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A REVIEW OF THE FACTORS AND INPUT PARAMETERS INFLUENCING THE RANGE OF AN EDISON ELECTRIC VEHICLE ACCORDING TO MEASUREMENTS

Key words: EV range, battery temperature, tyre condition, energy efficiency of the drive, acceleration, additional energy sources

Introduction

The increased global demand for electric vehicles (EVs) is due to an increase in the quality of life in cities. The EVs have almost zero carbon emissions (no exhaust emissions) and low noise in operation (Nanaki, 2021). The development of EVs was accelerated by the stricter tests of the Worldwide Harmonized Light Vehicle Test Procedure (WLTP).

However, the economic and environmental impact depends on the sources of electrical energy used to charge the EV batteries (Kucukoglu, Dewil & Cattrysse, 2021). In addition, environmental responsibility is often suppressed by the driver's increased fear (Franke, Rauh & Krems, 2016; Kavianipour et al., 2021; Miri, Fotouhi & Ewin, 2021) of the EV's range. The fear of limited EV range is called range anxiety. Increasing the battery capacity or the number of charging stations is not enough for drivers to overcome their fear (Kavianipour et al., 2021; Miri et al., 2021). It is reported in Ozatay et al. (2014), Hong, Park and Chang (2016) that accurate estimation of the remaining range can effectively alleviate the concerns of drivers. Range estimation of the EV is one function of a technology

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known as Energy Assistant (EA). The main function of EA is to inform drivers about the current range and how to avoid a critical situation while driving an EV.

It is known that battery capacity decreases over time due to an increase in internal resistance. The degradation of battery capacity causes significant problems with the efficiency and reliability of EVs (Vatanparvar & Faruque, 2017). Increasing or decreasing the range of the EV is directly related to energy consumption. Many factors can affect the energy consumption and range of an EV (Vatanparvar & Faruque, 2017; Xiong, 2020; Kucukoglu et al., 2021). Investigating these factors and parameters that could affect the range and energy consumption of an EV is the focus of this paper.

The information presented in this article can be used for the next development of the EA algorithm for EVs in further experimental work. The aim of this article is to review the parameters and input data based on measurements performed with a small EV under real driving and laboratory conditions. In the next part of the text, the basic technical parameters of the vehicle and the measuring device are presented. Sources of the input data are summarily presented in the last part.

TABLE 1. Factors influencing the EV energy consumption

I. Vehicle design and construction	Influence on driving resistance	Rolling resistance	Vehicle weight
			Tyre construction
		Air resistance	Aerodynamically clean vehicle shape and size
		Resistance from ascents	Vehicle weight
		Inertia resistance	Vehicle weight
	Inappropriate construction and structure of modules	Oversized total stored energy in the batteries	Weight of batteries
			Price of batteries
			Battery lifetime
			Space in the vehicle
		Incorrectly selected components	Recuperation system
			Insufficient performance
			Minimum compatibility within the functionality of the system
			Incompatibility with the operating environment of the electromechanical drive
II. Operational condition			Heavy urban traffic
			Road surface
			Chosen route
			Climatic conditions
III. Driver subjective influence			Driving style
			Preparation of the vehicle before driving
			Use of vehicle electricity for non-traction purposes
IV. Other energy sources			Recuperation
			Photovoltaic panels
			Other technical devices for extended range

Source: own work.

Factors influencing the energy consumption and range of EVs

In general, the energy balance expresses the ratio of the amount of energy input to the amount of energy output. It indicates the ratio of electrical energy received and stored in the batteries of the EV and the mechanical energy converted in the electric motor for traction purposes. The real use of energy is influenced by several factors. All factors which influence the energy consumption in EVs and range are presented in Table 1.

Factor I. Vehicle design and construction. The most significant negative design parameter is the vehicle weight, which can be influenced during the vehicle design (Chen & Crolla, 2007; Hrček, Medvecký & Bisták, 2017). Parts of an electric power train replace those of conventional vehicles, such as voluminous cylinder blocks, crankshaft, and transmission (Weiss, Cloos & Helmers, 2020). The weight of the vehicle is influenced by the size of the battery (Weiss et al., 2020; Xiong, 2020). The solution is a multifunctional and modular vehicle concept using today's advanced manufacturing technologies (Habek, Lavios & Krupah, 2020; Schmid, Tomek & Hanus, 2022), cutting-edge electronic systems, new construction materials, and miniaturization in the field of components for vehicles with unconventional power sources. The oversized total stored energy affects the size of the battery box, which subsequently affects the curb weight and price of the vehicle (Chang, Baek & Hong, 2014; Redelbach, Özdemir & Friedrich, 2014). The correct size of the battery can extend the range. If an EV is used, for example, to commute to work and the daily route does not exceed 50 km, then the total battery capacity may be 24 kWh. The EV is then lighter and has lower energy consumption (Münster, Schäffer, Kopp, Kopp & Friedrich, 2016). Nowadays, modular design is becoming a novel trend in helping to choose the appropriate size of the battery according to customer needs.

Factor II. Operational condition. The operational conditions can influence the driver's behaviour (Franke, Neumann, Buhler, Cocoron & Krems, 2012). For example, an intelligent traffic management system, such as a navigation system (Vatanparvar & Faruque, 2018), assists the driver in selecting the optimal route in heavy urban traffic. Next, the climatic conditions and the nature of the environment significantly affect the range of an EV. The range decreases at extremely low and high environmental temperatures (Lindgren & Lund, 2016; Vatanparvar & Faruque, 2018; Argue, 2021), and according to Vatanparvar and Faruque (2018) the optimal temperature for an EV is 21.5°C. Manufacturers attempt to limit this problem by using different cooling or heating systems for the batteries (Ji & Wang, 2013; Jaguemont, Boulon & Dubé, 2016; Geotab, 2021; MAHLE, 2021).

Factor III. Driver subjective influence. The driving style has a significant impact on the range of EVs. The drivers should adapt their driving habits to minimize unnecessary braking and acceleration, as well as other energy consuming modes. It is advantageous to use coasting, gliding or recuperation to convert kinetic energy into electrical energy during deceleration and braking. One way to influence the driving style is to use a system with a defined driving style. Before driving, the driver can reduce energy consumption by preparing the vehicle appropriately for driving, such as by removing any unnecessary load, checking the technical condition of the vehicle (pressure in the tyres, preparing an itinerary of the charging stations, and so on). While driving, the driver can reduce the energy consumption by rational use of the vehicle's electrical equipment, such as air conditioning, heating and various comfort features.

Factor IV. Additional energy sources to extend the range. Based on the design capabilities of the vehicle and its operating environment, the driver can assess the possibility of using additional energy sources to extend the range. For example, the effectiveness of brake energy recovery (Hu et al., 2020), the use of photovoltaic panels (Dwibedi, Jayaprakash, Siva & Gopinath, 2020; Li, Yu & Feng, 2020) directly on the vehicle, the method, and the type of charging, etc. Concerning additional energy sources for the operation of the vehicle, it is important to note that an EV has zero CO_2 emission if it uses energy produced with zero CO_2 emissions during its lifetime (De Pinto et al., 2016). Solar energy affords a simple and elegant method, by using solar radiation to make energy available to EVs (Li et al., 2020).

Experimental Edison EV

A small Edison EV is a research student project designed at the University of Žilina. The Edison EV serves to gain new information and experience in the development, construction, and operation of EVs and their infrastructure. The Edison EV project was carried out from conceptual design to a functional prototype. The technology used allows various settings, diagnostics, chassis and drive optimization, programming of control units, and monitoring of components for subsequent processing of the acquired data. Other uses of the vehicle include testing the EV infrastructure components, chargers, charging modes, vehicle motion monitoring, servicing, and diagnostics.

The Edison EV is a small urban two--seater EV (Fig. 1). The load-bearing part of the vehicle is a space-tube frame integrated into a single-space body. The drive is provided by an electric motor with a gearbox mounted in front of the rear axle, along with a programmable frequency converter to control it.

The technical specifications of the Edison EV are presented in Table 2. The electric drive of the vehicle consists of a three-phase asynchronous motor with a short armature. It is a maintenance-free and highly over--loadable electric motor originally designed for axle mounting similar to the smart EV. The Curtis frequency converter includes the control software. The two LiFeYPO4 traction batteries have 25 cells, 300 Ah capacity, and 80 V traction voltage, along with battery management system (BMS) control unit and balancers. For the Edison EV it is possible

FIGURE 1. Design of the Edison EV, carried out at the University of Žilina (image credit: the authors)

TABLE 2. Technical specification of the Edison EV

Parameter	Value
Vehicle dimension (length / width / height) [mm]	3 100 / 1 600 / 1 700
Wheelbase (front / rear) [mm]	2130 / 1320
Tyre dimension [-]	165 / 65 R14
Consumption energy per 100 km [kWh]	11.0–14.7
Combined range of Edison EV [km]	150–200
Battery capacity / Charging time [$kWh \cdot h^{-1}$]	24 / 15
Curb weight [kg]	1 050
Weight per axle (front / rear) [kg]	520 / 530
Total weight [kg]	1300
Battery weight [kg]	250
Power of the electric motor (maximum / nominal) [kW]	30 / 15
Maximal speed [$km \cdot h^{-1}$]	90

Source: own work.

to use the 16 A/83 V on-board charger, and its parameters define the charging time. A BMS is an electronic system that controls the flow of energy while charging the batteries (Cieslik et al., 2021). The BMS monitors their state, recalculates the data and displays it. The BMS also manages the distribution of energy during charging and recuperation back to the batteries.

Measurement of selected factors and input parameters for the Edison EV

The measurements were carried out under real-life driving conditions. The dynamometer, a MAHA MSR 1050 Roller, was used for the laboratory test work (Commission Regulation (EC) 692/2008, Commission Regulation (EC) 2017/1151; Pavlovič, Ciuffo, Fontaras, Valverde & Marotta, 2018; Li, Wang, Wu, Tian & Tian, 2021). It is possible to perform complex field research activities concerning the use of unconventional vehicle drive systems. The laboratory is involved in working with the organizations that form part of the E-Mobility platform. The laboratory is accredited, making it possible to perform measurements for legislative changes. Comprehensive testing of conventional vehicles with internal combustion engines, EVs, and unconventional vehicles is performed. A full description and the technical data for the testing are accessible on the web page: maha-france.fr.

On-board computers with an internal combustion engine after refuelling, and for EVs after charging the batteries, measure the fuel consumption (l per 100 km) or electricity consumption (kWh per 100 km). The range is continuously updated according to the amount of fuel in the tank or the remaining charge in the batteries.

The function of an EA not only determines the range of a vehicle, calculated as the difference between energy received and

TABLE 3. Source of input data for parameter factors, Part I

Climatic conditions	Monitored parameter	Source of input data	
		Installed in the EV	Laboratory measurement
Environment	Temperature	Sensor	–
Batteries	Temperature	BMS	–
	Discharge characteristic for different temperatures	–	✓
	State of charge	BMS and frequency converter	–
Technical condition of components	Monitored parameter	Source of input data	
		Installed in the EV	Laboratory measurement
Tyres	Design of tyres and effect on rolling resistance	–	✓
	Pressure in tyre and effect on rolling resistance	–	
Batteries	Number of charging cycles	BMS	–
	Battery lifetime	–	–
Mechanical drive components	Energy transmission efficiency	–	✓
Electrical drive components	Temperature	Sensors	–

Source: own work.

TABLE 4. Source of input data for parameter factors, Part II

Driver subjective influence	Monitored parameter	Source of input data	
		Installed in the EV	Laboratory measurement
Route selection	GPS routes (3D maps)	✓	–
	Pressure in tyre and effect on rolling resistance	–	–
Driving style	Energy consumption converted into periodic intervals	–	✓
Dynamic driving parameters	Vehicle speed, lateral and longitudinal acceleration	Sensors	–
Vehicle drive	Drive efficiency map	–	✓
Energy sources	Monitored parameter	Source of input data	
		Installed in the EV	Laboratory measurement
Batteries	Energy	BMS	–
Brake recuperation	Energy	BMS	–
Photovoltaic panels	Energy	BMS	–
Range extender	Energy	BMS	–
Charging station	GPS (3D maps)	–	–

Source: own work.

consumed. The EA helps, controls, manages, updates, and communicates with the driver. The EA informs the driver about the risk of discharging the batteries, before reaching a charging station, and suggests precautions to ensure that the driver stops at the nearest charger. The EA performs tasks before and during the entire drive to the charging station. An investigation of the factor parameters is summarized in Tables 3 and 4.

Results and discussion

Operating an EV at low temperatures has the effect of increasing energy consumption, which means a shorter range. "Self-heating" the batteries in our experimental Edison EV with a total stored energy of 24 kWh reduces the range by 7–10 km. The EA could correct the range value before driving based on battery temperature data and the discharge characteristic for different EA temperatures. It would limit the energy from recuperation, limiting the maximum power output of the electric motor. If the Edison EV allowed fast charging, EA would limit the maximum charging current, all with the sole purpose of protecting undercooled batteries from high currents. Low temperatures reduce the performance of the batteries due to increased internal resistance and can also damage them. However, the increased resistance accelerates the heating of the accumulators. The Edison EV has LiFeYPO4 batteries with a capacity of 300 Ah and a traction voltage of 80 V. Low temperatures reduce the performance of the batteries while the energy consumption for heating shortens the range.

The Edison EV was parked for several days at sub-zero temperatures while at the same time consumption measurements were performed. The comparison with the latest consumption confirmed that by gradual warming of the batteries, electricity consumption decreases. At the beginning of the measurements, the consumption was 18.5 kWh per 100 km, and then after warming was up to 14.9 kWh per 100 km. For a better comparison, three cases were selected where the vehicle needed the same 10.4 kW of power from its batteries. In the first case, the batteries were cold at start-up, and then in the second case the cells were heated because the batteries were charged for 10 km of driving. In the first and second cases, the ambient temperature was 0°C. In the third case, the ambient temperature was 18°C. At low temperatures the increased internal resistance caused a significant voltage drop, i.e., the EV in winter at the same power consumed more current from the batteries.

The Edison EV does not feature a battery heating system. Producers attempt to heat the batteries, such as by a battery heating system or by the heat emitted by an electric motor, which is an efficient solution because it does not use the energy of the batteries (Jaguemont et al., 2016). We analysed the possibilities of using heat-to-heat batteries. Temperatures of the Edison electric motor and converter were recorded for eight cycles lasting 1.5 h. The ambient temperature was 0°C. The EV drove 14 km, the temperature of the electric motor was 74°C and the converter temperature was 46°C at the end of the run.

The degree of influence of the technical parameters of the tyres on the energy balance of an EV on the range is crucial for the development of an EA. The monitoring of electricity consumption was carried out under different driving and load modes by the Edison EV in a stable laboratory environment, with the elimination of the subjective influence of the driver.

Selected technical parameters of vehicle tyres were divided according to the type, into summer and winter sets of tyres, and in terms of operating conditions as tyres inflated to the prescribed pressure and to an underinflated pressure. While the driver is not influencing the construction of the tyre, he is responsible for taking care of the condition of the tyres. Underinflated tyres negatively affect not only the energy consumption and range, but also the safety of the vehicle.

The Edison EV with tyres set to the prescribed pressure travelled a distance of 147 m during deceleration from an initial speed of 30 $km \cdot h^{-1}$ to a stop. For low-pressure tyres, the distance averaged 118 m. The deceleration difference between low and prescribed tyre pressure was 29 m. The deceleration from a speed of 50 $km \cdot h^{-1}$ was an average difference of 59 m.

The WLTP test was performed in laboratory conditions. Under defined measurement conditions the methodology allows the simulation of realistic driving characteristics for the vehicle. Despite the speed limit of the Edison measuring vehicle being up to 90 $km \cdot h^{-1}$, three of the four-speed phases were implemented on the measuring device, each phase having several braking, stopping, and acceleration modes according to the track profile. The results demonstrated that if the vehicle travelled an average distance of 10.77 km, the electricity consumption per 100 km was on average 16.795 kWh per 100 km for underinflated tyres and 16.08 kWh per 100 km for correctly-inflated tyres. This means that underinflated tyres have a 4.26% higher consumption. In real-life conditions, consumption can be even higher because of the subjective influence on the driver, natural conditions, and various other situations.

An important parameter in monitoring the electricity consumption of an EV is the energy efficiency of energy transfer from batteries to the drive wheels. Therefore, the aim was to determine the drive mode in the area with the best efficiency to thus optimize the driving style. The vision was that the EA would inform the driver based on the drive efficiency map and real-time data, such as speed and battery performance. A decisive part of Edison EV driving takes place in a mode that corresponds to the map of the area with lower efficiency.

The Edison EV, like most EVs, has a single-speed planetary gearbox. Due to this, the movement of the vehicle in the higher efficiency area is limited. The gear ratio of the gearbox is designed so that the entire drive provides the required dynamic parameters. The advantage of an EV is that it allows kinetic energy to be recovered during braking, which is highly convenient in urban traffic. On the other hand, the most effective option is to use deceleration. Based on the analysis and measurement of the acceleration, at higher acceleration, the energy consumption is identical to that at low acceleration. There was the possibility to increase the efficiency of the Edison EV by developing a special driving style.

This driving style assumed that a longer period of favourable energy efficiency of the idle wheels would compensate for higher acceleration. The driving style was designed for urban transport, which means that the speed was usually 50 $km \cdot h^{-1}$. The up-down cycle used acceleration from 45 to 55 $km \cdot h^{-1}$ and maintained a deceleration mode from 55 to 45 $km \cdot h^{-1}$. Although there was a difference between stable driving and this driving style, the drive would operate more efficiently during the up-down cycle.

The vehicle must overcome higher driving resistances, but energy consumption will be zero if it is coasting. This is an advantage of an EV over a conventionally powered vehicle with an internal combustion engine. The up-down driving cycle was compared with the stable driving cycle. The distance and time were identical in both cycles, and the distance was 2.4 km. The energy consumption of the batteries was 0.33 kWh for both the up-down driving cycle and the stable driving cycle. The situation was different in the field of energy, which was measured on the tyres.

The up-down cycle was more energy intensive than stable driving, and measurements confirmed this finding. The average energy required to complete the up-down cycle was 0.21 kWh, while at stable speed the energy required was 0.17 kWh. It shows that the vehicle needed more energy to overcome the rolling resistance during the up-down cycle. The total energy consumption was identical for both driving cycles. The efficiency of the drive system was 62% with the up-down cycle, more than a 10% difference compared to a stable driving cycle. The energy consumed by the batteries was identical in both cases. Using the up-down driving style was not useful in normal traffic because it did not extend the range of the vehicle.

The number of planned stops, traffic density, and charging station network specified in the selected route influenced the EV range as well. The usable input value would be more accurate if intelligent traffic management data was available. The EA would be able to correct the range value based on a database of available digital maps.

Driving style is a purely subjective indicator of the influence of the driver. From the point of view of energy consumption, it is more advantageous to slow down by coasting rather than braking when entering a village or at an intersection. For maximum use of the kinetic energy at the right time in order to reduce speed or come to a complete stop if the traffic situation requires it. The route profile and traffic situation, the weight and speed of the vehicle, the recuperation effect, and the database of measured data can comprise several main input parameters for the decision-making process of the EA system, which can communicate with the driver by visual or audio signals. The aim is to provide the driver with information on how to achieve the lowest electricity consumption.

Acceleration is another subjective parameter of driving style, as it is more energy intensive than a smooth ride. By a suitable combination of the time required to travel a certain distance and by mapping the overall efficiency of the electric drive, it is possible to optimize the acceleration of the motor. Using the map of the overall efficiency of the drive, the EA can decide and inform the driver whether he is in the most efficient mode at the beginning of the acceleration – in the highest efficiency mode. Suppose a driver has to accelerate from an intersection. The system uses GPS position to evaluate the final speed during acceleration to 50 $km \cdot h^{-1}$. Based on the drive efficiency map, the system can inform the driver by a graphical display on the instrument panel which acceleration mode should be selected, fast or slow. The system can help the driver achieve the optimal mode.

An analysis of three types of acceleration from 0 to 50 $km \cdot h^{-1}$ was performed. The distance travelled was 200 m under all three accelerations. The first acceleration lasted 27 s, the second acceleration was 22 s, and the third acceleration was 19 s. Five measurements were performed for each acceleration test. The average energy consumption was 0.069 kWh for the first acceleration, 0.072 kWh for the second acceleration, and 0.072 kWh for the third acceleration. The measurements indicated that the Edison EV had almost the same energy consumption for slow and fast accelerations. Although the vehicle overcomes higher driving resistances at fast acceleration, this compensates for the overall higher efficiency of the drive at higher loads. During deceleration, it is more efficient to use deceleration and then recovery. The disadvantage of driving is the longer deceleration time, which that is compensated by faster acceleration. Energy consumption is not affected due to the efficiency of the Edison EV.

Updating the number of kilometres travelled requires continuous monitoring of electricity consumption. The monitoring has three primary indicators: operational (under which conditions the vehicle is driven), the subjective influence of the driver (driving style), the use of other equipment (vehicle lighting, heating) or the use of energy sources (energy recovery, photovoltaic panels). The EA can update the number of kilometres travelled according to the current value of the energy stored in the traction batteries (SOC) and the monitoring of the energy consumption mode. This is not a final value, because if the EA works with data on the current route of the EV, the value continues to be recalculated. The relationship between the discharge characteristics of the traction batteries used and the capacity drop was measured in the areas of 80% SOC and 20% SOC, with a direct effect on the range of the Edison EV.

In conclusion, the EV driver does not directly support the control and protection of the electrical components. The continuing healthy condition of all the electrical components is required for the correct EA function. The EA must control all the appliances in the vehicle, including the ability to switch off selected systems to allow the driver to adapt the driving style and control the conversion of electrical energy into traction energy. It is not directly controlled by their condition. The protection of electrical components is the task of the EA, such as at low and high battery temperatures, the electric motor, and the converter. What is important is the communication between the EA and the driver, such as through the communication panel. Using audio-visual communication, the EA can help the driver to optimize their driving style and minimize energy consumption. Modern components in the EV can collect a wide range of parameters, and therefore it is possible to change the set parameters and to monitor their impact on energy consumption. The data measured under real conditions can be verified on a cylinder dynamometer.

Conclusions

According to the conducted surveys, 60–65% of customers interested in buying an EV are afraid of the short range and the lack of availability of charging options. The Energy Assistant (EA) is one of the tools to eliminate the stress and concerns of customers by assisting and realistically evaluating the current drive or the conditions of the required range. It assists even before driving, when it evaluates the effect of temperature on battery discharge, during driving and in the event of a crisis situation, when the expected driving distance is shorter than the distance to the nearest charging station. The EA needs data for their decision-making. The data is the subject of the research description. Research is still ongoing and the data is constantly being supplemented. Supplementing the data improves the EA's ability to more accurately evaluate the range of the electric car. The research can be further used for autonomous vehicles, as the autonomous driving system can be configured in such a way that the EV operates in an optimal mode for energy consumption.

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Summary

A review of the factors and input parameters influencing the range of an Edison electric vehicle according to measurements. Research and development help to improve the reliability of an EVs range, battery capacity, and trouble-free charging (or service). These factors affect the consumers' interest in EVs. The quality of EV use can be supported by a modern technology called Energy Assistant (EA). The task of EA is to inform the driver about the current range, the necessity to recharge the batteries, and so on to avoid a critical situation. The main aim of this article was to investigate factors and input parameters for the proposal of an EA. The Edison EV, designed at the University of Žilina, was used for experimental work under real conditions and in an accredited lab with MAHA equipment.