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Effect of electric vehicle mass change on energy consumption and the range

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Abstract. The use of industrially produced electric cars has increased significantly in the last 13 years. The year 2010 can be considered the initial stage of mass production of electric cars when the manufacture of the Mitchubishi I–MiEV and the Nissan LEAF was started. For modern electric cars, the battery mass can reach up to 770 kg. If the electric car is intended for long distances, the large mass and capacity of the battery is justified because it is put to good use. If the electric car is mainly used in urban driving mode, an increase in the mass of a heavy battery can reduce the range or energy consumption per km. To identify the effect of change in the mass of an electric car on the amount of electricity consumed, experimental studies were carried out with a converted electric car Renault Clio. A 10 kWh battery with a mass of 125 kg was used for the electric car. A road experiment was conducted in Jelgava city on a route that included streets of different traffic intensity with two different loads for the electric car. With an additional load for the electric car, the mass increase was simulated as if the mass of the battery was doubled. The road experiment showed that on the same city route, an increase in the mass of the electric car increased energy consumption by 5.8%, which in turn increased operating costs.

Key words: current, electric car, energy consumption, speed, voltage.

INTRODUCTION

The development of electric cars began about 150 years ago at the same time as the development of internal combustion cars. Although a large number of electric cars were produced at the beginning of the 20th century, the use of internal combustion cars expanded more rapidly. Such cars, despite their many shortcomings, began to be widely used in non-urban driving because they had a longer range per tank of fuel than per charge of the battery. Electric drive regained popularity only at the beginning of the 21st century when the electric drive was used in the first hybrid car Toyota Prius. Industrially produced electric cars Mitchubishi I–MiEV, Paugeot iOn and Citroen C–Zero (designed based on Mitchubishi models) appeared in 2010. For the first electric cars, the lithium-ion battery capacity was usually in the range of 16–24 kWh and the mass did not exceed 300 kg. The production of the electric car Tesla Model S started in 2012. The range of this electric car was 3 times the average range of electric cars of that period. The first generation of electric cars was mainly intended for use in a city, as the driving range per charge was not long.

Electric batteries are one of the most important components, which the main parameters of an electric car depend on. The main battery parameters that affect the driving range are the capacity and the mass of the battery system. As the battery wears out, the range of an electric car decreases. The mass of an electric car also depends on the mass of its batteries, and the larger the capacity and mass of the batteries, the larger the total mass of the electric car. An increased rolling and air resistance and mass of an electric car can affect its range per charge. Wen Li et al. have classified factors in electricity consumption into 6 groups. Experimental research was also conducted on the Nissan Leaf with a mass of 1,521 kg, a battery capacity of 24 kWh and a voltage of 345 V (Young et al., 2013; Li et al., 2016).

Already in 2020, reports on the introduction of electric cars stated that by 2030, the consumption of minerals is going to increase significantly, e.g. lithium 3.4–fold and cobalt 1.5–fold. According to the trend identified, the reserves of lithium ore used for producing electric car batteries will last 109 years, which could be the most optimistic forecast (Jones et al., 2020).

A rapid acceleration of electric cars, just like internal combustion cars, affects the amount of energy consumed (Graba et al., 2021). A. Desreveaux et al. compared internal combustion and electric cars (Renault Clio 3 and Renault Zoe) of the same segment through simulation. The analogous electric car was 350 kg heavier than the heaviest internal combustion engine car. The researchers simulated energy consumption and global warming potential. The simulation found that fuel consumption for a petrol car was 4.8 l $(100\ \text{km})^{-1}$ and 4.6 l $(100\ \text{km})^{-1}$ for a diesel car, while energy consumption for an electric car was 17.1 kWh $(100\ \text{km})^{-1}$. The simulation used real driving regimes based on GPS data. GWP calculations revealed that in some simulation regimes, the GWP for an electric car was 3.5 times lower than that for internal combustion cars (Desreveaux et al., 2023).

Frederick Spaven et al. have analysed the greenhouse gas and energy consumption trend for electric vehicles with large battery packs, i.e. with a capacity of above 60 kWh. With an improved battery charging infrastructure, an optimal battery capacity should not exceed 25 kWh, which would improve the ecological performance of the electric car because of no need for additional batteries and lower energy consumption owing to a decrease in the mass the electric car (Degen & Schütte, 2022; Spaven et al., 2022). The ambient temperature can also significantly affect the range of an electric car per charge. After examining GPS data on 68 electric cars, it was discovered that an optimal temperature for electric car operation to achieve the longest driving range was 17.5 °C (Wang et al., 2017).

A two-gear gearbox was used to achieve an increase in the driving range and a decrease in energy consumed by reducing the mass of the electric car. The simulation found that it was possible to reduce energy consumption by 7.21%, which was a relatively good result because the mass of the electric car was reduced by only 30.9 kg (Xin & Chengning, 2017). The energy consumption of an electric car could be decreased when driving on roads with a lower rolling resistance coefficient (Yao et al., 2013).

Although trucks and buses usually use heavy assemblies, the mass of batteries is relevant in this segment as well. In Brazil, an electric bus used in a road experiment was powered by batteries whose mass reached 3,290 kg (Vargas et al., 2019).

Francesco Del Pero et al. have examined the effect of change in the mass of an electric car on the amount of electricity consumed by employing the analytical calculation method and the MATLAB–Simulink model. The calculation algorithm proposed by the researchers included an energy economy factor for a decrease of 100 kg in the mass of the electric car. The simulation involved three different driving cycles: NEDC, WLTP and ALDC and a car mass decrease of 5–20%. The calculations were performed separately for cars of different classes to identify averages for each class. Different average values of energy consumption were identified for different driving cycles, which varied from 0.55 kWh (100 km 100 kg)$^{-1}$ in the NEDC cycle to 0.97 kWh (100 km 100 kg)$^{-1}$ in the ALDC cycle. An estimate of a decrease in CO_2 emissions for the reduced mass of electric cars of different classes was performed as well (Pero et al., 2020).

Our previous research had designed an analytical calculation methodology for identifying the effect of change in the mass of an electric car for various electric cars (Berjoza & Jurgena, 2017). This methodology could be employed to identify the effect of increasing the mass of batteries; however, available theoretical data on electric cars (for example, a range per full charge) might differ from those obtained in real experiments under real driving conditions.

Scientists conduct research in the field of energy economy not only on electric cars but also on other alternative energy vehicles, e.g. pneumatic cars using compressed gas as an energy source. A research study has analysed the possibilities of using two gases, nitrogen and argon, as well as the efficiency factor (Gailis, 2020).

Various research studies on the effect of change in electric vehicle mass on energy consumption and the range are based on analytical research applying simulation tools, the results of which could differ from those using real experimental cars. Decreasing the mass of an electric car could give a larger energy economy effect when operating the electric car in urban driving. In urban driving, a decrease in car mass results in energy economy, as the energy required to accelerate the electric car is lower. The present research aims to conduct a road experiment on an electric car in urban driving conditions, simulating a 2–fold change in battery mass, and to identify the difference in energy consumed.

MATERIALS AND METHODS

The experiment used a converted electric car Renault Clio 2. The car was equipped with a battery pack whose mass together with the frame and the BMS system totalled 125 kg. The experiment was done at two stages. At the first stage, the electric car was loaded with a driver and an experiment operator. At the second stage, the electric car was additionally loaded with 125 kg weights. In this way, a 2–fold increase in the mass of electric car batteries was simulated. The main technical parameters of the experimental electric car are summarized in Table 1.

A Garmin Edge 830 GPS logger was used to record the road experiment route. The logger recorded the main parameters of the route, e.g. average speed, driving time, as well as instantaneous speed.

After finishing the route, the data were graphically represented on the map and analysed. The electric car was weighed by means of an automotive shock absorber diagnostic stand VTQ 2100i having a weighing function. The weighing was carried out with an accuracy of ±1 kg. A Graphtec GL220 Midi Logger was used to record electrical data for the electric car. This device recorded battery voltage, instantaneous amperage of charging or discharging current, instantaneous temperature of the battery and the controller and rotation frequency of the motor. The instantaneous charge or discharge capacity of the battery was calculated based on the voltage and current recorded.

Table 1. Electric car renault Cli main parameter

No.	Parameter characteristics	Parameter value
1	Motor nominal power	30 kW
2	Maximum speed	120 km h^{-1}
3	Type and number of batteries	$LiFePO_4$, 32pcs
4	Total battery voltage	102.4 V
5	Battery energy	10.5 kWh
6	Range per charge	60 km
7	Battery capacity	100 Ah
8	Curb weight	1,080 kg
9	Weight in road test 1 (2 operators)	1,218 kg
10	Weight in road test 2 (2 operators and additional weights)	1,218 + 125 = 1,343 kg
11	Degree of regenerative braking set	76%

The experiment was conducted in Jelgava in urban driving mode in April 2023. The selected road experiment route included both the streets of the city centre and of the outskirts, which were intended for truck traffic to bypass the central part (truck transit traffic was not permitted in the central part of Jelgava). The maximum speed permitted on the entire route was 50 km h^{-1}. The route is presented in Fig. 1.

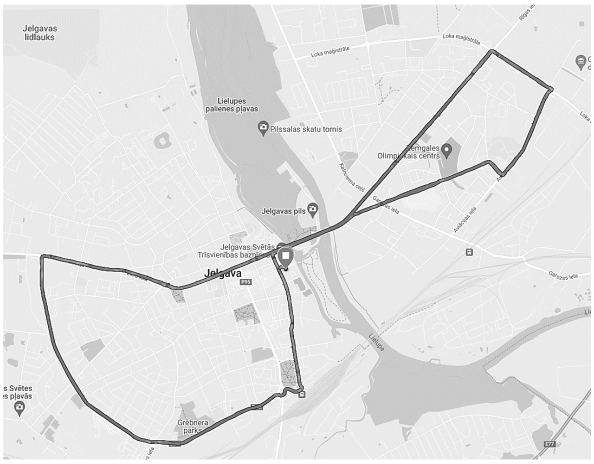

Figure 1. Road experiment route in Jelgava City.

The start and finish points of the route were located at 5 Cakste Boulevard. A road test was performed by completing the entire route twice. The length of one full route cycle was 14.7 km. The total length of one road test was 29.4 km long, or two full route cycles. At first, a road test was performed without an additional load with 3 replications. After that, a road test was done with an additional load of 125 kg.

The road experiment was done at an ambient temperature of +10 to +15 °C. Wind speed during the road experiment did not exceed 2–3 m s^{-1}. On the route, the asphalt was in good condition, and the average rolling resistance coefficient was 0.012–0.013. A road test was started with a fully charged battery. Immediately after the road test, the electric car's battery was charged. Both during the road test and during the charging, the data were recorded by the electronic data recorder (logger) Graphtec GL220 Midi. The route logger and the electrical data logger were switched on shortly before starting the movement and stopped immediately after stopping at the finish point of the route. No stops were made during any road test, except when required by traffic circumstances. After the road tests, the data from the data logger were imported into and processed in an Excel spreadsheet. Fig. 2 shows a fragment of data imported from the electrical data logger Graphtech in the Excel spreadsheet. Abbreviations in Fig. 2: CH1; CH2; CH3– corresponding data logger channels; Amp– electric car current;rpm– rotation frequency of the electric motor.

20	Time	CH1	CH2	CH3
21	ms	Voltage	Amp	rpm
22	0	105.78	3.87	0
23	0.2	105.78	3.87	0
24	0.4	105.78	3.78	0
25	0.6	105.77	3.78	0
26	0.8	105.77	3.69	0
27	1	105.78	3.78	0

Figure 2. Sample of electrical data processed.

During the road tests, the data were saved at 0.1 s intervals when driving and at 1 second intervals during charging.

RESULTS AND DISCUSSION

After the road experiment, the data were processed to identify maximum, minimum and average power, current and voltages when driving. The calculations also identified the energy that the electric car consumed when driving, as well as the energy that was generated during regenerative braking.

The speed parameters recorded on the route indicate the suitability of the route for road experiments and the accuracy of replications. Fig. 3 summarizes the average speed ($v_{average}$) and the maximum speed (v_{max}) during the road tests.

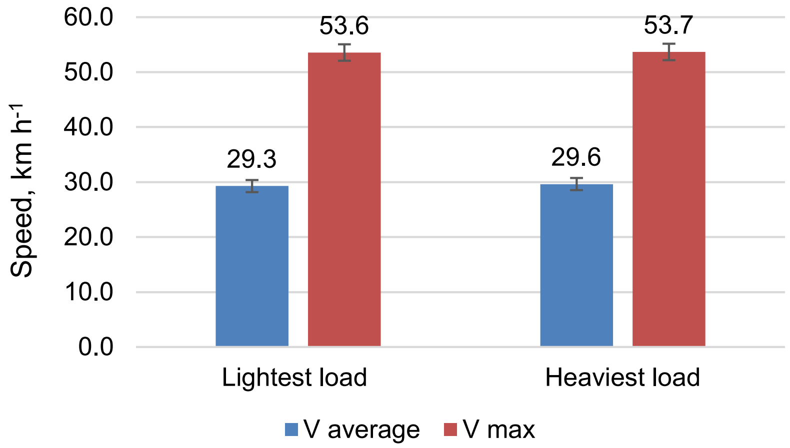

Figure 3. Speeds of the electric car during the road tests.

The average speeds of the electric car with the lightest load and the heaviest load were 29.3 and 29.6 km h^{-1}, respectively. The difference in speed between the two experimental regimes was only within 1%. There was a similar trend in relation to the maximum speed, which did not exceed 54 km h^{-1}, and the difference was even smaller. The maximum speed was achieved during acceleration when it was necessary to merge with the traffic flow, change the lane or in other similar situations.

Current readings indicate the range and average values of the power required for the car when driving on the route. The maximum current was recorded during acceleration and when accelerating from a standstill or increasing the speed. The highest current was usually recorded with a relatively discharged battery and a voltage drop. To achieve the same wattage with a relatively discharged battery as with a fully charged battery, the current increased. Changes in current during both road tests are summarized in Fig. 4 ($I_{average}$– average current; I_{max}– maximum current; I_{min}– minimum current). In the second experimental regime, the highest current, which reached 562.3 A, was recorded within an interval of no more than one second. A higher amperage was caused by the effect of the heavier mass of the electric car on the operation of the electric motor.

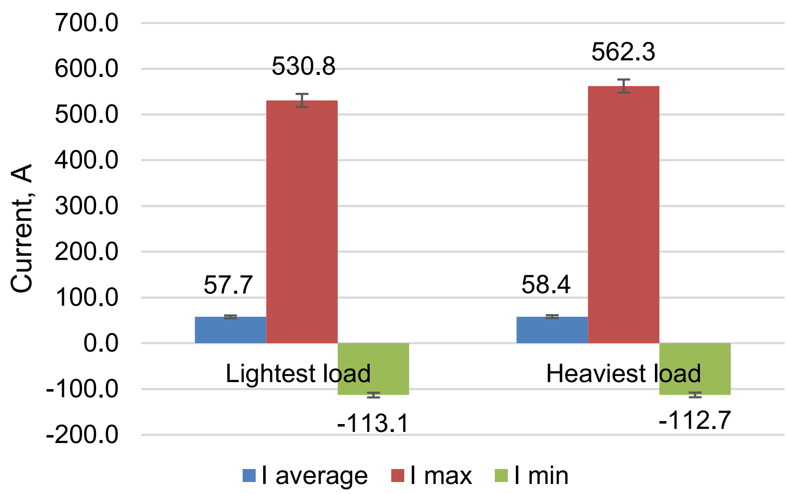

Figure 4. Current readings for the electric car.

The direction of electric current flow during regenerative braking is opposite to that when accelerating and cruising; therefore, this range of current is assigned a negative value. In both experimental regimes during regenerative braking, similar current were recorded in the range of 112.7 to 113.1 A. More precise characteristics of regenerative braking are given in an analysis of the energy generated during regenerative braking. In the road experiment, the average current indicates the average energy consumed. With the heaviest load for the electric car, a current of 58.4 A was recorded, which was 1.2% higher than that for the lightest load.

The energy consumed during the road experiment can indicate a potential change in the driving range, as the mass of the electric car increases if installing an additional battery pack. A balance of energy consumed by the electric car during the road experiment is presented in Fig. 5.

In the graph, the highest values show the energy consumed by the electric car during the road experiment. Operating the electric car with the lightest load required 5,943 kWh of energy, while 6,389 kW, which was 5.8% more, was required in the case of the heaviest load. The energy balance also includes the part of the energy that was put into the battery from the grid. With the heaviest load for the electric car, the energy generated during regenerative braking increased from 0.444 kWh to 0.539 kWh, which was 21.1% more. However, the energy generated during regenerative braking cannot offset the energy that must be additionally consumed for transporting the additional battery.

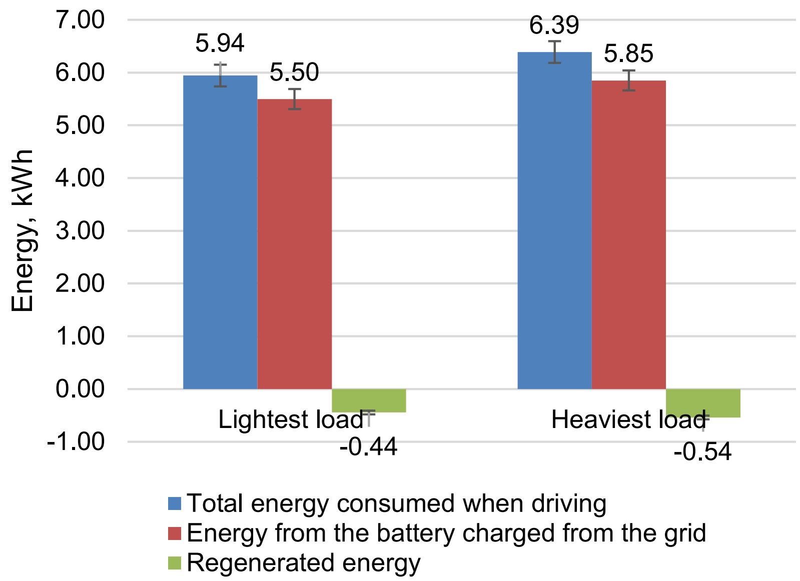

Figure 5. Energy consumed by the electric car.

A recalculation of energy consumption per 100 km distance travelled revealed that 20.21 kWh of energy was consumed in the case of the lightest load and 21.73 kWh in the case of the heaviest load. In their research, Francesco Del Pero et al. have simulated different driving cycles, and the energy consumed was in the range of 0.55–0.97 kWh (100 km 100 kg)$^{-1}$. In the present road experiment, the energy consumption was higher in the range of 1.62–1.66 kWh (100 km 100 kg)$^{-1}$. The relatively large difference could be explained by the fact that the energy consumed is usually lower in simulated driving cycles than in real driving conditions.

CONCLUSIONS

1. An increase in the mass of a car affects the energy consumed, especially in urban driving, because the proportion of acceleration and braking periods is higher than that in non-urban driving mode.
2. Most of the research studies on the effect of vehicle mass on energy consumption have been conducted using simulation and driving cycles on roller stands. The results might differ from those obtained under real driving conditions.

3. According to the results of the road experiment, the electric car Renault Clio demonstrated an increase in energy consumption by 5.8% in urban driving mode if increasing the battery capacity from 10.5 kWh to 21 kWh and the mass of the electric car by 125 kg.

4. In solutions to the design of future electric cars, it is recommended to seek new technological solutions to battery energy replenishment, not only to an increase in the battery capacity.

5. In the case of the heaviest load, the experimental electric car generated 21.1% more energy during regenerative braking. Despite this fact, the proportion of energy regenerated was low in the balance of energy, as the energy regenerated represented only 7.4% of the total in the case of the lightest load and 8.5% in the case of the heaviest load. This additional energy recovered cannot offset an increase in energy consumption due to an increase in the mass of the electric car.

6. The negative aspects of increasing the capacity of the battery for an electric car relate to an increase in the mass of the battery and the car as well as energy consumption per 100 km distance covered, a decrease in the energy efficiency of the electric car, waste of lithium and other resources and an increase in the price of the electric car.

7. The negative aspects of increasing the mass of an electric car represent also the need to increase the dimensions of the braking mechanism, which requires a larger braking force for a heavier car. More powerful brake mechanisms are structurally more massive and more material-intensive.

8. When choosing an electric car for operation in urban conditions, it is necessary to evaluate in detail the need for large batteries because it increases the cost of operation and also the purchase price of an electric car.

9. In the next stages of research, with the developed research methodology, it is planned to conduct more extensive research with industrially produced electric cars.

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