Analysis of factors affecting the energy consumption of an EV vehicle - a literature study

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Abstract. One of the most requested information about an electric vehicle is its energy consumption. This parameter is particularly important for electric vehicles users who drive them in real conditions. This paper aims to conduct literature research on the factors affecting the energy consumption of a vehicle. The article contains a set of information concerning how the temperature, traffic conditions, or properties of an electric vehicle translate into energy consumption. The results of studies presented in various publications were compared. The literature analysis allowed for the creation of a list that can be used as a compendium of knowledge on the energy consumption of electric cars.

Key words: hybrid electric vehicle, vehicle, energy consumption

1. Introduction

Electric vehicles are becoming more and more common. According to the publication [1], in 2020 the number of newly registered electric vehicles in Europe amounted to 11% of all vehicles, of which 6% were BEVs (Battery Electric Vehicle) and 5% were PHEVs (Plug-In Hybrid Electric Vehicle). Compared to the previous year, this share increased almost tripled, because in 2019, 3.5% of electric cars were registered.

Due to the increase in the number of electric vehicles, and the still limited access to charging stations (especially fast ones) for drivers traveling on the roads, the phenomenon of range anxiety, known in the literature, has emerged. The problem in their work was taken up by the authors [2] who decided to estimate energy consumption using neural networks. A similar topic also appeared in [3], where they analyzed how speed management affects range anxiety.

Energy consumption in electric vehicles appears as the topic of many publications and determines the range achieved. Various models have been created to determine energy consumption, allowing to predict energy consumption depending on many factors. In [4] a statistical model based on environmental conditions was presented. Its purpose is to determine the energy consumption of a vehicle using multiple linear regression. The authors in [5] showed an analytical model that used engine and drivetrain efficiency information. The publication [6] proposes three stages of modeling based on real driving profiles, simulated energy consumption, and driver behavior. Their purpose is to determine the primary energy consumption. The influence of individual factors on changes in the energy intensity of an electric vehicle also appears in the development of models for estimating energy consumption. In the work [7], in order to build the model, components were collected under real
conditions. The change of slope, the use of auxiliary devices or the type of roads and traffic conditions were taken into account. This allowed the construction of the ECR (Energy Consumption Rate) and the fitting of its components.

Energy consumption is also related to the traffic conditions on the road. Therefore, driving cycles are created, i.e. a speed profile, which has been supplemented with information on braking, acceleration, driving with constant speed, and idling periods. The most popular cycle is NEDC (New European Driving Cycle), WLTC (Worldwide Harmonized Light-Duty Vehicles Test Procedure), HWFET (Highway Fuel Economy Test Cycle), FTP (EPA Federal Test Procedure) etc. The cycles mentioned were used in [8-11] to test electric vehicles, e.g. over energy consumption.

For many areas, driving cycles have been created that better represent the conditions of the roads there. The authors of the paper [12] created a cycle for the Chinese city of Xi’an to determine energy consumption and emissions under the conditions prevailing on the roads there. In publication [13], the electric vehicle test drive cycle was created for the Dublin area. It was shown that it differs from the legislative cycles and reliably reflects the real road conditions. The paper [14] shows how the energy consumption changes when variable speeds are applied to a highway in Perth, Australia. The authors of [15] created a real driving cycle based on the road driving in Shanghai to determine energy consumption and economic benefits.

2. Analysis of factors affecting energy intensity

One of the basic factors analyzed in the study of the energy consumption of electric vehicles is the ambient temperature. It affects the battery life and, consequently, the possible range of the vehicle. Energy consumption studies are most often carried out by comparing various temperature values and are the subject of numerous publications. This is because batteries are cooled down at high temperatures and heated up at temperatures below zero.

In [16], the authors conducted simulation studies for 5 selected temperature values: −20°C, −10°C, 0°C, 25° C, 45°C, at which the vehicle moved. 25°C was indicated as the nominal temperature. The simulation was performed for the NEDC test cycle. While driving at temperatures: -20°C, -10°C and 0°C, the vehicle range decreased by respectively: 36.7%, 28.76% and 24.96%, compared to the nominal temperature. During this time, energy consumption increased by 58.02%, 40.40% and 33.31%, respectively. The inverse relationship was recorded at an ambient temperature of 45°C. Then the range of the vehicle increased slightly, by 2.02%, and consumption decreased by 1.93%.

In publication [17] examined energy consumption based on real driving conditions in the Dutch city of Nieuwegein. The temperature range from 0°C to 35°C was analyzed with steps of 5°C. Driving was carried out in calm, normal and aggressive driving and speeds of 30 km/h and 130 km/h. was shown that at lower speeds, the lowest energy consumption occurs at 20°C and the highest at 0°C. The difference in this case is about 0.04 kWh. At 130 km/h the consumption is lower the higher the ambient temperature is.

Research on the influence of temperature on vehicle range is directly related to the use of auxiliary devices, i.e. air conditioning and heater. They are used to maintain the optimal temperature inside the vehicle and the battery.

In [18], a study was carried out comparing vehicle energy consumption in four test cycles, ie: NEDC, WLTC (Worldwide Harmonized Light Vehicles Test Cycle), WMTC (Motorcycle emission Test Cycle), and MAC (Mobile Air Conditioning). In each of the cycles, the vehicle was operated at a temperature of 23-25°C and -7°C. Additionally, the measurement was carried out with both the HVAC (Heating Ventilation and Air-Conditioning) system turned on and off (battery heating at negative temperature and cooling at positive temperature). The results showed that with the auxiliary system switched off, energy consumption is higher at -7°C than at +23°C. The difference varies from 6% to 14% depending on the cycle. It was also shown that energy consumption increases from 11% to 17% when using cooling and from 52% to 94% when using heating.

The authors in [19] discussed the influence of temperature on energy consumption and the range of an electric vehicle based on the Nissan Leaf. The simulation was also presented in four driving cycles,
in the temperature range from -15°C to 20°C. It was shown that the range of the electric vehicle decreased from 150 to 85 km, i.e. by more than 40% at 0°C and to 60 km (by 60%) at -15°C. This is due to the influence of the cabin interior heating. On the other hand, the authors in [20] examined the annual variability of energy consumption during driving in the French city of Lille. The results of the analysis show that when the vehicle interior is heated, energy consumption increases by up to 33%. In summer, when cooling is used, the energy consumption increases to about 15%.

The authors of the paper [21] determined the energy consumption during heating at 18%, and at 14% during cooling. This analysis was based on the research of the Renault Zoe vehicle for daytime and nighttime journeys. On the other hand, in the work [22], a model was created to determine the energy consumption, the state of SOC or the influence of auxiliary devices. Popular driving cycles such as NEDC or WLTC were used to validate it. The results showed that using a heating system at -5°C can increase energy consumption by between 10% and 32%. For cabin interior cooling, energy consumption increases between 1% and 3% at an ambient temperature of 25°C and between 3% and 11% at an ambient temperature of 35°C. This is dependent on the cycle in which the vehicle is driven, but no actual cycle was used in the study.

The weather parameter that also affects the energy consumption of an electric vehicle is wind. This factor is the direct cause of the additional aerodynamic drag. In publication [23], the authors discussed in detail the influence of wind on energy consumption. For this purpose, they chose two routes: the first one was flat, with high exposure to wind, marked as LBR. The second was hilly and longer, marked as UBR, where wind gusts were much lower. At a wind speed of 18.5 km/h, energy consumption increased by 14% on the LBR route and by 5% on the UBR. At a wind speed of 50 km/h, the increase in energy consumption is already 31% and 15%, respectively. These results apply to free movement along the route.

Variable energy consumption also occurs with varying inclination. The energy intensity varies depending on whether the vehicle moves along the route as the altitude increases when ascending a hill or as the vehicle descends. Detailed research on this subject is presented by the authors in [24]. They carried out a study based on an analysis of the journeys of 492 electric vehicles over two years in Japan. Out of these, 68 cars were selected that traveled in the Aichi area. Twelve gradient ranges were extracted, from which a logarithmic model and a linear model were determined to predict energy consumption. According to the models, the higher the inclination increases the energy consumption. At the same time, the study showed that due to regenerative braking (energy recuperation), electric vehicles are more efficient on mountainous routes than conventional vehicles. In the work [25], a study of energy consumption with various road inclinations showed that a vehicle driving on a road with an inclination of 3% increases the specific energy consumption by 50%. When going downhill with a gradient of -3%, it reduces it by 80%. In contrast, in the work [26] the energy consumption of an electric vehicle was determined mathematically. A series of equations were used to determine how the energy consumption changes with a change in the angle of inclination. Based on these, general conclusions were made. It was determined that energy consumption increases with an increase in the angle of inclination and decreases with a decrease in the angle of inclination.

In addition to the inclination of the route, it is also important to take into account other information related to the route from the point of view of energy intensity, such as traffic conditions along the route, type of road, speed values, etc. In [25] it was shown that the road conditions under which a journey takes place can reduce or increase energy consumption. Attention was paid to the length of the route over which the trip takes place. If the trip is made on a road shorter than 4 kilometers, the energy consumption is higher than for a 16-kilometer route. When driving on a motorway, the difference can be as much as 29%. In urban traffic, reducing the average speed can increase consumption by 19% on a route of fewer than 4 kilometers and by 15% on a longer route. When the proportion of stopping time increases from 12%-18% to 24%-34%, the energy intensity of the vehicle increases by 20%.

The authors in [14] used research of electric vehicles (Nissan Leaf and Mitsubishi i-Miev) moving at speeds in the range of 60-110 km/h on a section of a motorway in Perth, Australia, with a step of 10 km/h. It was determined that energy consumption increased with increasing speed. Then the
authors repeated the measurements in four scenarios in which the load, battery charging protection and headwind changed. The increase in load contributed to an increase in energy consumption and a reduction in range for both vehicles. Also, the occurrence of a 20 km/h headwind increased the energy intensity of the vehicle.

In [27], the authors made predictions of energy consumption based on road conditions. To this end, they created models to determine how energy consumption develops as a function of driving speed, acceleration or route topography. They supported their analysis with graphs presenting energy consumption on the urban, suburban and motorway routes. The first two routes were driven by four drivers according to their driving style. On the motorway, measurements were taken at 90, 100 and 110 km/h. It can be seen that the energy consumption is different in each case. On each route, the vehicle was the most energy-consuming when it reached the maximum permitted speed.

The authors of the paper [28, 29] studied, among others, the influence of driving style on the energy consumption of an electric vehicle. From the results presented, it can be seen that the more aggressive the driving, the more energy-consuming the vehicle becomes. According to [29], the difference between aggressive and eco-driving at high speeds is relatively even 17%. The occurrence of speed oscillations can increase consumption. For 0.3 m/s it is 14% for eco-drivers, 37% for normal and 54% for aggressive ones.

In the paper [30], the authors investigated the influence of road conditions on the energy consumption of an electric vehicle. For this purpose, the AMESIM program was used. The results from the simulation were compared with real data obtained for the WLTC and RDE (Real Driving Emissions) cycle on a chassis dynamometer. Then, after establishing the consistency of the results, more than 100 driving cycles were used as input data for the program. The trips were grouped into congested, normal, uncongested and congested traffic conditions. The results showed that a change in traffic conditions causes a change in energy consumption. Changing conditions from congested to normal at low speeds reduces energy consumption by 15% and at high speeds increases it by 2%. Conversely, changing traffic conditions from normal to congested at low speeds reduces energy consumption by 6% at low speeds and 20% at high speeds. In addition, the authors determined that the use of traffic control measures, traffic calming measures, or roundabouts also changes energy consumption. Depending on the measure used, energy consumption decreases between 2% and 28%. This is due to the occurrence of regenerative braking.

In [31, 32], a vehicle-related factor was taken up as a part of research on energy consumption and vehicle range. The authors of [31] investigated, among others, the influence of load on energy consumption. The load was selected in the range from 50 to 250 kg with steps of 50 kg. It was shown that an increase in load causes an increase in the discharge of the vehicle battery. Energy consumption increases by up to 7% at the highest load compared to the lowest. At the same time, according to [32], the weight of the vehicle and the battery affects the range of the vehicle. The heavier the vehicle is, the less distance it can cover. It has been shown that the use of higher capacity batteries does not necessarily have a positive effect on energy consumption. This is due to the weight of the battery, which is much higher when using one with a higher capacity. The energy consumption per kilometer is then higher.

According to the authors of the papers [31, 33], attention should also be paid to factors such as SOC (State Of Charge) battery charge status or regenerative braking. According to [31], the state of charge of the battery at the start of the journey is not the most significant factor. The way to travel the route is more important. Regardless of whether the battery was 100% or 60% charged, the depth of discharge was the same. The authors in [33] showed that regenerative braking can improve energy transfer by over 40%, and range - even by almost 25%.

A summary of the energy consumption of the different factors is presented in Table 1. It includes the name of the most important factor, a diagram showing its value and the increase or decrease in energy consumption.
Table 1. Summary of energy consumption by the factors analysed.

| Type of factor                  | Value of factor | Energy consumption |
|---------------------------------|-----------------|--------------------|
| Negative temperatures           | ~6% -14%        |                    |
| High temperature                | ~2%             |                    |
| HVAC heating (in winter)        | ~52% -94%       |                    |
| HVAC cooling (in summer)        | ~11% -17%       |                    |
| Wind                            | ~5% -14%        |                    |
| Inclination                     | ~50%            |                    |
| Route length                    | ~15-29%         |                    |
| Traffic conditions (proportion of stopping time) | ~20% | |
| Load                            | ~7%             |                    |
| Driving style                   | ~17%            |                    |
The paper [34] uses data on Nissan Leaf journeys in Sydney. Based on this, an experimental design
was created, the results of which determine which factors have the greatest importance. It was shown
that among: topography, climate, road traffic and infrastructure, it is the first two factors that have the
greatest impact on energy consumption.

The authors [35] decided to determine the influence of driving conditions, driver aggressiveness
and the use of auxiliary devices on the energy vehicle energy consumption. It was shown that the
influence of auxiliary devices varies from 15% to 40% at a speed of 20 km/h. At higher speeds, this
range is reduced from 5% to 15%. Driving style has a different effect on energy consumption.
For aggressive drivers, it can be as much as 40% at low speeds (20 km/h) and 15% at higher
speeds (60 km/h).

The authors of the study [36] analysed the ECR index and the factors influencing its change. They
showed that energy consumption is higher in winter, as ECR increases by up to 34%. In addition,
according to the study, the vehicle range is lower when trips are made over short distances. It was also
shown that the effect of specific driving conditions on ECR is polynomial (e.g. initial battery charge
level) or quadratic (e.g. driving speed).

3. Conclusions
The factors affecting the range of an electric vehicle are a very extensive subject for research and
analysis. Hence the great interest of researchers in these issues, taking into account the variety of
variable parameters whose influence on energy consumption varies

It is apparent that weather conditions can have a significant impact on the energy consumption of a
vehicle. Negative temperatures can reduce it by up to 37%, while at a temperature of 40°C, it is
possible to extend the range by about 2%. A similar relationship applies to the occurrence of
headwinds. The greater the wind, the more energy a vehicle needs to overcome resistance to motion.

In addition, weather conditions are related to other factors, e.g. the use of auxiliary systems.
In studies, it has been shown that heating a vehicle is more energy intensive than cooling its interior.

The analysis of other factors, such as vehicle load, battery weight, and driver's driving style showed
variability in energy consumption. Both an increase in load and battery weight increase the energy
consumption of the battery. Aggressive drivers should also be aware of the reduced range. Sudden
acceleration and frequent acceleration of the vehicle have a negative effect, causing the battery to
discharge faster.

Furthermore, some of the authors decided to identify and evaluate the factors that influence energy
consumption on a comparative basis. By comparing several factors, they calculated which one has a
greater influence on a vehicle's energy consumption.

The energy consumption of a vehicle is related to many factors. To maximise the battery range,
many variables need to be taken into account that can reduce the range. An electric vehicle can’t run
only at temperatures close to 20°C, on a windless day, on a flat road, without passengers and during
smooth traffic hours. However, drivers, taking into account the different influences of the parameters
mentioned in this paper, among other things, plan their route to ensure its completion without
unloading the vehicle. This will avoid range anxiety and stress while driving.

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