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Article

CO_2 Emissions—Evidence from Internal Combustion and Electric Engine Vehicles from Car-Sharing Systems

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Abstract: Car-sharing services are developing at an ever-increasing pace. Taking into account the reduction of carbon dioxide emissions and pursuit of the sustainable development of transport, implementing electric cars in car-sharing fleets is being proposed. On the one hand, these types of vehicles are referred to as emission-free, but on the other hand, their environmental friendliness is questionable due to the emission of carbon dioxide during the production of energy to power them. Although many scientific papers are devoted to the issue of reducing emissions through car sharing, there is a research gap concerning the real production of carbon dioxide by car-sharing vehicles during car-sharing trips. To fill this research gap, the objective of the article was to analyze the actual level of carbon dioxide emissions from combustion and electric vehicles from car-sharing systems produced when renting rides. The test results showed that the electric car turned out to be significantly less emitting. The use of electric vehicles in car-sharing fleets can reduce carbon dioxide emissions from 14% to 65% compared to using cars with internal combustion engines. However, the key role during car-sharing trips is played by the driving style of the drivers, which has been omitted from the literature to date. This should be properly regulated by service providers and focus on the proper use of energy from electric vehicle batteries, especially at low temperatures. The article provides support for operators planning to modernize their fleet of vehicles and fills the research gap concerning car-sharing emissions.

Keywords: electromobility; electric vehicles; car sharing; shared mobility; sustainable mobility

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1. Introduction

Ensuring the sustainable development of transport is a global trend aimed at achieving economic and ecological stability [1]. According to the assumptions, sustainable transport is associated with the promotion of movement in an effective way that meets the expectations of society and is economically efficient, while minimizing the harmful impacts on public health, the natural environment, the economy, and urban planning. It assumes focusing both on the control of emission of harmful compounds in exhaust gases as well as (in the long-term) on the transition from fossil fuel combustion to renewable energy [1]. Therefore, economic sectors, especially those considered extremely harmful to the environment, such as the transport or automotive industries, are expected to undertake various types of activities to achieve the results set by the European Union or the United Nations. In the case of the European Union, the latest declarations under the "2050 long-term strategy" emphasize that all relevant institutions of the European Union have agreed to legislate the EU target of net-zero emissions by 2050 [2]. The law also includes the goal of reducing carbon dioxide emissions by 55% of 1990 levels by 2030 [2]. In turn, in the case of the UN, an action plan (Sustainable Development Goals—SDGs) was announced for the transformation of the world in which the needs of the present generation can be met in a sustainable manner, with respect for the environment and considering the needs of future generations [3]. The plan contains 17 sustainable development goals and 169 related actions, which are to be achieved by all parties—governments, international organizations, non-governmental organizations, science and business sectors, as well as citizens. They focus on five areas: people, planet, prosperity, peace, and partnership. The developed goals are the basis of the new 2030 agenda for sustainable development of the world, considering the economic, social, and environmental aspects. This roadmap identifies the major challenges of our time. It presents a vision of building a better world for the benefit of the inhabitants of the planet and its repair [3]. Among the 17 goals, one is specifically related to the transport industry and the reduction of carbon dioxide emissions—the 13th climate action goal is to take urgent action to combat climate change and its impacts [4]. As a result of the implementation of various types of pro-ecological activities, research, politics, and laws, various types of vehicles and transport solutions have appeared on the market, which are to affect, among others, the reduction of harmful exhaust emissions and thus improve the quality of life of society and the condition of the natural environment [5,6].

One of the solutions to reduce the negative impact of transport by eliminating transport by individual cars in cities is car-sharing services. Car sharing refers to short-term automated car rentals used in cities [7]. Car-sharing systems, with the implementation of subsequent transport restrictions in cities, as well as the growing problem of traffic congestion, are gaining popularity every year [8]. The main advantages associated with the growing interest in car-sharing systems are their availability, self-service, and high autonomy of use [8]. Furthermore, from the point of view of urban centers, car-sharing systems free up public space because one car from the car-sharing system can replace seven to thirteen cars used by individuals [9]. Another of the features that characterizes car-sharing services is their assumption of improving the condition of the natural environment by offering the public new eco-friendly vehicles that are more and more often equipped with electric engines, which helps to reduce carbon dioxide emissions [10].

When analyzing the global literature for studies in the field of energy consumption by car-sharing vehicles, a limited number of works are available. Among the available literature, main thematic areas can be distinguished that relate to the life cycle of car-sharing vehicles, analyses of the functioning of car-sharing systems in terms of the use of electric vehicles, general system development policies considering electric vehicles, or case studies of carbon dioxide emissions for various examples.

From the point of view of the impacts of the car-sharing life cycle on energy use and greenhouse gas emissions, authors of a previous study indicated that current car-sharing members reduce the average individual energy consumption in transport and greenhouse gas emissions by approximately 51% after joining a car-sharing organization [11]. Therefore, car sharing can contribute to a real reduction in carbon dioxide emissions [11]. In turn, in their work on reducing greenhouse gas emissions through car sharing, Amatuni et al. emphasized that car sharing participation reduced annual mobility emissions by 3–18% for the average member [12]. This conclusion was also underlined by Grischkat et al., who indicated that the reduction of greenhouse gas emissions is achievable through mobility services, which includes car sharing [13].

Taking into account issues in the functioning of car-sharing systems in terms of the use of electric vehicles, one can find studies on the differentiation of charging electric vehicle batteries depending on the time of day [14], users' preferences in terms of using vehicles [15,16], and the impact of the type of vehicle on the interest in using electric car-sharing services and ecological issues [17]. Despite the interesting research prospects in the field of car-sharing vehicles and their optimization, these studies did not identify the level of carbon dioxide emission reduction depending on the different conditions of vehicle travel.

Another thematic area related to carbon dioxide emissions is system development policies. For example, the authors Vanheusden et al. indicated, based on data from 170 cities in 30 European countries, that awareness campaigns and cooperation between carsharing operators positively contributed to the spread of car sharing and affected the reduction of transport emissions [18]. In turn, von Wieding et al., based on car sharing research in Gothenburg, Sweden, indicated that car sharing can also bring benefits in terms of commuting to work and, by reducing travel, translate into a reduction of emissions produced by employees commuting by individual vehicles, which often may not meet current standards of exhaust emissions [19]. Moreover, Velez et al. indicated ways to reduce emissions in cities by actively promoting car sharing [20]. These authors emphasized the importance of changing transport habits and the need for cities to strive to discourage car ownership by residents [20]. The indicated works, as in the case of analyses of the functioning of car-sharing services, despite emphasizing the reduction of emissivity thanks to car sharing, did not present detailed results in terms of the level of reduction of exhaust gas emissions. Additionally, there is a lack of studies in the literature that consider the latest technological changes that have taken place in the automotive industry in recent years along with the development of low-emission cars.

The last of the thematic areas related to the emissivity of car sharing includes aspects related to case studies of the use of car sharing and the level of reduction of carbon dioxide emissions. This kind of research has been conducted for different case studies and, interestingly, shows conflicting values for CO_2 consumption. For example, the Society of Motor Manufacturers emphasized in its 2018 report that if 20% of the vehicles currently on the market were replaced by cars from car-sharing systems, CO_2 emissions would be reduced by 15% [21]. In turn, the authors Baptista et al., who conducted a case study in Lisbon and Portugal in 2014, indicated that the replacement of individual cars with car-sharing vehicles can mean a reduction in energy consumption from 35% to 65% for hybrid and electric cars [22]. In comparison, the authors Nijland et al., in a study in the Netherlands in 2015, achieved a reduction in carbon dioxide emissions from 8% to 13% [23]. In turn, the authors Lee et al., in their 2014 study in Korea, achieved results between 5.31% and 13.37% [24]. It should be noted that their research was based mainly on surveys conducted among users, on vehicle data provided by manufacturers, or on data received from operators on fuel costs. However, no reference was made to detailed analyses based on the authors' research in the form of journeys using cars from car-sharing services (real condition road tests). Moreover, it is commonly believed that electric cars are completely emission-free vehicles [25]. This statement is true for car travel. However, the controversial fact is that the vehicle's battery is powered by energy that still mostly comes from non-renewable sources, which generate carbon dioxide during the production of electricity. Therefore, it can be assumed that charging the batteries of electric vehicles from such sources contributes to the generation of CO_2 emissions by the vehicles that uses this type of energy.

On the one hand, electric vehicles seem to be real substitutes for combustion engine cars in car-sharing systems. On the other hand, business practices indicate that many car-sharing companies based on electric cars ended their operations very quickly, citing technical problems with electromobility. For this reason, many systems, especially in countries that are latecomers in terms of electromobility, are still based on cars with internal combustion engines. A perfect example is Poland, where combustion engine-powered cars still prevail in the majority of operator fleets. However, due to the requirements of sustainable development and ongoing legislative work on the implementation of carbon dioxide emission taxes, there is a need to determine the real level of carbon dioxide emissions for owners of vehicles exceeding the statutory guidelines for CO_2 emissions in car sharing and identify savings opportunities for operators.

The purpose of this article was to analyze the real level of carbon dioxide emissions from combustion and electric vehicles from car-sharing systems achieved during ride rentals. The article fills the research gap concerning the lack of scientific papers devoted to the results of actual and not projected carbon dioxide emission values achieved during road tests. The article was based on the authors' plan of an experiment carried out in real conditions during trips using car-sharing vehicles. The research was conducted for the

Polish market of shared mobility services. The Polish market was not chosen accidentally, both from the point of view of shared mobility and the general background of the Polish transport sector and its energy issues. According to current data in Poland, it is estimated that approximately 20% of carbon dioxide emissions come from the transport sector [26]. The Polish energy mix is mainly based on lignite and hard coal power plants [27,28]. The dominance of coal technologies in the Polish energy sector has a historical background. After World War II, due to political conditions, coal was practically the only available energy resource and the developing economy needed more and more energy [28]. Domestic hydrocarbon fuel resources were relatively small, and their prices on international markets were relatively high. After the geopolitical transformation in 1989, actions to improve the economy of the energy sector and environmental protection were given high priority [29]. The Energy Law Act in 1997 introduced legal and economic solutions in the Polish energy sector, similar to those contained in the first market directive of the European Community [29]. Since 2004, after Poland acceded to the EU, most Polish energy legislation has been determined by or resulted from EU law. Therefore, the biggest challenge for the Polish power sector is currently transformation as part of the implementation of climate and environmental policies. With the dominance of coal technologies, measures are needed to quickly reduce emissions CO_2 and pollutants. The Polish energy sector is currently at a turning point, and any initiatives taken to reduce emissions are advisable. One of the mobility services that contributes to reducing transport emissions in Poland is car sharing.

Although car-sharing systems appeared in Poland relatively recently, i.e., in 2016, it is a dynamically changing market [30]. In 2017, which was the peak of car-sharing system development in Poland, services were provided in over 250 cities by 17 operators [31]. The revenue from car-sharing services in Poland was more than PLN 50 million in 2019, and it doubled to over PLN 100 million in 2021 [32]. It is predicted that the Polish shared mobility market will develop dynamically, supplementing and modernizing the vehicle fleet at the same time [33]. Therefore, undertaking all kinds of research on the real impact of vehicles on the environment seems to be justified.

This work has been divided into five sections. The first section discusses the general outline of carbon dioxide emissions in car-sharing systems. The second section focuses on the presentation of the methodology based on the use of a polyselective experimental research plan. Subsequently, in the third section, the obtained results are presented, which are discussed in the fourth section. The fifth section provides a summary of the work, an indication of the authors' further research plans, and discusses the limitations of the study.

2. Methodology

The research was carried out according to the assumed four-stage research plan presented in Figure 1.

Following the research plan, the experiment plan was selected in the first step. Due to the desire to consider car-sharing vehicle journeys from the point of view of various factors, it was decided to choose a polyselective experimental research plan. The polyselective experimental research plan describes phenomena based on three input quantities, with three different values used for each input quantity. The main principle of polyselective plans is the deliberate selection of combinations of input values within a predetermined range in such a way that it is possible to obtain the required scientific information in limited conditions [34]. The development of the plan consists of determining the dependence of the input quantities and their location relative to the base point (center), i.e., zero. The polyselective experimental research plan developed for three input factors is based on a hypercube for which the coefficient $\alpha = 1$ [34]. Subsequently, the vehicles on which the tests were carried out were selected. The two most popular car models used in car-sharing systems in Poland were selected for the study [35]. These models represented groups of vehicles with internal combustion engines (ICEs) and electric engines. Both cars represented class B vehicles, i.e., cars mainly intended for driving in the city that allow for a relatively comfortable ride for four people on the road [36]. Detailed characteristics of the selected models are presented in Table 1.

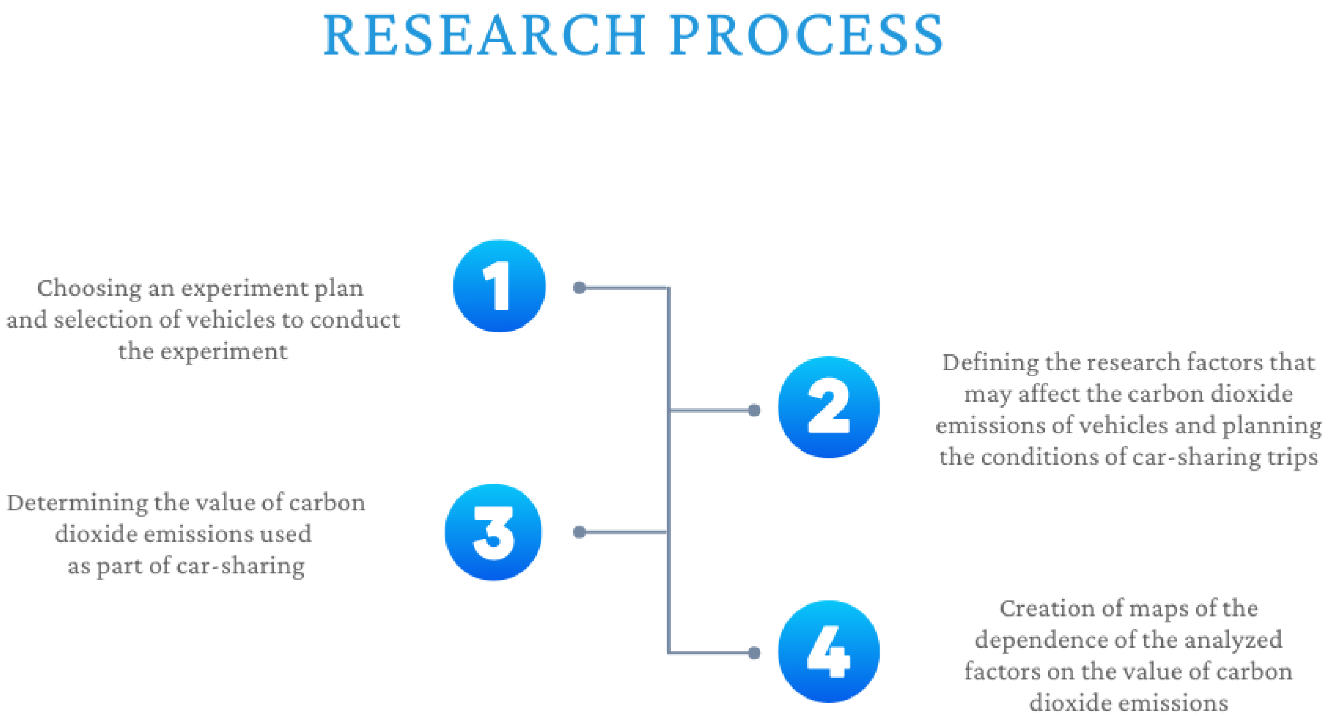


Figure 1. Research process.

Table 1. Characteristics of the vehicles used in the experiment.

	Electric Engine (EE)	Internal Combustion Engine (ICE)
Engine power [kW]	80	48
Maximum torque [Nm]	225	95
Vehicle length [mm]	4085	4050
Vehicle width [mm]	1787	1798
Vehicle weight [kg]	1502	1190
Top speed [km/h]	135	178
Number of seats [-]	5	5
Range [km]	395	970

The selected vehicle models, indicated in Table 1, were used as research objects to conduct road tests in real urban traffic conditions. To define the conditions of the road tests, the factors that had the greatest impact on the value of carbon dioxide emissions by a given vehicle were determined, i.e., the time of driving a given section (x_1), the distance of the route covered (x_2), and the temperature (x_3). Subsequently, the test routes for cars from the car-sharing system were defined. The travel time for a given section ranged from 10 to 30 min, the distance of the routes ranged from 2 to 4 km, and the temperature ranged from 15 to 25 °C. The results of the conducted experiment are presented in the third section.

3. Results

The road tests carried out as part of the research plan were conducted with a vehicle with an ICE and one with an electric engine. Section 3.1 focuses on the results for a vehicle with an ICE, while Section 3.2 presents the results for a vehicle with an electric engine.

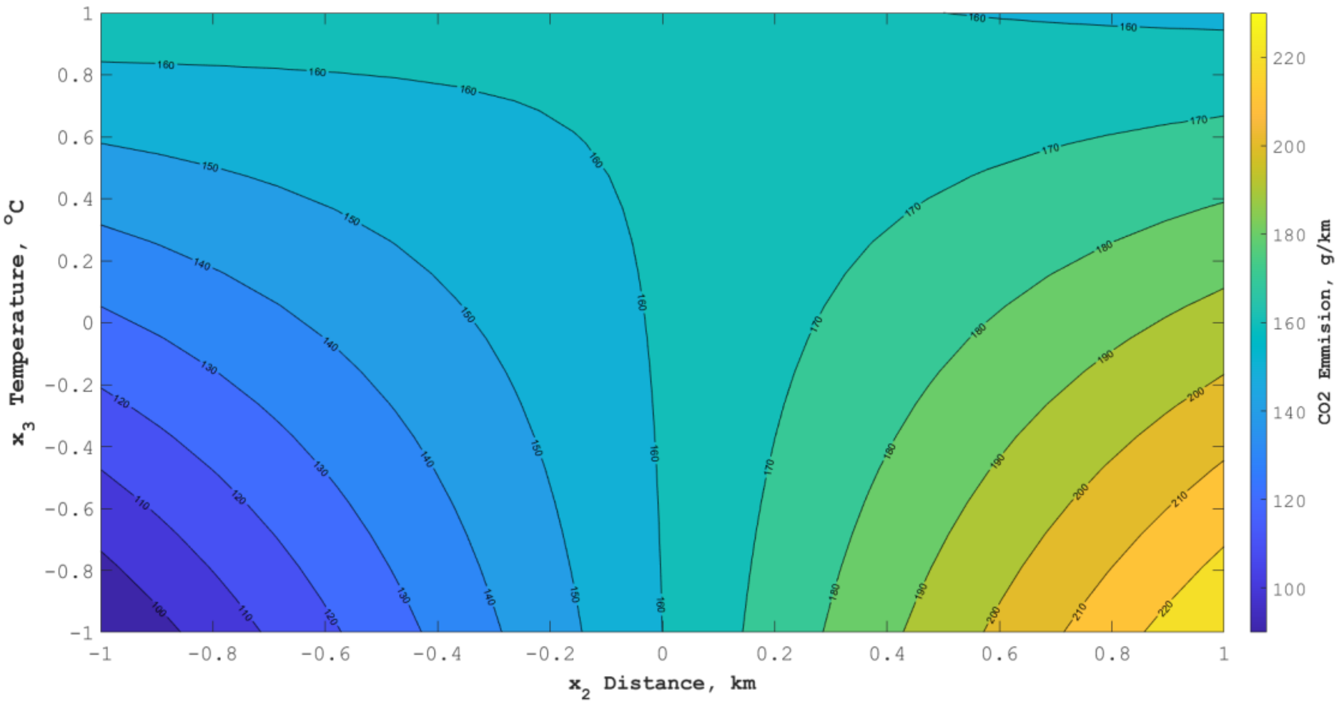
3.1. Road Test Results for a Vehicle with an ICE

Table 2 presents the conditions of the road tests carried out along with the CO_2 emission values obtained for a vehicle with an ICE.

Table 2. Road test conditions and CO_2 emission values—vehicle with an ICE.

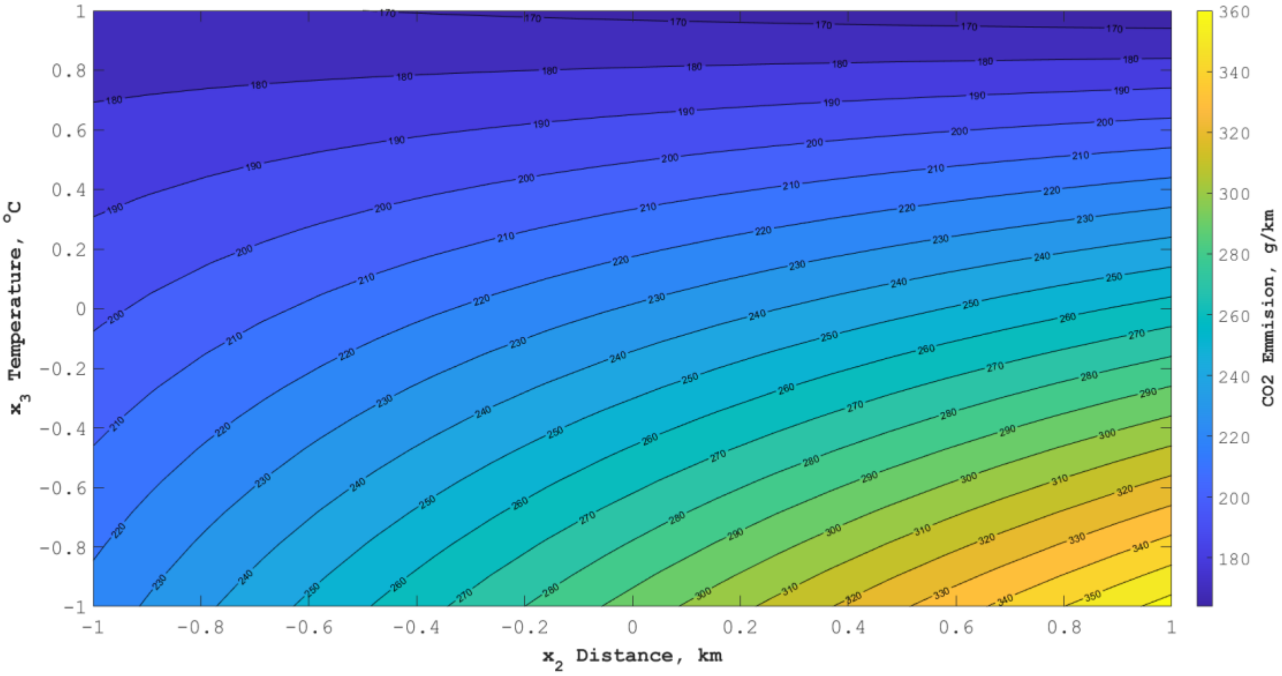
Sample No.	Standardized Scale Input Factors			Real Scale Input Factors			Results
	x_1 Time (min)	x_2 Distance (km)	x_3 Temperature (°C)	x_1 Time (min)	x_2 Distance (km)	x_3 Temperature (°C)	CO_2 emission (g/km)
1	–1	–1	1	30	2	25	167.1
2	1	–1	–1	10	2	15	306.3
3	–1	1	–1	30	4	15	177.4
4	1	1	1	10	4	25	169.9
5	$-\alpha$	0	0	30	3	20	153.3
6	α	0	0	10	3	20	294.6
7	0	$-\alpha$	0	20	2	20	194.6
8	0	α	0	20	4	20	260.7
9	0	0	$-\alpha$	20	3	15	275.4
10	0	0	α	20	3	25	149.8
11	0	0	0	20	3	20	236.2

Based on the test results presented in Table 2 and the use of a previously defined test plan, it was possible to determine the character of changes in the values of factors x_1, x_2, and x_3 on the values of CO_2 emissions for a vehicle with an ICE. Figures 2–4 present the results of the nature of the change in the value for factor x_1—the time of the distance traveled—depending on the external temperature (x_3) and length of the route (x_2).



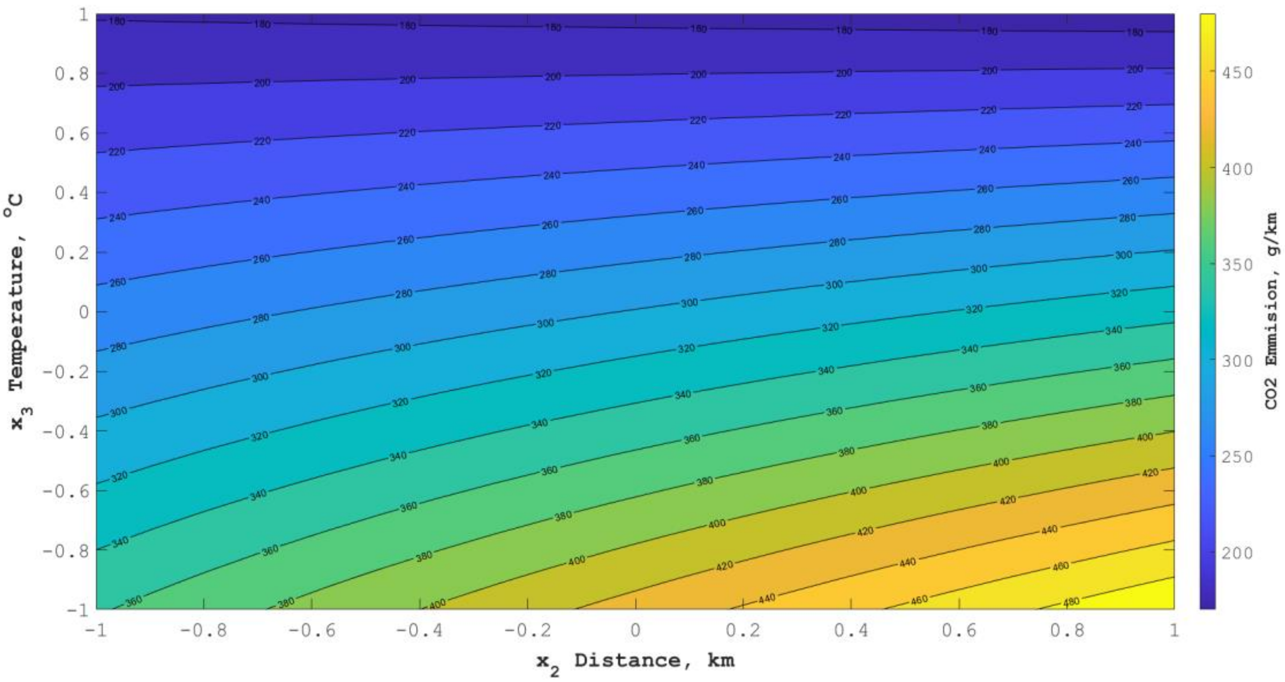
$$x_1 = -1 \ \forall \ y(x_2, x_3) = -37x_2x_3 + 33x_2 + x_3 + 161$$

Figure 2. Change in CO_2 emissions depending on the variability of factors x_2 and x_3 for a vehicle (ICE) moving for 30 min ($x_1 = -1$).



$$x_1 = 0 \; \forall \; y(x_2, x_3) = -37x_2x_3 + 33x_2 - 63x_3 + 231$$

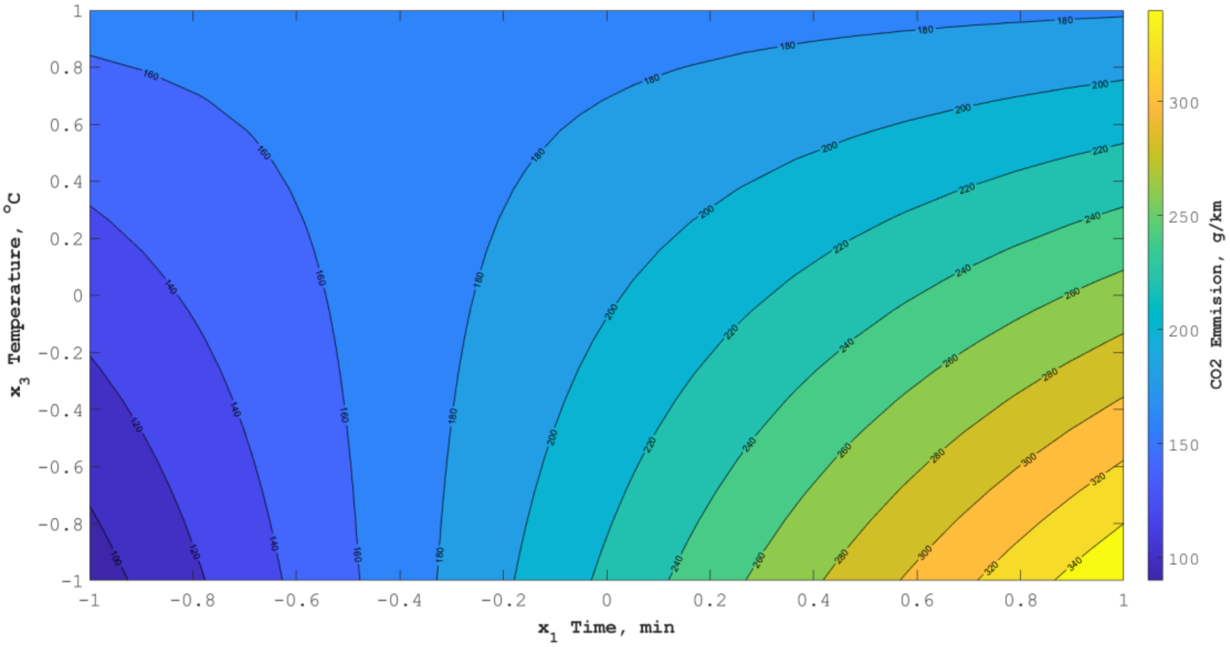
Figure 3. Change in CO_2 emissions depending on the variability of factors x_2 and x_3 for a vehicle (ICE) moving for 20 min ($x_1 = 0$).



$$x_1 = 1 \; \forall \; y(x_2, x_3) = -37x_2x_3 + 33x_2 - 127x_3 + 301$$

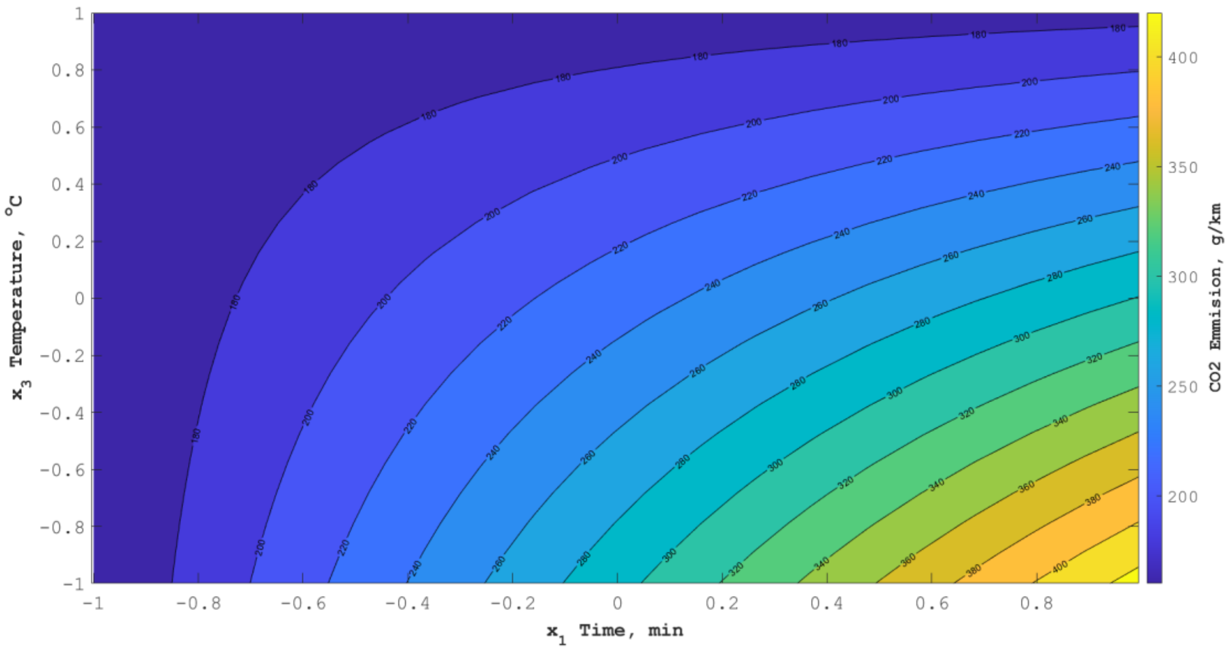
Figure 4. Change in CO_2 emissions depending on the variability of factors x_2 and x_3 for a vehicle (ICE) moving for 10 min ($x_1 = 1$).

Subsequently, Figures 5–7 present the results of the nature of the change in the value of factor x_2—the distance travelled—depending on the external temperature (x_3) and travel time (x_1).



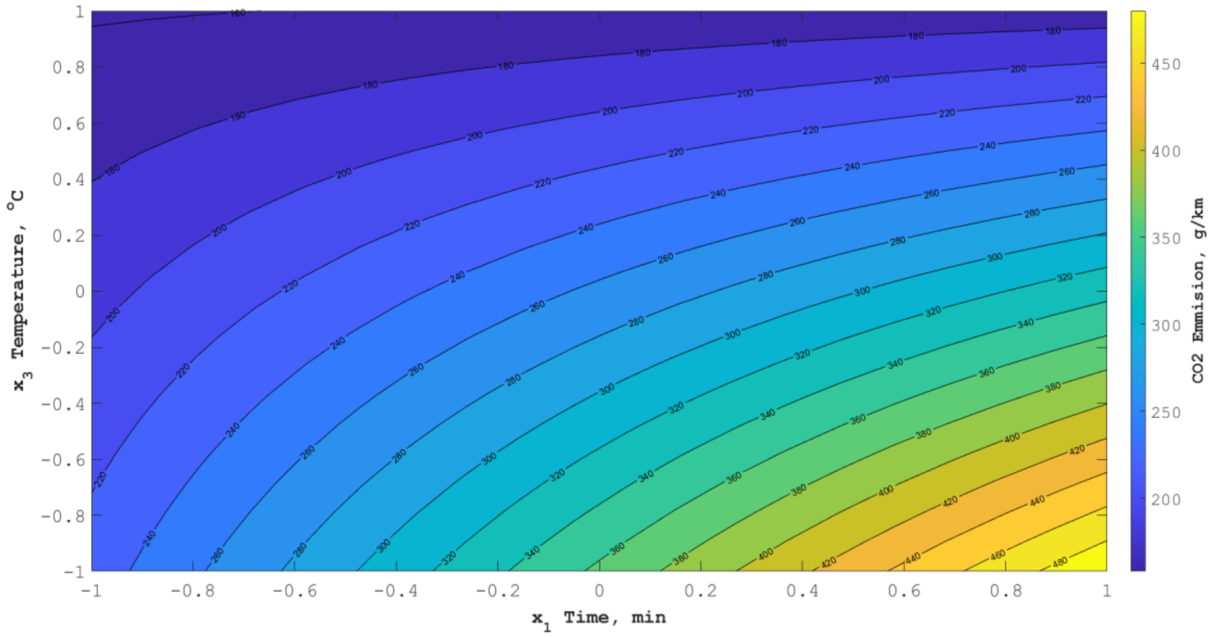
$$x_2 = -1 \,\forall\, y(x_1, x_3) = -64x_1x_3 + 70x_1 - 26x_3 + 198$$

Figure 5. Change in CO_2 emissions depending on the variability of factors x_1 and x_3 for a vehicle (ICE) covering a distance of 2 km ($x_2 = -1$).



$$x_2 = 0 \,\forall\, y(x_1, x_3) = -64x_1x_3 + 70x_1 - 63x_3 + 231$$

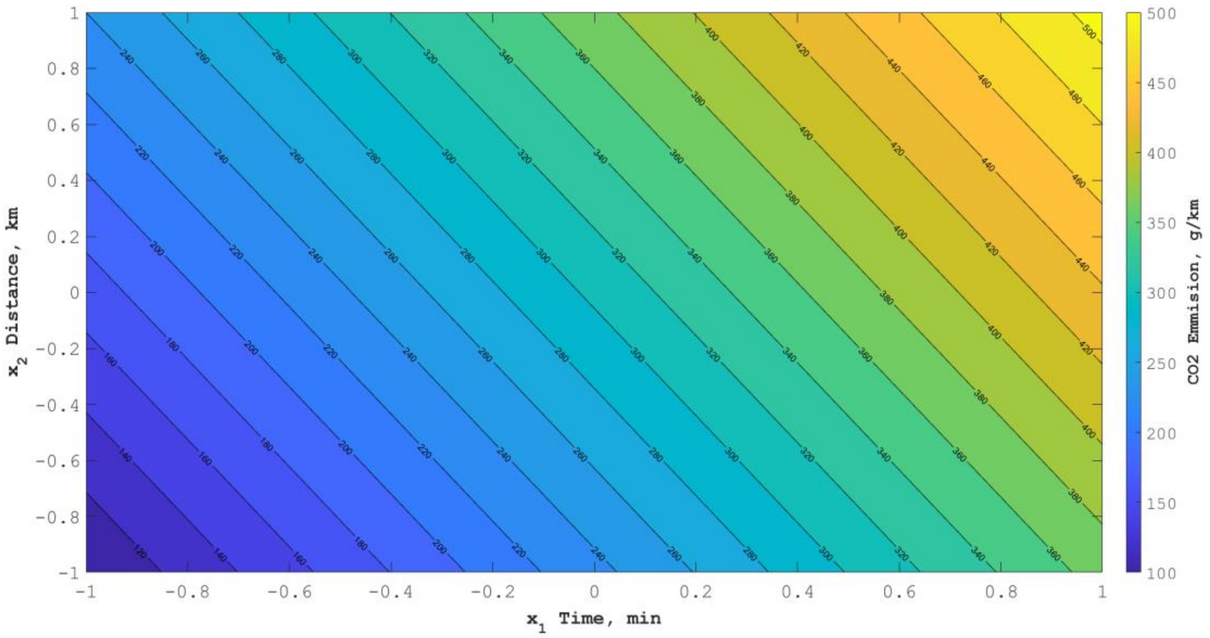
Figure 6. Change in CO_2 emissions depending on the variability of factors x_1 and x_3 for a vehicle (ICE) covering a distance of 3 km ($x_2 = 0$).



$$x_2 = 1 \,\forall\, y(x_1, x_3) = -64x_1x_3 + 70x_1 - 100x_3 + 264$$

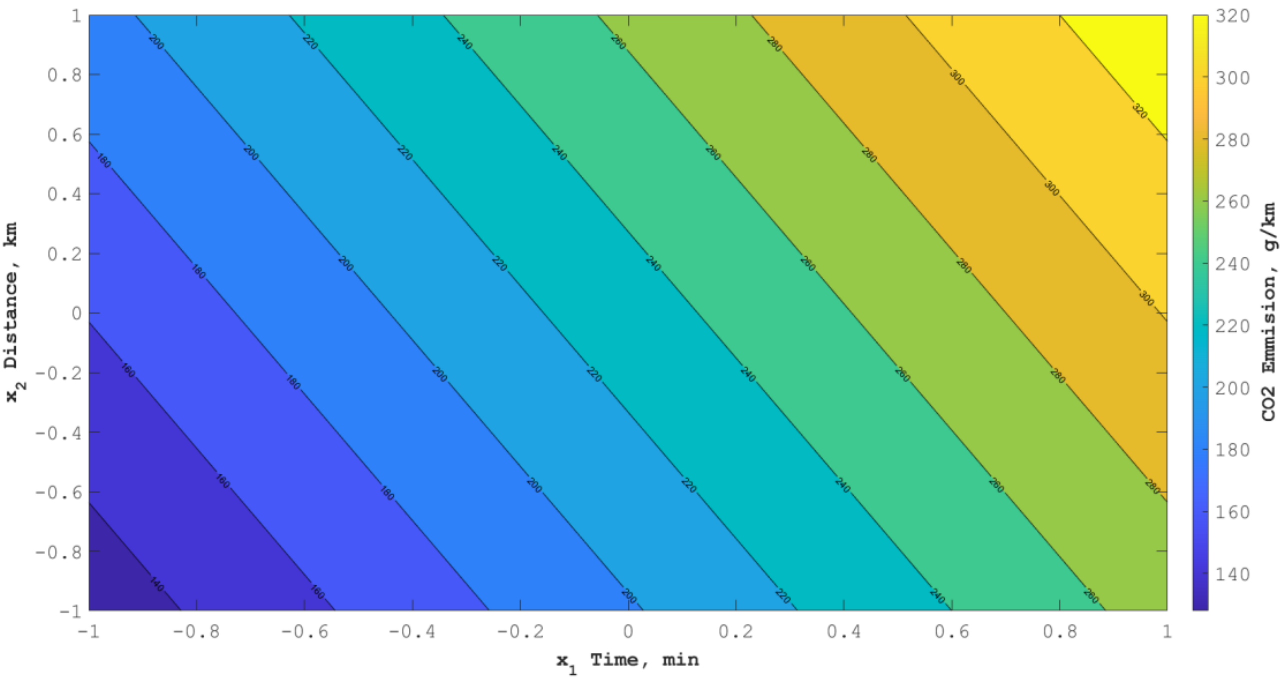
Figure 7. Change in CO_2 emissions depending on the variability of factors x_1 and x_3 for a vehicle (ICE) covering a distance of 4 km (x_2 = 1).

Then, in Figures 8–10, the results of the nature of the change in the value of factor x_3—external temperature—are presented depending on the travel time (x_1) and length of the route traveled (x_2).



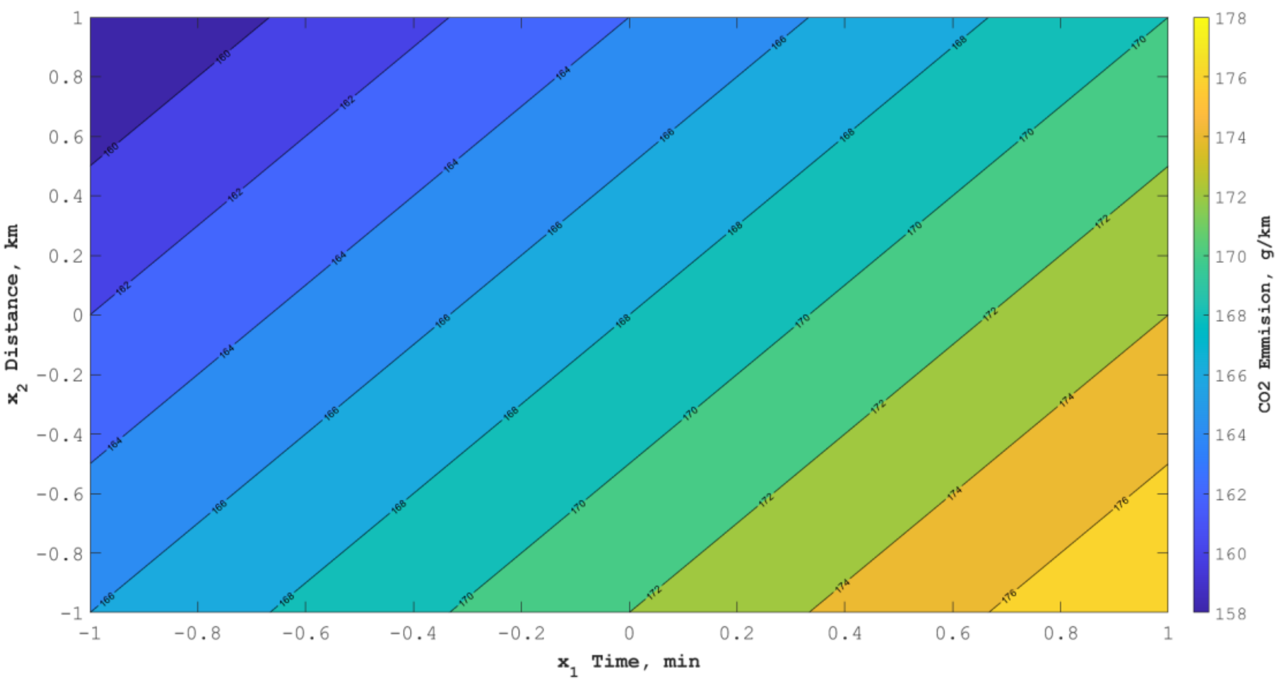
$$x_3 = -1 \,\forall\, y(x_2, x_3) = 134x_1 + 70x_2 + 304$$

Figure 8. Change in CO_2 emission depending on the variability of factors x_1 and x_2 for a vehicle (ICE) moving at a temperature of 15 °C (x_3 = −1).



$$x_3 = 0 \; \forall \; y(x_2, x_3) = \; 70x_1 + 33x_2 + 231$$

Figure 9. Change in CO_2 emission depending on the variability of factors x_1 and x_2 for a vehicle (ICE) moving at a temperature of 20 °C (x_3 = 0).



$$x_3 = 1 \; \forall \; y(x_2, x_3) = \; 6x_1 - 4x_2 + 168$$

Figure 10. Change in CO_2 emissions depending on the variability of factors x_1 and x_2 for a vehicle (ICE) moving at a temperature of 25 °C (x_3 = 1).

Analyzing the results presented in Figures 2–10, it can be concluded that the factors describing the time of the distance traveled ($x_1 = -1 \vee x_1 = 0 \vee x_1 = 1$) and the length of the route covered ($x_2 = -1 \vee x_2 = 0 \vee x_2 = 1$) were characterized by a nonlinear relationship. The linear relationship was maintained by the ambient temperature factor ($x_3 = -1 \vee x_3 = 0 \vee x_3 = 1$). The highest value of the final CO_2 emission results occurred when the ambient temperature was the lowest $x_3 = -1$ (15 °C). The lowest volatility of issue results—CO_2 $\Delta_{CO2Emmision}$ = 20 g/km of the vehicle (ICE)—was observed when $x_3 = 1$ (25 °C).

3.2. Road Test Results for a Vehicle with an Electric Engine (EE)

The next stage of the research was to perform road tests using a vehicle equipped with an electric engine. Table 3 presents the conditions of the road tests carried out, together with the results obtained of the CO_2 emission values for a vehicle with an electric engine.

Table 3. Road test conditions and CO_2 emission values—vehicle with an EE.

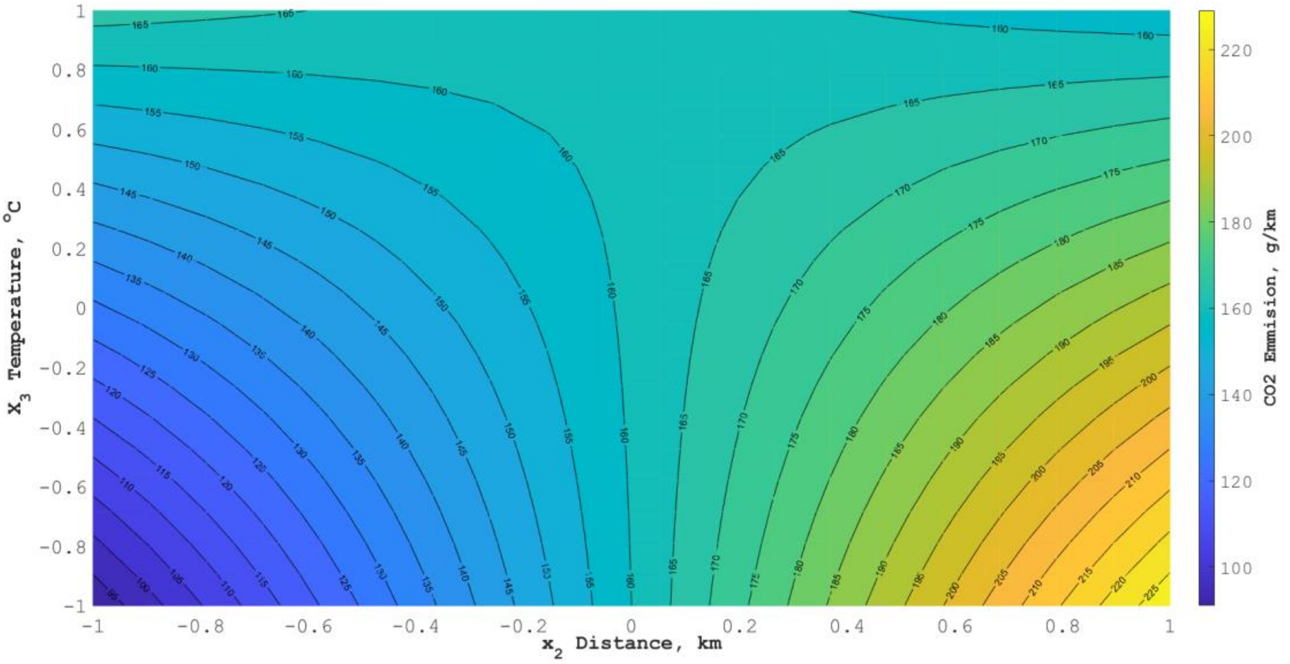
Sample No.	Input Factors on a Standardized Scale			Real Scale Input Factors			Results
	x_1	x_2	x_3	x_1 Time (min)	x_2 Distance (km)	x_3 Temperature (°C)	CO_2 Emission (g/km)
1	–1	–1	1	30	2	25	102.0
2	1	–1	–1	10	2	15	272.3
3	–1	1	–1	30	4	15	161.3
4	1	1	1	10	4	25	102.0
5	–α	0	0	30	3	20	93.8
6	α	0	0	10	3	20	249.0
7	0	–α	0	20	2	20	170.3
8	0	α	0	20	4	20	204.0
9	0	0	–α	20	3	15	226.5
10	0	0	α	20	3	25	90.8
11	0	0	0	20	3	20	204.0

Based on the test results presented in Table 3 and the application of a previously defined test plan, it was possible to determine the nature of changes in the values of factors x_1, x_2, and x_3 on the values of CO_2 emissions for a vehicle with an electric engine. Figures 11–13 present the results of the nature of the change in the value for factor x_1—the time of the distance traveled—depending on the external temperature (x_3) and length of the route (x_2).

Subsequently, Figures 14–16 present the results of the nature of the change in the value for the x_2 factor—the distance traveled—depending on the external temperature (x_3) and travel time (x_1).

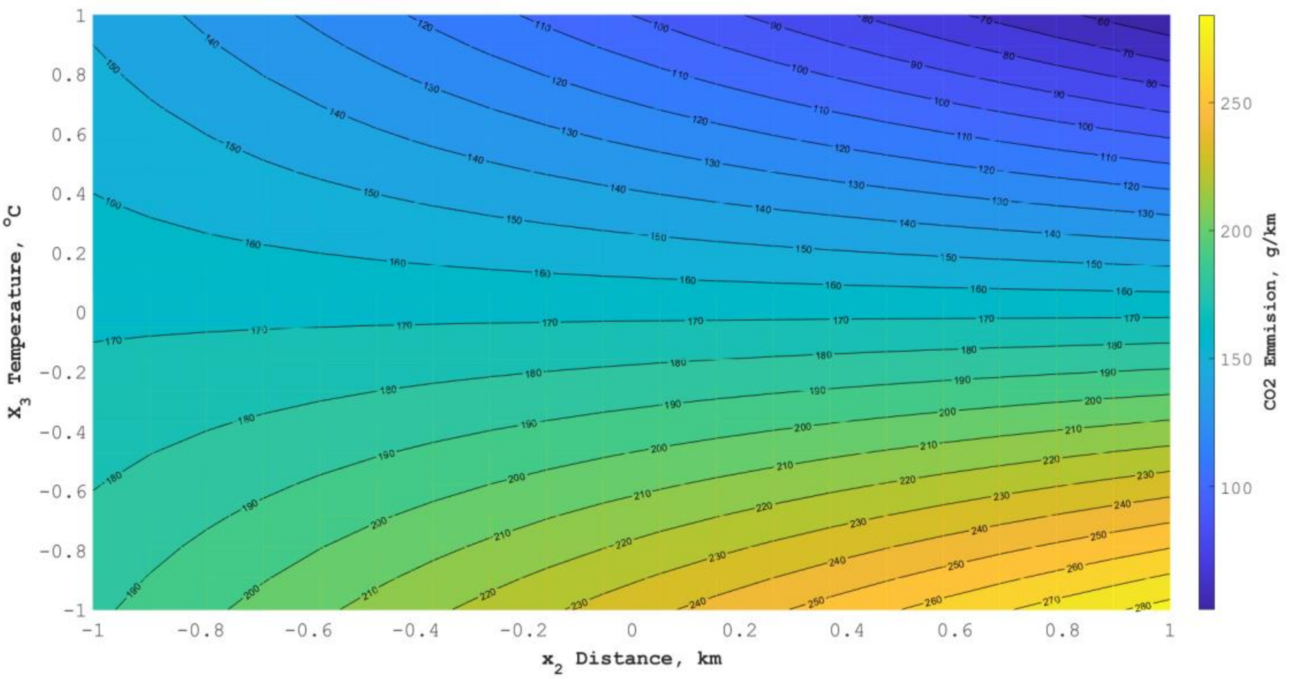
Then, in Figures 17–19, the results of the nature of the change in the values for factor x_3—external temperature—are presented depending on the travel time (x_1) and length of the route traveled (x_2).

Analyzing the obtained results presented in Figures 11–19 it can be concluded that for an electric vehicle, the factors describing the time of the distance covered ($x_1 = -1 \vee x_1 = 0 \vee x_1 = 1$) and the length of the route covered ($x_2 = -1 \vee x_2 = 0 \vee x_2 = 1$) were characterized by a nonlinear relationship. An important fact is the existence of constant CO_2 emission values for some conditions. As in the case of the vehicle with an ICE, the vehicle with an EE also showed a linear relationship for the influence of outside temperature (x_3) on CO_2 emissions, but it achieved lower emission values.



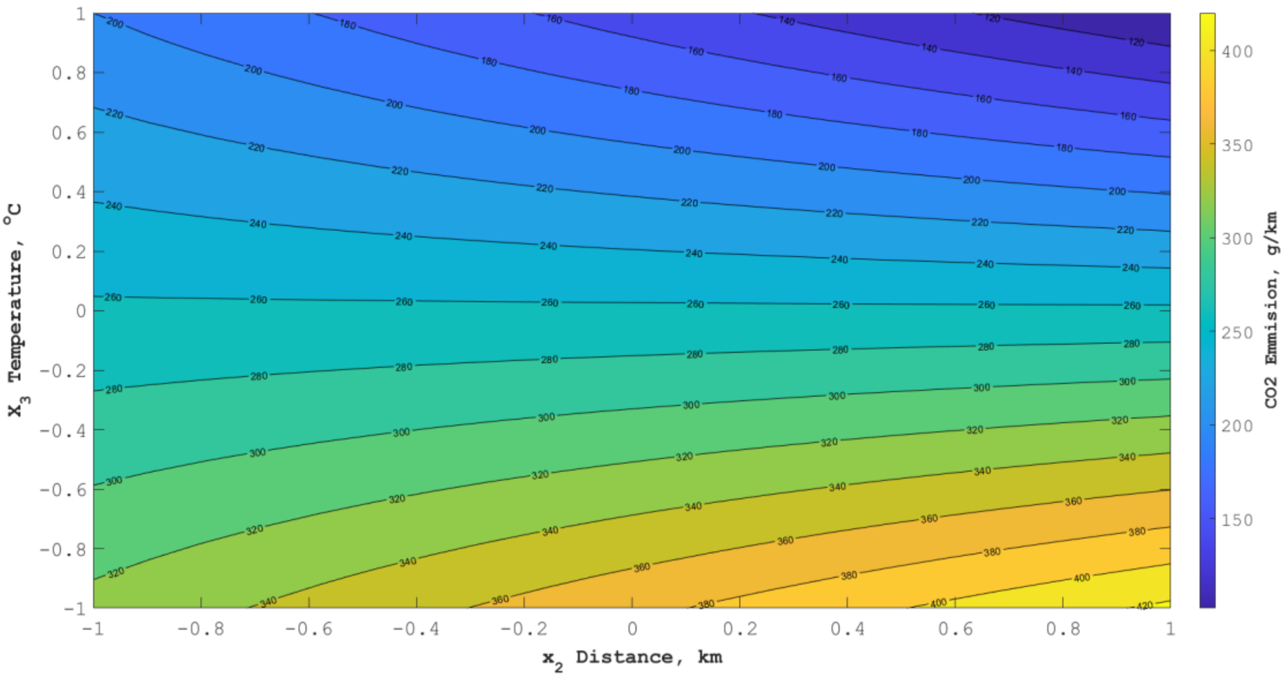
$$x_1 = -1 \; \forall \; y(x_2, x_3) = -49x_2x_3 - 24x_3 + 109$$

Figure 11. Change in CO_2 emissions depending on the variability of factors x_2 and x_3 for a vehicle (EV) moving for 30 min ($x_1 = -1$).



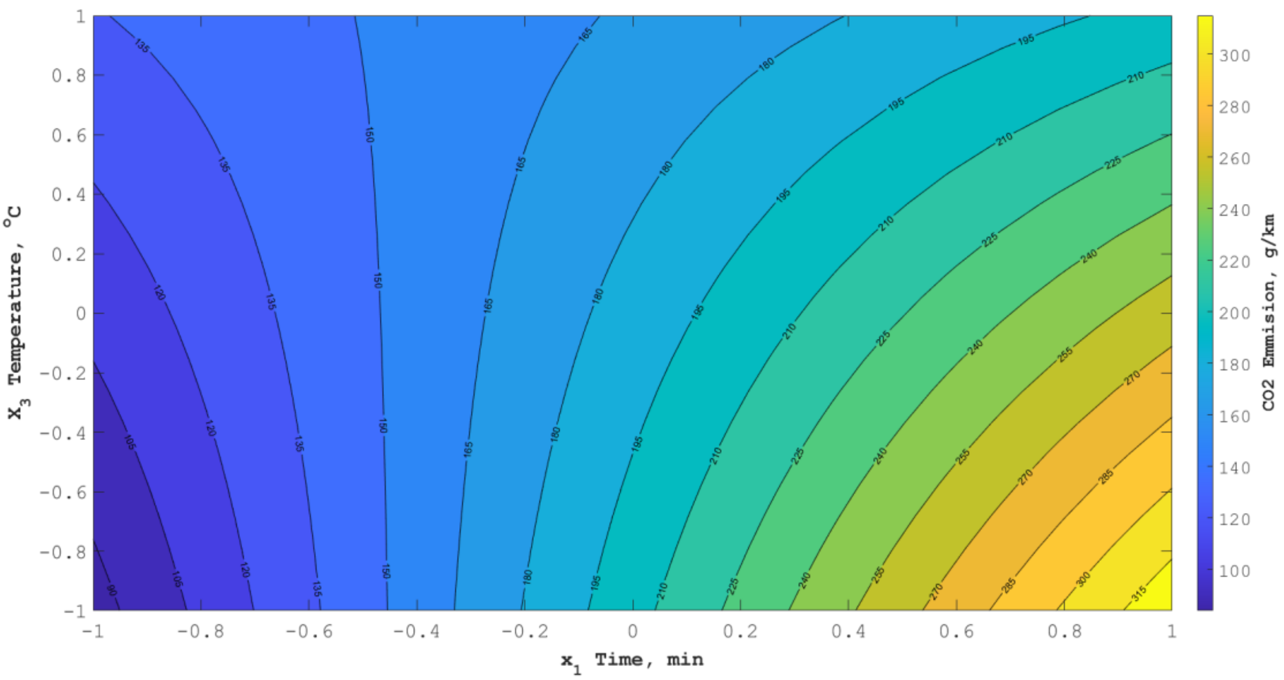
$$x_1 = 0 \; \forall \; y(x_2, x_3) = -48x_2x_3 - 68x_3 + 168$$

Figure 12. Change in CO_2 emissions depending on the variability of factors x_2 and x_3 for a vehicle (EV) moving for 20 min ($x_1 = 0$).



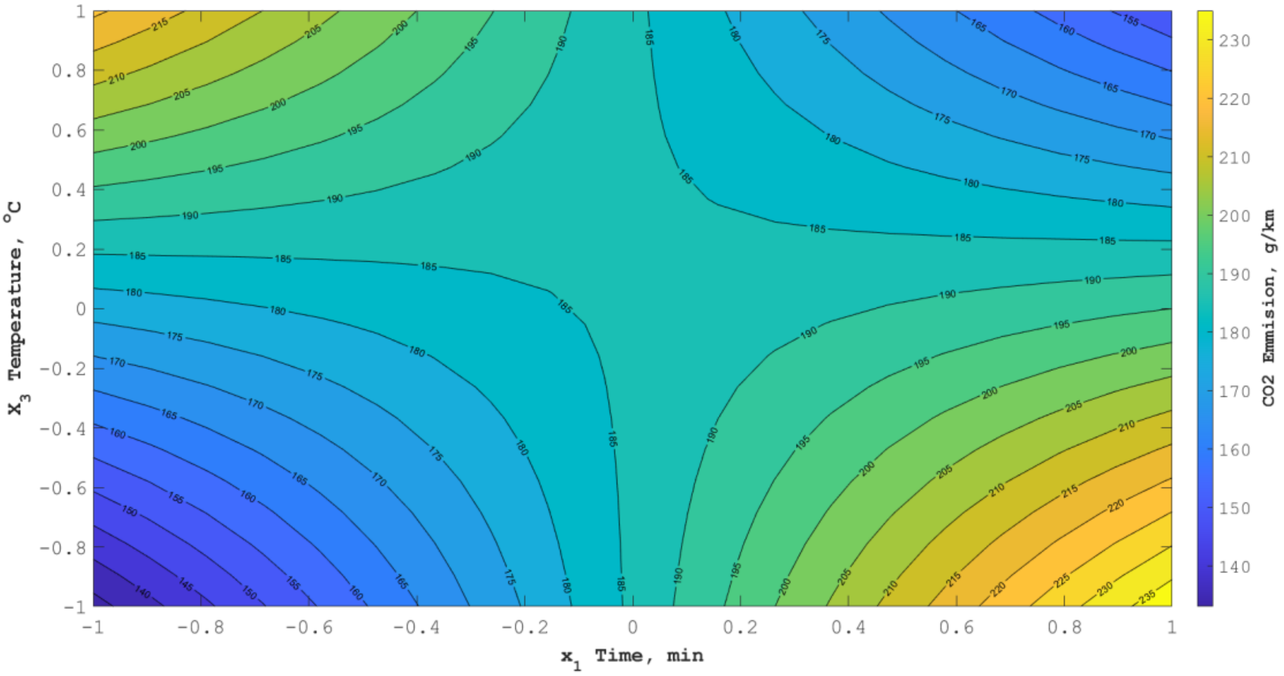
$$x_1 = 1 \ \forall \ y(x_2, x_3) = -49x_2x_3 - 112x_3 + 263$$

Figure 13. Change in CO_2 emissions depending on the variability of factors x_2 and x_3 for a vehicle (EV) moving for 10 min (x_1 = 1).



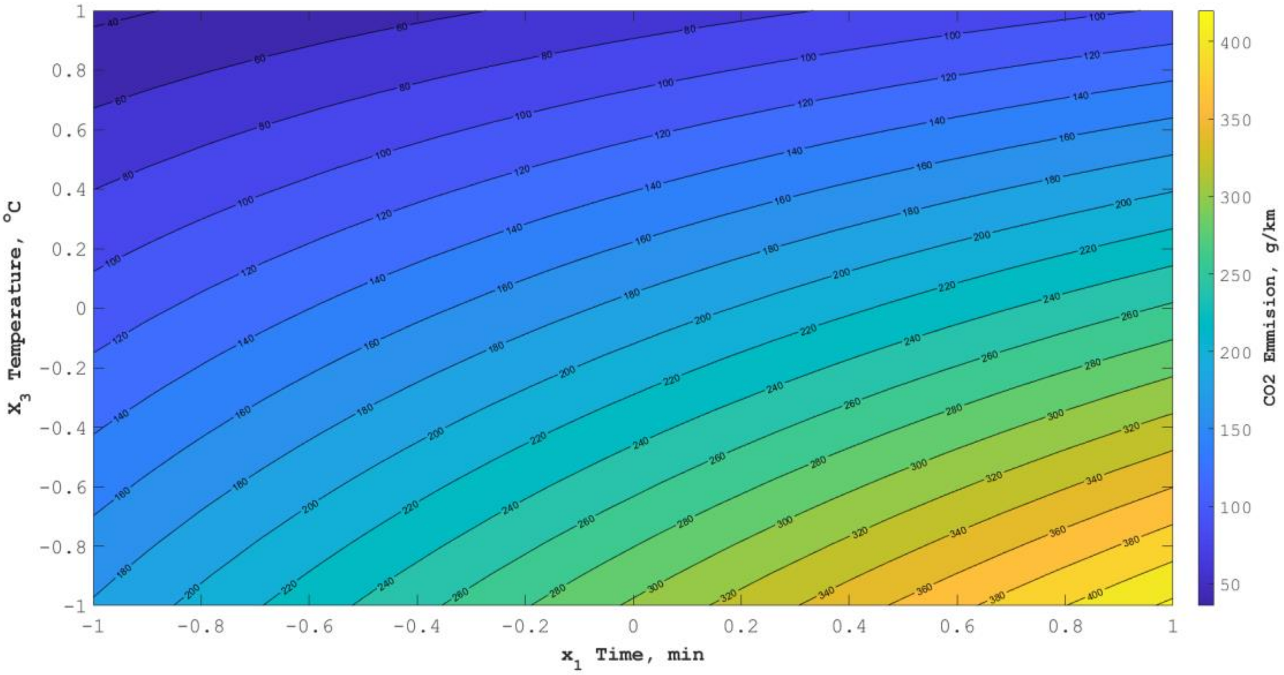
$$x_2 = -1 \ \forall \ y(x_1, x_3) = -44x_1x_3 + 77x_1 - 19x_3 + 186$$

Figure 14. Change in CO_2 emissions depending on the variability of factors x_1 and x_3 for a vehicle (EV) covering a distance of 2 km ($x_2 = -1$).



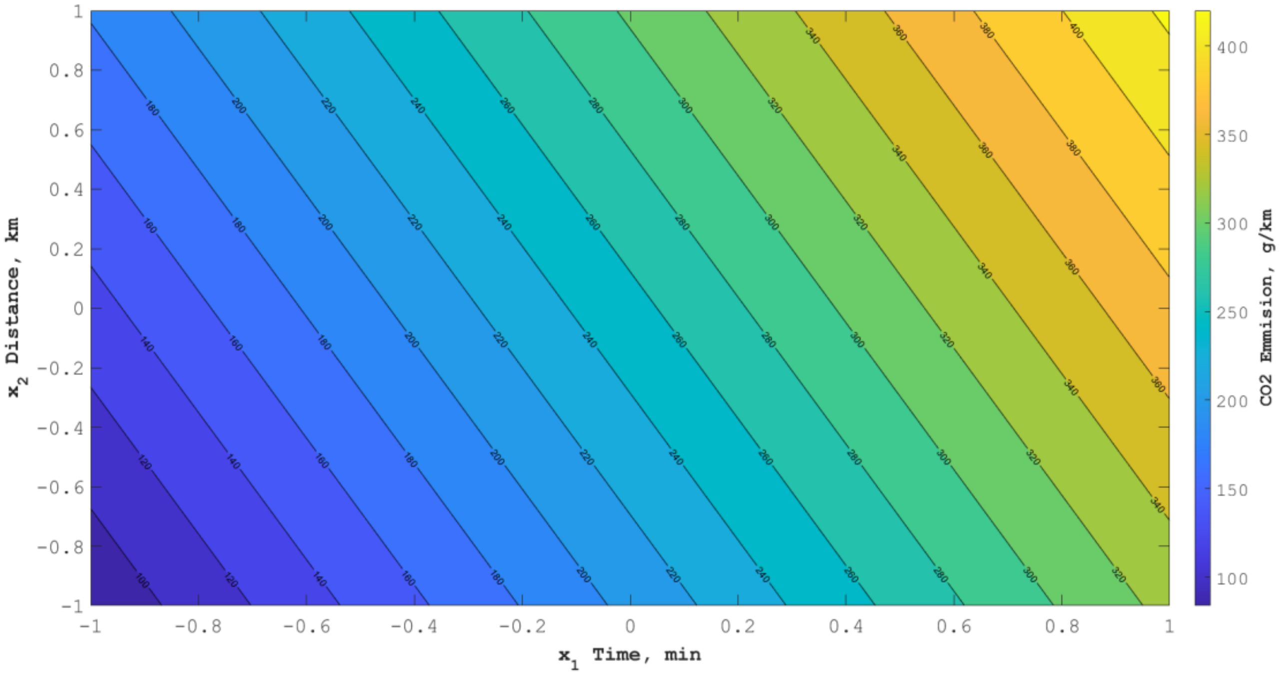
$$x_2 = 0 \forall y(x_1, x_3) = -44x_1x_3 + 77x_1 - 68x_3 + 186$$

Figure 15. Change of CO_2 emissions depending on the variability of factors x_1 and x_3 for a vehicle (EV) covering a distance of 3 km (x_2 = 0).



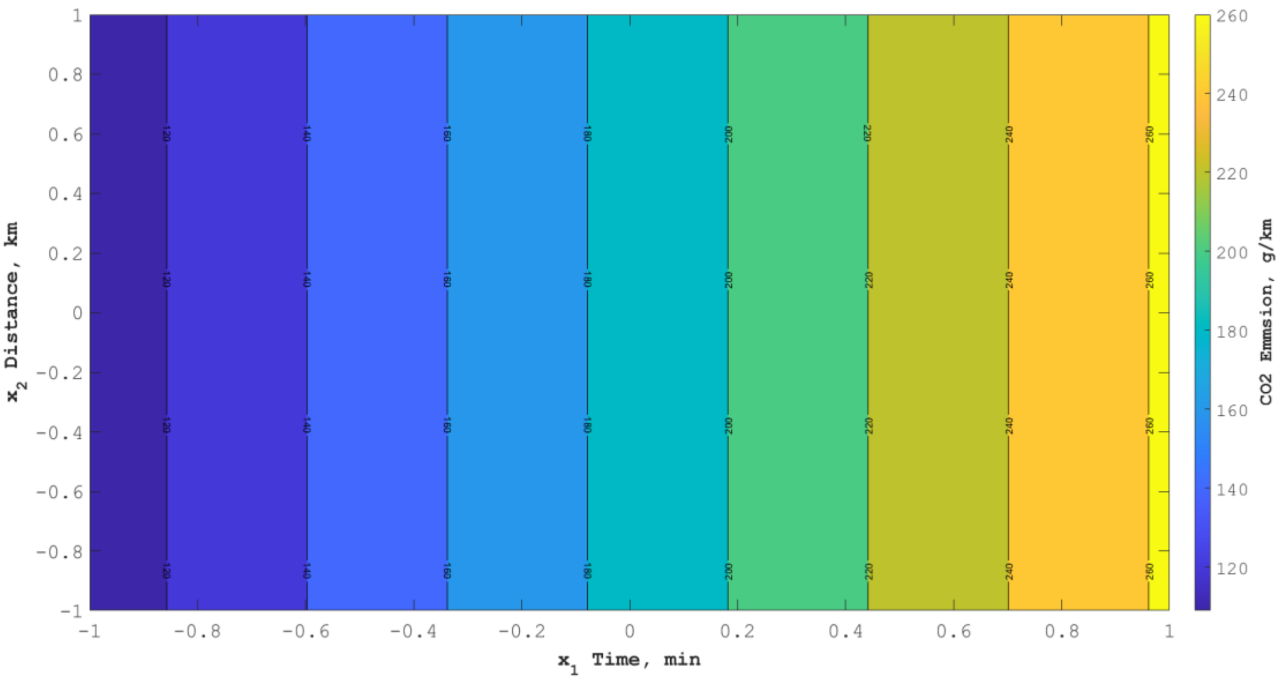
$$x_2 = 1 \forall y(x_1, x_3) = -44x_1x_3 + 77x_1 - 117x_3 + 186$$

Figure 16. Change in CO_2 emissions depending on the variability of factors x_1 and x_3 for a vehicle (EV) covering a distance of 4 km (x_2 = 1).



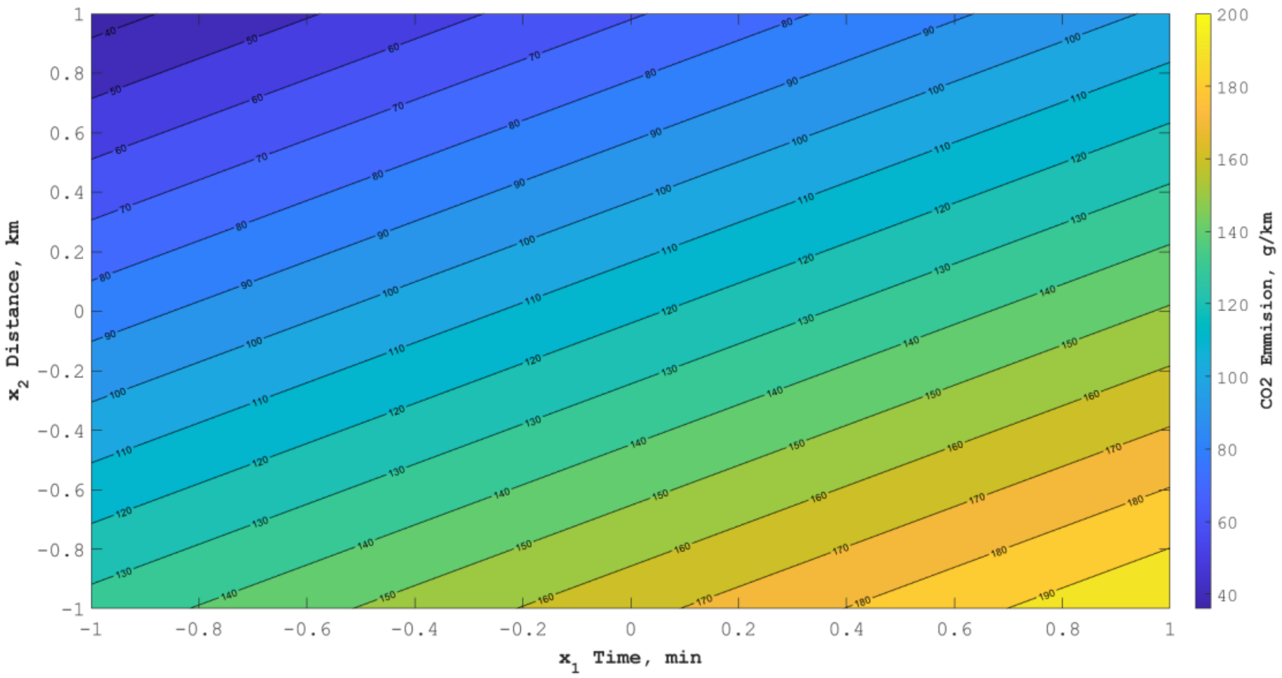
$$x_3 = -1 \; \forall \; y(x_2, x_3) = \; 121x_1 + 49x_2 + 254$$

Figure 17. Change in CO_2 emissions depending on the variability of factors x_1 and x_2 for a vehicle (EV) moving at a temperature of 15 °C ($x_3 = -1$).



$$x_3 = 0 \; \forall \; y(x_2, x_3) = \; 77x_1 + 186$$

Figure 18. Change in CO_2 emissions depending on the variability of factors x_1 and x_2 for a vehicle (EV) moving at a temperature of 20 °C ($x_3 = 0$).



$$x_3 = 1 \; \forall \; y(x_2, x_3) = \; 33x_1 - 49x_2 + 118$$

Figure 19. Change in CO_2 emissions depending on the variability of factors x_1 and x_2 for a vehicle (EV) moving at a temperature of 25 °C (x_3 = 1).

4. Discussion

Analyzing the results in detail revealed that the electric car, regardless of the road conditions, achieved lower carbon dioxide emissions, in the range of 10–65%, compared to the car with a combustion engine. The emission map of the tested electric vehicle showed high stability, regardless of the distance covered and the time of the given route. Among the factors analyzed, the temperature had the greatest impact, which directly translated into faster electricity consumption and, as a result, was associated with more frequent charging of the vehicle battery, which translated into an increase in carbon dioxide emissions. Therefore, it is particularly important that operators of car-sharing systems properly reward how the vehicle is driven at low temperatures and reward the appropriate behavior of drivers. In the currently available systems on the market, elements of gamification are introduced, such as rewarding drivers for an eco-friendly driving style. However, no detailed guidelines or offered prizes or discounts regarding driver conduct in the event of low temperatures were identified.

The second important conclusion is to draw attention to the correlation between the travel distance and travel time. The results indicated that extending the driving time by a factor of three will significantly affect the consumption of energy from the vehicle battery. This, in turn, will contribute to a two-fold reduction in carbon dioxide emissions by charging the vehicle's battery less often. This conclusion was reached by changing the way a car-sharing vehicle was driven from a dynamic to a smooth manner. It is also worth mentioning that companies operating in Poland following the environmental regulations of the Minister of the Environment [37] are required to annually report the fuel consumption of each vehicle used. One of the key factors affecting fuel consumption, and thus the vehicle's CO_2 emissions, is the way a given driver drives a vehicle (i.e., the driving style).

This is a very important conclusion for operators of car-sharing systems, which may translate into improved profitability of the fleet of vehicles used in the systems. It is also an indication that the fare in car-sharing systems should depend on the distance travelled (kilometer charge) and not on the time of travel (minute charge). First, it will allow cars to achieve lower CO_2 emissions and increase the safety of journeys by limiting dynamic and fast journeys to obtain the shortest possible car-sharing times. What is more, longer journeys will enable drivers to adapt to car-sharing systems, which in the future may encourage them to use the services more often. The results indicated that the inappropriate use of electric vehicles (i.e., improper driving style) can result in achieving higher carbon dioxide emissions than those achieved by internal combustion engine vehicles.

Moreover, considering the need for operators to pay high fees for increased carbon dioxide emissions and follow all kinds of guidelines aimed at achieving the highest possible level of transport sustainability, analyzing the possibility of reducing CO_2 emissions is important. This type of research has not been previously conducted for car-sharing services. These analyses and their results may support the functioning of vehicle-sharing systems by presenting real values of vehicle emissions for the conditions defined in the road tests.

Subsequently, it is worth emphasizing that for the given parameters, the emission of carbon dioxide turned out to be much higher for the car with an internal combustion engine than for the electric vehicle. A detailed summary of the results obtained is presented in Table 4.

Table 4. Comparison of the CO_2 emission values of the tested vehicles.

Sample No.	Results ICE	Results EV		
	ICE CO_2 Emission (g/km)	EV CO_2 Emission (g/km)	Δ = ICE-EV CO_2 Emission (g/km)	Δ = ICE-EV CO_2 Emission %
1	167.1	102.0	65	64%
2	306.3	272.3	34	12%
3	177.4	161.3	16	10%
4	169.9	102.0	68	67%
5	153.3	93.8	60	63%
6	294.6	249.0	46	18%
7	194.6	170.3	24	14%
8	260.7	204.0	57	28%
9	275.4	226.5	49	22%
10	149.8	90.8	59	65%
11	236.2	204.0	32	16%

The confirmation of the validity of the obtained results can also be found in other studies in the literature. For example, Wang et al. conducted a study of motor vehicles with internal combustion engines, focusing on the effect of ambient temperature on CO_2 emissions. The results showed that at low temperature (−10 °C), the vehicle emitted more than twice as much CO_2 than a vehicle used at 40 °C. It is worth noting that the results achieved by a vehicle with a combustion (petrol) engine were approximately 300 g/km, which gave 30 kg CO_2/100 km [38]. In turn, Buberger et al. addressed the issue of total CO_2 emissions resulting from all stages of a vehicle's life. They found that vehicles powered by renewable fuels (e.g., compressed biogas) had a similar impact on climate change as electric vehicles. Furthermore, the exhaust emissions of hybrid and electric vehicles are up to 89% lower than those of vehicles with internal combustion engines. The total CO_2 emissions of a vehicle with an internal combustion engine burning 7 L/100 km are approximately 49,500 kg. In comparison, an electric vehicle emits approximately 5500 kg of CO_2 [39]. However, it is worth emphasizing that previous studies [38,39] were carried out for private car trips, without meeting the conditions specific to car sharing. The discussion did not refer directly to car sharing research because such analyses had not been performed before.

5. Conclusions

In summary, the research carried out for car-sharing vehicles has shown that the value of carbon dioxide emissions is strictly dependent on the travel time, temperature, and distance of the route for which the vehicle is rented. Referring to the obtained results, it can be concluded that for electric vehicles:

- factor x_1—time of travel—can reduce carbon dioxide emissions in the range of 16–63%,
- the second of the examined factors x_2,—distance—can reduce emissions in the range of 14–28%,
- factor x_3—temperature—can reduce emissivity in the range of 16–65%.

Studies have confirmed that electric vehicles, despite the need to charge their batteries and emit carbon dioxide at the same time, are characterized by significantly lower emissions than combustion vehicles. This is an important conclusion, especially in the era of criticism of electric vehicles and the argument that the production of energy used for the charging process of vehicles may be more environmentally unfriendly than fuel combustion in vehicles with ICEs.

The obtained results confirmed that in the case of carbon dioxide emissions in car sharing, the driving style of the driver is the most important factor. The frequency of charging the vehicle's battery will depend on how the vehicle is driven. Additionally, it will also have a significant impact on battery life by increasing the number of battery charging cycles. This is an important conclusion, especially in terms of battery recycling and the life cycle of an electric car-sharing vehicle.

Applying the obtained results to business practices, currently one of the main problems of electromobility in short-term vehicle rental services is the batteries used in cars. Chinese or French business practices are examples of failures in the development of car-sharing services based on electric cars, mainly due the inappropriate approach of users to traveling by electric cars. As a result, companies were forced to charge vehicle batteries frequently, which contributed to premature wear of the batteries. The research conducted demonstrated that it is particularly important to inform car-sharing vehicle drivers about proper driving behavior at low temperatures and maintaining a moderate not dynamic driving style, especially when covering long distances in a short time. It is worth noting that the fees for car-sharing services currently used in Poland are based on per-minute charges for vehicle rental, which is conducive to inappropriately driving electric vehicles. The two main recommendations of the article for car-sharing operators are:

- Implementation of appropriate rewards for the manner of driving the vehicle. For example, the remuneration for proper car-sharing journeys could be discounts for subsequent journeys or providing the possibility of traveling in premium or higher class cars (available only to customers meeting the conditions of eco-friendly driving). Furthermore, it is also possible to offer this kind of benefit in the form of gamification, which could increase the interest of users.
- Implementation of a kilometer fee not minute fee for vehicle rental.

In the event of changing to a per kilometer rate, it should be properly propagated or proposed in the form of a loyalty program to emphasize the possibility of also using car-sharing services over longer distances. Then, car-sharing rentals could even better replace the use of individual cars.

In summary, the results obtained indicate that it is reasonable to replace the fleet of vehicles with internal combustion engines in car-sharing systems with electric cars to reduce carbon dioxide emissions and implement the assumptions of sustainable transport development. However, for fleets in car-sharing systems to fulfill their task and reduce carbon dioxide emissions, it is important to ensure the appropriate driving style of drivers in car-sharing systems. This type of procedure may translate into a reduction in the costs associated with maintaining a fleet of vehicles in car-sharing, both in the case of electric and combustion engine vehicles, which in turn may give the intended financial effect in the form of profitable systems. This is especially important in the era of imposing additional charges and taxes on companies for carbon dioxide emissions from vehicles. It is worth bearing this in mind because, as one of the milestones of the National Reconstruction Plan (called the Krajowy Plan Odbudowy), the government has committed to introducing fees for registering and owning the most emission-intensive combustion engine cars. This is an important issue, especially since Poland is now one of the four EU countries (along with Lithuania, Estonia, and Slovenia) that does not charge fees to owners of the most emitting vehicles [40]. Therefore, the implications of the obtained results are prepared for the upcoming legislative changes.

Referring to the limitations of the completed work, two main limitations should be mentioned. The main limitation is the use of only three parameters for the analysis of carbon dioxide emissions. However, it is worth pointing out that focusing on these parameters made it possible to achieve the assumed goals of the work and develop recommendations for operators of short-term vehicle rental systems. The second limitation is the performance of tests using only two types of vehicles. However, these were the vehicles most often used in Polish car-sharing systems. These were also vehicles comparable with each other in terms of overall dimensions and the represented vehicle class, which allowed for a detailed analysis. In subsequent works, the authors plan to perform analyses using a larger number of factors to show further aspects affecting the emission of carbon dioxide in car-sharing vehicles.

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