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Article

Interior Heating and Its Influence on Electric Bus Consumption

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Abstract: This paper focuses on the statistical evaluation of various operating characteristics of electric buses. The data obtained for statistical evaluation come from practice. In this paper, we focus on electricity consumption—an important aspect of electric bus operation. The ambient temperature significantly affects electricity consumption. In this paper, we use applied mathematics—correlation analysis, we accurately identify the effect of temperature on the consumption of the electric bus. Our next goal was to define the relationship between the loss of energy from the battery and driving power. We used regression analysis to describe this relation. Our article also includes an example of the practical use of ANOVA analysis in identifying a statistically significant effect of a particular vehicle on average consumption. We also show results from previous research and compare two different types of electric buses in operation.

Keywords: electric buses; heater; mobility; battery; capacity; transportation; ANOVA

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1. Introduction

Recently, the general interest in electromobility has increased significantly. Now, people connect electromobility with individual transport, mostly with car transport [1,2]. In the future, this probably will change other sectors. There are several studies from agriculture [3], road freight transport [4], or public transport [5] that deal with electric vehicles. There is also a possibility to use electric buses in cities [6] and improve the environmental impact of city transport [7]. Indeed, electric buses offer benefits related to operational, energy, and environmental aspects [8]. In this case, it is primarily a matter of reducing greenhouse gas emissions [9,10]. Buses with fuel cells are also environmentally friendly [11,12]. We can therefore consider them as the future of public transport. It is for this reason that many scientists are interested in the construction of electric buses. It is necessary to research their power drives, batteries [13], their maintenance [14], and possibilities of recuperation [15]. It is the battery that is an essential part of such a vehicle [16,17]. It is precisely the capacity and life of the battery [18] that currently slows the broader expansion of electric buses in operation. For this reason, the authors of foreign studies often also deal with the energy management of electric buses [19–21].

According to [22], electric buses are a necessary part of sustainable urban development. Compared to buses with a conventional internal combustion engine (ICE), they are more energy-efficient [23]. Their advantage is also in the gradual reduction of dependence on fossil fuels. Electric vehicle batteries have the potential to store energy from renewable sources—wind, sun, and water. This can help to balance fluctuations in energy consumption throughout the day.

In the following paragraphs, there is a literature review of electric vehicles in general. This comprehensive information is necessary because electric buses are a significant subset of electric vehicle. From a microeconomic point of view, battery electric vehicles (BEVs) can be advantageous for the end-user, due to a lower price of electricity compared to the price of petrol or diesel [24]. However, electric vehicles have relatively high acquisition costs. Many scientific studies address their cost-effectiveness for households [25–27], often through total cost of ownership (TCO) [28,29]. However, electric vehicles also have other problematic aspects in terms of economy and operation; e.g., [30,31] mentions that they still have insufficient charging infrastructure and insufficient capacity of the BEV batteries. It causes the psychological concern of drivers regarding the charging time, the short range, and the discharge of the BEV while driving [32].

Some authors agree that electric vehicles currently need partial state subsidies [33,34]. There is an opportunity for publicly subsidized electric buses in public passenger transport [35]. For this area of public transport, attractiveness is more important than economic efficiency [36]. Vehicles with zero emissions and low noise emissions can improve the quality of urban public transport. This advantage is particularly evident in cities where buses are the only vehicles of the local public transport enterprise. In addition, regular bus transport has the advantage that buses ride on defined routes at predetermined intervals by the schedule [37]. Appropriate planning can thus ensure trouble-free charging of electric buses in various ways, e.g., using a cable or even a pantograph [38]. It is precisely the optimization of the layout of charging stations that several studies have addressed [39–41]. It is also necessary to deploy basic and fast charging stations as optimally as possible [42].

It is clear from the previous text that electric buses have their potential and advantages in regular bus transport, especially in short-distance urban traffic. There is the possibility that frequent charging from prebuilt infrastructure is possible, e.g., charging from the pantograph at the final stop. Our study focuses on currently used electric buses in the Slovak Republic. The Ministry of Economy of the Slovak Republic processes the statistics connected with electromobility [43]. In 2015, only 86 plug-in hybrids (PHEV) and 224 electric cars (BEVs) were registered in Slovakia. In 2020, their number increased significantly to 1021 PHEV and 1582 BEVs. We also have information on the composition of these BEVs: 606 motorcycles, 138 all-terrain vehicles (ATVs), 1582 cars, 124 small trucks up to 3.5 tons gross weight, 15 working machines (with registration numbers), and 47 buses (category M3, large bus). The number of electric buses in the Slovak Republic is therefore not so high. In the following chapter, we specify all these buses in detail. On a macroeconomic scale, it is necessary to compare the relative shares of electric buses in the entire vehicle fleet. According to [44], the share of electric buses in Europe was only 0.2%; this is significantly lower than in China (14%). According to this source, the situation is even more unfavorable in the USA, where the share of electric buses was only 0.03% in 2018. If we consider the Slovak Republic, as of 30 June 2020, exactly 8000 buses [45] were registered, of which 2891 were long-distance (36.14%), 3756 suburban (46.95%), 1348 urban (16.85%), and 5 special (0.08%). The share of electric buses in the total number was therefore only 0.59%.

In this article, we focus on the consumption of electric buses in the Slovak Republic. This essential characteristic has specifics due to large temperature fluctuations in the summer and winter seasons. For example, in 2020, the average daily temperature in Bratislava was more than 25 °C in summer and less than −5 °C in winter [46]. This temperature difference requires air temperature adjustment in the interiors of public transport vehicles. In winter, it is necessary to heat air in buses. On the other hand, air conditioning also makes public transport more attractive.

Our article has several benefits for researchers as well as for practice. As follows from the previous text, Slovak transport companies operate only with several electric buses. We can say that only three transport companies in the whole country have experience with their operation. A significant benefit is the study of the consumption of electric buses, which no-one has published for our conditions. The electric buses have been in operation for a relatively short time. We have managed to obtain and analyze data on their consumption. The published results are helpful for future decisions on investments in electric buses. At present, there is a general concern that electric buses will be unreliable in the winter—at low temperatures with a short range. It is this fact that we will try to verify in the following text. We will also focus on the differences in energy intensity caused by different ways of heating electric buses.

2. Materials and Methods

The previous section briefly described the theoretical basis of the current state of electric vehicles. The electromobility in the field of public passenger transport is not very developed in the Slovak Republic. There are only 47 electric buses in the Slovak Republic. We managed to identify and classify 46 of these vehicles. We show the list of all mentioned vehicles in Table 1.

Table 1. Electric buses operated in Slovakia. Source: [47], processed by authors.

Count	Brand	Type	Length (m)	Capacity (pax) *	Weight (kg)	E-Motor Power (kW)	Max. Speed (km/h)
18×	SOR	EBN 11	11.10	29 + 63	10,000	120	80
5×	SOR	EBN 10.5	10.37	19 + 54	10,200	120	80
2×	SOR	EBN 8	8.00	16 + 38	9020	120	80
16×	SOR	NS 12 electric	12.00	33 + 72	12,350	160	80
2×	Škoda	Perun 26SH01	12.00	28 + 42	12,835	160	80
1×	Škoda	Perun 26BB HE	12.00	28 + 42	12,835	160	80
2×	Troliga	Leonis EV	12.00	30 + 64	13,000	113	90

* Capacity in sitting + standing passengers.

In our research, we used the procedure that we graphically represent in the flowchart in Figure 1. The source dataset from the bus operator contains information from onboard units (OBUs), drivers, and dispatchers. It was also necessary to obtain temperature data for all analyzed days. The flowchart shows the complete data processing described in this study.

2.1. Analyzed Vehicles and Input Data Structure

For this study, we obtained data on the consumption of two SOR EBN 8 electric buses and sixteen SOR ENS 12 electric buses of the Bratislava Transport Company (Bratislava, Slovakia). We also obtained selected data on the consumption of Škoda Perun 26SH01 vehicles of the Žilina Transport Company (Žilina, Slovakia).

SOR EBN 8 is a city bus for 16 sitting passengers with a total length of 8 m. The drive unit is an asynchronous six-pole motor with a power of 120 kW and liquid cooling [48]. A battery has a capacity of 172 kWh. The air-conditioning system has a cooling capacity of 10 kW. This brand of buses uses independent diesel heating. The first two buses, which we analyze in this article, started their operation in the capital city at the beginning of 2018. The price of one vehicle was EUR 488,000. The purchase of electric buses was co-financed by the European Regional Development Fund under the Integrated Regional Operational Program 2014–2020 [49]. Vehicles have numbers 3901 and 3902. For both buses, we have traffic records for more than 1200 days.

SOR NS 12 electric is a city electric bus. It is 12 m long with 29 to 35 seats, according to the design. The drive unit is asynchronous and liquid-cooled, with an output of 160 kW [50]. Due to the size of the vehicle, the power of the air conditioning is up to 15 kW. The capacity of the traction battery is 242 kWh. The bus has independent diesel heating. Bratislava Transport Company uses 16 vehicles of this type. Along with electric buses, the company also supplies the charging infrastructure. The price of one electric bus was EUR 589,000 [51].

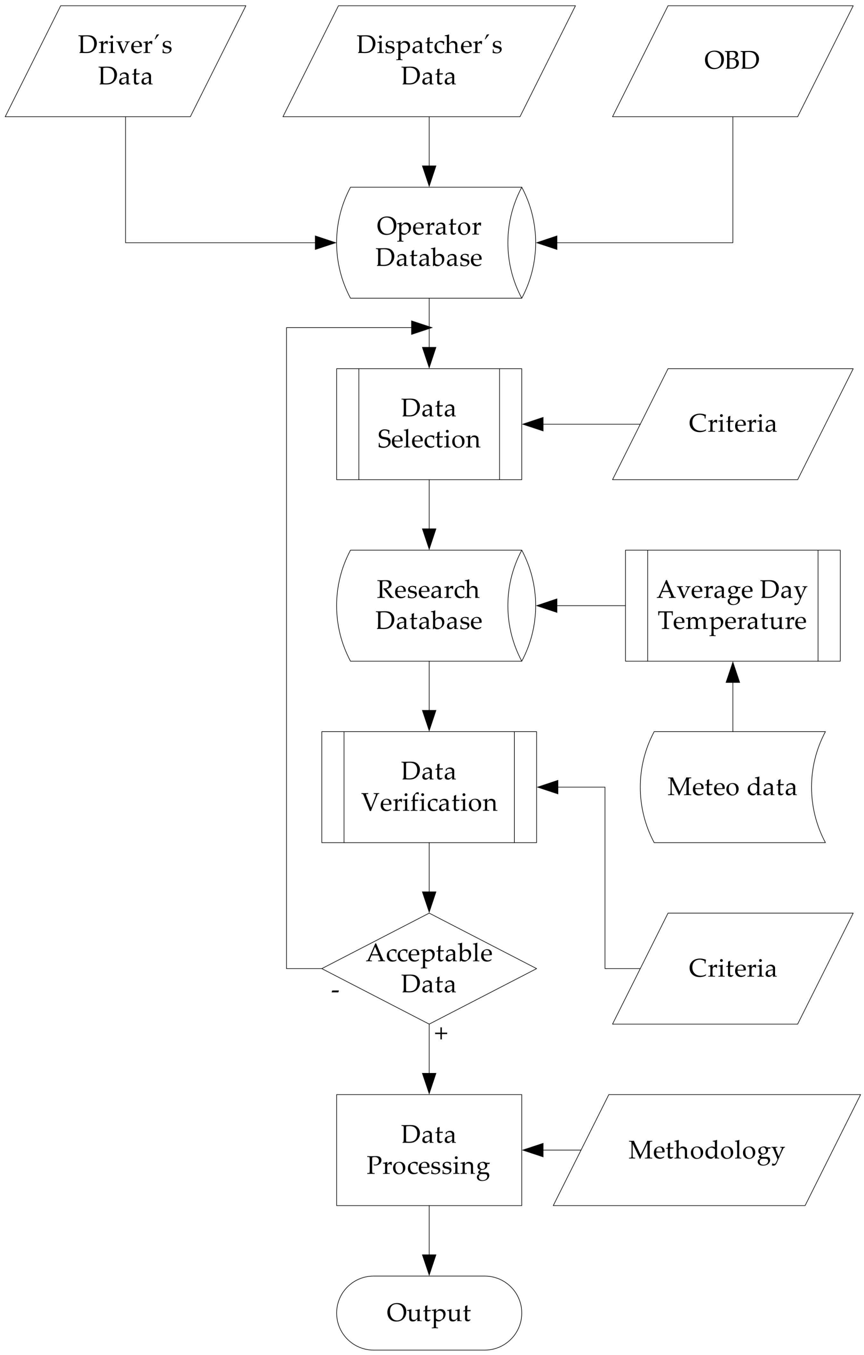

Figure 1. Flowchart showing the complete research process. Source: Processed by authors.

For both types of electric buses operated by Bratislava Transport Company, we have daily records of operating data (the part of the database is attached as Supplementary Materials—Table S1) in the following structure:

- Date—every day, regardless of whether the vehicle was in service, ready for service, or repaired.
- Day—indicates the day of the week.
- Driver's name—only one name is in this column if only one driver used this vehicle during the day. Vehicles used in the two-shift operation have the names of two drivers in this column.
- The following data is entered for both parts of the two-shift operation:
    - State of charge (%)—charge level before the start of the first and second shift.

- ○ Line—an indication of the defined daily route of an electric bus. It is not a single bus line.
- ○ Start and end of the ride (h:min).
- ○ Driving time (h:min).
- ○ Driving distance (km).
- ○ Battery balance after the first and second shift (%).
- ○ Charging after the first and second change (kWh).

- Refueling—all SOR electric buses have independent diesel heating. Therefore, the database also contains the consumption of diesel for heating. Drivers do not refuel buses very often: during winter, once every two days in a volume of about 10 to 60 L.
- Total driving distance—the total distance traveled by the electric bus for a day (km).
- Total electricity consumption (kWh).
- Total driving time (h:min).
- Average consumption (kWh/km).
- Notes—in this column, it is possible to find a charging station number or information about fast chargers using or charging from the pantograph.

The whole database is quite extensive. Therefore, in the following table (Table 2), we show the number of records and the driving distance of each vehicle. This information is necessary, as it proves that it is not a sample survey, but that we have analyzed the whole period of operation of electric buses from 2018. In the first year, tests of electric buses and their gradual start of the service took place. For that reason, values of driving distance are lower. We should also note that the database ends on 10 May 2021.

Table 2. Input data of operated electric busses. Processed by authors.

Vehicle Code	Type	Records	Annual Driving Distance (km)			
			2018	2019	2020	2021
V3001	NS 12 electric	856	36,640	60,340	45,311	23,658
V3002	NS 12 electric	993	44,380	48,538	62,754	18,430
V3003	NS 12 electric	846	14,598	57,668	65,442	20,660
V3004	NS 12 electric	804	21,906	57,978	57,712	8464
V3005	NS 12 electric	852	14,542	55,050	58,795	22,967
V3006	NS 12 electric	870	15,643	59,592	65,487	20,871
V3007	NS 12 electric	884	12,520	54,263	73,923	24,140
V3008	NS 12 electric	807	9114	56,555	61,542	13,585
V3009	NS 12 electric	751	9725	55,046	44,073	20,796
V3010	NS 12 electric	663	1770	28,964	64,147	24,316
V3011	NS 12 electric	785	7795	53,198	51,643	23,275
V3012	NS 12 electric	796	7279	57,015	53,111	23,157
V3013	NS 12 electric	830	7204	56,545	58,588	24,485
V3014	NS 12 electric	762	2677	47,481	61,085	23,685
V3015	NS 12 electric	800	5326	53,157	58,167	19,036
V3016	NS 12 electric	783	6730	50,969	54,156	23,247
V3901	EBN 8	867	28,691	25,497	30,575	10,032
V3902	EBN 8	936	22,626	36,196	36,317	11,826
Total		14,885	269,166	914,052	1,002,829	356,629

2.2. Data Collection

All the data we used for the statistical analysis came from two places. The operational department of the Bratislava Transport Company provided complete information on the daily operation of electric buses for the entire period of their service. This data is comprehensive and obtained from various sources:

- Information such as the state of charge of batteries, driving distance, battery balance, and charging in kWh are from electronic control units (ECU) of each electric bus.
- On the other hand, the driver writes down the exact volume of refueling heating diesel.

- There are also parameters that the dispatcher writes down. He decides the names of the drivers who will drive on each work shift. He also determines the exact "line" (not the single bus line, but the complete set of bus connections per one work shift).

We also obtained operation data for two electric buses owned by Žilina Transport Company (Žilina, Slovakia). In this case, the data have a substantially different structure:

- Identification data (bus number, VIN—vehicle identification number) and time range of data entry.
- Total travelled distance in km.
- Total electric energy in kWh:
    - Charged via pantograph.
    - Charged via the power cable.
- Total consumption divided into:
    - Internal consumption with energy redistribution: clean traction, auxiliary drives, heating, air conditioning, energy for 24 V appliances.
    - External consumption.
- The data log also contains daily data of charged energy, mileage, consumption, and number of battery balances.

2.3. Research Hypothesis

In this article, we test the following hypotheses:

Hypothesis 1 (H1). *There is a relationship between the ambient temperature and the electricity consumption of an electric bus heated by electric heaters in the winter months (Pearson's correlation coefficient* $|R| > 0.6$*). This dependence only arises if the vehicle has electric heaters, because they have a direct effect on the total consumed energy.*

The consumption of the electric bus is significantly affected by heating or air conditioning. In the previous research, we focused on analyzing the operating characteristics of the Škoda Perun 26SH01 electric buses. We want to identify the dependence of consumption and ambient temperature, so we add two more related hypotheses:

Hypothesis 2 (H2). *Electric buses with independent diesel heating show no or little dependence (Pearson correlation coefficient* $|R| < 0.3$*).*

Hypothesis 3 (H3). *There is a relationship between the ambient temperature and the electricity consumption of the air-conditioned electric bus in the summer months.*

Hypothesis 4 (H4). *Differences in average electricity consumption are statistically significantly different for different vehicles. For this, we use the ANOVA tool. We aim to find out whether the value of the independent quantity—a specific vehicle—has a statistically significant effect on the value of the dependent variable; in this case, the vehicle consumption in kWh/km.*

The last and significant task is to compile the most accurate equation of the dependence of two quantities—driving distance and energy consumption from the battery [52]. We express this dependence graphically and try to capture this dependence with a suitable function using regression analysis. This role is most important for planning the performance of electric buses in practice [53]. At present, the capacity of batteries in vehicles is still not sufficient. In addition, according to [54–56], it gradually decreases.

For statistical analysis and verifying hypotheses, we use advanced statistical methods described in the following subchapters. We have data on the operation of electric buses in Bratislava for each calendar day, including Saturdays, Sundays, and holidays. On these days, some vehicles were not in service. Therefore, it was necessary to filter all records of the database. There were also days with very short driving distance, which should not be involved. These could be related to, for example, vehicle repair or a test drive after repair. The last problem was the incorrect entries. They caused extreme values of electricity consumption (low or high). We did not consider them.

2.4. Correlation Analysis

Correlation analysis deals with the evaluation of the dependence of two random variables. This method evaluates the intensity of the relationship. The dependencies, which it examines, are primarily linear. It is a measure of a linear relationship. The well-known fact is that correlation is not causality. Quantities that correlate with each other can be interdependent. However, we cannot say with certainty that they are conditional.

Covariance *cov xy* describes the existence of a linear relationship between two variables. With the covariance, we can evaluate the relationship between two random variables x and y. The basic equation for its calculation is Equation (1):

$$cov\ xy = \frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y}) = \overline{xy} - \overline{x}\cdot\overline{y} \quad (1)$$

Values of covariance are in the interval $(-\infty; +\infty)$. It gives us only information about the dependence between the variables (existing or not). Usually, we want to calculate the dependence intensity. Therefore, we use the correlation analysis:

- The result of correlation analysis has values from the interval $\langle -1; 1 \rangle$ or $\langle 0; 1 \rangle$.
- As the dependence increases, the correlation coefficient also increases.
- The correlation coefficient must be independent (variables can have different units).

If we want to obtain the correlation coefficient, we need to divide the covariance by standard deviations of variables. We can use the following Equation (2):

$$R = \frac{cov\ xy}{s_x s_y} = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\cdot\left[n\sum y^2 - \left(\sum y\right)^2\right]}} \quad (2)$$

Typical correlation coefficient has values from the interval $\langle -1; 1 \rangle$. It measures the two-tailed linear dependence of two variables. There can be only three possible results according to the value of the coefficient:

- $R = 0 \Leftrightarrow$ variables X and Y are not linearly dependent.
- $R > 0 \Leftrightarrow$ a direct linear relationship between the variables X and Y.
- $R < 0 \Leftrightarrow$ an indirect linear relationship between the variables X and Y.

According to [57], the interpretation of the correlation coefficient depends on the context. For example, the correlation coefficient of 0.8 is very high for psychological research but very low for physics. In 1988, Cohen [58] described the correlation according to the coefficient value as follows:

- The correlation in the absolute value below 0.1 is trivial.
- The correlation in the range of 0.1 to 0.3 is small.
- In the interval of 0.3 to 0.5 it is medium.
- At values above 0.5 it is high.
- The correlation of 0.7 to 0.9 is very high.
- A correlation in the range of 0.9 to 1.0 is almost perfect.

2.5. ANOVA Analysis

ANOVA analysis, or analysis of variance, investigates the relationship between non-dependent and dependent variables, especially when evaluating experimental data. If we examine the effect of only one factor on one or more dependent variables, it is a single-factor ANOVA analysis. It assumes a single explanatory variable. In multivariate analysis of variance (MANOVA), we can have several explanatory variables simultaneously [59].

To determine whether the observed variability of the variable Y depends on the affiliation of the values in the groups, we break down the overall variability into components corresponding to different sources of variability. We express variability in the one-dimensional case using the sums of squares, and in the multidimensional case using matrices in which the sums of squares form the main diagonal. The analysis of the variance model is a specific case of the general linear model (GLM). Hypotheses about the influence of factors are a special case of the general linear hypothesis about the parameters of the model [60].

2.6. Regression Analysis

By regression analysis, we determine the dependence of the input (X_1, X_2, ...) on the output (Y). The regression analysis aims to estimate this relationship as accurately as possible. In contrast to correlation analysis, we are not just looking for a linear relationship. Thus, we try to overlay the measured data with the curve, which should describe and forecast the behavior of a sample of the measured data. In the simplest case, it will be a linear relationship, a linear regression.

When we want to select the correct regression function, we use the method of least squares. It should be such a function that its values are close to our data sample. It does not have to be linear. In some cases, we can use quadratic, cubic, logarithmic, or another function.

An indicator of the correctness of the model is the so-called coefficient of determination R2. This indicator of model adequacy expresses what percentage of output variability (Y) is caused by our inputs (X_1, X_2, ...). We also know the adjusted coefficient of determination R^2 (adj). It considers the number of predictors in the model.

3. Results

The first task was to filter the whole database of daily records. There were many empty lines for the days when the vehicle was not in service. During these days, the bus was technically ready (weekends, holidays, or other days when the bus was unnecessary) or repaired (service, technical inspections, etc.). It was equally important to remove any faulty records. These were raised due to errors on the measuring device or driver's mistake. After this data cleaning, 14,888 data records remained available for the analysis of 18 electric buses. The production data of three analyzed electric buses are in Table 3. According to the statements of electric bus producers Skoda Transportation (Plzen, Czech Republic) and SOR (Libchavy, Czech Republic), the batteries described in the table should have similar production years as the bus itself.

Table 3. Production data of analyzed electric buses. Source: [48,50,61], processed by authors.

Brand	Type	Price [EUR]	Production Year	E-Motor Type	Battery Capacity [kWh]	Battery Type	Battery Producer
SOR	EBN 8	488,000	2017	Asynchronous six-pole, liquid-cooled	172	Lithium-ion	Winston battery
SOR	NS 12 electric	589,000	2017/2018	Asynchronous six-pole, liquid-cooled	242/388	Lithium-ion	Winston battery
Škoda	Perun 26SH01	576,500	2018	Asynchronous	222	Lithium Cobalt Manganese Nickel Oxide	EVC Group

3.1. Electric Buses with Electric Heaters

In the previous research, we focused on other types of electric buses. These two vehicles, operated by the Transport Company of the City of Žilina (Žilina, Slovakia), have the type designation Škoda Perun 26SH01. These vehicles have lower emissions because they do not have independent diesel heating. We found that the impact of air conditioning on consumption is negligible overall. It was possible to make a regression analysis for the relationship between temperature and overall electricity consumption. We tested the suitability of chosen regression equation with the coefficient of determination. The linear regression explained approximately 77.4% of the values (R^2 = 0.774). Its equation was y = 3.71 − 0.08x. Then, we tried to explain the relationship with the exponential function. It was possible to explain more than 80% of the values (R^2 = 0.819). Its graphical representation is in Figure 2. Nodes of winter values are blue, and summer values are black.

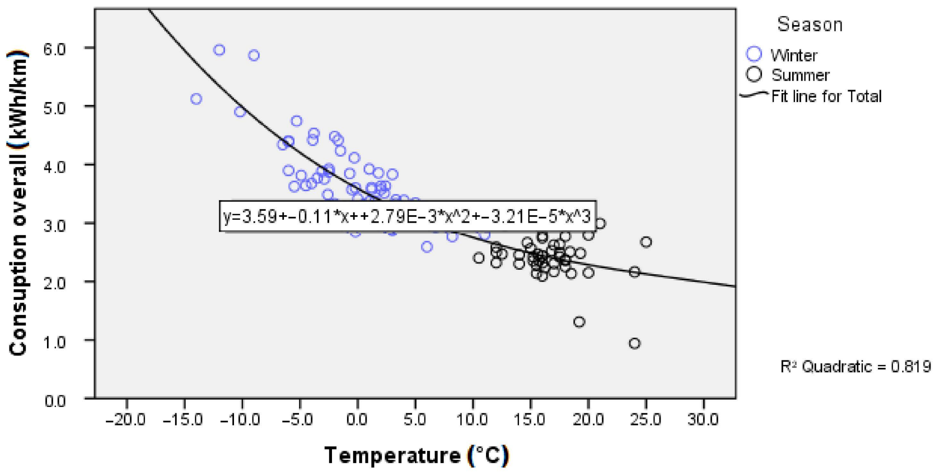

Figure 2. Dependence of temperature and overall consumption. Source: Processed by authors.

Figure 2 shows a graph of average electricity consumption. On the left side are four extreme values of electricity consumption. We should state that not just low temperatures but also high temperatures caused this consumption. The traveled distance of these four days was quite low. During the data cleaning, we had a minimum daily distance necessary for further evaluation. However, the electric bus traveled this minimal distance during these four days. We should also mention that the figure shows the total consumption that includes the energy for traction e-motor, heating, and for all other electrical appliances in the bus. Our data are from the diagnostic system Astrid, Škoda Electric (Škoda, Plzeň, Czech Republic).

The results of the second part of the research were quite different. We focused on the relationship between the electricity consumption of the e-motor and the ambient temperature. We could explain only about 25% of all values with the regression analysis. A low correlation coefficient (R = −0.496) caused these results. With linear regression, we obtained the coefficient of determination R^2 = 0.246. Better results produced the exponential function. The coefficient of determination was R^2 = 0.268.

3.2. Electric Buses with Diesel Heaters

In this article, we deal with electric buses that use independent diesel heating. The following figure (Figure 3) shows the total diesel consumption during the operation of all electric buses for the entire period. The consumption of diesel increases significantly in the winter months. We show average temperatures for each depicted month. These values are above 0 °C. For detailed calculations and analysis, we used average daily temperatures. These temperatures were calculated by the standard Equation (3).

$$t_d = \frac{t_7 + t_{14} + 2 * t_{21}}{4} \quad (3)$$

In Equation (4), *td* is an average daily temperature, t_7 is the temperature at 7:00 a.m., t_{14} is the temperature at 2:00 p.m., and t_{21} is the temperature at 9:00 p.m.

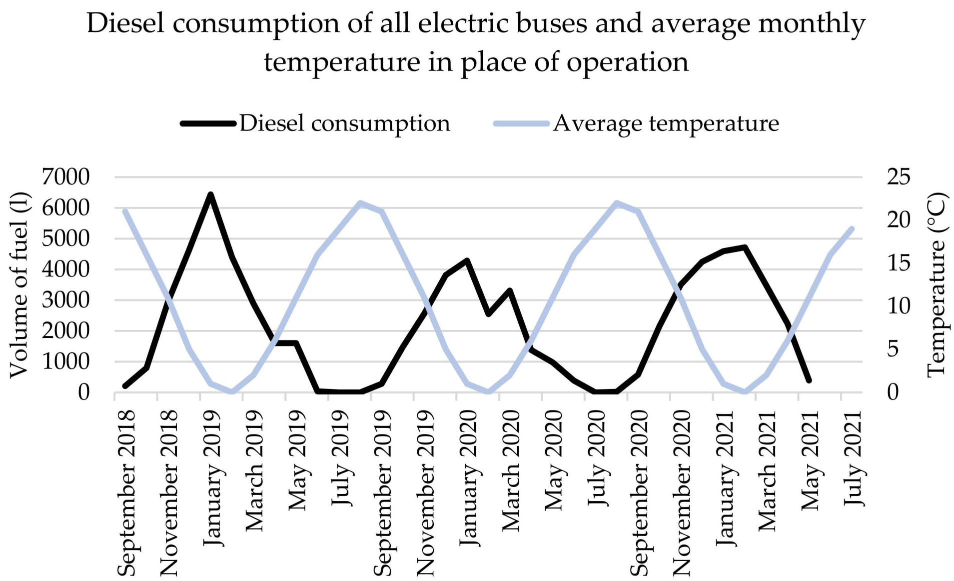

Figure 3. Volume of fuel used for heating in months with average monthly temperatures. Source: Processed by authors; temperatures from [62].

Figure 4 shows the comparable average consumption of a randomly selected electric bus with diesel and electric heating. The picture only captures the electricity consumption of the traction e-motor. Regardless of the method of heating, consumption increases in the cold winter months.

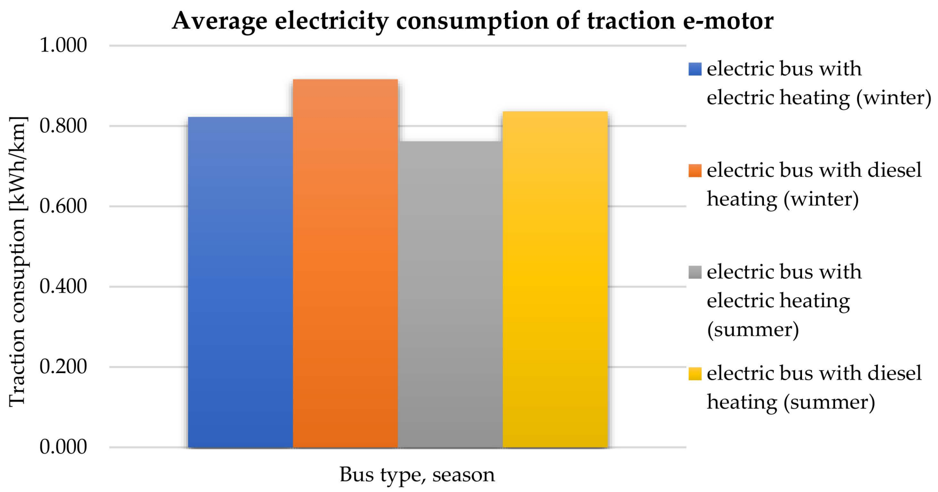

Figure 4. Average electricity consumption of traction e-motor for both types of electric bus. Source: Processed by authors.

Figure 5 compares the electricity consumption for heating in the summer and winter months. In the temperature conditions of Slovakia, it is necessary to heat the passenger area even during the summer months in the early morning hours. Therefore, we could calculate the electricity and fuel consumption also in the summer months. Electricity and fuel consumption are difficult to compare, so the chart has different left and right axes.

To answer the first hypothesis, we must also look at the electricity consumption of individual electric buses. We paired its almost 15,000 daily values with the daily average temperature at the place of operation of electric buses in Bratislava. Subsequently, we used correlation analysis to calculate the coefficients of correlation between consumption and temperature. Due to the independent heating, the coefficients reached significantly lower values. For better comparison, we expressed these values graphically for 12 m vehicles V3001 to V3016 and for 8 m vehicles V3901 and V3902 (Figure 6).

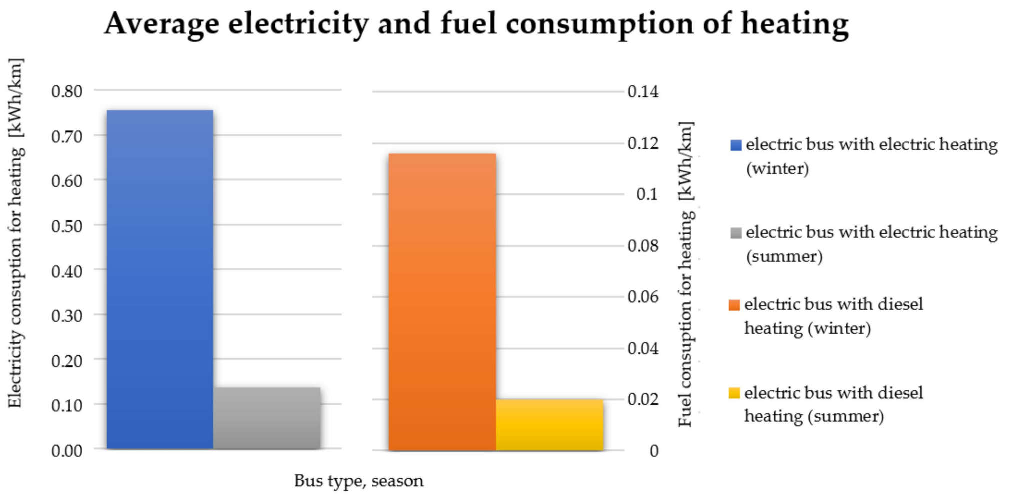

Figure 5. Average electricity and fuel (diesel) consumption of heating system for both types of electric bus. Source: Processed by authors.

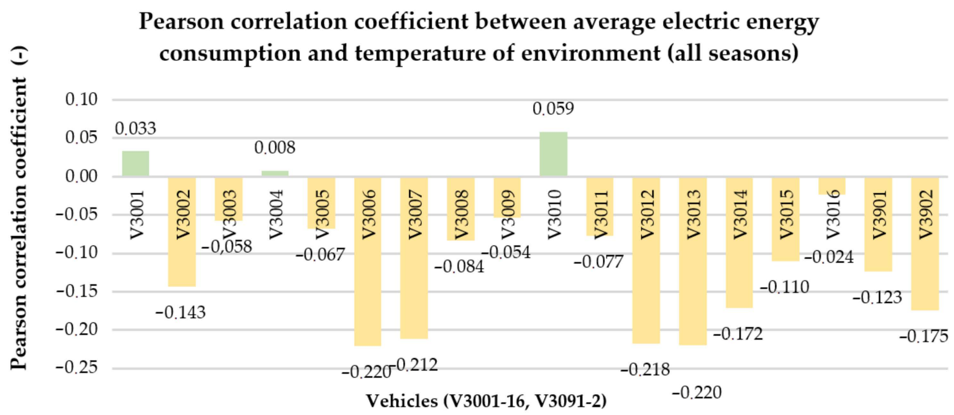

Figure 6. Volume of fuel used for heating in months with average temperatures. Source: Processed by authors; temperatures from [63].

Figure 6 shows that the Pearson correlation coefficient has mostly negative values for individual vehicles (indirect dependence). Its value is up to 0.3. Therefore, we can draw two conclusions on this part:

- The negative conclusion is that it is not possible to predict the consumption of an electric bus with independent diesel heating based on ambient temperatures.
- A positive conclusion is the unconfirmed concern about the higher electricity consumption during winter.

A related issue is an operation in the significantly warm (summer) months. It is the period when buses use air conditioning units. For this reason, we selected only three summer months for further correlation analysis—June, July, and August. Although the calculation confirmed the expected positive value, the value R = 0.1284 was too low. We can therefore conclude that there is no linear dependence.

Another part of the research is a comparison of vehicle consumption. For the further operation of electric buses, it is necessary to examine other relationships. We want to know if a particular vehicle affects average consumption. For these purposes, we use the ANOVA analysis. This tool determines whether the independent variable has a significant impact on the value of a dependent variable. In this case, each vehicle has a different number of values (cleaned days in operation). For this reason, we used ANOVA: single factor. We processed analysis separately for vehicles V3001 to V3016, and subsequently for vehicles V3901 and V3902.

Tables 3 and 4 show the results of the ANOVA analysis. The null hypothesis (applies if F < F crit) in this case reads as follows: the mean values are the same, i.e., the value of the independent variable (specific vehicle) does not affect the value of the dependent variable (average electricity consumption in kWh/km). The alternative hypothesis (applies if F> F crit) reads as follows: the mean values of the selection differ, i.e., the value of the independent variable affects the value of the dependent variable. In both cases, we have confirmed that F > F crit (46.95 > 1.67 for longer buses—Table 4; 40.24 > 3.85 for short buses—Table 5). In this case, we can therefore claim that a particular vehicle affects the average consumption expressed in kWh per kilometer within the specified reliability value. In the ANOVA analysis (Tables 4–6), we used the following abbreviations:

- SS—sum of squares.
- df—degrees of freedom.
- MS—mean squares.
- F—variation within the samples.

Table 4. ANOVA analysis for 16 operated electric buses with length of 12 m. Processed by authors.

Source of Variation	SS	df	MS	F	*p*-Value	F Crit
Between Groups	50.45908	15	3.363938	46.95345	1.5×10^{-136}	1.667151
Within Groups	936.102	13066	0.071644			
Total	986.5611	13081				

Table 5. ANOVA analysis for two operated electric buses with length of 8 m. Processed by authors.

Source of Variation	SS	df	MS	F	*p*-Value	F Crit
Between Groups	0.935762	1	0.935762	40.23961	2.83×10^{-10}	3.846619
Within Groups	41.95156	1804	0.023255			
Total	42.88732	1805				

Table 6. Regression analysis of travelled distance by electric buses for summer season (1902 observations). Processed by authors.

Regression Statistics		ANOVA	df	SS	MS	F	Signific. F
Multiple R	0.7519	Regression	2	1588.390	794,194.80	1234.68	0
R Square	0.5653	Residual	1899	1221.516	643.24		
Standard Error	25.3622	Total	1901	2809.906			
	Coefficients	**t Stat**	***p*-Value**	**Lower 95%**	**Upper 95%**	**Lower 95.0%**	**Upper 95.0%**
Intercept	−4.9919	−0.9845	0.3250	−14.9363	4.9525	−14.9363	4.9525
Battery	195.7488	47.1760	0.0000	187.6111	203.8865	187.6111	203.8865
Temperature	1.4073	6.7692	0.0000	0.9996	1.8150	0.9996	1.8150

In the last part of our research, we look for the equation of the dependence of driving distance on the consumed electricity. Even before this part of the analysis, we cleaned data. In practice, the transport company uses electric buses in two work shifts. The driver of the first (morning) work shift takes the vehicle. Before starting, he writes down the initial state of batteries. After his work shift, he records the number of kilometers traveled and the battery state after arriving at the depot. Subsequently, the battery charging starts. The driver coming for the afternoon shift ends the charging, writes the initial state of charge in percent, and then starts his work shift. When finished, he also records the number of kilometers traveled and the percentage of battery charge. From these two values, we can calculate the discharge of batteries in percentage. For this reason, the total "consumed" energy can be higher than 100% due to bus recharging during the day.

In the following tables and graphs, the driving distance on the Y-axis is an explanatory variable, and the percentage charge of the traction batteries on the X-axis is an explanatory variable. We divided the predictions of driving distance into winter and summer periods. In the following figure (Figure 7), we estimated the dependence of battery consumption and driving distance as a linear line. As you can see, its equation is y = 200.86x + 22.216. The correlation coefficient, which expresses the strength of the linear dependence, is at the level R = 0.7448.

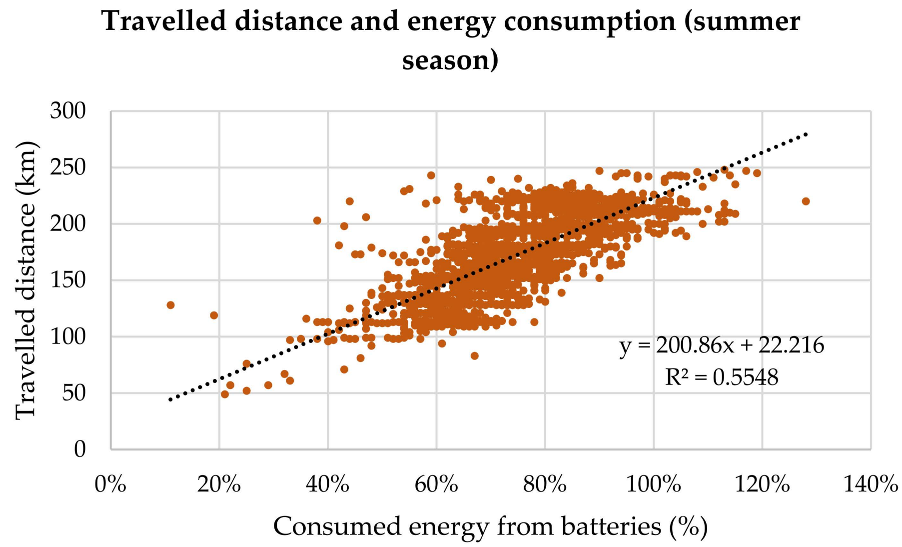

Figure 7. Relationship between consumed energy from batteries and travelled distance for summer season. Source: Processed by authors; temperatures from [63].

Previous research shows that as the ambient temperature increases in the summer months, consumption also increases, in part. This is due to the air conditioning. All electric buses that we monitored have an air-conditioning unit. For this reason, we added another independent variable to the linear regression analysis, namely temperature. Table 5 shows the results of the regression analysis.

In this case, we could explain 56.53% of the values, which is more than 55.48%. The result is thus an Equation (4) for determining the driving distance of an electric bus for the summer period.

$$y = 195.75 \cdot x_1 + 1.41 \cdot x_2 - 4.99 \quad (4)$$

In this equation, x_1 is the percentage state of battery charge and x_2 is the temperature in °C. In the same way, we prepared data for the winter months of bus operation. We analyzed 2374 vehicle days in three months (December, January, and February).

The following figure (Figure 8) shows a simple two-factor dependence of electricity consumption (expressed as a percentage of battery capacity) and driving distance in kilometers. Again, it is possible to describe this dependence with the equation. It explains about 52.54% of the values.

In this case, we also tried to add the ambient temperature to the overall calculation of the traveled distance. Table 7 shows the results of the regression analysis.

Using a new independent variable (ambient temperature), we slightly increased the accuracy of the resulting equation from 52.54% to 54.79%. The resulting equation based on the regression analysis has the form of Equation (5), in which x_1 is the state of charge (percentage value) and x_2 is the temperature in °C.

$$y = 204.61 \cdot x_1 + 1.74 \cdot x_2 - 8.53 \quad (5)$$

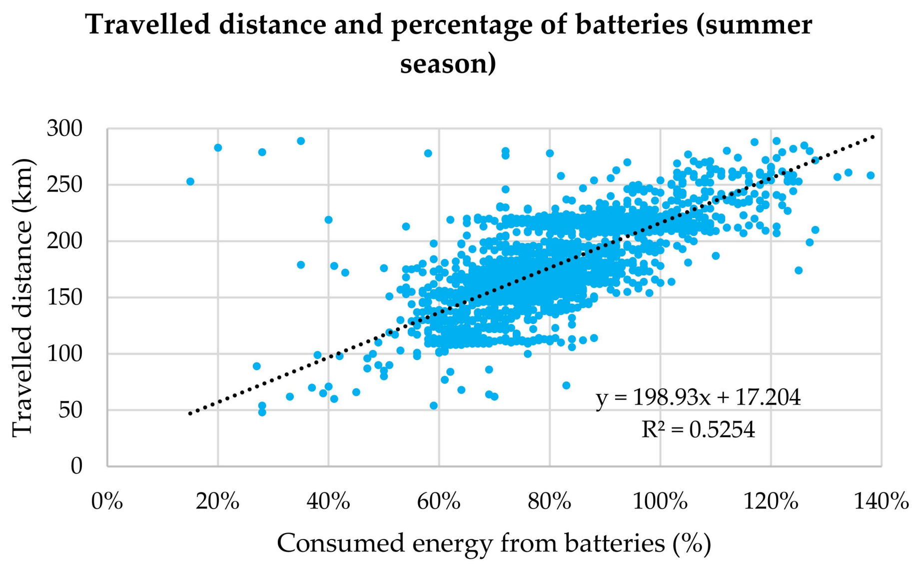

Figure 8. Relationship between consumed energy from batteries and travelled distance for winter season. Source: Processed by authors; temperatures from [63].

Table 7. Regression analysis of travelled distance by electric buses for winter season (2374 observations). Processed by authors.

Regression Statistics		**ANOVA**	**df**	**SS**	**MS**	**F**	**Signific. F**
Multiple R	0.7402	Regression	2	2284.778	1142.39	1436.99	0
R Square	0.5479	Residual	2371	1884.920	794.99		
Standard Error	28.1956	Total	2373	4169.698			
	Coefficients	**t Stat**	***p*-Value**	**Lower 95%**	**Upper 95%**	**Lower 95.0%**	**Upper 95.0%**
Intercept	2.6450	0.0082	2.2055	14.8506	2.2055	14.8506	4.9525
Battery	53.4885	0.0000	197.1133	212.1162	197.1133	212.1162	203.8865
Temperature	10.8725	0.0000	1.4250	2.0521	1.4250	2.0521	1.8150

4. Discussion

In this article, we focused on heating of electric buses. From a similar study [64] it is obvious that there are four types of bus heating. Fuel heaters burn a liquid fuel and provide the released heat of the burning process to the air, or in most cases, to the vehicle's cooling fluid. Electric heaters transform electric energy into thermal energy, which is transferred to the air or the cooling fluid. The source describes two other possibilities. The electric bus can have heat pumps that use a refrigerant circle that is mostly driven by an electric compressor [65].The compressor uses the electricity from the traction battery of the bus. The last option for heating is a thermal energy storage system. The stored heat is used for interior heating to keep the electric energy stored in the battery for driving.

We focused mainly on diesel heating because most electric buses operated in Slovakia have this type of interior heating. Based on the mathematical–statistical analysis of the obtained operational data, we can critically evaluate each hypothesis.

First, we verified hypothesis H1: There is a relationship between the ambient temperature and the electricity consumption of the electric bus heated by electric heaters in the winter months (Pearson's correlation coefficient $|R| > 0.6$). The electric heaters have a direct effect on the total consumed energy. In previous research, we analyzed the characteristics of Škoda Perun vehicles operated by the Žilina Transport Company. The correlation coefficient between total electric bus consumption and ambient temperature was –0.880 at a significance level of 0.01 (two-tailed test). We can accept this hypothesis.

We also focused on the related Hypothesis H2: Electric buses with independent diesel heating show no or little relationship (Pearson correlation coefficient |R| < 0.3). We confirmed this hypothesis, too. The absolute value of the correlation coefficient between ambient temperature and consumption is, for all vehicles, up to 0.3. The limitations of these outputs are other variables that could affect the result—a specific bus line or a specific driver.

We also examined whether the air conditioning of the electric bus had a significant effect on consumption in the summer months. The power of the air conditioning units is 10 kW for short buses and 15 kW for long buses. Given that the calculated correlation coefficient had a value of only R = 0.1284, we can reject hypothesis H3: There is a relationship between the ambient temperature and the electricity consumption of the air-conditioned electric bus in the summer months.

Furthermore, we investigated the statistical significance of a particular vehicle to average consumption (Hypothesis H4: Differences in average electricity consumption are statistically significantly different for different vehicles). We used the ANOVA analysis for this purpose and found that individual vehicles have statistically significant differences in average consumption expressed in kWh/km.

In the last part, we focused on the regression analysis. We found a regression function, which can help dispatchers calculate the driving distance according to the battery charging state, expressed as a percentage. However, the limitation of this study remains at $R^2 < 0.6$ in determining the function for both winter and summer seasons. Both equations are very similar. We also considered the ambient temperature. However, this does not significantly affect the driving distance of the vehicle. Evaluated electric buses have independent diesel heating. This heating consumes an average of 236 ± 59 L/vehicle/month in the three winter months (December, January, and February). As a result, it has a very positive effect on the consumption balance. From one percent of the battery capacity, one electric bus can run 2307 km in summer and 2202 km in winter. This difference is almost negligible. We can say that the operation of electric buses is very advantageous in in the range of tested temperatures.

We can compare the results obtained in our study with foreign sources. For example, in [66], the authors also examined the dependence of consumption on ambient temperature. Figure 9, which is from the mentioned study, shows a graphical dependence of these two quantities. Our buses with electric heaters have a significantly greater dependence. The consumption of electric buses is comparable to our values.

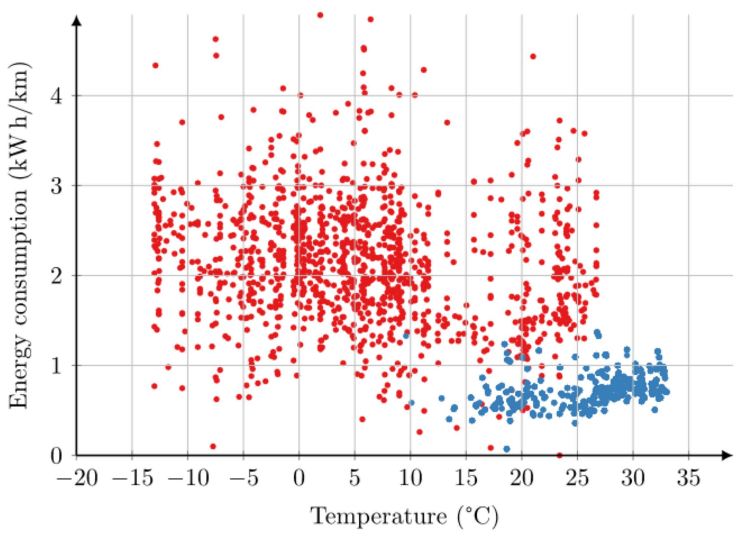

Figure 9. Observed energy consumption in kWh/km as a function of ambient temperature (two colors = two datasets) [66].

Study [67] also works with similar values of average electricity consumption. In this study, the authors examined not only the influence of ambient temperature but also occupancy. The study shows that the investigated electric buses had a consumption of 1.07 kWh/km in summer operation without passengers. In winter operation, they had a consumption of 1.19 kWh/km. At half-occupancy, consumption was 1.31 kWh/km (summer) and 1.64 kWh/km (winter). When fully occupied by passengers, the electric bus had consumption from 1.53 kWh/km in summer to 1.93 kWh/km in winter.

Similarly, we can compare the results with [68], in which the authors used real-world data and deep learning to estimate the consumption of electric buses. Based on [69], the authors state that energy consumption depends on many parameters (bus technology, traffic conditions, number of passengers, and profile of the route) and varies between 1.0 and 3.5 kWh/km.

Our research has several practical limitations. Many external factors affect electricity consumption in the urban environment. We are not able to record all of them in real conditions. These are the following factors:

1. Driver—human factor.
2. Traffic situation.
3. Geomorphology of the terrain.
4. Vehicle design and parameters (weight, rolling resistance, air resistance, etc.).
5. Vehicle load (occupancy in passenger transport).
6. Bus line (number and distance of stops).
7. Transport infrastructure (permitted speed, number of junctions, road surface, etc.).

We are aware of these influences and will investigate some of them in follow-up studies. We will record data in various ways in cooperation with the bus operator (GPS tracking, APC—automated passenger counters, or other techniques described in [70,71]).

This article brings new information regarding the energy-consumption of electric buses in the conditions of Central Europe. The most important benefits of the study are the following:

1. We found that electric buses with electric heaters show higher consumption in the winter months. This is due to the need to heat the passenger compartment.
2. Concerns about the high consumption of the electric bus in the cold season can be eliminated by suitable vehicle type. Diesel-powered electric buses show little or no dependence of electricity consumption on the ambient temperature.
3. Our study can be used when deciding on future investments of transport companies to their vehicle fleets—when buying electric buses.
4. We have analyzed and published the electricity consumption of buses in operation. They are comparable for future experiments.
5. We also showed a real fuel consumption for heating, which we want to use in future studies to calculate the exhaust emissions. Therefore, diesel-heated electric buses do not have completely zero emissions at the place of operation. This problem will be subject to further investigation.

5. Conclusions

The results that we published in this study can significantly improve the work of dispatchers in the deployment of electric buses in everyday operation. This article describes various advanced statistical methods and their use for evaluating the consumption of an electric bus or the entire vehicle fleet.

The research we carried out has confirmed that different electric buses have various properties. The way the passenger cabin is heated has an influence on electricity consumption in the range of tested temperatures. Therefore, the operation of electric buses needs to resolve this problem. Foreign authors, in the study [64], examined various heating options for electric buses.

The practical benefit of our research also lies in pointing out approximately the same energy consumption in winter and summer operation. It is possible to use electric buses even in the winter without concerns about significantly higher consumption and shorter driving distance.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/en14248346/s1, Table S1: Example part of the database of daily records from electric bus operation. We cannot share detailed operation data of electric buses.

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