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AVERAGE SPEED OPTIMIZATION OF ELECTRIC VEHICLES WITH CHARGING STOPS

Summary. The article discusses the issue of driving an EV over long distances when additional charging of the high-voltage battery is required. The optimization of driving speed between charges is considered. If the speed is too low, the electric car will spend too much time covering the distance between charges, and if the speed is too high, the charging time will increase significantly. In the article, the data on the charge consumption from the driving speed of eight EVs are considered and reduced to a single denominator. Both serial EVs and EVs manufactured in Ukraine in single versions were included in the review. Based on these data, the optimal speed of movement was calculated. It was found that these speeds largely depend on the average power of the next charging session on the way. An empirical

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formula for calculating the optimal driving speed with correction factors that depend on the design of the electric vehicle was obtained. It was also found that with large values of the preparatory and final time of the charging session, the average driving speed can increase by 40%.
Keywords: EV average speed, EV energy consumption, average charging session

1. INTRODUCTION

Legislative initiatives stimulate the growth of the number of electric vehicles in many countries. For example, in New Zealand, the renewal of public policy regarding electric vehicles has significantly increased the interest of the population in its purchase [1]. The total number of EVs in 2016 was slightly more than a million worldwide, and then in 2022, it came to about 18 million. Ukraine also has a number of laws and regulations that encourage buyers of electric vehicles. These are the preferential import of electric cars from abroad, preferential registration, reduction of the price of a mandatory insurance policy, a separate electricity tariff for public charging stations, and tax benefits for manufacturers of charging stations and electric buses [2]. Currently, the total number of electric cars in Ukraine is slightly more than 100,000.

Increasing the capacity of electric vehicle batteries allows for long trips. Most electric car models after 2020 have a range of at least 200 km on a single charge, according to the EPA cycle. For example, Audi e-tron GT can travel 425 km on one charge, BMW iX – 630 km, Cadillac Lyriq – 494 km, Citroën ë-C4 – 350 km, Dacia Spring Electric – 230 km, Fiat 600e – 406 km, Tata Nexon.ev – 312 km. The increase in the number of charging stations, the decrease in the cost of batteries, and the significant increase in the efficiency of electronic systems also actively contribute to long-distance trips.

Long trips are characterized by the fact that the distance traveled is greater than the mileage of a particular electric vehicle on a single charge. Thus, the time spent on long trips by electric car is divided into two components:

1. movement;
2. battery charging process:
    a. Search for a station in the parking lot;
    b. Connecting and disconnecting the cable, initializing the charging station;
    c. Charging process.

The average speed of covering the distance between two points is calculated as the weighted harmonic average of all speeds, including the speed equal to zero, during the charging process. When driving an electric car on long-distance trips within technical and legal limits, it is necessary to reduce both time components to achieve the maximum average speed.

2. MAIN PART

The significant growth of the charging infrastructure [3], which, for example, in Ukraine does not stop even despite the war [4-7], allows us to assume that the distance between charging stations at each stage of the route is less than the mileage of a specific model of an electric car on one charge. Accordingly, we will not take into account the capacity limitations of electric vehicle batteries in the calculations. This removes the restriction on movement speed due to the lack of capacity.

At the same time, the calculations will be carried out only within the limits of speeds allowed by the traffic rules of Ukraine for the movement of vehicles outside populated areas. To assess the charger's performance, the possibility of increasing the power of chargers beyond the limits set by manufacturers for specific brands of electric vehicles will be assumed in the calculations. This assumption is true given the fact that manufacturers are constantly increasing the capacity of electric vehicle charging ports [8].

Electricity consumption by electric vehicles is traditionally calculated in kilowatt-hours per 100 kilometers (kW/100km), and light electric vehicle meters in Wh/km. Some manufacturers, such as Nissan, may display consumption in kilometers per kilowatt-hour (km/kWh). This indicator shows how many kilometers an electric car can travel on one kilowatt-hour. To calculate the instantaneous consumption, it is more convenient to divide the current power drawn from the battery by the speed of movement.

Costs during uniform movement are divided into two components: electricity consumption by traction electric motors and electricity consumption by onboard systems. During research on a self-converted ZAZ Tavria Elektro, it was found that at speeds of less than 10 km/h, the power consumed by the traction motors does not exceed 300 watt. At the same time, about 1 kilowatt can be consumed for the electric vehicle's own needs, such as headlights, electric cabin heating, air conditioning, and power steering. This consumption practically does not depend on the speed of movement.

When the electric vehicle is parked, the instantaneous power consumption is infinite, because, according to the formula, the current power must be divided by the speed, which in this case will be equal to zero. With the start of movement, costs fall to some minimum value. But with the further increase in speed, the resistance to movement and, accordingly, costs begin to increase again. Therefore, the dependence of the instantaneous power consumption on the speed of the electric vehicle has a lower extremum.

When traveling at a steady speed, in addition to powering its systems, the electric car will expend energy to overcome losses. It can be classified by speed as follows:

1. Linear dependences on the speed of movement: rolling resistance of the wheels, the force of resistance to the movement of an electric vehicle on an inclined section of the road.
2. Nonlinear dependence on the speed of movement of the third degree: aerodynamic resistance.
3. Nonlinear dependences on the speed of the fourth stage: losses in the electric motor, losses in the power units of the electric motor controllers, losses in the wiring and battery cells.

   Losses in an electric motor depend on rotations and load. There is an extremum of minimal losses.

   Losses in wiring and battery cells are linear depending on the power consumed. However, the power required for movement is related to the speed by a fourth-degree dependence.

Accordingly, the power required for the movement of an electric vehicle is related to the speed of movement by a fourth-degree nonlinear dependence. The power required to move at a certain constant speed is directly proportional to the consumption of electricity. This allows us to approximate the experimental power plots with polynomials of the fourth order.

To analyze the consumption of electricity by an electric vehicle, it is necessary to know either the power or the instantaneous consumption of electricity at different speeds. In various literary sources, authors provide information in different forms. We will list the most characteristic ones, in which it was additionally indicated that the measurements were carried out without significant fluctuations in the topography of the road and comfortable weather conditions - without moisture, gusty wind, and low temperatures. Since the temperature of the outside air significantly affects the mileage of an electric vehicle [9], measurements at temperatures below +15°C were not taken into account.

1. Tesla Model S [10]: a graph of the mileage of an electric car with different battery capacities on a single charge is given. The 85kWh version has a range of 130 miles at 5 mph (miles/hour), 420 miles at 28 mph, 300 miles at 55 mph and 140 miles at 100 mph.
2. Renault Kangoo Electrcite [11]: given average consumption at speeds from 5 to 80 km/h. Measurements were carried out in different conditions and summarized in a general graph.
3. Renault Zoe [12, 14]: data on the maximum mileage of an electric vehicle on one charge at different speeds are given. The tests were carried out on the same road section with the same weather conditions. It is shown that the mileage decreases with an increase in speed, which is subject to an exponential law. It is indicated that the maximum theoretical range of an electric vehicle with a 22-kilowatt-hour battery can exceed 1000 km.
4. Nissan Leaf [13]: graphs of the maximum mileage of an electric vehicle on a single charge at different speeds are given. Additional options are calculated if the cabin is heated not from the main traction battery. It is indicated that turning on the cabin heater with a power of 5 kW at a speed of 20 km/h can reduce the mileage by a factor of 3.
5. Daewoo Lanos Elektro EV (independent conversion) [14]: measured power consumption in the range of 40 to 90 km/h in 10 km/h increments.
6. Peugeot Partner EV [14]: measured electricity consumption in the range from 50 to 80 km/h when driving on the Ukrainian highway M05 (international E95).
7. The ZAZ Slavuta Elektro (independent conversion) [15]: measurements were made in the widest range - from 20 to 120 km/h. In the power part, a serial asynchronous electric motor with a special type of winding was used.
8. Volkswagen E-up! [16]: At the economic driving competition, it was determined that the costs at speeds of 15 and 38 km/h are the same and reach 7 kW/100km, the extremum (minimum) is at a speed of 25 km/h and reaches 6 kW/100km. Consumption at a speed of 50 km/h – 8 kW/100km, at 90 km/h – 13 kW/100km, and at 110 km/h – 16 kW/100km. The maximum consumption was at a speed of 130 km/h – 21 kW/100km.

In the following section, the above numbering of electric vehicles will be used.

Based on the given data, the function was interpolated $C\{V\}$ a polynomial of the fourth order. That is, it can be presented in the form:

$$\mathrm{C}\{V\} = a_4 \cdot V^4 + a_3 \cdot V^3 + a_2 \cdot V^2 + a_1 \cdot V + a_0 \quad (1)$$

as well V – instantaneous speed of the electric vehicle, km/h;
a – interpolation coefficients.

In some electric cars, the coefficient at the term of the fourth order was equal to zero since practical measurements were not carried out in the extreme region, that is, below 30 km/h.

The electricity consumption in Fig.1 is given in watt-hours per kilometer.

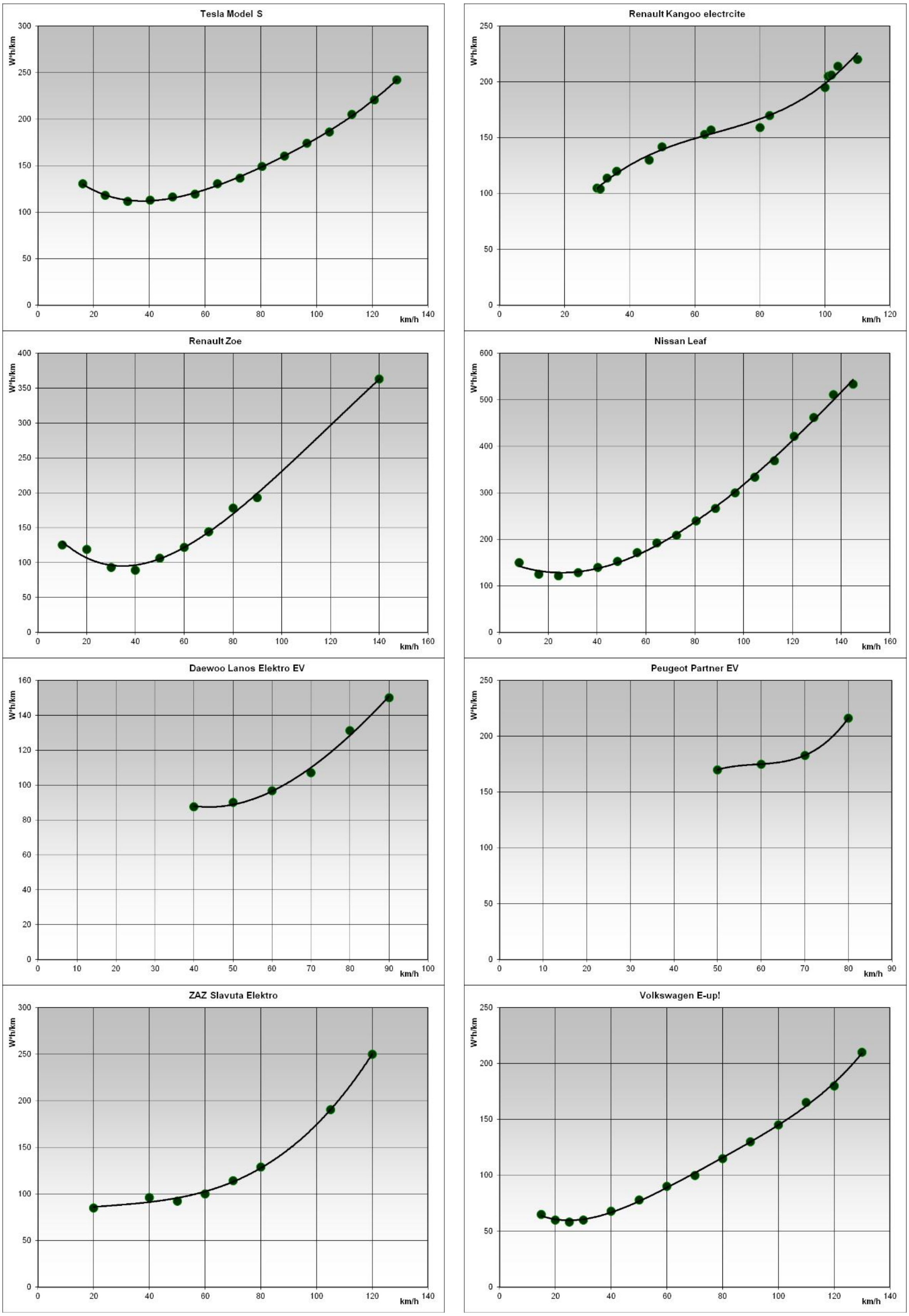

Fig. 1. Electricity consumption from the speed with the uniform movement

To simplify the calculation of the charging time of an electric car, we will use the average charging power. It is calculated as:

$$P_{av} = \frac{\int_0^{T_{ch}} \max_{P}(P_{st}; P\{t\})\, dt}{T_{ch}}, \tag{2}$$

where T_{ch} – total charging time, hours;
P_{st} – the maximum capacity of the charging station, watt;
$P\{t\}$ – is the instantaneous power function requested by the BMS module of the electric vehicle, watt.

The average speed of an electric car is equal to the ratio of the distance traveled to the total time spent. This time consists of components:

$$T_{all} = T_{dr} + n \cdot (T_{ch} + T_{pf}) = \frac{L}{V} + \frac{L \cdot C\{V\}}{P_{av}} + \sum_n T_{pf}, \tag{3}$$

where T_{dr} – electric vehicle travel time between charging stations, hours;
T_{pf} – start and switch-off operation time of the charging session, hours;
n – the number of charging stops on the way;
L – total distance covered, km;
V – speed of movement, km/h;
$C\{V\}$ – electricity consumption at the corresponding speed to formula (1), Wh/km.

In this study, a simplification was made that every charging station has a free port. However, the start and switch-off operation time of the charging session is not equal to zero and consists of:

- time to overcome the access sections from the route to the charging station in both directions;
- connecting and then disconnecting the charging cable;
- starting and stopping the charging station.

Start and switch-off operation time in the range of 5-20 minutes has quite a strong influence on the average speed of movement. Its influence increases in direct proportion when the number of charging stops increases. It is more convenient to evaluate the influence of the start and switch-off operation time depending on the time of movement and direct charging.

Figure 2 shows that with long distances between charges (more than 250-300 km), the influence of the start and switch-off operation times is minimal. In the worst case, it is no more than 10%. The average start and switch-off operation time is within 4-8 minutes. Accordingly, the share of its influence on the speed of overcoming the entire distance does not exceed 4%.

The influence of the start and switch-off operation time significantly increases with short distances between charging stations. At a distance of 50 km and the mean value T_{pf} 8 minutes its effect is 12-16% depending on the charging time. In the worst cases, the coefficient of start and switch-off operation time K can reach 0.6.

The equation (3) does not include the distance between charging stations. It is taken into account by adding start and switch-off operation time. In further research, we will assume that the distance between charging stations is more than 300 km, and the start and switch-off operation time is less than 6 minutes. In this case, the factor K can be neglected.

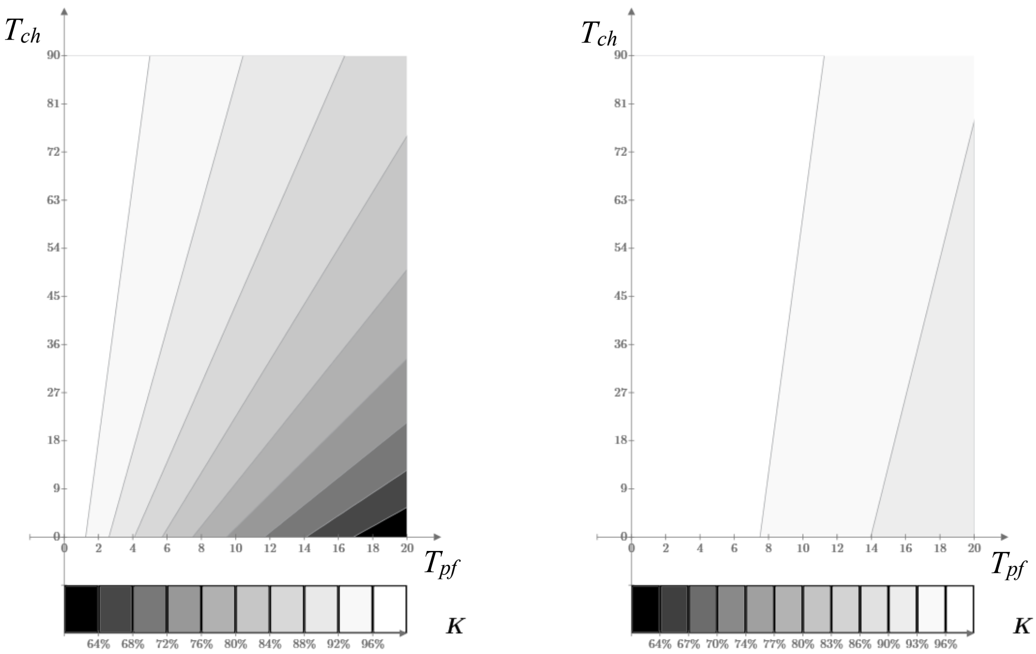

Fig. 2. Coefficient of start and switch-off operation time when moving 30 and 180 minutes, respectively (T_{ch} – total charging time, minutes; T_{pf} – start and switch-off operation time of the charging session, minutes)

Currently, in Ukraine, AC charging stations with a power of up to 22 kW (in limited cases, 43 kW) and DC 50 kW (in some cases, 250 kW) are widely available. Not all electric vehicles described in this study have the ability to charge in the entire range of capacities indicated. Therefore, for large capacities for some brands of electric cars, the further calculation will be purely theoretical. The speed of movement along the lower limit will depend on the available experimental data. The upper speed limit of the electric car will be limited by the traffic rules of Ukraine at the level of 130 km/h.

There is an extreme of the average speed of movement, because at high speeds the charging time increases significantly. Conversely, if the speed of movement on the distance is too slow, the time to overcome it increases significantly.

The average speed of movement over long distances with several stops for charging is equal to L/T_{all}. By substituting equations (1) and (3) into the average speed formula, we get the average speed function depending on the speed of movement over the distance and the average power of the charging session. We find the extremum of this function by the method of finding the zero value of the derivative function related to the speed of movement.

Analyzing the derivative, it was found that the interpolation of the optimal speed of any of the electric vehicles from the power of the charging session is possible by a polynomial function of the third order. The extremum was sought by the graphical method. The results of the calculations are low-scattered, which is shown in Figure 3. The scatter range of optimal speeds for various models of electric vehicles reaches 20-30 km/h. All eight electric vehicles fall into this corridor between the blue and red lines.

We brought the road test conditions to driving on a flat surface, at almost the same temperatures without rain and other precipitation. The difference between the tests was only in the aerodynamics of the electric car bodies and the efficiency of their internal systems.

This difference creates a small difference between electric cars in the optimal speed of movement depending on the average power of the next charging session.

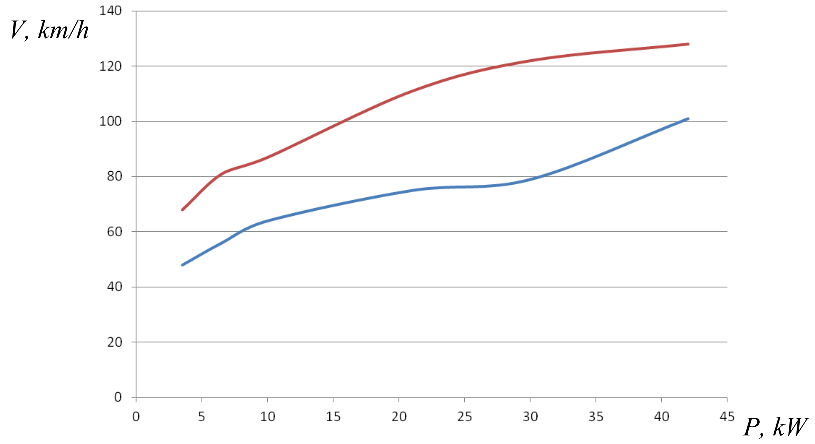

Fig. 3. Limits of the optimal speed of an electric vehicle depending on the average power of the charging session (blue - low-efficiency electric vehicles; red - most efficient electric vehicles)

Thus, the optimal speed of movement of any electric vehicle can be calculated by the formula:

$$V = (1{,}3 \cdot 10^{-3} + \delta_3) \cdot P_{av}^3 - (0{,}11 + \delta_2) \cdot P_{av}^2 + (4 + \delta_1) \cdot P_{av} + 46 + \delta_0, \qquad (4)$$

where δ - correction factors characterizing the aerodynamic features and efficiency of the power plant of a certain model of an electric vehicle.

Each of the correction factors correlates with individual performance indicators. For example, δ_3 characterizes the aerodynamics of the body, and δ_0 – the total efficiency of the power plant and consumption of auxiliary systems. Table 1 shows the values of the coefficients δ for electric vehicles that were studied.

Tab. 1

Optimum speed correction factors for average charging session power from 3.5 to 40 kW

Model electric car	Correction factors			
	$\delta_3 \cdot 10^{-4}$	$\delta_2 \cdot 10^{-3}$	δ_1	δ_0
Tesla Model S	0	19	1,04	-1,5
Renault Kangoo electrcite *	19	107	1,46	6
Renault Zoe	-12	-85	-1,43	-3
Nissan Leaf	-5	-37	-0,76	-8
Daewoo Lanos Electric EV *	17	112	1,73	4
Peugeot Partner EV *	-1	-38	-2,26	13
ZAZ Slavuta Elektro	-15	-94	-1,75	9,5
Volkswagen E-up!	3	62	2,73	-14

** – power limits up to 30 kW.*

If you move at a higher speed than the speed calculated by formula (4), the total speed of overcoming the entire route decreases due to the charging time. Accordingly, there is a minimum power of the charging session, at which the speed limit will be regulated exclusively by the rules of the road. In Ukraine, the maximum permitted speed is limited to 130 km/h [17]. Not all of the electric vehicles listed in Table 1 have the technical ability to move at this speed. Therefore, Table 2 shows only some of them. It is this power of the charging session, together with a road speed of 130 km/h, that provides the maximum average speed.

Tab. 2

Minimum power of a charging session for driving between charges at a speed of 130 km/h

Model electric car	The power of the charging session P_{of}, kW
Tesla Model S	46
Renault Zoe	54
Nissan Leaf	94
ZAZ Slavuta Elektro	91
Volkswagen E-up!	43

If the power of the charging session is equal to or greater than that given in Table 2, then when overcoming the distance between charges, the driver will not limit the speed for the sake of economy. The data are given without taking into account the coefficient of start and switch-off operation time and limitations of the battery capacity.

3. CONCLUSIONS

Most researchers study rerouting [18-21] or charging queue interaction [22, 23] to optimize EV traffic. We draw conclusions from a more practical option, where an EV travels a considerable distance along the road under current infrastructure conditions. Our conclusions are based only on practical measurements of electricity consumption by different models of electric vehicles.

There is an extremum of electric vehicle speed between charging stations, at which the average speed of covering the entire distance becomes maximum. The EVs average speed on long trips depends on the power of the charger, the efficiency of the electric car, and the start and switch-off operation time.

If the start and switch-off operation time is not taken into account, then the average speed of the electric car is not affected by the distance between the charging stations.

In the worst cases, but those that still make sense for further travel, the average speed decreases to:

- 2-3 times - due to the power of the charging station;
- 40% – with large values of start and switch-off operation time;
- 30-40 km/h - due to various electric vehicle designs.

To drive an electric vehicle at a speed of 90 km/h, it must have a charger capacity of at least 12 kW. And for movement at a speed of 120 km/h – at least 31 kW. At the same time, the average speed of overcoming the entire distance will be an average of 35 km/h and 50 km/h, respectively.

A charging session power of less than 10 kWh is impractical for long-distance travel. This is due to the fact that in this case the average speed of the electric vehicle will be below 40 km/h.

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