

Article

Operational Aspects of Electric Vehicles from Car-Sharing Systems

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Abstract: The article was dedicated to the topic of energy consumption of driving cars equipped with an electric motor. Due to the emerging demands for the excessive use of energy by vehicles (including car-sharing system vehicles), the authors carried out research to determine factors that affect the energy consumption. Due to the occurrence of a research gap related to the lack of reliable scientific information regarding real electricity consumption by vehicles used in car-sharing systems, the authors attempted to determine these values based on the proposed research experiment. The purpose of the research was to identify factors that increase energy consumption while driving in the case of car-sharing systems and developing recommendations for users of car-sharing systems and system operators in relation to energy consumption. Based on data received from car-sharing system operators and to their demands that users move cars uneconomically and use too much energy, the authors performed a scientific experiment based on Hartley's plan. The authors made journeys with electric cars from car-sharing (measurements) in order to compare real consumption with data obtained from operators. As a result, the authors developed a list of factors that negatively affect the energy consumption of electric vehicles from car-sharing systems. As conclusion, a number of recommendations were developed for car-sharing system operators on how to manage their systems to reduce excessive energy consumption in electric vehicles.

Keywords: electric vehicles; energy consumption; car-sharing systems; electric car-sharing systems; e-car-sharing; shared mobility; transport; transportation engineering; civil engineering; urban transport systems

1. Introduction

Currently, one of the main trends aimed at improving the condition of the automotive in accordance with the assumptions of sustainable transport development is the use of vehicles with alternative drives. That trend is especially directed towards the use of electric vehicles. In reference to this, there are more and more electric vehicles that belong to individual owners or that are part of a car-sharing system fleet. The number of electric vehicles on the world's roads is rising fast.

In 2018, the global electric car fleet exceeded 5.1 million, up 2 million from the previous year and almost doubling the number of new electric car sales [1]. It is predicted that in 2030 global sales of electric vehicles will reach 23 million units [1]. Such results are satisfactory for ecology enthusiasts or vehicle manufacturers. However, on the other hand, they cause many fears related to the probability of

a situation when there is a problem of insufficient energy to power such a large number of vehicles [2,3]. Or there may occur problems in regards to the recycling of batteries from electric vehicles.

Due to comments relating to the “dirty side” of energy acquisition, there are a lot of demands for the proper use of energy and its use in motor vehicles [4]. Hence, all actions to shape new habits in the field of sustainable mobility in society are created. That is why now—at the beginning of the path of electro-mobility development—it is important to educate the public on how to move electric vehicles. Excellent tools to educate and create new habits related to e-mobility and eco-driving are car-sharing systems [5,6].

The increase of car-sharing services in cities is observed year by year all over the world. The increasing popularity of car-sharing services using electric cars among society has led to a growing interest of scientists in this type of subject. According to that fact many of scientific research was carried out. There are also a lot of scientific articles published in the topics related to the selection of a fleet of electric vehicles to use in electric car-sharing systems [7], vehicle relocation due to the need to charge their batteries [7], the design of smart car return policies [8], optimal placement of charging stations and optimal charging issues [9,10], aspects related to depreciation costs of vehicles and chargers [9], electric car-sharing business models [10], life cycle assessments analysis in electric car-sharing management [11,12], optimal charging issues [13], or modeling and optimal planning in the case of traffic engineering [14]. In the case of car-sharing systems, no literature related to factors affecting energy consumption in vehicles has been identified.

Therefore, the literature review was extended to the general subject of electric vehicles. In terms of the impact of factors on energy consumption in electric vehicles, scientific research has been carried out, including, for example, by the UK center of excellence in low-carbon technologies and Canex fuel cells [15,16]. However, the tests were conducted on special lanes that were supposed to simulate various driving cycles, such as high speed, city route, hill routes, and route routes with a total length of 11.8 km [16]. The results of the research are, however, treated as preliminary and unfortunately are not consistent with vehicle journeys from car-sharing systems because they assume the presence of one type of driver. Subsequent authors carried out simulations of journeys in various types of conditions, but they did not consider real changing urban conditions and problems, for example, charging vehicles by an independent service center as in the case of cars from car-sharing systems [17,18]. Other authors have constructed various types of models related to energy consumption in electric vehicles. Among others, Li et al. [19] identified six factors affecting energy consumption and constructed a binary model to conduct an empirical experiment in Sydney focusing on topography, infrastructure, movement, and climate. However, the verified binary model was not easy to transfer to urban areas other than Sydney due to contextual specificity and excessive simplification compared to the microscopic model with more parameters [20,21].

Based on research and analysis of worldwide expertise in electric vehicles, Hu et al. [16] determined that the factors causing energy consumption in electric vehicles include the following:

- external factors related mainly to the state of the infrastructure, availability of the infrastructure, climate, weather, and other factors that are beyond the control of users;
- indirect factors, which include for example appropriate route and vehicle selection;
- internal factors, related to the driver behavior, as well as parameters of used vehicle.

Due to the fact that research on energy consumption was strongly focused on issues related to battery performance and the use of classic vehicles—not considering the specifics of car-sharing systems—the authors decided to fill the research gap by analyzing energy consumption in vehicles from car-sharing systems. The studies proposed by the authors focus on aspects of operational and technical aspects of vehicle use. In addition, they raise the aspect related to the education of users and recommendations for operators in the use of this type of vehicles in the systems. It is also worth mentioning that the need to conduct research in this direction arose from the side of car-sharing

operators who noticed a too high energy consumption compared to the technical specifications of the vehicles purchased for their fleet. That is why they asked to perform detailed analyses in this area.

Due to problems reported by car-sharing system operators with the use of the electric vehicle fleet, the authors dedicated their research to operational aspects affecting energy consumption in car-sharing cars and mainly address it to the business and systems operators. Based on the data received from car-sharing system operators (and their suggestions about the occurrence of irregularities) and their own scientific research carried out using electric vehicles from car-sharing systems, the authors determined factors that affect the energy vehicles consumption in the context of car-sharing systems.

The purpose of the research was to identify factors that increase energy consumption during driving in the case of car-sharing systems. Based on the conducted research and prepared research experiment, the authors also developed recommendations that may have a positive effect on reducing energy consumption. The results of the research may be a kind of support for car-sharing operators, car-sharing users, and everyone who would like to drive her/his electric car in a 'eco-friendlier' way.

2. Car-Sharing and Electric Car-Sharing Systems—Main Issues

Car-sharing is one of the modern, sustainable mobility forms. These kinds of systems include services that are based on the principles of short-term rental for vehicles. The idea of car-sharing is to limit the number of vehicles in cities and to reduce society's need to own a car [22].

Initially, the systems were based on the possibility of renting a vehicle and returning it in the exact same place (round-trip system) [8,9]. Subsequently, the rules evaded the possibility of leaving the vehicle in different places accepted by the operator (based system) [23,24]. Finally, the option of freely renting and returning cars within the area of functioning of a given system operator has been introduced (free-floating system) [25,26]. Currently, the most commonly used form of car-sharing is the free-floating model.

The first car-sharing system was established on the market in 1948 [27]. However, the main development of car-sharing systems began after 2006 [28]. In 2008, in Europe, car-sharing was created by automotive potentates like the Daimler or BMW concerns [29]. Due to the high interest in systems in 2009, there were already 14 operators offering car-sharing services on the market [29]. In the following years, systems gained popularity. In 2006–2014, they existed in countries such as Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, the Netherlands, Norway, Portugal, Russia, Spain, Sweden, Switzerland, Turkey, and the United Kingdom [30]. At that time, Europe represented 46% of the entire car-sharing industry in the world—in October 2016, car-sharing operated on all continents, except Antarctica [30]. The years 2017 and 2018 brought more crowds of users interested in car-sharing [31,32]. Detailed data on the increase in the number of vehicles and users of car-sharing systems in Europe are presented in Figure 1. Forecasts indicate that in 2020 there will be over 16 million registered users of car-sharing systems in Europe [28].

Significant progress in the field of sustainable development policy and directing it towards electro-mobility has led to a growing interest in expanding the fleets of car-sharing operators' vehicles with electric cars. The results show that electric car-sharing systems operate in 29 European countries. The development of e-car-sharing systems in Europe from 2008 to 2018 is presented in Figure 2.

Due to the growing development of electric car-sharing services, the system's operators began to report problems with their functioning. One of the problems is too much energy consumption by users of the system. According to the predictions, that kind of systems will develop very quickly. In the future, that development can cause the situation of insufficient number of charging stations in operators' systems. Because of that fact, the authors found that it is important to make the research, to meet the factors that can cause too much energy consumption in car-sharing systems.

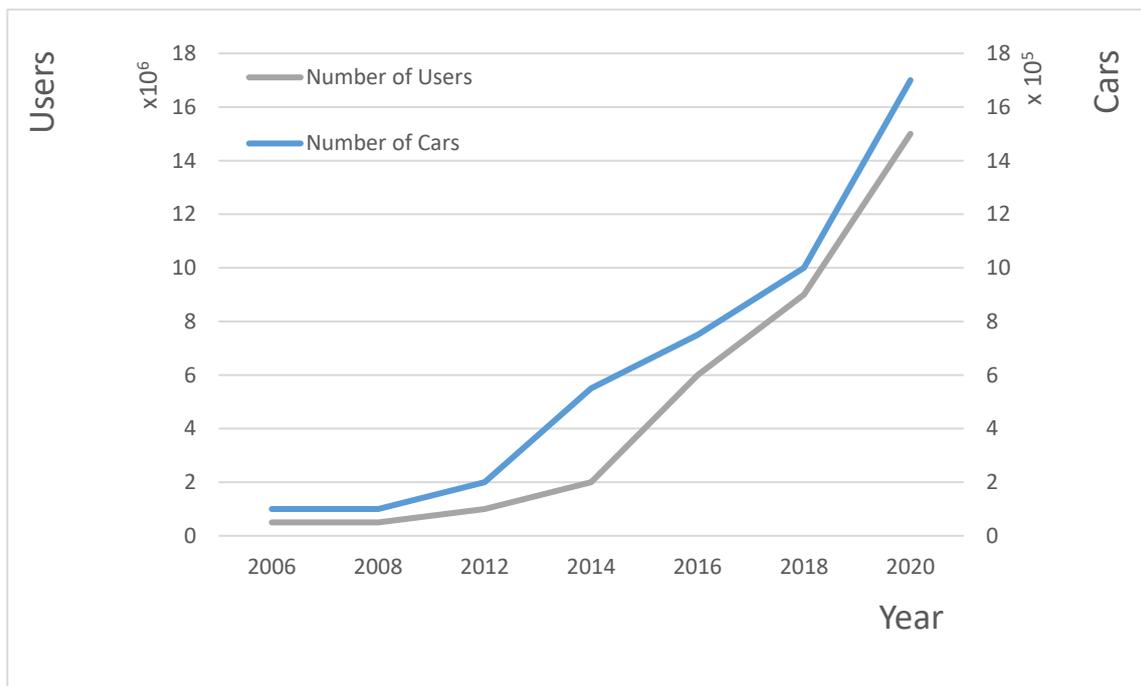


Figure 1. Development of car-sharing systems in Europe in the case of car-sharing cars and registered users. Source: author's own collaboration based on [28,31].

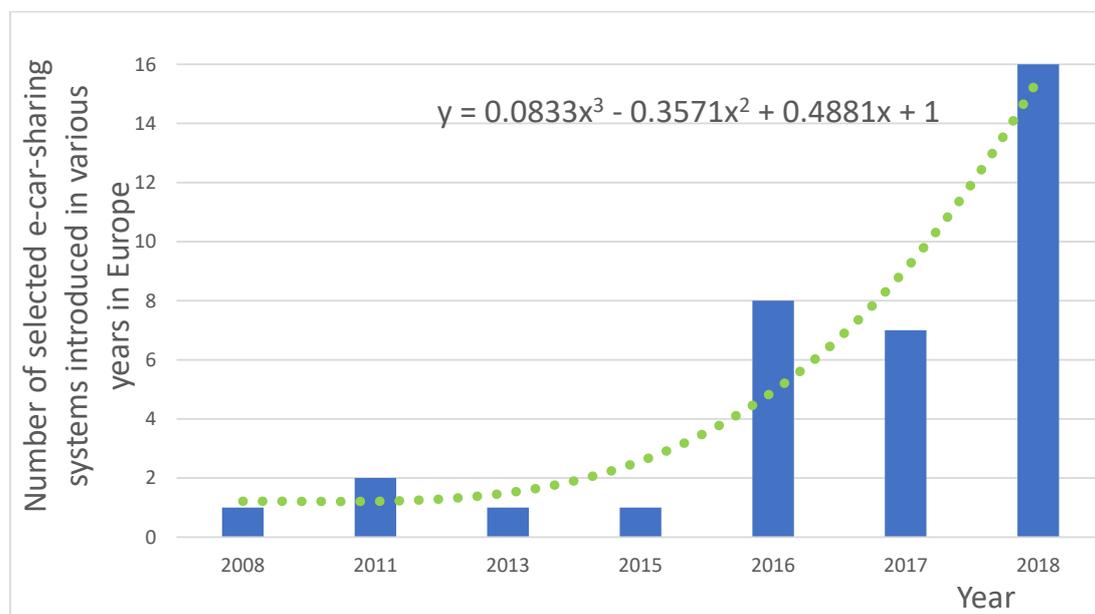


Figure 2. Development of electric car-sharing systems in Europe from 2008 to 2018. Source: author's own collaboration based on car-sharing operator's data [33–60].

3. Research Experiment

3.1. Purpose and Description of the Experiment

Due to the occurrence of a research gap related to the lack of reliable scientific information regarding the real consumption of electricity by vehicles used in car-sharing systems, the authors attempted to determine these values based on the proposed author's research experiment. The purpose of this experiment was to demonstrate the impact of selected operational parameters on the vehicle's electricity consumption from the point of view of vehicles used in car-sharing systems. Based on a

literature review, experience with electric vehicles, and postulates from car-sharing system operators, a plan for this experiment was developed.

Below is the theoretical part related to performing the experiment, followed by a detailed research plan.

The selection of the correct and proper plan of a research experiment is one of the most important decisions that must be made when starting experimental research. At least two basic premises influence the right choice [61]:

- information about the examined object, i.e., type and its properties;
- definition the purpose of the research: cognitive, utilitarian or both.

Experimental studies and calculations were made according to a statistically determined poly-selective experiment plan. This is one of the most common experimental plans for conducting experiments in technology. The development of the plan consists in determining the dependence of input values, their location relative to the base point—central, zero. There are two types of Hartley's plan types depending on their structure: based on a hypercubula or hypercube. The experimental plans developed for the three input factors are based on the hypercube for which the coefficient $\alpha = 1$. For plans based on the hypercubula, $\alpha = 1.732$ [62–64]. The experiment plan for three input factors is presented in Table 1.

Table 1. The experiment plan for three input factors [62].

Sample No.	Input Factors on the Standard Scale		
	x1	x2	x3
1	-1	-1	1
2	1	-1	-1
3	-1	1	-1
4	1	1	1
5	$-\alpha$	0	0
6	α	0	0
7	0	$-\alpha$	0
8	0	α	0
9	0	0	$-\alpha$
10	0	0	α
11	0	0	0

In Table 1, the values 0,1, α specify the maximum variability of a given factor, where 0 = base value, α (for the hypercube plan $\alpha = 1$) the maximum value of the factor variability. In the created plan of the experiment, the mathematical model is a second-degree polynomial whose general formula [63] is (1):

$$y = b_0 + \sum b_k(xk) + \sum b_{kk}(xk)^2 + \sum b_k(xk)(xj) \quad (1)$$

where:

y —result factor;

xk, xj —input parameters;

b_0, b_k, b_{kk}, b_{kj} —regression coefficients.

Based on the analysis of the significance of b_i coefficients carried out using the Student's t test, the coefficients deemed to be insignificant were rejected at a significance level of 0.05.

Based on the above Hartley's plan, a detailed research plan for an electric car was proposed. The detailed plan is presented in the next subsection.

3.2. Details for the Author's Research Experiment on Electric Vehicles from Car-Sharing Systems and Used Methods

The detailed author's research plan based on research of the electric vehicle from the car-sharing system is shown in the next six steps.

1. The research used the vehicle most often used in car-sharing systems [65]. That car is characterized by the following parameters [66]:
 - Maximum speed—135 (km/h);
 - Battery capacity—41.0 (kWh);
 - Engine power—109 (HP);
 - Electric motor torque—220 (Nm).

The example of the electric vehicle from a car-sharing system is shown in Figure 3.

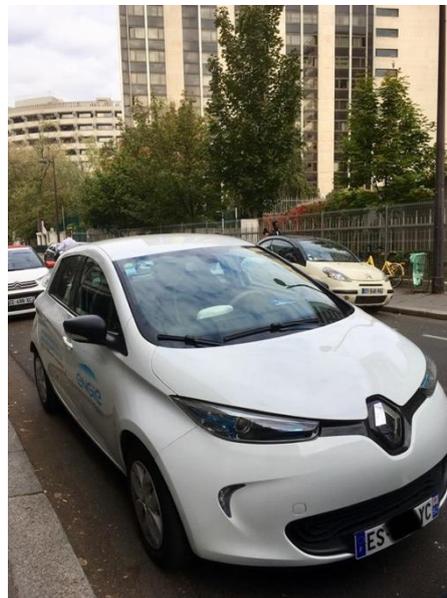


Figure 3. Example of an electric vehicle from a car-sharing fleet used for the experiment. Source: author's own collaboration.

2. Based on the literature review [65,67] three main operating parameters relating to the electric vehicles were selected. They were defined as input factors controlled on a real scale as
 - Travel time—(min);
 - Distance—(km);
 - Outside temperature—(°C).
3. The experiment plan was created based on the d-optimal poly-selective experiment plan, which was supplemented with input values on a real scale. The values of the factors' values were determined on the basis of data received from car-sharing system operators. These data determined:
 - The length of travel routes most frequently covered by users of car-sharing systems;
 - Outside temperature at the time of travel by car-sharing users;
 - The times users covered certain travel routes.

- Measurements were made successively (journeys reflecting the conditions of using car-sharing vehicles) in accordance with the experiment plan presented in Table 2. Each journey was repeated five times;

Table 2. The list of experiment value factors on a standardized scale and a real scale. Source: author's own collaboration.

Sample No.	Input Factors on a Standardized Scale			Real Scale Input Factors		
	x1	x2	x3	x1 Time (min)	x2 Distance (km)	x3 Temperature (°C)
1	-1	-1	1	30	2	25
2	1	-1	-1	10	2	15
3	-1	1	-1	30	4	15
4	1	1	1	10	4	25
5	$-\alpha$	0	0	30	3	20
6	α	0	0	10	3	20
7	0	$-\alpha$	0	20	2	20
8	0	α	0	20	4	20
9	0	0	$-\alpha$	20	3	15
10	0	0	α	20	3	25
11	0	0	0	20	3	20

- After each journey, parameter readings were recorded and stored in the vehicle's on-board computer (Figure 4);



Figure 4. Data from the on-board computer. Source: author's own collaboration.

- The results of the research based on the presented experiment plan allowed to determine the dependencies of operational factors as a function of wear.

Based on the conducted tests and their results, the values of electricity consumption were obtained depending on the input parameters given in the Hartley's plan presented in the last chapter. The values were saved in the form of mathematical equations. Table 2 presents the plan of the experiment supplemented with input values on a real scale.

4. Results

As a result of experimental research, changes in the energy consumption value of the vehicle as the function of selected input parameters were determined. The values were read from the on-board computer after the distance traveled. Figure 4 shows the view of data from the on-board computer.

Table 3 presents the results of the conducted experimental studies.

Table 3. Results of conducted experiment. Source: author's own collaboration.

Test No.	Energy Consumption, kWh/100 km	Standard Deviation
1	13.6	0.5
2	36.3	2.0
3	21.5	1.0
4	13.6	0.8
5	12.5	0.5
6	33.2	2.0
7	22.7	1.0
8	27.2	1.4
9	30.2	1.8
10	12.1	0.7
11	27.2	1.5

Based on the data from the Table 3 and formula for three input factors (2) presented below, the authors developed formulas and graphs determine the dependence of energy consumption in the context of the journey time, distance, and outside temperature. Detailed values of electricity consumption are presented in Figures 5–16.

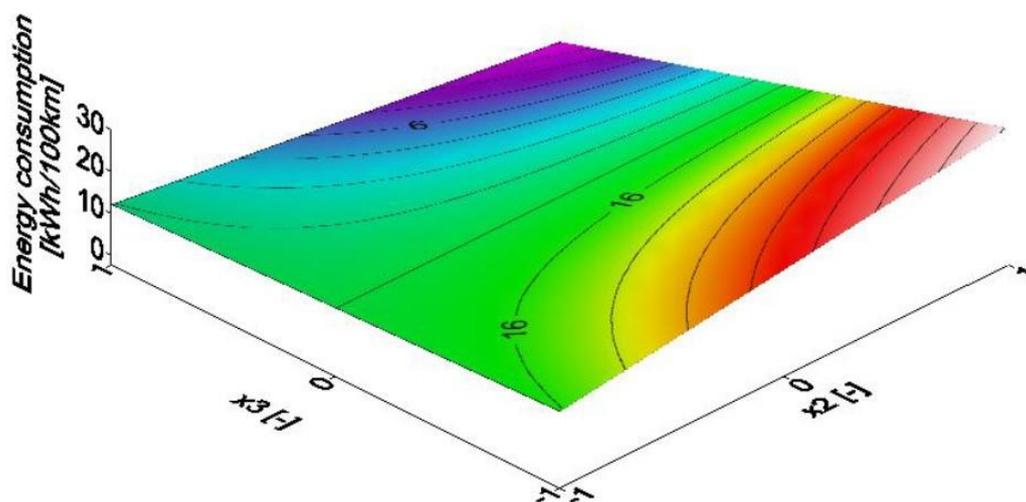
$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \quad (2)$$

where:

y —result factor;

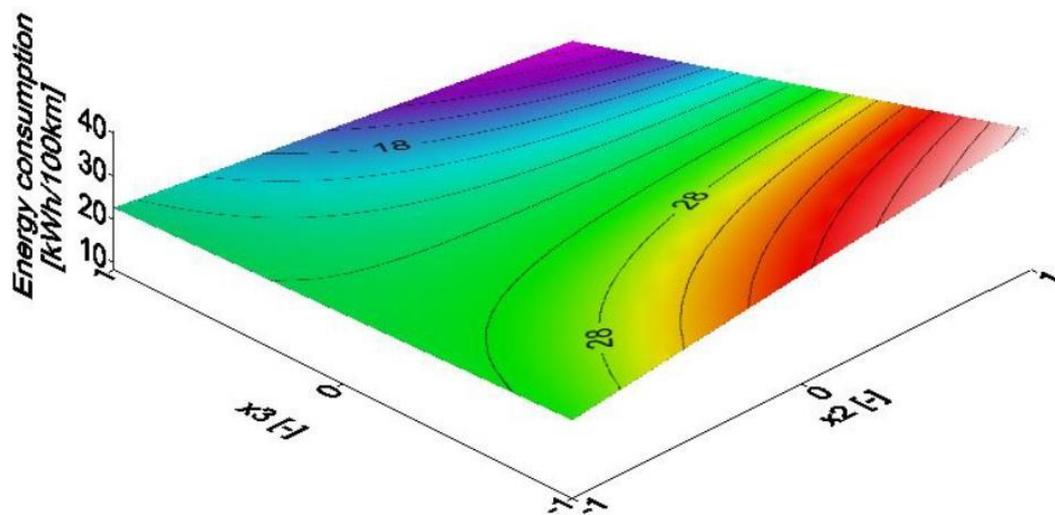
x_1, x_2, x_3 —input parameters;

$b_0, b_1, b_2, b_3, b_{11}, b_{22}, b_{33}, b_{13}, b_{12}, b_{23}$ —egression coefficients.



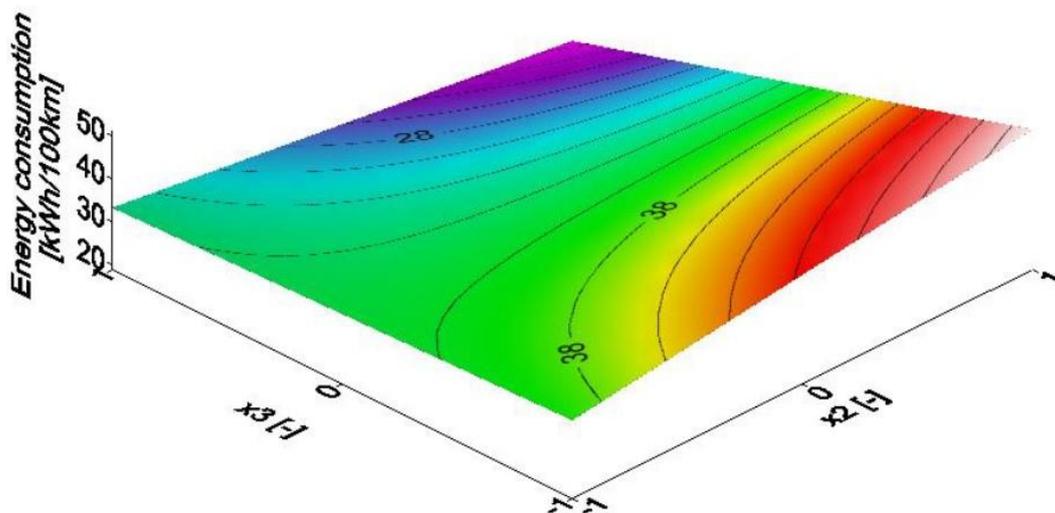
$$y(x_2, x_3) = 14 - 7.2x_2x_3 - 9.1x_3$$

Figure 5. The value of electricity consumption depending on the temperature and distance, with a travel time of 30 min. Source: author's own collaboration.



$$y(x_2, x_3) = 24 - 7.2x_2x_3 - 9.1x_3$$

Figure 6. The value of electricity consumption depending on the temperature and distance, with a travel time of 20 min. Source: author's own collaboration.



$$y(x_2, x_3) = 35.2 - 7.2x_2x_3 - 9.1x_3$$

Figure 7. The value of electricity consumption depending on the temperature and distance, with a travel time of 10 min. Source: author's own collaboration.

Based on Figures 5–7, it can be concluded that the lowest energy consumption of the vehicle during the tests was obtained at journeys at 25 °C and a distance of 4 km. An important parameter affecting consumption is the time taken to travel.

Figure 8 shows the impact of travel time on the value of vehicle energy consumption when covering a distance of $x_1 = 0$ (3 km), at a temperature of $x_3 = 0$ (20 °C).

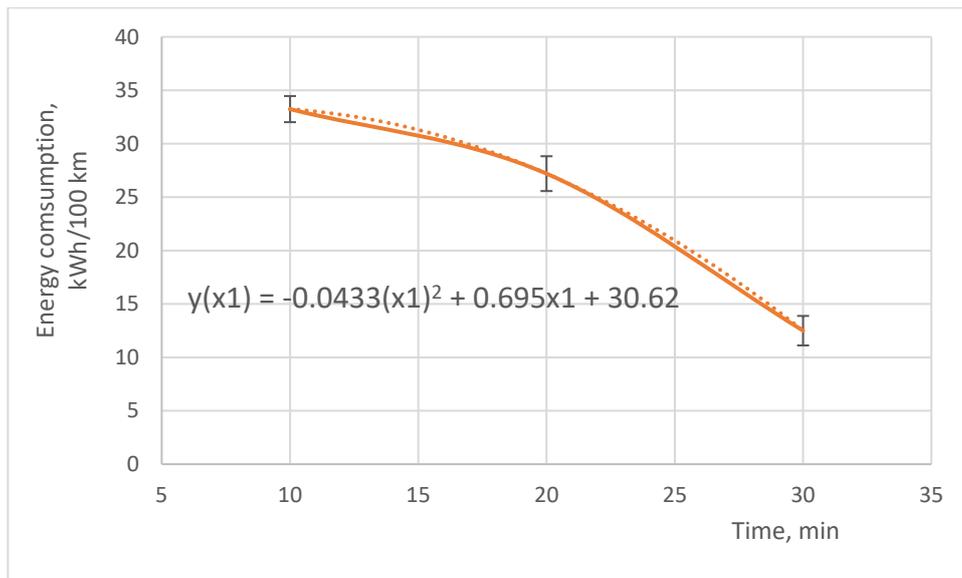


Figure 8. Dependence of energy consumption on the travel time for a distance of 3 km and a temperature of 20 °C. Source: author’s own collaboration.

The value of consumption decreases with the increase of travel time. By covering the distance in three times longer, we reduce the value of energy consumption more than twice. This is caused by using a different driving style. The route was defeated in a more smooth and safe way. In this way, rapid acceleration and braking of the vehicle were avoided.

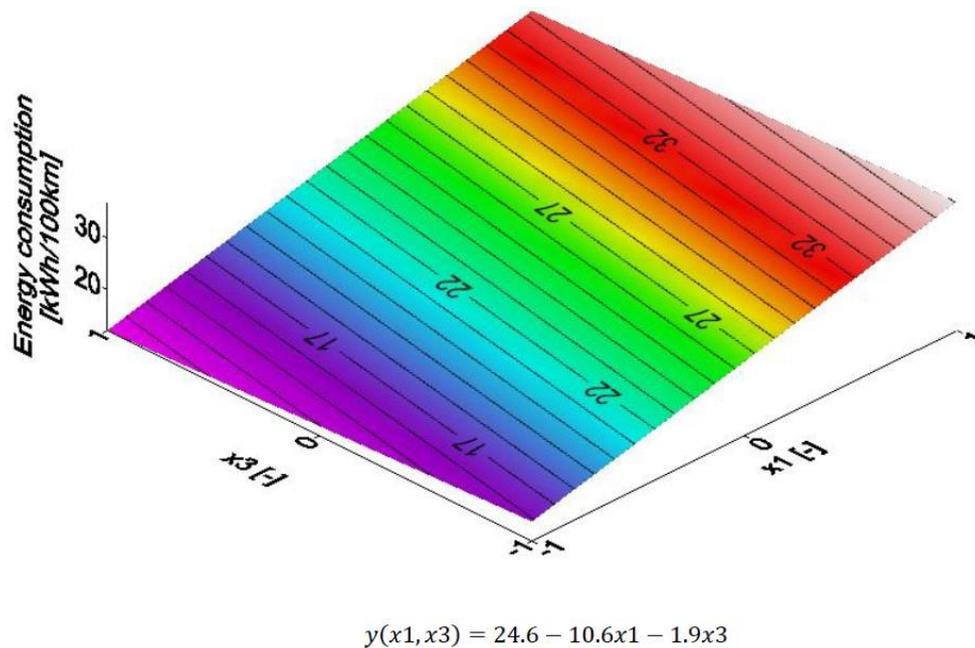
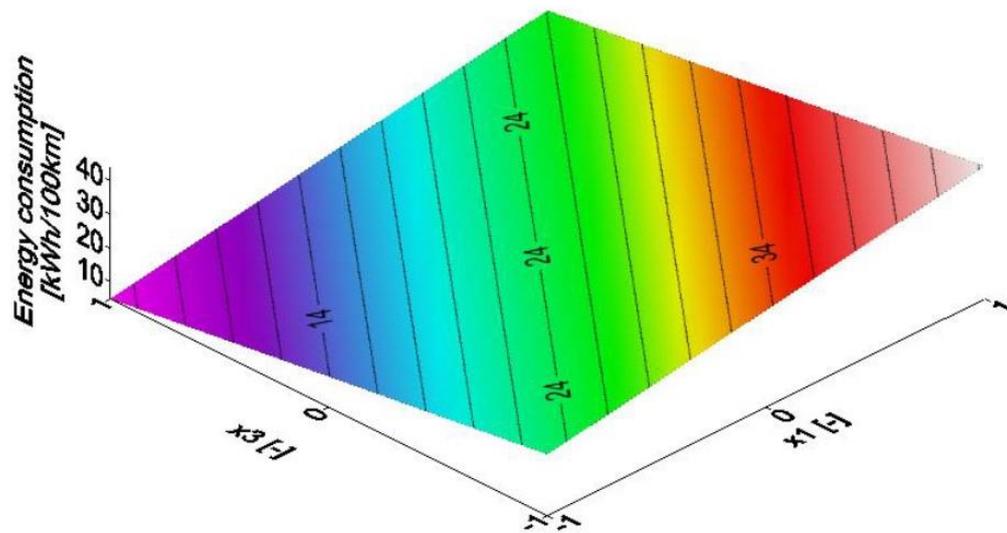
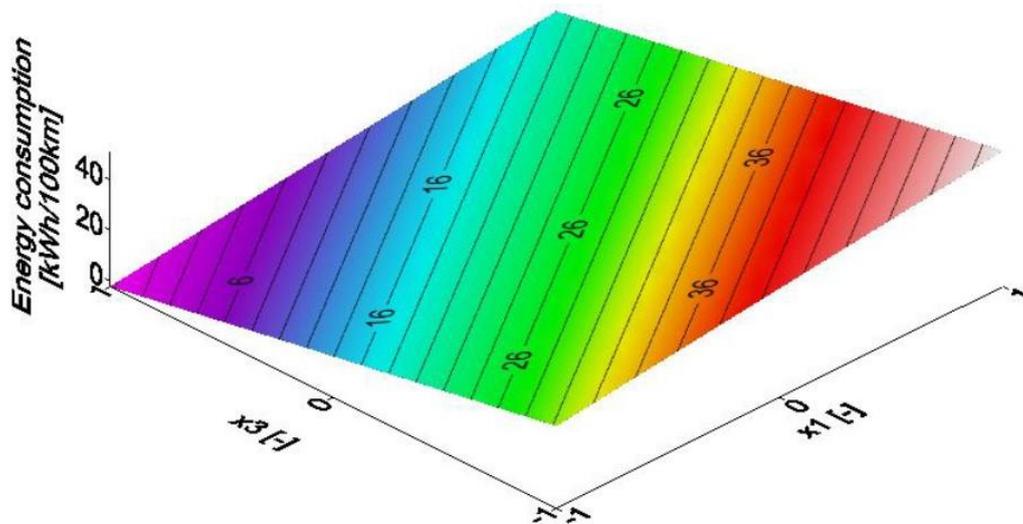


Figure 9. The value of electricity consumption depending on the temperature and time of travel, overcoming a distance of 2 km. Source: author’s own collaboration.



$$y(x_1, x_3) = 24.6 - 10.6x_1 - 9.1x_3$$

Figure 10. The value of electricity consumption depending on the temperature and time of travel, overcoming a distance of 3 km. Source: author's own collaboration.



$$y(x_1, x_3) = 24.6 - 10.6x_1 - 16.3x_3$$

Figure 11. The value of electricity consumption depending on the temperature and time of travel, overcoming a distance of 4 km. Source: author's own collaboration.

Based on Figures 9–11, it can be concluded that the lowest energy consumption of the vehicle during the tests was obtained for a distance of 2 km.

The impact of travel length is shown in Figure 12, assuming the route is completed in $x_1 = 0$, i.e., 20 min, and temperature $x_3 = 20$ °C. Consumption values are similar and their trend is stable.

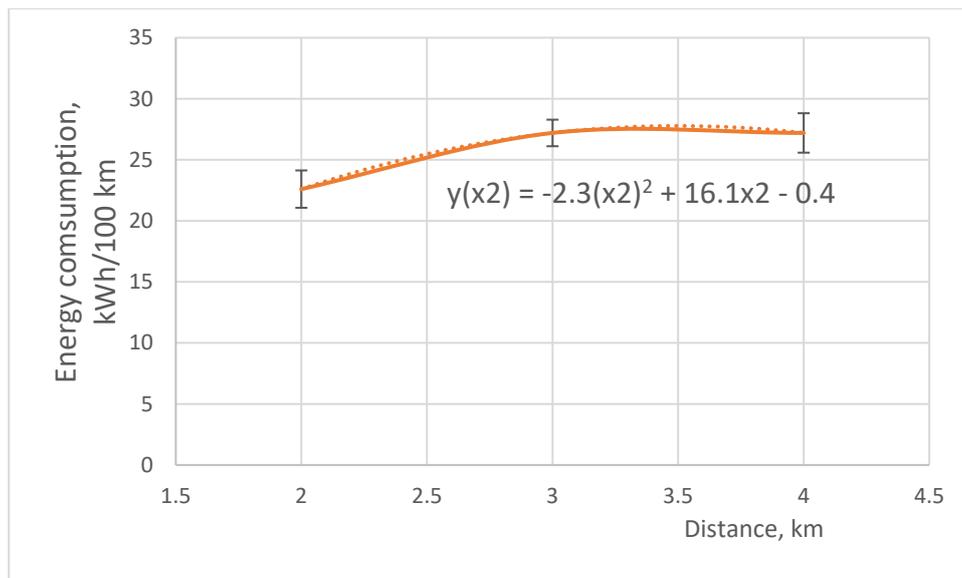


Figure 12. The value of energy consumption depending on the travel distance for a travel time of 20 min and a temperature of 20 °C. Source: author’s own collaboration.

The last input parameter that has an impact on consumption is the temperature. The dependencies of the vehicle’s electricity consumption for various temperature values are shown in Figures 13–15. For a temperature of $x_3 = 15\text{ °C}$, the lowest consumption values were at the shortest travel time $x_1 = -1$ and the distance $x_2 = -1$. For the temperature $x_3 = 0$ (20 °C), the value of energy consumed depended only on the time of travel. For temperature $x_3 = 1$ (25 °C), the highest energy consumption was obtained by covering the longest distance $x_2 = 1$ (4 km) and the shortest travel time $x_1 = 1$ (10 min).

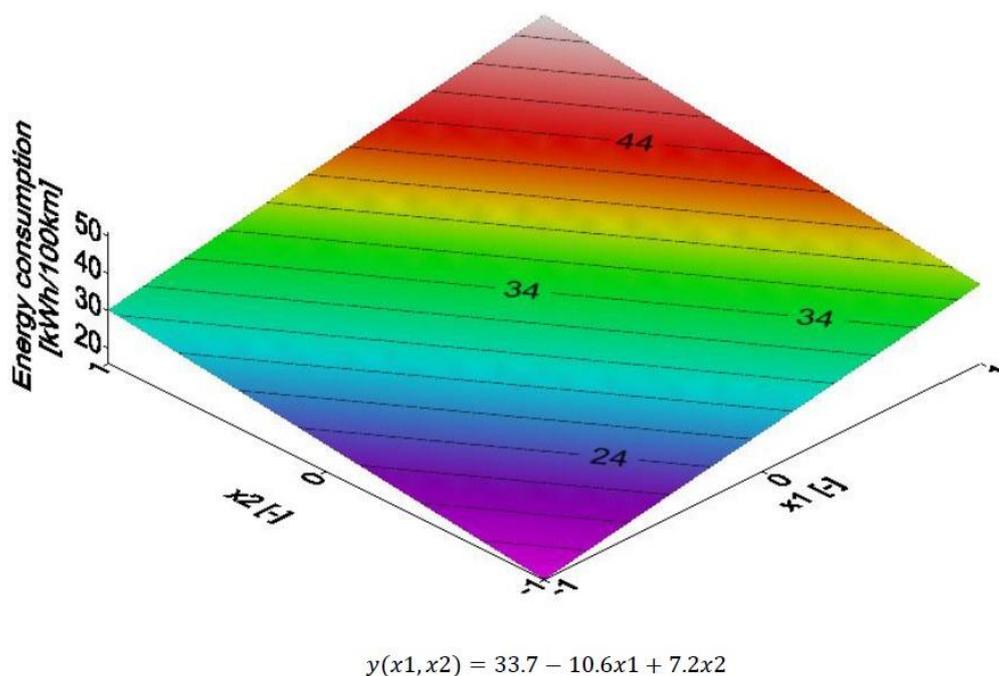
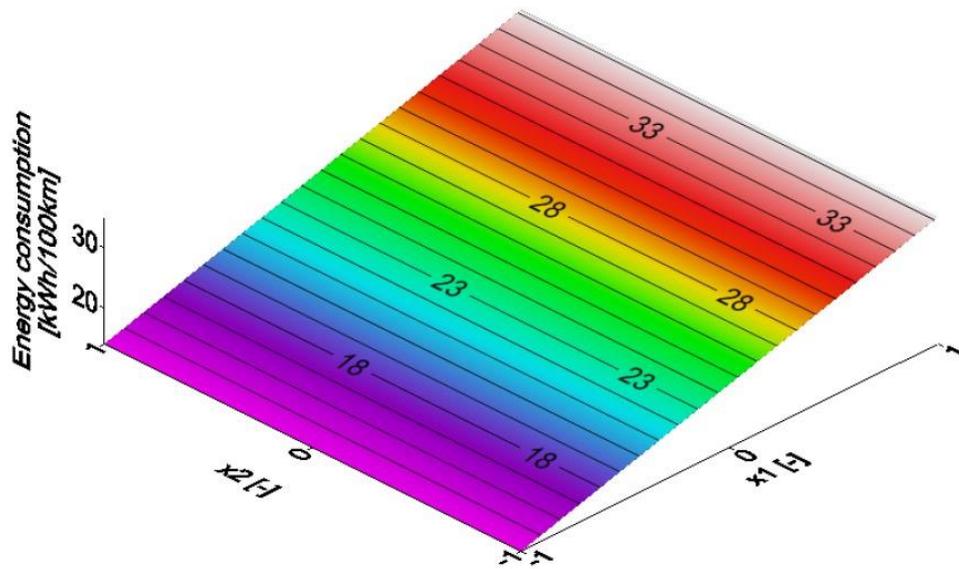
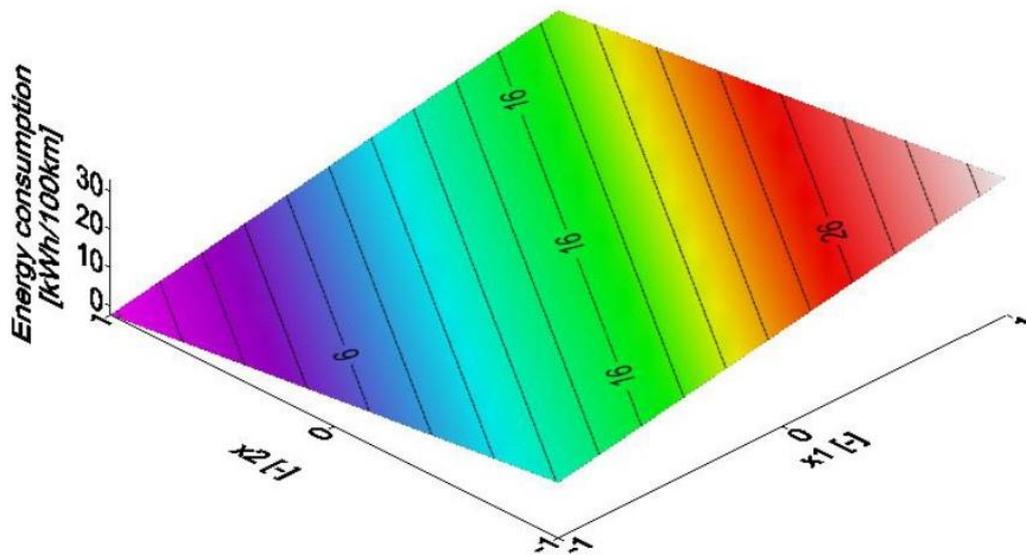


Figure 13. The value of electricity consumption depends on the distance and travel time at 15 °C. Source: author’s own collaboration.



$$y(x_1, x_2) = 24.6 + 10.6x_1$$

Figure 14. The value of electricity consumption depends on the distance and travel time at 20 °C. Source: author’s own collaboration.



$$y(x_1, x_2) = 15.5 + 10.6x_1 - 7.2x_2$$

Figure 15. The value of electricity consumption depends on the distance and travel time at 20 °C. Source: author’s own collaboration.

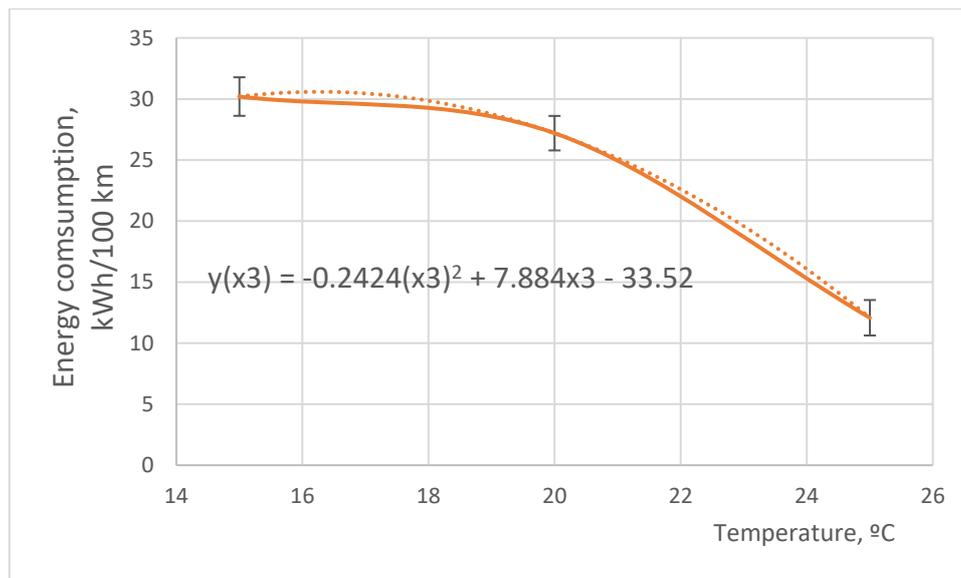


Figure 16. Dependence of energy consumption on the outside temperature for a travel time of 20 min and a travel distance of 3 km. Source: author's own collaboration.

In summary, the research carried out, according to the experiment plan, confirmed the impact of selected factors on the value of energy consumption. The value of energy consumption depends significantly on the following operational factors: travel time, distance, and external temperature. Based on the graphs, energy consumption can be predicted for other input parameters within $\langle -1; 1 \rangle$.

5. Discussion and Conclusions

In conclusion, the results of the research show that users of car-sharing systems using electric vehicles often do not pay attention to the energy consumption of cars. As a result, energy consumption is much higher than in the vehicle specification provided by the manufacturer. This type of procedure exposes car-sharing system operators to higher costs associated with charging the vehicle fleet battery. In addition, more frequent charging negatively impacts the environment through excessive power consumption. It is also worth mentioning that frequently charged vehicle batteries are subject to faster wear, and thus become another poisonous element for the environment. Therefore, the authors propose the following recommendations for operators of car-sharing electrical systems:

1. It is worth monitoring the energy consumption of vehicles by analyzing the users' driving modes. On this basis, it is worth introducing a rewarding system for users who travel correctly with the vehicles. For example, offering them the opportunity to use services at a cheaper price or offering various types of rewards, also introducing elements of gamification;
2. It is worth paying attention to the level of battery charging. And also it is important to initiating the charging of vehicle batteries within a certain range, depending on the specific vehicle type to achieve the 100% battery charge.
3. It is worth choosing vehicles for the fleet based on real energy consumption and not on catalog values, which may significantly differ from real parameters;
4. It is worth paying close attention to programs educating users on how to use electric vehicles. The conducted experiment indicates that proper education in the field of responsible driving of an electric car can realistically reduce the value of consumed electricity and, as a result, reduce the operating costs of the system.

Research shows that it is important to perform similar tests on other types of vehicles used in electric car-sharing systems to get a full picture of energy consumption in fleets. This way, it is possible to focus on the appropriate modeling to optimize energy consumption. In subsequent studies, the

authors plan to expand the proposed research experiment with a greater number of journeys, the use of other vehicles, including hybrid cars, and considering the issue of vehicle charging.

Author Contributions: K.T. discovered a problem in electric car-sharing systems, performed the analyses, and proposed a research scheme. A.K. conducted the experiments and analyzed the experimental results. F.C. provided guidance and key suggestions for this study.

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