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Effects of change in the weight of electric vehicles on their performance characteristics

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Abstract. One of the parameters of electric vehicles that can affect their dynamic and range characteristics is their weight. Converting a vehicle with an internal combustion engine into an electric one, it is possible to vary its batteries and their placement. It is also possible to choose batteries of various capacities for serial electric vehicles, for example, Tesla Model S. Not only the costs of electric vehicles but also such performance characteristics as dynamics and travel range per charge depend on the number of batteries and the total weight of the electric vehicles. The research developed and approbated an algorithm for calculating comparative parameters for electric automobiles. The algorithm was approbated on 30 electric automobiles of various makes. Energy consumption per km distance travelled shows the exploitation cost of an electric automobile. According to this indicator, the most economical electric automobiles were as follows: Renault Twizy (67.8 Wh km^{-1}), Tazzari Zero (87.9 Wh km^{-1}) un Renault Zoe ZE22 (93.6 Wh km^{-1}).

Key words: batteries, range, batteries capacity, energy consumption, weight coefficient, gross weight.

INTRODUCTION

One of the technical parameters of vehicles is their weight. The weight of vehicles and its distribution on axles can affect such performance parameters as fuel consumption and acceleration dynamics. An analysis of the historical trends in vehicle weight change shows that auto manufacturers used the designs of massive automobiles in the 1950–70s, not seeking lower vehicle weight. Later, from the 1970s to the middle of the 1980s, the use of lightweight materials became popular, and steel was replaced with lightweight composite materials (plastics) in vehicle design. Consequently, the average weight of the same class automobiles decreased, on average, by 15–20%.

However, a too large decrease in the weight of vehicles resulted in lower passenger safety and design durability. To enhance the safety of passengers, in the 1980–90s vehicles started to be equipped with various safety systems, e.g. safety airbags, the automatic braking system (ABS) and stability control systems. A number of passive safety systems were designed as well. The introduction of new safety systems and their installation on automobiles again resulted in higher vehicle weight, which was observed at the end of the 20th century.

Changes in the weight of internal combustion engine vehicles of the same model are usually insignificant. Small weight changes are usually observed if vehicles are equipped with the engines of different capacities and modifications and various devices. Changes in the weight of commercial cars are possible due to their freight compartments of different sizes.

A change in the weight of an automobile can affect the automobile's average fuel consumption. Such a trend is usually observed if driving in the urban driving regime when the automobile is often accelerated and stopped. An analysis of annual changes in automobile fuel consumption shows that in the middle of the 1980s the average fuel consumption for cars considerably decreased, while later this trend was not so explicit (Heavenrich, 2008). A similar trend in the historical evolution of automobiles was observed in relation to weight reduction; the smallest decrease in weight was specific to the automobiles manufactured in the period 1981–1987. The average weight of automobiles produced later tended to increase again. The weight increase trend does not considerably affect the acceleration dynamics of automobiles of new designs, which may be explained by the introduction of modern engine designs (Heavenrich, 2008).

Energy capacity per unit battery weight for electric vehicles (EV) is very high – from 60 to 96 Wh kg^{-1}. If an automobile is equipped with 20 kWh lithium batteries, their weight might reach 200 kg. The cost of batteries is high, up to 1,000 EUR kWh^{-1}. (Huh et al., 2011). To reduce the cost of vehicles, it is advised to choose a custom-made pack of EV batteries, as it is economically inefficient to carry the excessive weight of the batteries.

If an electric car is equipped with modern lithium-ion batteries, the current technologies allow achieving a travel range of 40–480 km per battery charge. Such batteries are not only heavy but also occupy a large space – 450–600 litres – inside the car. By using the fuel cell technology, the occupied space may be reduced by half (Thomas, 2009).

Electric vehicles may be equipped with batteries of various types. Electric vehicles are usually equipped with lead (PbA), nickel (NiMH) and lithium (Li-Ion) batteries. Today, electric vehicles have lithium-ion batteries, yet slow-moving electric vehicles are equipped with lead batteries as well. Lead batteries increase the weight of an electric vehicle the most, compared with the other kinds of batteries.

If an electric automobile is equipped with lead batteries for a range of 60 km per charge, the weight of the automobile can reach 1,700 kg. If the electric automobile is equipped with a greater number of batteries and its weight increases to 3,500 kg, the travel range increases to 170 km. If equipping electric automobiles with NiMH batteries, a medium class electric automobile with a weight of 1,500 kg can achieve a travel range of 100 km per charge. If using batteries of this kind, an automobile can reach a range of 300 km, yet its weight increases to 2,650 kg. To achieve a range of 100 km per charge by using modern lithium-ion batteries, the weight of an automobile reaches 1,350 kg and the weight of its batteries is approximately 150 kg. In order for an electric automobile to achieve a travel range that is similar to the travel range of internal combustion engine automobiles and exceeds 400 km, the weight of the electric automobile has to be increased to 2,000 kg (Thomas, 2009).

According to research investigations by other authors too, the travel range of electric vehicles is directly affected by the capacity of batteries, which depends on the weight of the batteries that can be installed on the electric vehicle. If using a 1.1 kWh lithium battery weighing 10 kg, a medium class automobile can travel a distance of 8 ± 1 km. A 7.4 kWh lithium battery weighing 80 ± 20 kg allows covering a distance of 50 ± 7 km. However, if using 31.8 kWh batteries weighing 290 ± 160 kg, the automobile can travel a distance of 250 ± 37 km (O. van Vliet et al., 2011).

Exploiting an internal combustion engine automobile after it has been fuelled up, regardless of the kind of fuel used, the weight of the fuel and therefore the weight of the automobile decreases; for a medium class automobile the weight decrease is in the range of 50–5 kg. In electric automobiles, the energy storage device – the battery – is many times heavier that the fuel tank; besides, its weight does not change depending of the battery's charge level – whether it is fully charged or fully discharged (Hauffe et al., 2008).

If equipping an electric automobile with higher capacity and heavier batteries, its total weight increases, and a higher power electric motor with a higher weight is necessary for dynamic driving. In this case, if purchasing an electric automobile, the cost increases owing to costlier accessory parts for the electric automobile as well as higher 'fuel' or electricity cost per 100 km kilometrage. By means of simulation methods, optimum parameters may be chosen for electric automobiles with various battery packs, motors and travel ranges (Hauffe et al., 2008). However, the key or at least a very important factor in choosing parameters for an electric automobile is the vehicle's driver's driving habits, daily kilometrage and maximum and average driving speeds. At present, the available assortment of electric automobiles in Latvia may not be characterised as being very broad and as meeting all the wishes of consumers, compared with that of internal combustion engine vehicles.

A comparison of the same class automobiles shows that the automobiles with a longer travel range are also heavier. The lowest average weight is specific to diesel and petrol engine automobiles, followed by HEVs (hybrid electric vehicles) and BEVs (battery electric vehicles). Besides, the average weight of BEVs can exceed that of other kinds of automobiles by up to 200 kg (Faria et al., 2012). A higher weight of an automobile can worsen not only the automobile's performance characteristics but also decrease the lifetime of assemblies of its suspension.

MATERIALS AND METHODS

The weight of vehicles and a change in it is an essential characteristic. For some vehicles when carrying the freight of various weights, the real exploitation weight can change even more than two times. Such changes are associated with the specifics of exploitation of vehicles and the structural qualities of the vehicles. Some transport enterprises calculate tonne-kilometres (t km) for their lorries, which indicate the work done by the lorries. The enterprises also set fuel consumption limits both for empty lorry runs and for full runs, i.e. t km done. Weight is also an essential factor for electric automobiles, especially in cases where large-size batteries are used, which are intended for traveling long distances.

To compare the efficiency in respect to electric vehicle weight, a specific weight coefficient for batteries has been introduced, which is calculated according to the formula:

$$k_m = \frac{m_{Acum}}{m_{EV}} \tag{1}$$

where: m_{Acum} – electric automobile's battery weight, kg; m_{EV} – electric automobile's weight, kg.

To identify the efficiency of a battery pack used in an electric automobile, the weight of the electric automobile is taken into consideration. The higher the km indicator, the higher weight batteries are used in the electric automobile and the more it is loaded. Serial electric automobiles are usually equipped with lithium-ion batteries that allow traveling a range of 120–150 km. The latest generation electric automobiles tend to increase their travel ranges. The specific weight coefficient for batteries does not completely indicate the efficiency of a battery pack, as the Eq. (1) does not include the battery pack's capacity.

The capacity of a battery pack for electric automobiles is measured in kWh. The higher the indicator is, the more electrical energy can be stored during charging the electric automobile. The simplest way how to identify this indicator for a particular electric automobile is to measure the electrical energy consumed during charging.

Batteries are different in terms of their chemical composition and therefore their weight per energy unit. Modern electric automobiles are equipped with lithium-ion batteries that have one of the highest energy densities. The energy capacity of a battery pack installed on an electric automobile is lower than that of all the individual battery elements combined, as a battery system involves a battery management system (BMS), an air conditioning and cooling system etc. The energy capacity of a battery is calculated by the following formula:

$$\rho_A = \frac{E_{Acum}}{m_{Acum}}, \text{Wh kg}^{-1} \tag{2}$$

where: E_{Acum} – energy capacity of a battery pack for an electric automobile, Wh.

Technical characteristics usually specify an electric automobile's travel range per charge based on comparable experimental cycles done on a roller test bench, e.g. in an NEDC (New European Driving Cycle) test. Since experiments are done under ideal conditions, the data acquired not always are consistent with an automobile's travel range identified under real conditions. Under real road conditions, an automobile's travel range is affected by the wind, the road's resistance (climbing resistance, rolling resistance), the speed as well as the driving style (Renault, 2017). Therefore, the results acquired performing an NEDC test could be even 25–30% higher than those identified under real conditions. Since the technical characteristics for any electric automobile specify its travel range identified performing an NEDC test, the further analysis is done based on the data acquired for electric automobiles through doing an experiment.

The performance of a battery pack installed on the particular experimental automobile may be characterised by energy consumption per km distance travelled:

$$l_{E-1} = \frac{E_{Acum}}{L_{EV}}, \tag{3}$$

where: L_{EV} – distance travelled by the electric automobile per charge (range), km.

To measure the performance of a battery pack per 100 km distance travelled, the Eq. (3) is supplemented:

$$l_{E-100} = \frac{100E_{Acum}}{L_{EV}} \tag{4}$$

Energy consumption per km distance travelled can indicate the effect of the total weight of an electric automobile as well as the total cost of electricity for the distance travelled.

The suitability of a battery pack for an electric automobile in terms of an energy storage criterion may be measured by a ratio of energy to gross weight:

$$k_E = \frac{E_{Acum}}{m_{EV-Gros}}, \text{Wh kg}^{-1} \tag{5}$$

where: $m_{EV-Gros}$ – gross weight of an electric automobile, kg.

The performance of an electric automobile per charge may be measured by the on-board energy-range factor:

$$F_{E-L} = \frac{E_{Acum}L_{EV}}{m_{EV-Gros}}, \tag{6}$$

where: E_{Acum} – energy capacity of a battery pack of the electric automobile, kWh.

A higher energy-range factor means the performance of an electric automobile is better in terms of battery capacity, distance travelled and gross weight.

The factor may be increased or decreased by either reducing the weight of an electric automobile, which is not always possible due the design of the automobile, or increasing the battery pack's capacity that can increase the travel range.

To perform an analysis of the parameters of electric automobiles, the research summarised data on 30 electric automobiles in a table. A fragment of the data needed for the analysis is presented in Table 1.

Table 1. Technical parameters of Renault electric automobiles

Automobile model	Power, kW	Curb weight, kg	Gross weight, kg	Battery weight, kg	On-board power, kWh	NEDC range, km
Renault Zoe Expression Nav R90 ZE22 New	68	1,470	1,965	290	22	235
Renault Zoe Dinamique Nav R90 ZE40	68	1,480	1,966	305	41	400
Renault Twizy	13	474	690	100	6.1	90
Renault Kangoo	44	1,410	2,126	260	22	170

RESULTS AND DISCUSSION

The Eq. (1) allows calculating the specific weight coefficient, and the data are summarised in Fig. 1. The higher the weight of a battery pack, the higher the gross weight of an electric automobile.

An analysis of specific weight coefficient values shows that high coefficient values were specific to both large class electric automobiles, e.g. Tesla Model S, reaching 0.25, and small class ones, e.g. Aixam Electric (0.27), Tazzari Zero (0.26) and Think City (0.28).

Average coefficient values were specific to the electric automobiles equipped with lightweight battery packs that consisted of either the latest technology batteries with a low weight or low-capacity battery packs, and, therefore, the per-charge distance travelled by the electric automobile was short. The specific weight coefficient values for selected electric automobiles were as follows: Nissan Leaf (24) – $k_m = 0.15$; Nissan e-NV200 and Kia Soul – $k_m = 0.14$; Mercedes B Class electric – $k_m = 0.12$. These electric automobiles are medium class ones with a relatively high curb weight.

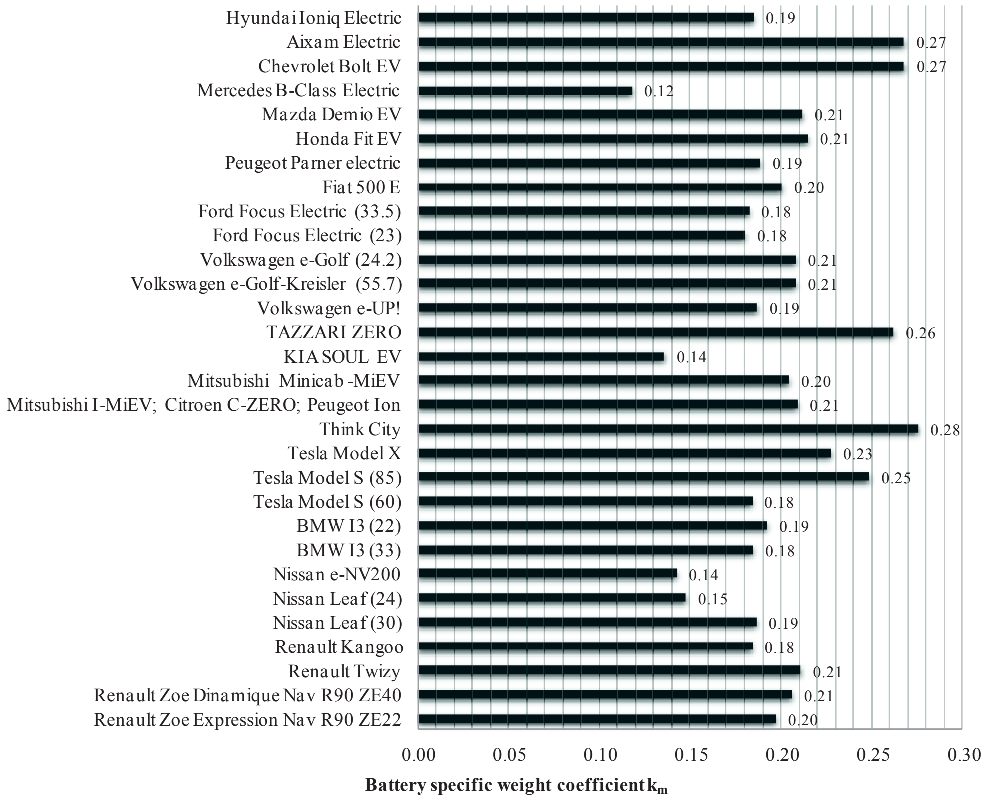

Figure 1. Battery specific weight coefficient for selected electric automobiles.
*Information in brackets represents the battery capacity.

The battery energy capacity coefficient values calculated according to the formula (2) are presented in Fig. 2. To analyse the problem of battery weight, the scientific literature often refers to energy capacity. The battery system of electric vehicles involves a number of elements for battery security, e.g. a hermetic cover that protects the battery from impacts and the surrounding environment.

Among the selected electric automobiles, Tesla Model X had the highest energy capacity value, $\rho_A = 184$ W kg^{-1}. The following models had the energy capacity in the range of 140–180 W kg^{-1}: BMW i3 (33), Tesla Model S (60), Tesla Model S (85), Kia Soul EV and experimental electric automobiles Volkswagen e-Golf-Kreisler (55.7). Tesla electric automobiles were still the best performers. The lowest energy capacity was specific to small class electric automobiles Renault Twizy ρ_A = 61 W kg^{-1}, Honda Fit EV ρ_A = 63 W kg^{-1} and Aixam Electric ρ_A = 67 W kg^{-1}. These values were 2.5–3 times lower than those for the electric automobiles having the highest energy capacity values. Such a trend may be explained by the use of older technology batteries in such electric automobiles or heavy battery protection and management systems that result in a high weight percentage of the batteries installed on a small electric automobile.

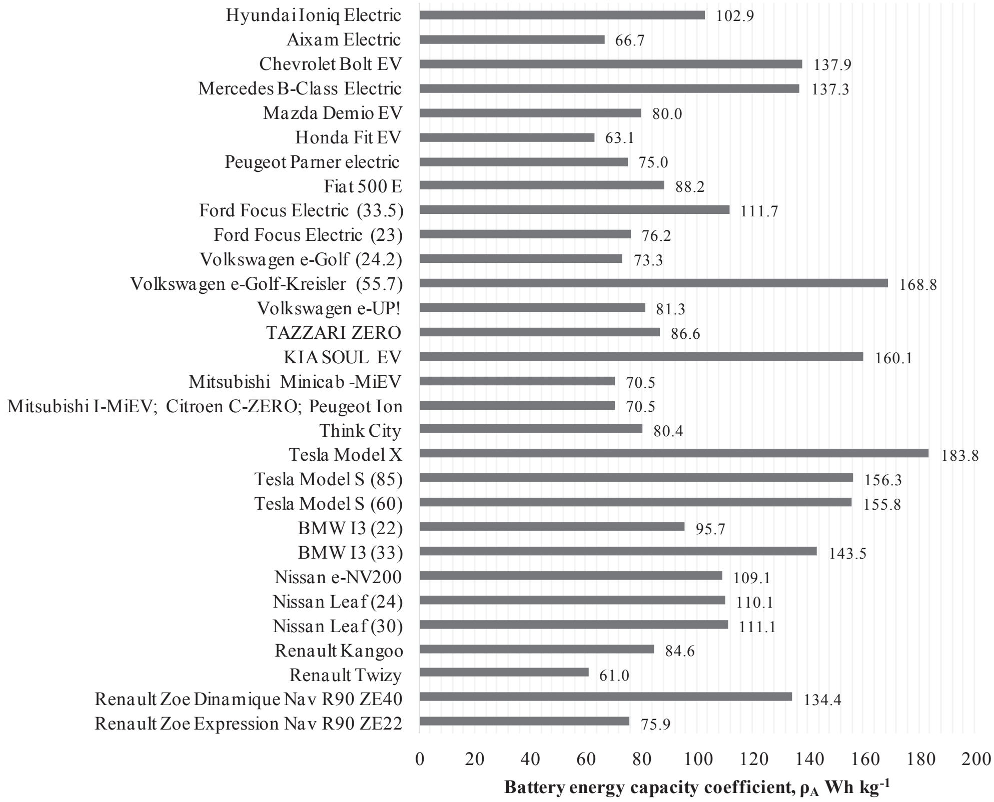

Figure 2. Battery energy capacity coefficient for selected electric automobiles.

The energy consumed per 1 km distance travelled is calculated according to the Eq. (3) and the results are summarised and showed in Fig. 3. The calculations took into account the travel ranges identified in an NEDC cycle test, and, under real road conditions, this indicator might be different from the calculated one. The best performers are the electric automobiles consuming the smallest amount of energy per 1 km distance travelled. The best performers are the following small class electric automobiles: Renault Twizy – 67.8 Wh km^{-1}, Tazzari Zero 87.9 Wh km^{-1} and Renault Zoe Expression with a 22 kWh battery (93.6 Wh km^{-1}). An analysis of electric automobiles of the same modification and design equipped with different capacity batteries revealed that in all cases the electric automobiles equipped with higher capacity batteries had a higher value of this indicator, showing lower performance, e.g. Tesla Model S (85) by 23.7%, Volkswagen e-Golf-Kreisler by 9.3% and Renault Zoe Dinamique (41) by 9.5%, compared with models equipped with lower capacity batteries. This indicates that with the battery energy capacity increasing in electric automobiles, they become less economically efficient. The only electric automobile that was not subject to this trend was Nissan Leaf (30) whose energy consumption improved, compared with the base model, by 0.5%. The highest energy consumption was specific to the following electric automobile models: Tesla Model S (85) – 199.5 Wh km^{-1}, Tesla Model X – 200.0 Wh km^{-1} and Kia Soul EV –216.7 Wh km^{-1}. These electric automobiles were the most economically inefficient in terms of energy consumption.

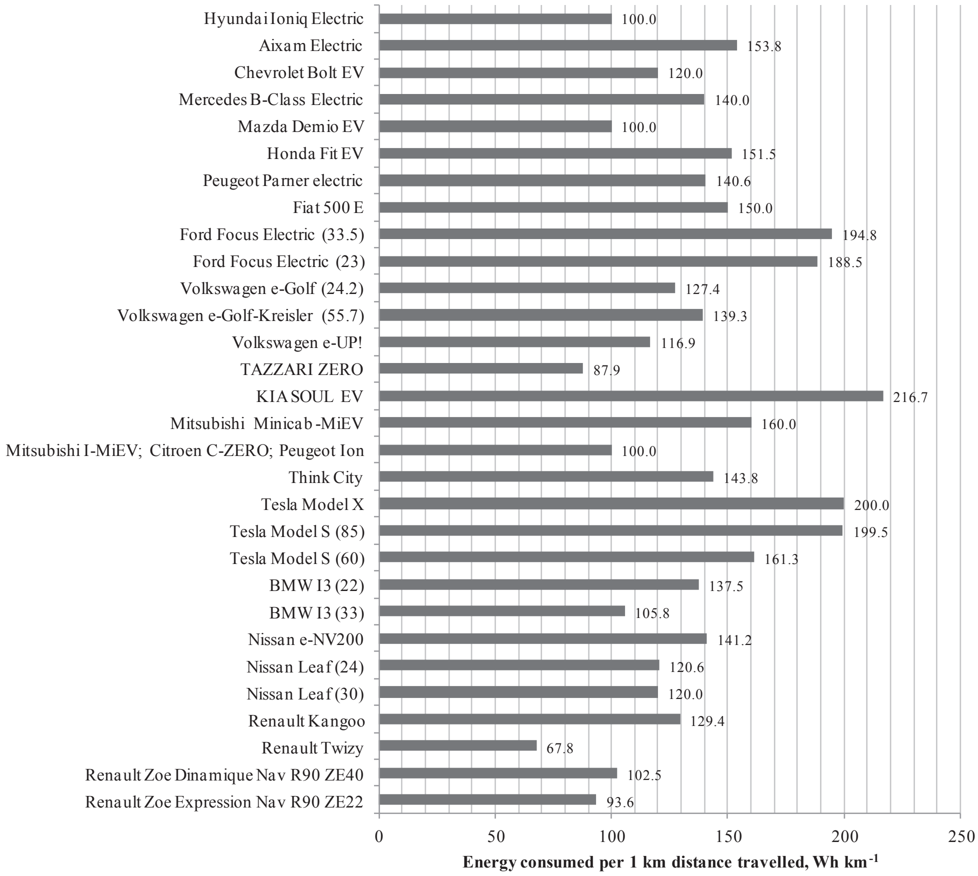

Figure 3. Energy consumed per 1 km distance travelled for selected electric automobiles.

The amounts of electrical energy stored per kg gross weight were calculated by the Eq. (5) and are showed in Fig. 4. The higher the indicator, the performance of an electric automobile is higher, and its batteries can store more energy. The highest indicator value is usually specific to the electric automobiles equipped with high capacity batteries.

The highest energy-gross weight values were specific to the following electric automobile models: Tesla Model S (85) – k_E = 30.36 Wh kg^{-1}, Tesla Model X – k_E = 32.57 Wh kg^{-1}, Volkswagen e-Golf Kreisler (55.7) – k_E = 28.42 Wh kg^{-1} and Chevrolet Bolt EV – k_E = 29.27 Wh kg^{-1}. The poorest performer was Renault Twizy with 8.84 Wh kg^{-1}. The energy-gross weight values for Peugeot Partner electric, Honda

Fit EV, Mitsubishi Minicab Miev, Nissan e-NV 200 and Renault Kango were in the range of 10.11–10.81 Wh kg^{-1}. The electric automobiles had low battery capacities relative to their gross weights. Based on this parameter, one can provisionally assume that this group of electric automobiles, compared with the other ones, has a short travel range.

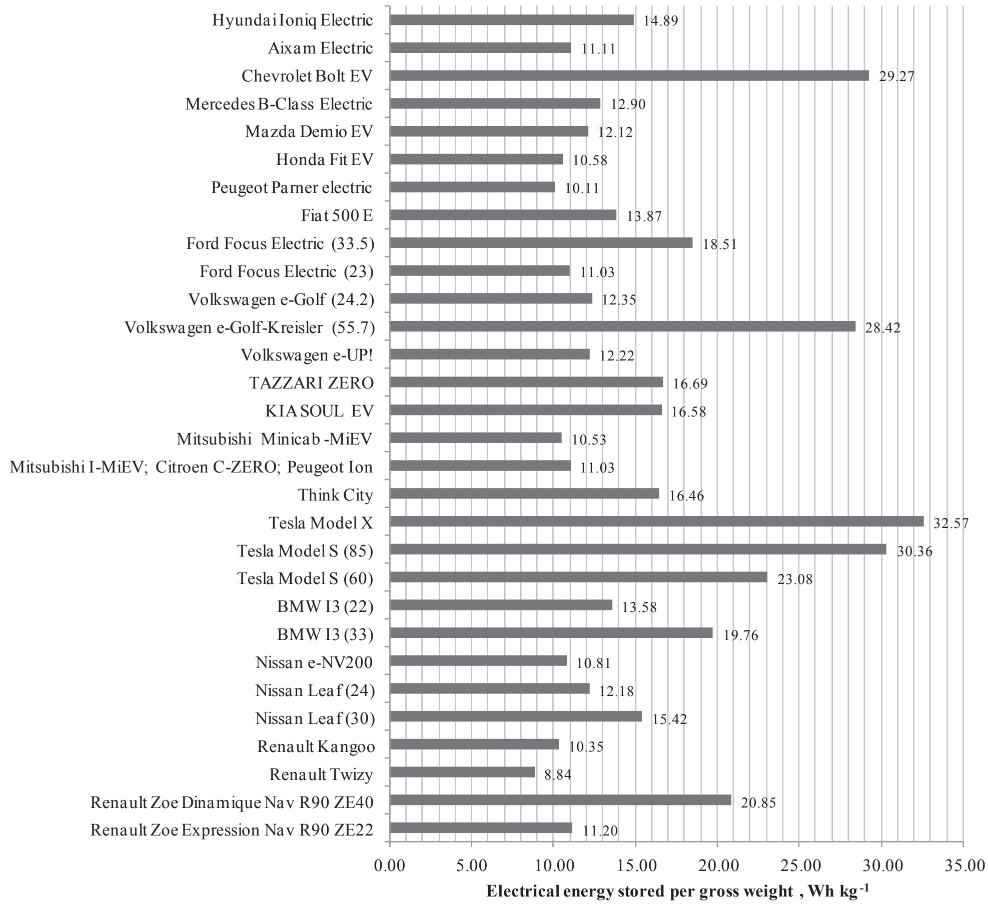

Figure 4. Electrical energy stored per kg gross weight for selected electric automobiles.

The energy-kilometrage factor was calculated by the Eq. (6) and the calculation results are summarised in Fig. 5. Electric automobiles with a factor of more than 6.0 are considered to be higher performance ones than those having a lower factor.

The best performers were the following automobile models: Tesla Model X – $F_{E\text{-}L}$ = 16.29, Chevrolet Bolt EV – $F_{E\text{-}L}$ = 14.63, Tesla Model S (85) – $F_{E\text{-}L}$ = 12.93 and Volkswagen e-Golf Kreisler – $F_{E\text{-}L}$ = 11.37. The electric automobiles with a relatively high gross weight and a low battery capacity had a factor value that was lower by about 2 kWh km kg^{-1}.

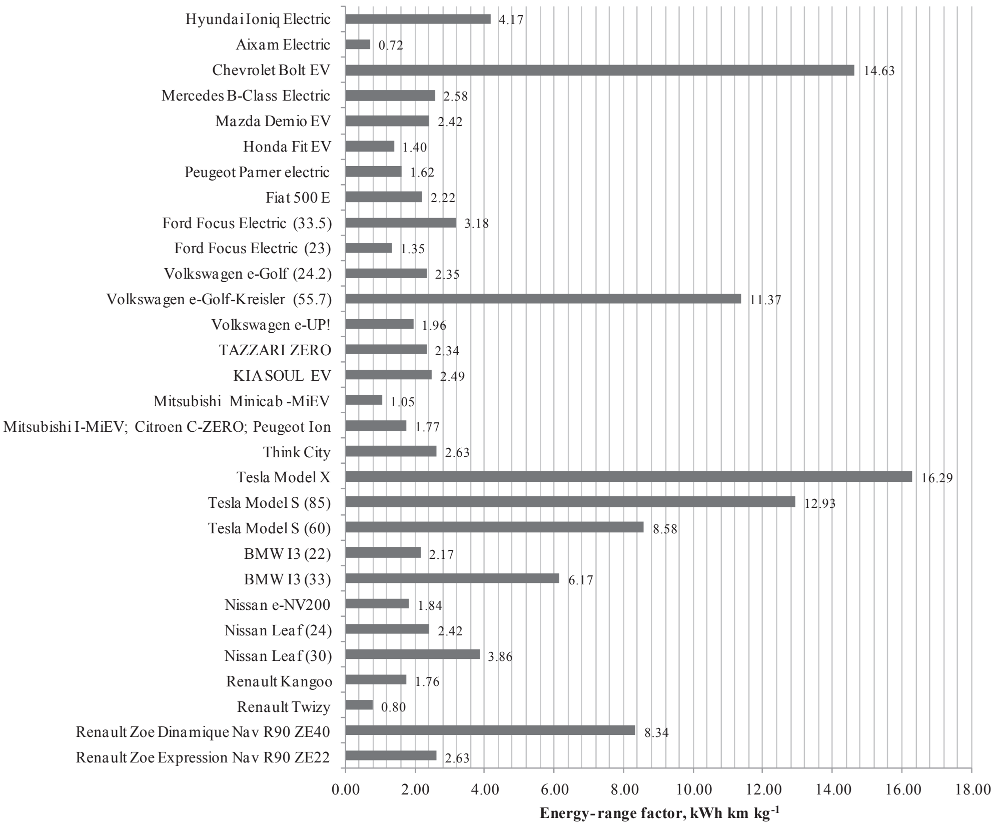

Figure 5. Energy-range factor for selected electric automobiles.

An analysis of the parameters regarding battery capacity and range showed that higher performance electric automobiles or models were as follows: Tesla brand electric automobiles, Volkswagen e-Golf Kreisler, Chevrolet Bolt EV and Renault Zoe ZE 40, yet in terms of energy consumption per 1 km distance travelled the electric automobiles with lower capacity batteries and lower weight were more economically efficient.

To perform an in-depth examination of the effects of increasing the weight of batteries for electric automobiles on such performance parameters as fuel consumption per 1 km distance travelled, range per battery charge, acceleration intensity, maximum acceleration etc., it is necessary to design a mathematical model for simulation of interrelationships among the parameters and to compare the calculated data with road experimental data. It is intended to design the model at the future stages of the research.

CONCLUSIONS

1. An analysis of the historical evolution of vehicles reveals that the average weight of automobiles decreased in the 1980s with the use of the latest generation materials, yet an increase in the weight was observed later, which was associated with higher safety standards.

2. The research developed a calculation algorithm (Eq. 1–6) for the most essential characteristics of electric automobiles based on their technical parameters, which was approbated on 30 electric automobiles of various models.

3. Specific weight coefficient values for a pack of batteries of electric automobiles do not explicitly tend to increase depending on the automobile class. High values are specific to both small, two-seater electric automobiles, e.g. Think City, $k_m = 0.28$, Axam Electric, $k_m = 0.28$ and Tazzary Zero, $k_m = 0.26$, and five-seater ones such as Tesla Model S (85), $k_m = 0.25$, and Chevrolet Bolt EV, $k_m = 0.27$.

4. Low values were identified for medium class electric automobiles with an average curb weight, e.g. Nissan e-NV200 and Kia Soul, $k_m = 0.14$; Mercedes B Class Electric, $k_m = 0.12$. The battery packs installed on such electric automobiles are relatively light and weigh less than 220 kg.

5. The highest battery energy densities were specific to the electric automobiles with high capacity batteries: Tesla Model X, $\rho_A = 184$ W kg^{-1}, Volkswagen e-Golf-Kreisler (55.7), $\rho_A = 168.8$ W kg^{-1} and Kia Soul EV, $\rho_A = 160.1$ W kg^{-1}.

6. The lowest battery energy densities were specific to the small electric automobiles: Renault Twizy, $\rho_A = 61$ W kg^{-1}, Honda Fit EV, $\rho_A = 63$ W kg^{-1} and Aixam Electric, $\rho_A = 67$ W kg^{-1}. These values were 2.5-3 times lower than those for the electric automobiles having the highest energy capacity values.

7. Energy consumption per km distance travelled is an essential indicator that directly affects the exploitation cost of an electric automobile. This indicator for electric automobiles with high capacity and weight batteries (Kia Soul EV, Tesla) was 80–95% higher than for the electric automobiles with a low gross weight.

8. Energy stored per kg EV gross weight for Tesla and Volkswagen e-Golf Kreisler (55.7) was the highest and ranged from 23.08–32.57 Wh km^{-1}. For most of the electric automobiles analysed, this indicator was in the range of 10.11–12.35 Wh kg^{-1}.

9. The highest energy-kilometrage factor values were identified for the electric automobile models Tesla Model X, $F_{E\text{-}L} = 16.29$ and Chevrolet Bolt EV, $F_{E\text{-}L} = 14.63$. This indicator for the electric automobiles with a relatively low gross weight and battery capacity was lower by 2.5 kWhkm kg^{-1}. Of the electric automobiles analysed, 56.6% belonged to this value group.

10. When purchasing an electric automobile, it is advised to carefully examine the need for a large capacity battery pack ($E_{Acum} \geq 50$ kWh) and choose an electric automobile that is best suited for the conditions of its exploitation and the average daily range, thus reducing the energy cost per 1 km distance covered.

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