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Investigation into the performance characteristics of electric automobiles by means of a data logger

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Abstract. Fossil fuel deposits are constrained in the world. Various alternative energy sources are introduced in vehicles to limit the depletion of fossil fuel reserves and to reduce environmental pollution. One of the alternative energy sources is electricity. The use of electric automobiles has begun in the Baltic States too, yet accurate performance parameters of the automobiles, which could sometimes differ from the technical characteristics specified, are not always known. Road testing an electric automobile was performed using a data logger that recorded the battery's voltage, current, temperature and the automobile's speed. These parameters allowed computing changes in the electric automobile's power output under various driving regimes, e.g. acceleration or braking. Road testing the electric automobile was done under two driving regimes – urban and non-urban – on a certain route. The experiment represented a full cycle road test, with the batteries fully charged, that lasted until the batteries were discharged to a minimum level, which was limited by the battery management system (BMS). The experiment identified the maximum current as well as the effectiveness of the regenerative braking system.

Key words: electric vehicle, energy consumption, current, voltage, driving regime, cruising.

INTRODUCTION

In the world, electric vehicle (EV) progress began along with internal combustion vehicle progress. Electric vehicles were equipped with lead-acid batteries that could not provide a sufficient driving range, and the electric vehicles could not compete with internal combustion vehicles. Even though historical electric automobiles had a lot of advantages in comparison with internal combustion automobiles, e.g. quiet operation, an easy startup and an easy movement startup, the electric automobiles were not widespread until the 21st century (Berjoza & Jurgena, 2013). Nowadays a problem with electric automobiles is the same as it was long ago – a small driving range per charge. This relates to the low weight-to-energy capacity ratio for batteries, compared with that for liquid fuel.

The key electric parameters of electric automobiles – voltage, current and power consumed – recorded during driving depend very much on the driving regime. The parameters can be, to a smaller extent, affected by other powerful electrical devices, e.g. an air conditioner or an interior heater. The energy consumed by the mentioned devices is usually quite constant, whereas the energy consumed by the electrical motor can change several times within a very short moment. The standard driving regimes of an electric automobile, like those of an internal combustion automobiles, are as follows: acceleration, cruising, smooth deceleration or coasting and braking.

Vehicle movement simulations by means of computer tools began in the late 1990s. Various hybrid electric vehicle (HEV) and electric vehicle models were researched by using the Matlab-Based Modelling and Simulation software. The simulation results were obtained during both simple driving regimes – acceleration, cruising and braking – and more complicated driving cycles, e.g. the FTP–75, a federal highway drive cycle. The research investigations analysed various vehicle driving strategies after determining CH, NOX and CO emissions and fuel consumption (Butler et al., 1999) and compared electric vehicle current changes, simulating the selected driving cycles. The research investigations did not consider emissions, assuming that no emissions were produced, yet the latest research investigations provide data on indirect emissions produced by electric vehicles (Berjoza & Jurgena, 2016) from electricity production. In Latvia, for example, average CO2 emissions from the production of a kWh of electricity equal 115 g $(\mathrm{kWh})^{-1}$. The planned research intends to analyse changes in current and voltage at diverse driving regimes, and an electric vehicle is going to be road tested.

American Control Conference researchers have published their research findings on plug-in hybrid electric vehicle (PHEV) control strategies. The research object was a Toyota Prius, and a Control Strategy and a Proposed Strategy for the car was examined by means a mathematical model. The Proposed Strategy achieved a 16% longer driving range of the PHEV than the standard one did. The mentioned research examined current and torque changes under both strategies. A comparative examination was performed in UDDS and EPA driving cycles. The research also found an optimum PHEV control strategy model that could yield the best economic and performance characteristics (Banvait et al., 2009).

An analysis of the literature revealed that most of the research investigations focused on HEVs, optimising the inter-related operation of the electric motor and the internal combustion engine and designing algorithms aimed at reducing fuel consumption and impacts on the environment (Musardo et al., 2005). An investigation produced motor torque curves and sought optimum HEV operation regimes by using Simuling modelling software. It also developed a mathematical model for fuel consumption reduction. The investigation compared the Dynamic Programming and the Equivalent Consumption Minimization Strategy in six various driving cycles, yet the results did not differ by more than 0.4% (Musardo et al., 2005).

Chilean scientists have developed an energy management system for a hybrid electric vehicle. The system exploits ultracapacitors that allow reducing energy consumption and using various energy sources, e.g. fuel cells, microturbines and zinc-air batteries. The energy could be also generated by the regenerative braking system. The research developed and analysed a mathematical model and performed road tests in a 14.2 km driving cycle. The lowest energy consumption was achieved under the Optimal Neural Network Control System with regenerative braking, which performed 28.7%

better than the standard system did. The road tests measured momentary vehicle speed, voltage and current (Moreno et al., 2006). The planned road tests intend to identify the effect of the regenerative braking system with the controller set to 45%.

Chinese scientists have done research on a plug-in hybrid electric vehicle with a Fuzzy Logic System. The system allows optimally using batteries depending on the charge level and temperature of the batteries. The scientists developed vehicle, motor-controller, engine-generator and vehicle drive mathematical models. They performed a simulation, producing current-voltage curves, in the USA Urban Dynamometer Driving Schedule (UDDS) and the New European Driving Cycle (NEDC). The research found that the Fuzzy Logic System was effective in preventing a battery from being overcharged as well as enhanced the capability of the motor control system to provide optimum motor operation (Li et al., 2011).

The literature provides a few research studies on EV road tests. There are more research studies focusing on a system analysis of hybrid electric vehicles and plug-in hybrid electric vehicles, the development of mathematical models for various systems and the enhancement of control system algorithms. For this reason, it is useful to do research on the effect of electric vehicle driving regimes on the electric parameters of the electric vehicle in urban and non-urban driving, which is the key aim of the research.

MATERIALS AND METHODS

The experimental research was performed using an electric car Renault Clio. This car was converted from an internal combustion car equipped with a 1.2 l engine into an electric car. The car was equipped with a 30 kW electric motor with a maximum power of 50 kW as well as 30 lithium-iron hybrid batteries with a capacity of 100 Ah. The battery system was controlled by the battery management system (BMS). The BMS was set to prevent the batteries from being discharged by more than 2.4 V or from being overcharged by more 3.8 V. The total battery voltage was 96 V. The distance covered per charge was 60 km, while the maximum speed was 120 km h^{-1}.

The road tests were done on several road sections that are presented in Fig. 1.

Two diverse routes were chosen for the road tests: Jelgava city for the urban driving regime and general road P97 between Jelgava city and Dobele town for the non-urban driving regime. In non-urban driving, the road test was done back and forth, while in urban driving it was done on a circle route (Fig. 1). The length of a full urban circle route was 14.7 km, while the length of a non-urban route in one direction was 25.1 km.

The road surface on both routes was in good condition; the average rolling resistance coefficient was 0.010−0.012. In accordance with the Road Safety Rules, the road tests used LED lamps with a total power of 15 W. Each road test was replicated five times (Fig. 2). The electric data were registered and stored by a logger Graphtec midi Logger GL220. The road test was conducted with fully charged batteries until the battery charge level reached 5−6% of the total battery capacity. The batteries were recharged after every road test, and the data on the five replications were stored in the logger Graphtec midi Logger GL220. After the batteries were fully recharged, the next road test was performed. The driving regime was changed during every replication, which means that a road test started in the city was continued outside the city, and then again in the city. In this way, the weather factor was excluded. The road tests were done in October and November 2017 at an ambient temperature from +5 to +10 °C. After the road tests, the data were processed and represented graphically. The car’s interior heating system – an Eberspacher heater – running on ethanol was used during the road tests. An electric heater would consume too much energy, and an examination of it was not intended in the present research.

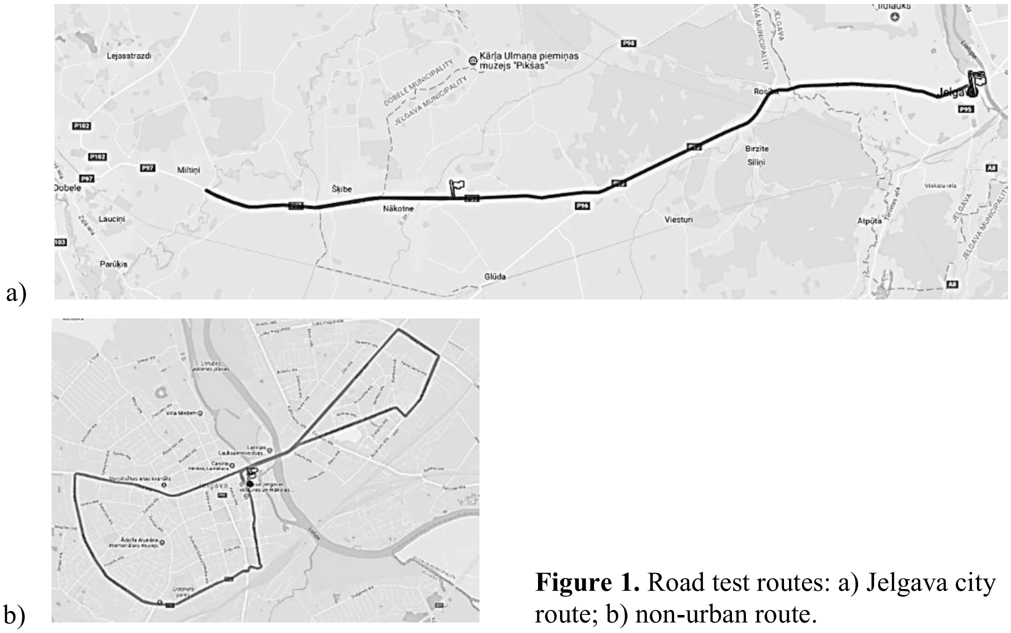

Figure 1. Road test routes: a) Jelgava city route; b) non-urban route.

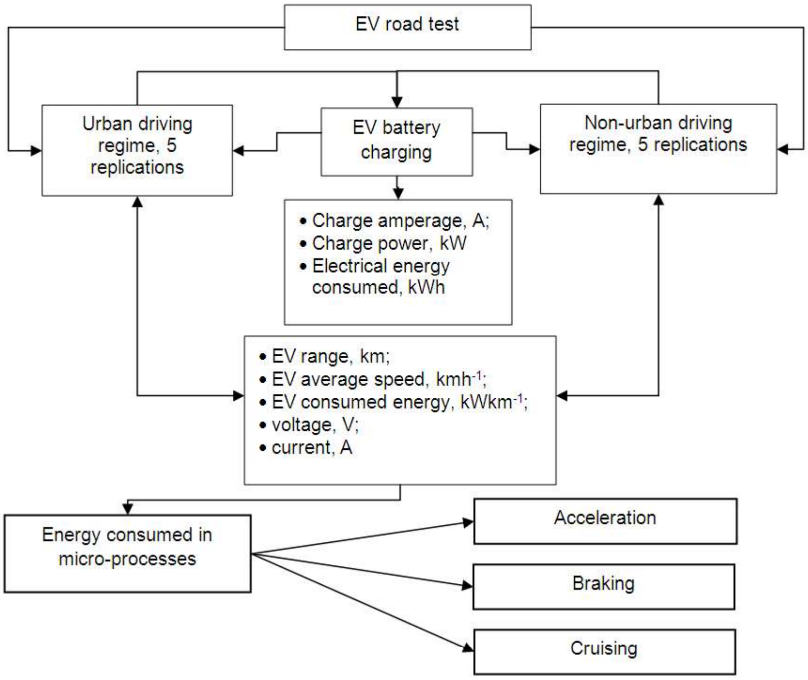

Figure 2. Road test scheme.

A logger HOLUX GP Sport 245 was used to store the route data. The logger had a 512 kB memory and the capacity of its batteries was sufficient for a 28 h operation. The logger could store 200,000 waypoints, measure speed, time, distance and store the route data. The logger could operate in a temperature range from -10 °C to +50 °C. The scheme for connecting a data logger to the electric automobile is presented in Fig. 3.

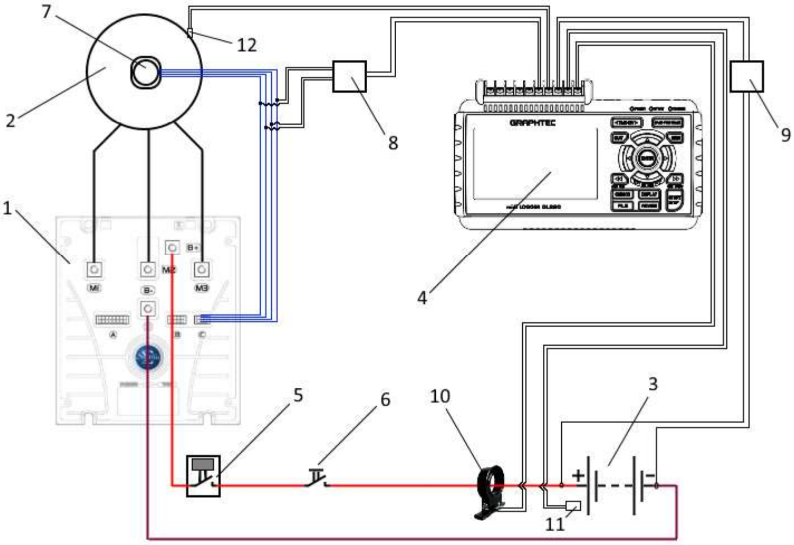

Figure 3. Scheme for connecting experimental equipment: 1 – motor controller; 2 – electromotor; 3-96 V accumulator; 4 – data logger; 5 – electromagnetic safety switch; 6 – mechanical safety switch; 7 – electromotor speed sensor; 8 – frequency-voltage converter; 9 – voltage divider; 10 – current sensor; 11 – accumulator temperature sensor; 12 – electromotor temperature sensor.

A data logger Graphtec midi Logger GL220 was used to record the electric car's electric parameters. The logger's sampling interval ranged from 10 ms to 24 h, a time scale was from 1 s to 24 h. This device was equipped with a 4.3 inch TFT LCD display, a 8.5–24 V power supply and 10 analogue input channels.

RESULTS AND DISCUSSION

After the road tests, the logger data were transferred to a computer and processed, interpreted and analysed.

A GPS data logger recorded speed in urban and non-urban driving. Changes in speed in both driving regimes are shown in Fig. 4. Urban driving involves frequent acceleration and braking, and the speed is very volatile. The average speed in urban driving during the road tests was 31.15 km h^{-1}. In non-urban driving, the beginning and the end of a road test was in Jelgava city, therefore, it was urban driving. The average speed in non-urban driving was 57.71 km h^{-1}.

To analyse various electric parameters of the electric car under various driving regimes, the recorded data were aggregated to produce synchronised graphs v = f(t), U = f(t), I = f(t) and P = f(t). A graph for urban driving is shown in Fig. 3. In the road test, the speed in urban driving is very volatile due to all the regimes: acceleration, braking, cruising and coasting. Urban driving is appropriate for the structure of the electric car, as electrical energy is consumed by only on-board devices when stopping at intersections, whereas it is generated when braking.

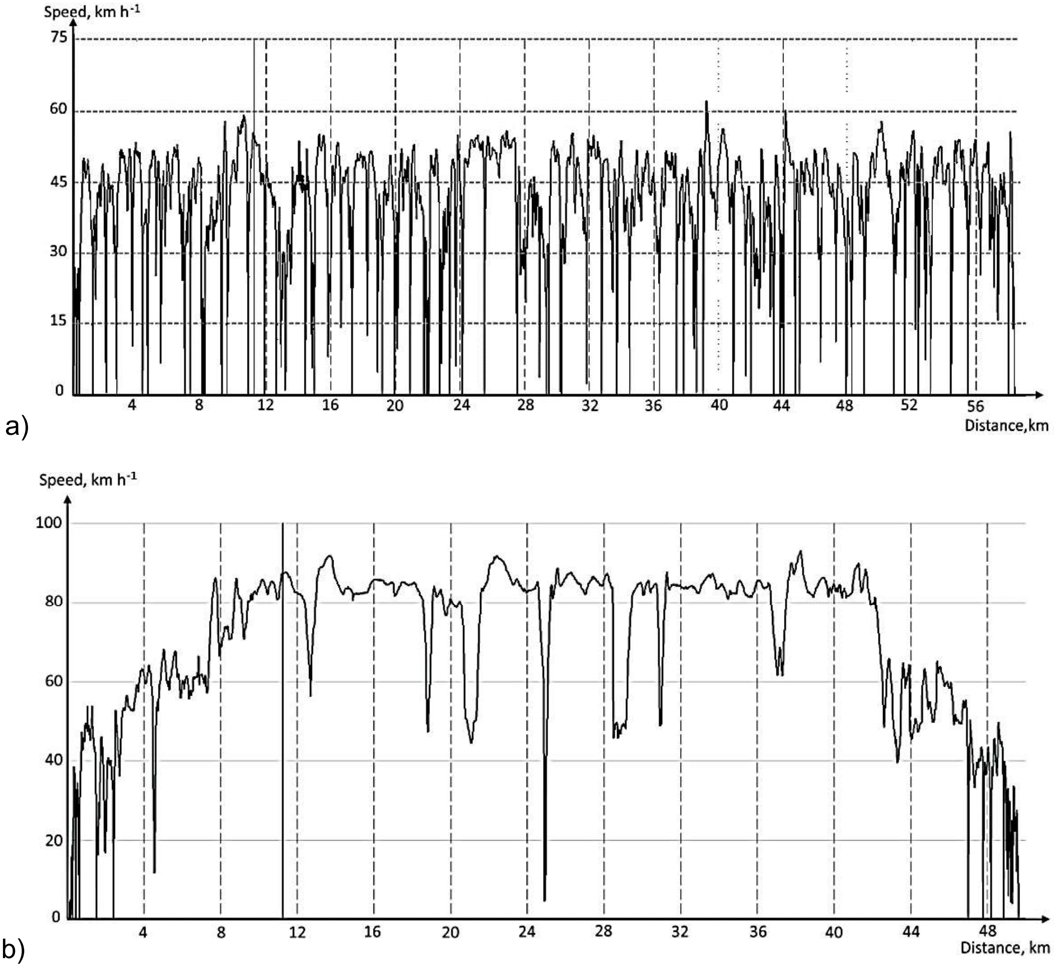

Figure 4. Speed on road test routes: a) Jelgava city route; b) non-urban route.

In view of the fact that the electric car had a 96 V battery system, in the driving regimes when a lot of current was drawn from the batteries, e.g. when accelerating, the voltage considerably decreased. The nominal voltage of every battery was 3.2 V. The BMS was set to stop the charging process if the voltage of some battery had reached 3.8 V. During charging, the total voltage of the battery pack reached 113−114 V. Immediately after the charging, the voltage decreased to 100−101.5 V. At the beginning of the road test in urban driving, the voltage decreased to 95 V during medium-intense acceleration. During very intense acceleration, the voltage of a fully charged battery-pack decreased to 87 V. At the beginning of the road test, the voltage returned to the previous level when stopping at intersections. After covering half of the road test route, the voltage did not exceed 96.3 V when stopping, yet it decreased to, on average, 87.5 V when accelerating and to 86 V when intensively accelerating (Fig. 5). When cruising at

50 km h^{-1}, the voltage, on average, decreased to 92.6 V. At the end of the road test, when no electrical energy was consumed or when stopping, the voltage did not exceed 92.1 V; when accelerating, the voltage could decrease to 82.7 V. One can conclude after completing the road tests that if taking into account only the voltage of the batteries, a voltage of 92 V in the stopping regime was the lowest level, and the batteries needed to be immediately recharged. After driving only 1−2 km more, the batteries were almost fully discharged, reaching the minimum allowable discharge level. After driving on average 50 km in urban driving, the BMS often started giving warnings; it was activated when the momentary voltage of some battery element had decreased to 2.5 V (the critical level was 2.4 V).

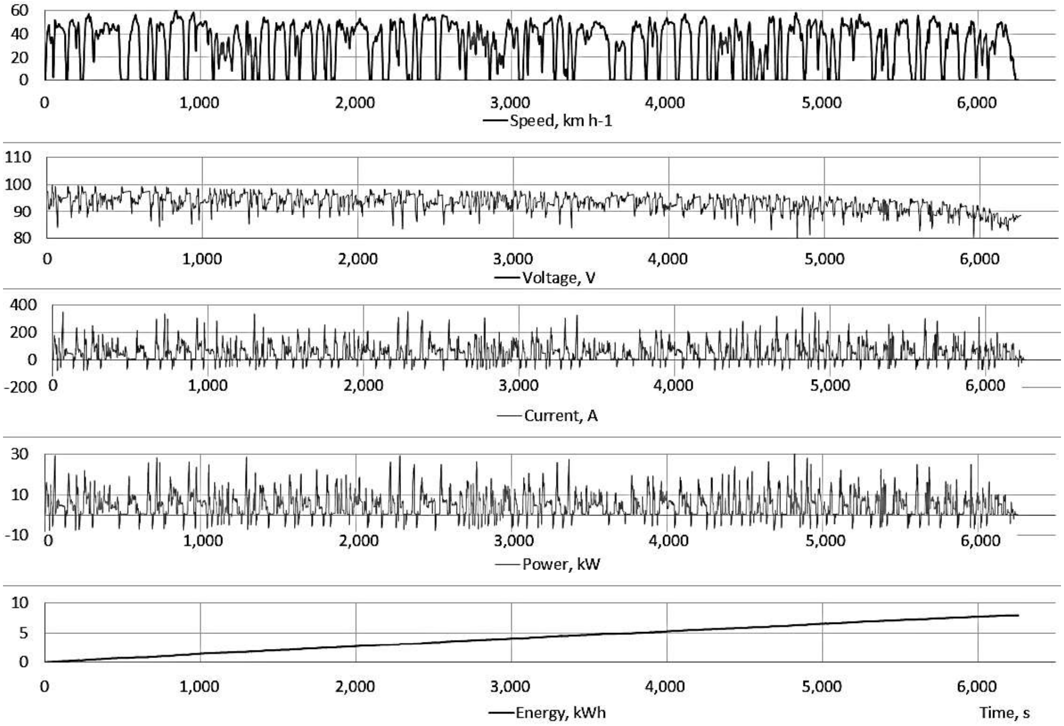

Figure 5. Electric car parameters in urban driving.

In urban driving, current and power changes were proportionally related to speed (Fig. 5). At the beginning of the road tests, the current reached 240–250 A during smooth acceleration, while the motor power output was 20−21 kW. During fast acceleration, the current could reach 350 A. The maximum power output at the mentioned peaks was 30 kW. The regenerative braking of the electric car Renault Clio was activated by pushing the brake pedal, while in the casting regime the regenerative braking was not activated. In the braking regime, the regenerative current reached 75 A, while the power – 7.5 kW. Compared with non-urban driving, this regime increased the electric car's range in urban driving. The regenerative level of the electric car Renault Clio was controllable, and it was set at 45% for the road tests. A regenerative level of above 50% creates an inadequate increase in braking force caused by the regenerative braking system before the main brakes have been activated. This results in a braking force increase to be difficult to control by means of the braking pedal. When stopping, the electric car consumed an current of 4.8−5.0 A. With the batteries being partially discharged, no significant changes in current and power were observed under various driving regimes. When cruising at 50 km h^{-1}, the current reached 67−70 A. When accelerating fast during the final part of the road tests, the current reached 385 A, while the motor output power was 31 kW. The increase in current might be explained by a lower voltage of the battery pack, and a higher current is requited to ensure the necessary motor output power.

Road testing the electric car in non-urban driving was started as well as finished in the centre of Jelgava city. For this reason, the initial section of the route 6.5 km in length and the final one (6.5 km) are typical of urban traffic, and no electric parameter analysis was performed for the mentioned route sections (Fig. 6).

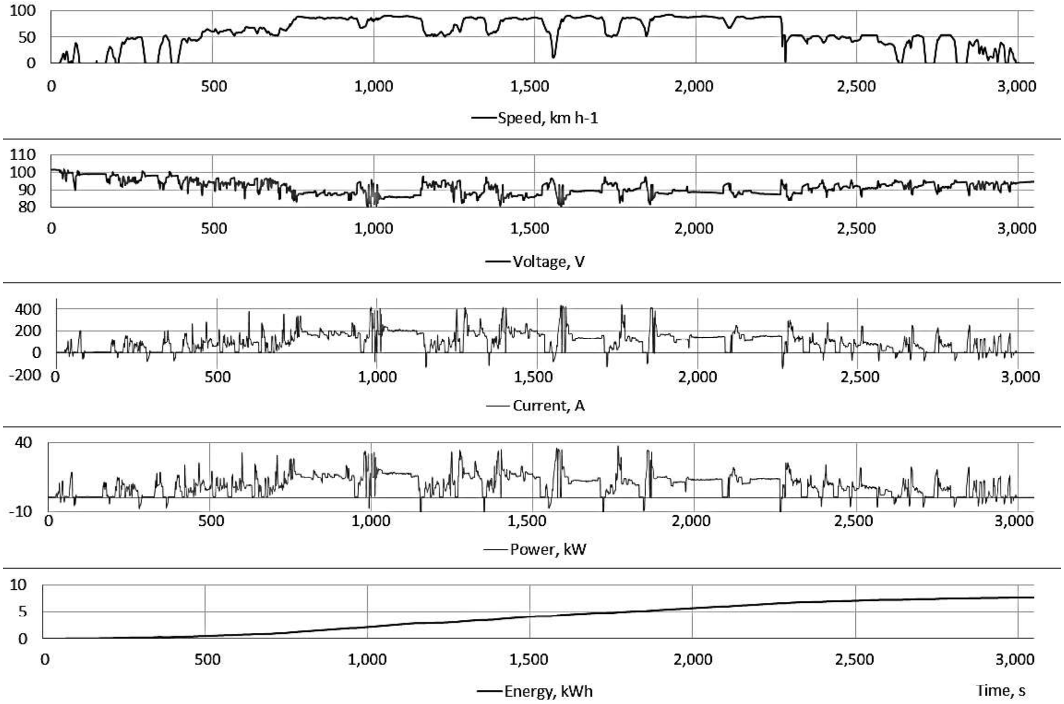

Figure 6. Electric car parameters in non-urban driving.

When starting the non-urban route section, the average voltage was 96.5 V. When accelerating, e.g. from 73.5 to 87.1 km h^{-1}, the voltage of the batteries decreased to 87.9 V. In the cruising regime at 87 km h^{-1}, the voltage of the batteries equalled 91.5 V, while the current reached 353 A. When accelerating fast, the maximum current reached 450 A, which was the highest value set for the motor controller. The motor output power at the maximum points reached 38.6 kW. A careful examination of the power and current curves reveals that the average values of these parameters were higher when driving away from the start than driving back down the route. This could be explained by a small average road slope angle of $\alpha = 0.6°$, which increases road resistance when driving away from the start and decreases it by the same value when driving back. Regenerative braking application in non-urban driving was less frequent, yet the values of electric parameters were much higher in non-urban driving than in urban driving. Braking from a speed of 86.3 km h^{-1} to 50.5 km h^{-1}, the batteries were charged at an current of 140 A or a power of 13.2–13.4 kW. Cruising at 85 km h^{-1} consumed a 149–150 A current, which ensured a motor output power of 13.2–13.4 kW. It has to be noted that these parameters were measured right after the batteries were recharged, which means that the power supplied to the motor was lower than the value of the efficiency factor of the wiring-inverter-motor system, while the power transmitted to wheels was lower than the value of the efficiency factor of the motor-transmission system.

Due to higher average battery discharge current values when driving the last 10 kilometres of the route, the BMS tended to give warnings more often in non-urban driving than in urban driving, which indicated the negative effect of fast acceleration on the battery lifetime.

Based on the road test results, it is intended to do road tests with a 6.4 V higher voltage of the battery pack, which is within the allowable limits for the motor and the control system.

An excessive voltage drop in the battery pack during acceleration indicates a decrease in the working capacity of some battery cells. It is required to control the voltage of every individual battery pack cell during acceleration and, in necessary, change the defective battery cell. An alternative option for the cell change is to set the controller Sigmadrive to limit the maximum current to less than 400 A, which would allow saving the batteries. An expected decrease in the dynamics of the electric automobile should be minimum.

If converting a vehicle to electric power in next projects, it is necessary to choose a system with higher voltage, e.g. 144 V. Such a system decreases the maximum current during fast acceleration and ensures a safer mode for the batteries and a longer lifespan of the batteries.

CONCLUSIONS

1. A methodology for electric vehicle road tests in urban and non-urban driving was developed and approbated by means of a data logger for measuring electric parameters.

2. After recharging, the voltage of the battery pack was within a range of 113–114 V. Upon starting the road test immediately after the batteries were charged, the battery voltage was 100–100.5 V. After starting driving, the battery voltage decreased to 97–98 V in the no-load regime.

3. During the road tests, the battery voltage tended to decrease, which could be observed most explicitly at a no-load voltage. After the voltage has decreased to 92 V, the electric car batteries have to be recharged, as a full battery discharge occurs after driving as many as 1–2 km.

4. The maximum current of 450 A was reached in non-urban driving. The corresponding maximum motor output power was 38.6 kW. In urban driving, the maximum current was 350 A and the corresponding power was 30 kW.

5. When smoothly accelerating in urban driving, the current did not exceed 240–250 A. When cruising at 50 km h^{-1}, the current reached 70–75 A.

6. When braking in urban driving, the regenerative current reached 75 A, while the power – 7.5 kW at the regenerative level of 45%. A regenerative level of above 50% creates an inadequate increase in braking force caused by the regenerative braking system before the main brakes have been activated.

7. The regenerative braking system performed more effectively in non-urban driving, generating an current of 140 A; however, its proportion in the energy balance was insignificant and could not considerably increase the non-urban distance travelled.

8. After driving a distance equal to 70% of the total distance covered, the BMS started giving warnings when accelerating the electric car, which indicated that the voltage of the weakest battery element had decreased to 2.5 V and the no-overload driving regime was activated. This driving regime does not allow exceeding the pre-set speed.

9. More energy was consumed in non-urban driving before the route turnaround point was reached (25 ± 0.1 km), as the average road slope angle in this route section was $\alpha=0.6°$. The road slope angle allowed saving energy on the way back.

10.Due to a decrease in the voltage of the battery pack when accelerating, it is intended to increase the voltage by 6.4 V, which is within the allowable limits for the motor and the control system.

11.Due to the fast voltage drop in acceleration regimes, it is necessary to do a battery test for the electric automobile or set the controller to limit the maximum current to less than 400 A.

12.If converting a vehicle to electric power, it is required to choose a system with higher voltage that ensures a lower peak current and a safer way of exploitation of the batteries.

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