to the distance unit covered by the vehicle. It may be assumed that the specific energy is positive when it is delivered from the drive system to the vehicle's wheels (e_{out}); on the other hand, the energy recovered in the recuperation process will be negative (e_{in}), and the general energy output from the drive system will be the sum of the two above energies. Of course, a reduction in energy amounts consumed by the vehicle may be obtained through a reduction of e_{out} or an increase in e_{in} . In both cases, the efficiency of the drive system is crucial.

The parameter optimization of the EV's drive system was conducted with the heuristic method, using a genetic algorithm (GA) [31, 32]. GA methods are characterized by stability, which translates to minimizing the influence of the obtained and executable solutions (which might feature smaller values than the defined parameter vectors) into an optimal solution. Recently, GA-based methods have been used by many individuals designing and constructing EVs [29]. Genetic algorithms were first elaborated on and presented by John Henry Holland [33]. This is a global method of optimization, which mimics the natural process of biological evolution. In comparison with the traditional optimization methods, GAs solve problems without gradients and global optimization. The optimal result collected with the GA method may be obtained through the implementation of the iteration procedure. The subsequent steps of this method are (Figure 10):

- i. Population initiation. Creation of a random, initial population, with consideration for upper and lower limits of the decisive parameters.
- ii. Individual evaluation. Each individual in the population is evaluated through the realization of the aim or efficiency function.
- iii. Parental chromosome selection. Owing to the selection method, chromosomes with better values of allowable results have better chances of providing 'good' genes to subsequent generations.
- iv. Crossover and Mutation Crossover. Both phenomena may spur the individuals to evolve into even better offspring by turning the gene exchange mechanism on.
- v. Iteration and termination. The above steps are iterated until a criterion is fulfilled.

To create a space-defining population of parameters, a stochastic generator is used. The remaining GA parameters are provided in Table 3. In this paper, using a genetic algorithm, the optimization of drive transmission was conducted for a vehicle travelling in various conditions (Table 4). The EV's trial run with initial parameters of the transmission system (Table 5) was carried out in the RTC cycle with the exclusion of the road profile (#2), but — contrary to the registration during a test run (#1) — with the use of hybrid energy storage and recovery system and the share of e_{in} in comparison to e_{out} was defined with the value of 14.42 %. At the same time, the distance covered during the trial run, in comparison to the test run, was limited to the value of 7.784 km, and the predictable range per one charging increased twofold.

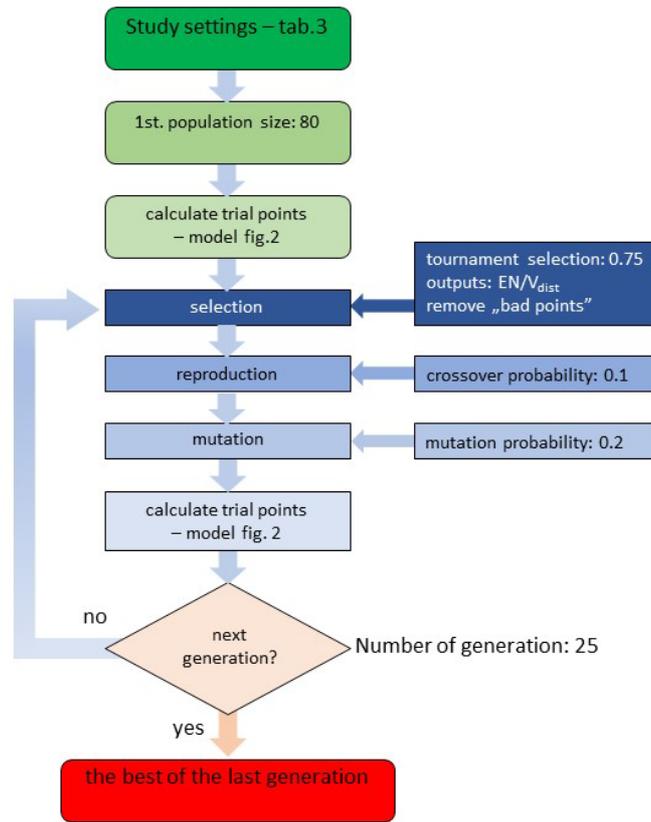


Figure 10. Optimization process algorithm using GA.

Table 3. GA parameters.

Parameter	Value
Study settings	
Population size	80
Number of generation	25
Tournament selection	0.75
Crossover probability	0.1
Mutation probability	0.2
Study parameter definition	
inputs	
Main gear ratio	3-7
1 st gear ratio	2.8 – 5
2 nd gear ratio	1.8 – 2.7
3 rd gear ratio	1.1 – 1.7
4 th gear ratio	0.5 – 1.05
outputs	
the specific energy consumption	

RESULTS AND DISCUSSION

The actual road profile that was considered for calculations in option (#3) changes the energy ratio considerably. The energy share in recuperation e_{in} increases to the value of 16.754 %, and, at the same time, the total value of energy consumed by the vehicle conditioned by travelling over various road elevations increases the distance covered during the test run to 8.164 km. Optimization of transmission parameters, with the results provided in Table 4 as #4, decreased the e_{sum} value, which increased the share of the e_{in} value to 19.61 %. Owing to this, the predicted range of the EV per one charging increases to 92.42 km.

Evaluation of the objectiveness of the used optimization method with consideration for the road profile allows for the analysis of the next test series. To this end, in the simulation model, the WLTP cycle (Figure 3(a)) was adopted for execution as the velocity profile. Calculation of the results (#6) for the run with this profile made it possible to register the increase of e_{sum} , used for covering a similar distance by 30 %. Concurrently, the share of e_{in} in relation to e_{out} is observed to increase to the value of 24.02 %. This stems from the fact that in the WLTP cycle there are numerous stop-and-go events, and thus there are many braking events when the system is able to recover energy in the recuperation process. In this mode, the estimated vehicle range is 66.18 km. The executed optimization for the WLTP cycle (#7) reduced e_{sum} and, at the same time, increased the share of e_{in} to the level of 27.9 %. This value confirms the conclusion

presented in [34], who averaged e_{in} 27 % of the total average energy delivered to the vehicle’s wheels. A comparison of results of #4 and #7 also confirms the conclusion [34] that the increase in the share of city traffic increases the energy share coming from recuperation in the total energy balance of the EV.

Table 4. Results of the EV’s drive system optimization.

Driving cycle	$dist.$, km	e_{out} , kJ/km	e_{sum} , kJ/km	e_{in} , kJ/km	ΔSoC / km
RTC (EV, Table 1)	8.179	252.344	252.344	no recuperation	2.127
RTC without road slope	7.784	185.039	158.343	26.771	1.201
RTC with road slope	8.164	197.066	164.057	33.008	1.094
RTC optimisation	8.167	180.749	145.482	35.267	1.082
RTC with WLTP optimisation	7.906	179.598	150.506	29.092	1.105
WLTP	7.819	270.607	205.544	65.062	1.511
WLTP optimisation	7.819	256.981	185.280	71.701	1.453

The calculation results for #5, obtained with the use of optimized parameter value for the transmission system in the WLTP cycle are especially interesting. According to the selected criterion of e_{sum} , the result is not the best, and the share of e_{in} and the predicted range per one charging is also reduced. The reduction of the distance covered during the run from 8.167 km to 7.906 km shows that there is a discrepancy between the set and the obtained velocity profile. The comparison of results of #4 and #5 shows the influence of the road profile.

A comparison of initial and optimal gear ratios in the transmission gearbox (in Table 5) shows the influence of the road profile and the method of driving a vehicle on the values of the demanded parameters. Optimal gear ratios are lower than the initial ratios, except for the optimal value for the 2nd and 3rd gear in the RTC cycle, with road slope (#4), where there is a change, respectively, from 2.053 to 2.611 and from 1.342 to 1.37. In the case of #4, it is justified to use the gearbox with four gears. Concurrently, in the case of trial #7, the approximated values of gear ratios for 2nd and 3rd gear show the possibility of diminishing the number of gears to as few as three. The obtained minimum value of nu during optimization in the RTC cycle, without road slope, and in the WLTP cycle amounts to 3,000 rpms.

Table 5. Parameters of the EV’s drive system.

Parameter	Optimization			
	Basic point	RTC without road slope	RTC with road slope (#4)	WLTP (#7)
powered axle gear ratio	4.267	4.177	3.8046	4.038
1 st gear	3.25	3.096	2.998	2.537
2 nd gear	2.053	2.611	2.168	1.485
3 rd gear	1.342	1.37	1.1476	1.1466
4 th gear	0.956	0.879	0.786	0.746
upshift velocity n_u , rpm	-	2,946	3,472	3,001
downshift velocity n_d , rpm	-	2,239	1,888	1,820

A considerable difference in energy consumption in these two cases indicates how important the share of the braking process is in the total cycle (which is much higher in the WLTP cycle). In the case of the RTC cycle, with road slope, the optimal selection of nu value is 1.18 times higher than for the same cycle without road profile consideration. If the n_u/n_d ratio is taken into account, the highest value of this ratio may be observed for the RTC cycle with road slope ($n_u/n_d = 1.839$). For the RTC cycle without road slope, the ratio reaches 1.315. It must be noted that in these two cases, there is only one difference with respect to the cycle; one considers the road profile, and the other one does not.

CONCLUSION

This article discusses a set of solutions for creating a city electric car with a low-voltage power supply system for a DC motor. The described EV has a single electric motor driving the front wheels through a drive system with a gearbox. The proposed design of the drive system uses hybrid energy storage and recuperation system consisting of batteries and super-capacitors. The issue of optimization has been formulated to minimize the vehicle’s power consumption. To mirror the actual road conditions as much as possible, the RTC cycle registered over an actual route was used in the process of optimization, with the cycle’s velocity profile and recording of the road slope angle used in the simulation program. As a result of optimization with the use of the genetic algorithm, optimum parameters of a gearbox were obtained, and an algorithm for controlling gear shifts based on actual RPMs of the motor shaft was elaborated. As an outcome of employing the described design solutions and optimization of transmission parameters, an over 40 % reduction in the vehicle’s energy consumption in the considered RTC cycle was reached. Further research is needed to optimize the hybrid power source of the electric vehicle and to find optimal solutions to further reduce energy consumption in city conditions. The

obtained minimum value of n_u during optimization in the RTC cycle, without road slope, and in the WLTP cycle amounts to 3,000 rpm. A considerable difference in energy consumption in these two cases indicates how important the share of the braking process is in the total cycle (which is much higher in the WLTP cycle). Further research should focus on the synergistic aspect of hybrid braking and energy storage systems, as well as developing the concept of a multi-speed gearbox for EVs, in order to better adjust the torque value, in particular in off-road applications.

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