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A Comparative Study of the Availability of Electric Buses in the Public Transport System

Andrzej Niewczas [1], Łukasz Mórawski [1,*], Ewa Dębicka [1], Joanna Rymarz [2], Dariusz Kasperek [3] and Piotr Hołyszko [4]

[1] Motor Transport Institute, 80 Jagiellonska St., 03-301 Warsaw, Poland; andrzej.niewczas@its.waw.pl (A.N.)
[2] Department of Sustainable Transport and Energy Sources, Lublin University of Technology, 20-618 Lublin, Poland; j.rymarz@pollub.pl
[3] Faculty of Transport and Information Technology, WSEI University, 20-209 Lublin, Poland; dariusz.kasperek@wsei.pl
[4] Municipal Transport Company Lublin Ltd., 56 Antoniny Grygowej St., 20-260 Lublin, Poland; pholyszko@mpk.lublin.pl
* Correspondence: lukasz.morawski@its.waw.pl

Abstract: This study deals with the assessment of the progress of the electromobility programme with regard to the technical availability of public transport buses. The aim of this study was to conduct a comparative assessment of the availability of electric buses in relation to diesel buses (of analogous capacity). The study was carried out in real operating conditions using the example of Lublin city. Over a period of 33 months, the availability of electric buses and diesel buses was tested in a sample of 18 vehicles for each type of bus. Availability indices were compared using the method of variance analysis. It was found that electric buses had a higher level of availability and no trend during the study period. The applied research method can be used in operational practice to monitor the risks associated with vehicle failure rates and the continuity of fleet operations.

Keywords: urban bus transport; electric buses; technical availability; variance analysis

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1. Introduction

The subject of the research described in this article is the availability (readiness) of electric buses as an important component of their operational quality in the public transport system [1–3].

Availability can be considered as a ratio of the expected uptime of a system to the total amount of observed time. The total amount of observed time is the sum of the uptime and downtime of the system. In reliability engineering, availability is expressed as a ratio of the Mean Time to Failure (MTTF) and the Mean Time Between Failure (MTBF). Depending on what is taken into account when determining the uptime and downtime, different types of availability are distinguished [4].

From the carrier's point of view, availability is one of the most important indicators characterising the operational quality of vehicles and the efficiency of the transport system [5–7].

Low availability in the transport system can have a significant impact by increasing costs within the company, as well as reducing the fluidity of the company's operations [8]. In contrast, high fleet availability enables a haulier to reduce the number of operational vehicles and the number of reserve vehicles [9].

Regarding the factors determining fleet availability in a public transport system, the following breakdown can be proposed, among others [10,11]:

- Random external factors not attributable to the carrier, e.g., sudden weather conditions, road traffic collisions, and information misunderstandings due to contractors;
- Internal system factors relating to day-to-day operational management;
- Technical factors resulting from the reliability of vehicles.

Delivering a guaranteed transport service in line with passenger expectations requires that the carrier continuously monitors the technical availability of the means of transport and infrastructure and that the reasons for insufficient availability are systematically analysed [12,13].

Classifications of the factors affecting technical availability can also be presented as follows [14]:

- Non-damageability of vehicles—resistance to the wear and tear of structural components and operational forcing, which determine the frequency of damage;
- Serviceability—effective maintenance management, the availability of spare parts, and the efficiency of service processes that minimise operational downtime;
- reliability—the use of vehicle condition monitoring systems to plan maintenance work;
- Operating conditions—the intensity of use and the impact of the operating environment determine the wear and tear dynamics of vehicles and their availability for transport.

Vehicle availability studies are widely reported in the literature. In relation to the topic of this thesis, this literature review mainly considers publications on the following:

- The availability of vehicles for intervention tasks, e.g., police cars, military vehicles, and aircraft;
- The availability of urban public transport vehicles.

This study highlights, among others, references [15–19]. In [19], to model the exploitation system of special vehicles, a semi-Markov process was used based on three exploitation states: use, use stoppage, and repair. Using a statistical sample of police cars as an example, an experimental study of the intensity of fleet use and the time of failure-free operation of vehicles was carried out, and it was shown that the studied transport system is characterised by a satisfactory stationary availability factor. The developmental possibilities of the presented modelling method are highlighted.

Reference [15] presents an analysis of the impact of contractual categories of bus downtime due to maintenance and repair on the technical availability index. A retrospective study covering a period of 12 years of vehicle use was carried out using the example of a selected urban transport company. The share of each downtime category in the total vehicle downtime was analysed. The Spearman rank correlation coefficient was used for the analysis. The study covered seven brands and types of buses and six categories of downtime. Technical availability was shown to be strongly correlated with outage categories and loosely correlated with bus age.

Reference [16] presents the influence of selected factors of technical availability of public transport buses using the examples of Solaris and Mercedes-Benz buses in the Municipal Transport Company. A study of changes in technical availability was carried out with a division into two periods of use: warranty and post-warranty. A one-factor analysis of variance was used to test the significance of differences in mean availability values depending on the bus brand and depending on the periods of use. It was shown that in the warranty period, the technical availability of buses of both brands is comparable, while in the post-warranty period, it is significantly different.

Reference [17] describes a mathematical model of the operation process of vehicles supplying fuel to aircraft prior to flight. The phase space of the investigated process was mapped using a seven-state vehicle operation model. Markov chains and processes were used to calculate the technical readiness index, $K_G(t)$. Optional methods for determining the vehicle's technical readiness index based on the total operating time of the facility in each state are presented.

Reference [18] proposes an author's method for assessing helicopter availability using Markov processes. An assessment of the availability of Mi8 helicopters equipped at the Transport Aviation Base is presented. Based on the analysis of the exploitation process, nine exploitation states are distinguished, for which boundary probabilities are calculated in discrete and continuous time.

In the field of public transport, there has been a rapid increase in the number of electric vehicles in recent years. This trend is expected to continue into the future. The use of electric propulsion, especially in public transport, is primarily aimed at reducing local emissions, i.e., dust and gases that are harmful to human health, as well as carbon dioxide, which contributes to the global warming process [20,21].

The characteristics of the size of the urban bus fleet in Poland in 2023, including the share of electric vehicles, are shown in Figure 1.

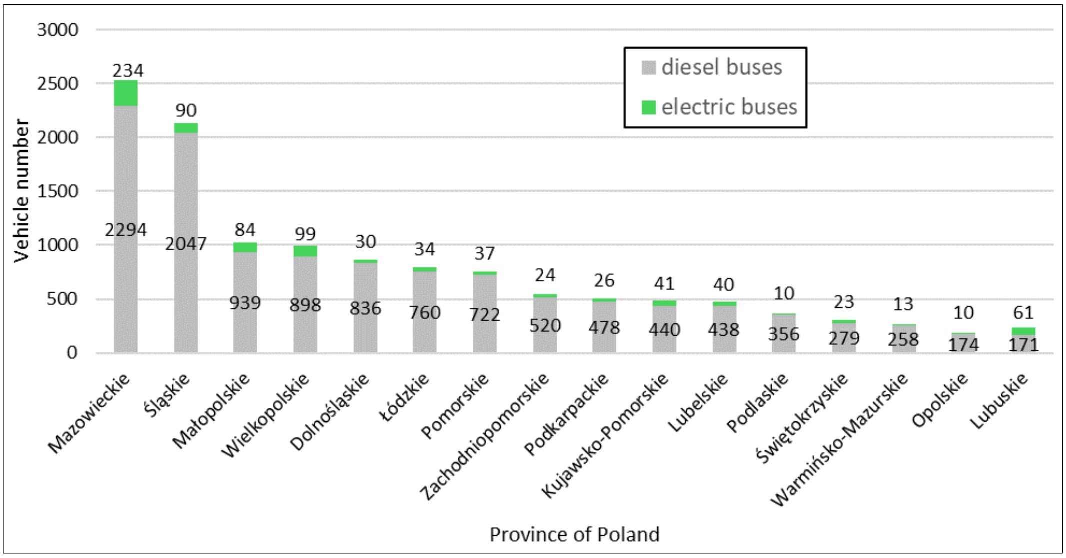

Figure 1. Public transport fleet by province in 2023; authors' own elaboration based on [22,23].

Currently, in Poland, the share of electric buses in the total number of public transport buses is about 7%. The leading manufacturer of electric buses in the country is Solaris [24]. In view of the dynamic development of electromobility programmes, there is a need to assess new electric vehicles being launched on the market from environmental, economic, and technical points of view. In the literature, examples of assessing the operational maintenance of electric buses are quite few and methodologically diverse [25,26].

Lublin is a city with a very long tradition of using electric vehicles in public transport. It is one of three cities in Poland, apart from Gdynia and Tychy, where trolleybuses are used. What distinguishes Lublin trolleybuses from other electric vehicles used in Poland and Europe is the fact that all of them are equipped with autonomous energy sources. These are serial hybrid systems and lithium-ion batteries of various types, mainly NMC, LFP, and LTO batteries. The experience gained during the operation and servicing of trolleybuses by Municipal Transport Company Lublin (MTCL) resulted in the creation of a system of electric buses 'tailor-made' for the city of Lublin. These buses have a relatively short range, around 70 km. Thanks to the knowledge, years of experience and appropriate use of battery technologies, together with appropriate charging infrastructure, these buses can perform transport tasks without downtime needed for charging. Properly designed infrastructure for electric vehicles allows for charging times to be minimised and for the vehicles to be used similarly to diesel vehicles [27].

In Lublin, there are eight main end-route stops at which chargers with two or four charging points with a nominal power of 450 kW each are installed. The length of the route covered by the bus between subsequent charging stations, on a full all-day schedule, does not exceed 40 km, and the energy consumption is 43 kWh. Therefore, the charging time does not exceed 6 min and corresponds to the times of breaks in the schedule at end-route stops. Pantographs are used in the buses for fast charging, and their special design allows them to be connected for charging in a short time.

The charging infrastructure was also equipped with stationary chargers installed in the road with a nominal power of 40 kW. This system was created with the aim to meet the assumptions of charging a bus in three hours, so a bus leaving the route at 0:00 am, after performing service activities related to its preparation for running the following day, would be ready to leave at 4:00 am to provide transport tasks. The chargers are also used to charge buses dispatched on a given day to perform tasks on peak schedules.

The infrastructure for electric buses in Lublin ensures that the routes can be served by both diesel and electric vehicles, which do not need additional time for charging.

The authors of the present study attempted to assess the progress of electromobility in a selected example of a public bus service with regard to the problem of vehicle technical availability. The aim of the study was to evaluate the comparative availability of electric buses in relation to buses of similar capacity with diesel engines. It was assumed that the study will be carried out in real operating conditions with the example of the city of Lublin.

2. Research Methodology

2.1. Technical Availability Index for Vehicles

The availability of a technical facility is defined as the probability that the facility will be in a state of serviceability at any randomly selected time [28]. In practice, the technical availability index is used to quantify availability. It is a basic parameter that determines how often a vehicle is available to perform transport tasks. The technical availability index is expressed by the following relationship [5,11,12]:

$$K_G(t) = N_z/(N_z + N_n) \quad (1)$$

where

N_z—the number of buses available for use in a given operating period;

N_n—the number of buses unavailable for use in a given operating period.

The above relationship regarding the technical availability index formed the basis for determining the technical availability of the vehicle fleets presented in this study.

2.2. Method of Statistical Analysis of Results

It was assumed that the basis of the analysis would be the availability reports produced by the company under study for each vehicle and that the scope of this analysis would include the determination of descriptive statistics and the performance of statistical significance tests for differences in mean values. In order to assess the influence of the drive type on the technical availability index, $K_G(t)$, the analysis was carried out for a total observation period of 33 months and for annual observation periods. In addition, a comparative analysis of technical availability, $K_G(t)$, was carried out between consecutive annual vehicle operating periods and between drive types.

The following research hypotheses were formulated:

1. The first null hypothesis, $H_{1.0}$, states that there are no significant differences in technical availability, $K_G(t)$, between electric and diesel buses over the observed operating period.
2. The second null hypothesis, $H_{2.0}$, states that there are no significant differences in technical availability, $K_G(t)$, between the operating periods of vehicles.

Hypothesis verification was performed using a one-way ANOVA (analysis of variance). The use of ANOVA is conditional on the following assumptions:

- All observations are randomly selected and independent;
- The dependent variable is measured on a quantitative scale;
- There is equality of observations in the groups—individual categories of the independent variable should be statistically equal;
- The distribution of results in the analysed groups is close to a normal distribution;
- The variances in the groups are homogeneous [29].

The Kolmogorov–Smirnov and Shapiro–Wilk tests were used to check the normality of the distribution across groups. $p = 0.05$ was used as the required significance level. The condition of homogeneity of variance was analysed using Levene's test. The results of the statistical analysis are presented in the box-and-whisker plots in Section 3.2.

3. Experimental Procedure

3.1. Test Facilities and Conditions

The research was carried out at the Municipal Transport Company in Lublin using samples of buses of two makes, SOLARIS URBINO12 ELECTRIC with electric drive and URSUS BUS CF 12 LFD with internal diesel drive, with 18 vehicles of each make. All the vehicles tested were new units with no previous operating mileage. The technical characteristics of the vehicles tested are shown in Table 1.

Table 1. Technical and operational parameters of tested buses.

Parameter	URSUS BUS CS 12 LFD	SOLARIS URBINO12 ELECTRIC
Bus type	two-axle, low-floor, urban	
Length [m]	12.0	12.0
Door layout	2 –2 –2	2 –2 –2
Total number of seats	105	81
Number of seating places	28	29
Battery capacity [KWh]	not applicable	120
Charging power [KWh]	not applicable	Up to 450
Engine characteristic	6 cylinders, 6.7 L, 221 kW	Two asynchronous motors in rear drive axle, maksimum total power of 240 kW
Maximum permissible weight [kg]	19,000	18,745
Exhaust emissions standard	Euro VI	not applicable

The tests were conducted under standard operating conditions in the Municipal Transport Company in Lublin. The tests were conducted over the calendar time period from 2021 to 2024, with a total of 33 months of bus use.

The studied buses operated on regular public transport routes in urban traffic. The average daily mileage was about 238 km for electric vehicles and 243 km for diesel vehicles; the deviation of the extreme values did not exceed 85 km. The average monthly mileage was 4860 km for electric buses and 4920 km for diesel buses.

Any of the studied vehicles that were technically efficient could be sent to serve one of the operated lines. The lines were operated in a two-shift, all-day operating pattern or only during the peak period. During full service on all lines, a bus could also remain at the depot in a state of technical availability as a reserve vehicle.

Damage incurred or discovered during the run was a signal to the driver to stop transport work and take the bus to the depot. Each repair was carried out, depending on the time of departure, either immediately or starting from the next mechanic's shift.

In this study, the source data base was the company's vehicle technical availability reports. The availability reports contained a record of the operating states of each vehicle, broken down by the next day of each month. Due to limited access to data, a vehicle was considered unavailable when a failure occurred on a given day. If a vehicle performed tasks without faults during a shift (two-shift, all-day, or peak period), it was counted as an unavailable vehicle. Two states were considered: the availability state, denoted as '1', and the unavailability state, denoted as '0' (Figure 2). The same indicator defined in Equation (1) was used to calculate the technical availability index of diesel and electric vehicles.

Filter:
- Brands: : SOLARIS URBINO12 ELECTRIC, URSUS CS 12 LFD, URSUS CS 12 LFD "Z"

Day of month

Vehicle	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	combined %
22462	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100
22463	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100
22464	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	84
22465	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	61
22466	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100
22467	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	0	0	0	0	1	1	0	0	0	1	1	1	1	1	1	1	71
22468	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	97
22469	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0	0	0	1	77
22470	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	97
22471	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	94
22487	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100
22488	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100
22489	1	1	0	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	90
22490	1	1	1	1	0	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	81
22491	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	45

Figure 2. Bus technical readiness report, January 2022.

The readiness reports were prepared by the carrier using the integrated IT management system MUNICOM TARAN. At the end of each work shift, as part of the use of the aforementioned system, the technical support (service) employee monitored the vehicle's operational status. The data recorded in the system were sent to dispatchers at the company's traffic headquarters. For a faulty vehicle, the system prevented issuing a road card on the next working day, which meant stopping the vehicle at the service and repair base. The aforementioned technical readiness reports were the basis for warranty settlements with individual vehicle manufacturers, as well as for meeting the implementation of the transport task plan.

In a later section of the article, abbreviated names of the tested vehicles are introduced according to the type of drive, and it is assumed that Ursus buses will be labelled as 'diesel' and Solaris buses as 'electric'.

3.2. The Results of the Study

The results of the $K_G(t)$ availability tests are presented in the form of graphs in Figure 3 and in numerical form in Table 2. The graphs presented in Figure 3 illustrate the values averaged over each month of operation of the vehicle sample and the 3-month moving average of the $K_G(t)$ index values.

An analysis of the data in the column chart shows a higher level of $K_G(t)$ indexes for electric vehicles in each of the observed monthly periods. Higher $K_G(t)$ technical availability of diesel vehicles was only observed in the 1st, 2nd, and 11th months.

The mean technical availability, $K_G(t)$, of diesel vehicles for the whole observation period was $K_G(t) = 0.79$ with a standard deviation of $S(K_G) = 0.08$. For electric vehicles, the mean statistic was $K_G(t) = 0.89$ with a standard deviation of $S(K_G) = 0.12$. When comparing the median, similar values were found for $K_G(t) = 0.80$ and $K_G(t) = 0.92$ for diesel and electric vehicles, respectively. The lowest availability value for electric buses, $K_G(t) = 0.28$, was recorded in 1 month of operation. The lowest availability of diesel buses, $K_G(t) = 0.58$, was recorded in the 15th month of operation.

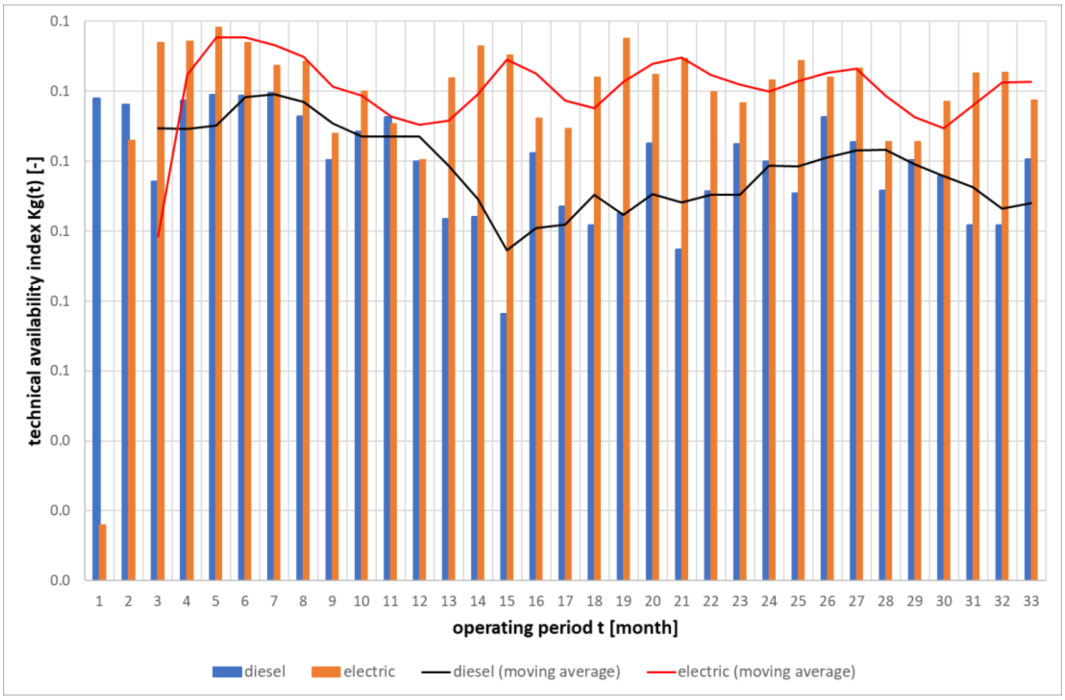

Figure 3. Technical availability, $K_G(t)$, of diesel and electric buses and 3-month moving average as function of monthly operating period, t.

Table 2. Descriptive statistics of technical availability.

Statistics	Diesel				Electric			
	33 Months	1st Year	2nd Year	3rd Year	33 Months	1st Year	2nd Year	3rd Year
Average	0.79	0.85	0.74	0.78	0.89	0.86	0.92	0.90
Median	0.80	0.87	0.74	0.78	0.92	0.92	0.92	0.92
Variation	0.01	0.00	0.01	0.00	0.02	0.04	0.00	0.00
Std. deviation	0.08	0.06	0.07	0.05	0.12	0.19	0.04	0.04
Minimum	0.58	0.71	0.58	0.71	0.28	0.28	0.85	0.83
Maximum	0.90	0.90	0.83	0.86	0.99	0.99	0.98	0.94
Interquartile range	0.32	0.19	0.25	0.15	0.71	0.71	0.13	0.11
Coefficient of variation [%]	0.14	0.08	0.10	0.08	0.09	0.14	0.06	0.07

A graphical illustration of technical availability is shown in the box-and-whisker figures. Figure 4 shows the results for the whole observation period, and Figure 5 shows the results for the 'drive type' and 'operating period' groups. An analysis of the box–whisker plots indicates that there are outlier observations. Further analysis and calculations were carried out excluding these observations.

The condition of independence of observations, required for a univariate analysis of variance, was considered to be met. It was assumed that there are no latent relationships between observations. The measurability condition was also assumed to be met, as technical availability, $K_G(t)$, as the dependent variable is considered on a quantitative scale.

The normality of the distribution in the analysed groups–'drive type' and 'operating period'—was verified using the Kolmogorov–Smirnov and Shapiro–Wilk tests (Table 3). For all analysed types of 'operating period' and 'drive type', the null hypothesis of normality of distribution was fulfilled in at least one verification test. Ambiguous results from both tests were only obtained for diesel vehicles at the 1st year of operation, and for electric vehicles, at the 2nd and 3rd years of operation. Of the aforementioned groups, the normality condition of the distribution ($p > \alpha = 0.05$) was only met by one of the two tests. Due to some robustness in the one-way analysis of variance to deviations from the normality of the distribution, the condition was considered to be met [30].

Another condition for the validity of the analysis of variance was to check the homogeneity of the variances. Therefore, Levene's test was further performed in four variations: based on the arithmetic mean, median, median and adjusted df, and truncated mean. Table 4 shows the results of Levene's tests in relation to $H_{1.0}$. The results of the analysis of homogeneity of variance for the entire observation period (33 months), and for the 2nd and 3rd years of operation, indicate that the null hypothesis of homogeneity of variance should be considered. On the other hand, the homogeneity of variance is not fulfilled for the mean value and the trimmed mean.

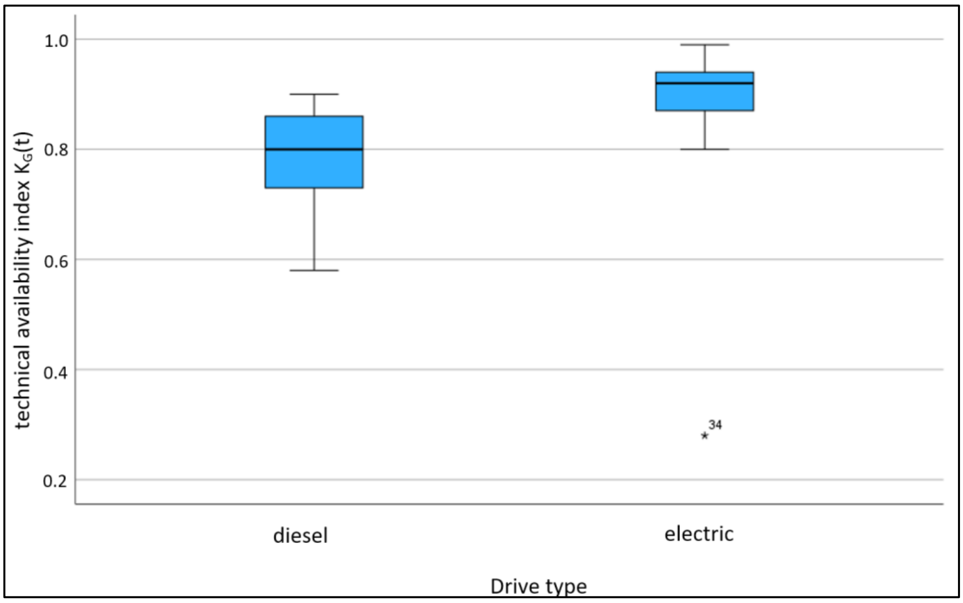

Figure 4. A box-and-whisker plot of the dependent variable of technical availability, $K_G(t)$, of buses for the 'drive type' groups (* 34 – outlier).

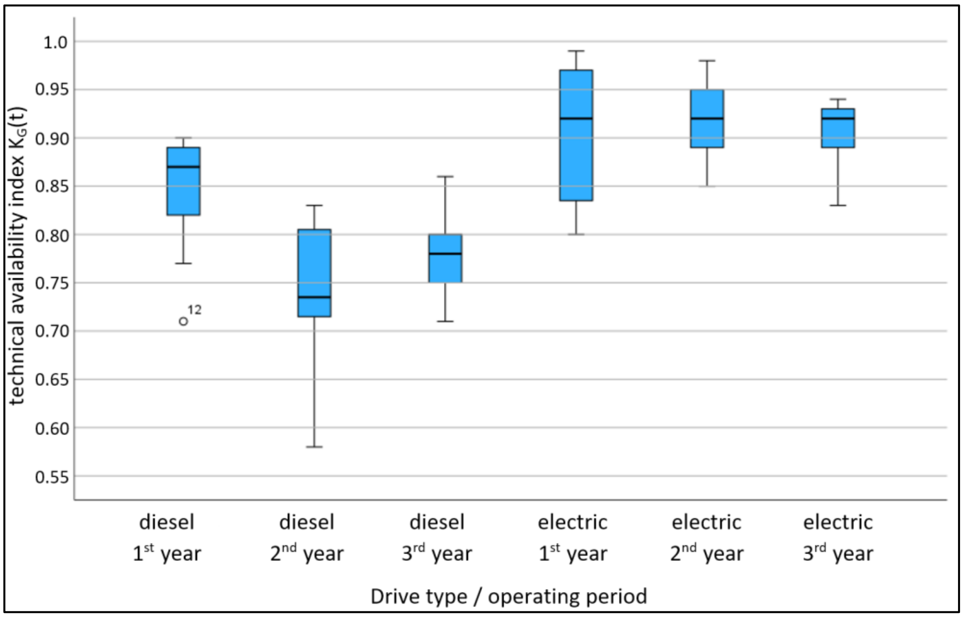

Figure 5. A box-and-whisker plot of the dependent variable technical availability, $K_G(t)$, of buses for the groups 'drive type' and 'operating period' (° 12 – outlier).

Table 5 shows the results of the test for $H_{2.0}$. The results of the analysis indicate that the homogeneity of variance should be recognised for both diesel and electric vehicles when comparing the 1st and 2nd years of operation and the 2nd and 3rd years of operation.

Table 3. The results of the normality test analysis of the technical availability distribution, $K_G(t)$.

Drive Type/Operating Period	Kolmogorov–Smirnov		Shapiro–Wilk	
	Statistics	Significance *p*	Statistics	Significance *p*
diesel/33 months	0.79	0.85	0.89	0.86
diesel/1st year	0.80	0.87	0.92	0.92
diesel/2nd year	0.01	0.00	0.02	0.04
diesel/3rd year	0.08	0.06	0.12	0.19
electric/33 months	0.58	0.71	0.28	0.28
electric/1st year	0.90	0.90	0.99	0.99
electric/2nd year	0.32	0.19	0.71	0.71
electric/3rd year	0.14	0.08	0.09	0.14

Table 4. Results of Levene's test for homogeneity of variance for 'drive type'.

Operating Period	Variable	Effect	Based on:	Statistics	Degree of Freedom df1	Degree of Freedom df2	Significance *p*
33 months	$K_G(t)$	Drive type	Average	0.004	1	64	0.952
			Median	0.031	1	64	0.860
			Median and adjusted df	0.031	1	42.642	0.861
			Average cut	0.013	1	64	0.908
1st year			Average	5.457	1	20	0.030
			Median	2.150	1	20	0.158
			Median and adjusted df	2.150	1	18.281	0.160
			Average cut	5.322	1	20	0.032
2nd year			Average	2.328	1	22	0.141
			Median	2.371	1	22	0.138
			Median and adjusted df	2.371	1	17.332	0.142

		Average cut	2.537	1	22	0.125
3rd year		Average	0.230	1	16	0.638
		Median	0.276	1	16	0.606
		Median and adjusted df	0.276	1	15.456	0.607
		Average cut	0.250	1	16	0.624

Table 5. Results of Levene's test for homogeneity of variance for 'operating period'.

Drive Type	Variable	Effect	Based on:	Statistics	Degree of Freedom df1	Degree of Freedom df2	Significance *p*
diesel	$K_G(t)$	1st and 2nd years of operation	Average	1.667	1	21	0.211
			Median	1.628	1	21	0.216
			Median and adjusted df	1.628	1	19.403	0.217
			Average cut	1.849	1	21	0.188
		2nd and 3rd years of operation	Average	0.524	1	19	0.478
			Median	0.519	1	19	0.480
			Median and adjusted df	0.519	1	16.240	0.482
			Average cut	0.589	1	19	0.452
electric		1st and 2nd years of operation	Average	3.575	1	22	0.072
			Median	2.419	1	22	0.134
			Median and adjusted df	2.419	1	11.500	0.147
			Average cut	3.027	1	22	0.096
		2nd and 3rd years of operation	Average	0.193	1	19	0.665
			Median	0.055	1	19	0.817
			Median and adjusted df	0.055	1	17.568	0.818
			Average cut	0.183	1	19	0.674

The univariate analysis of variance in the 'drive type' group indicates that a statistically significant difference was found for the total (33 month) operating period and the 2nd and 3rd years of operation (Table 6). For these operating periods, a significance level of $p < 0.001$ was found. Thus, the null $H_{1.0}$ about the absence of statistically significant differences in technical availability $K_G(t)$ between bus makes (drive type) should be rejected. A different result was obtained when comparing the technical availability of $K_G(t)$ in the 1st year of operation. The level of significance was found to be $p = 0.065$, and there were no grounds to reject $H_{1.0}$. Thus, the availability of $K_G(t)$ is not significantly different. Due to the lack of homogeneity of variance for the technical availability of $K_G(t)$ in the 1st year of operation, Welch and Brown–Forsythe tests were additionally performed. The significance level of $p = 0.068$ for both tests indicates that there is no basis for rejecting $H_{1.0}$ (Table 7).

The results of the analysis of variance obtained are consistent with the results of the box-and-whisker plots (Figures 4 and 5).

In verifying $H_{2.0}$ in the sample of diesel vehicles, it was found that statistically significant differences exist only between the 1st and 2nd years of operation. In contrast, in the period groups of the 2nd and 3rd years of operation of diesel vehicles and in all period groups of operation of electric vehicles, the differences are not statistically significant.

Table 6. Results of calculations of one-way analysis of variance for 'drive type'.

Operating Period	Variable	Effect	Source	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio [1]	Significance p
33 months	$K_G(t)$	Drive type	Between phases	0.165	1	0.165	16.187	<0.001
			Inside phases	0.652	64	0.010		
			Total	0.817	65			
1st year			Between phases	0.012	1	0.012	3.814	0.065
			Inside phases	0.064	20	0.003		
			Total	0.077	21			
2nd year			Between phases	0.187	1	0.187	56.346	<0.001
			Inside phases	0.073	22	0.003		
			Total	0.260	23			
3rd year			Between phases	0.066	1	0.066	29.796	<0.001
			Inside phases	0.035	16	0.002		
			Total	0.101	17			

[1] Mean square between groups divided by mean square within groups.

Table 7. Results of Welch and Brown–Forsythe tests for 1st year of operation.

Test	Statistics	Degrees of Freedom df1	Degrees of Freedom df2	Significance p
Welch	3.814	1	16.877	0.068
Brown–Forsythe	3.814	1	16.877	0.068

4. Discussion of Results

The results of the study indicate that electric buses have higher availability compared to diesel buses. The differences were shown to be statistically significant. The average technical availability in the sample of electric buses is in the range $K_{G,avg}$ (0.76 ÷ 0.92) while that of diesel buses is in the range $K_{G,avg}$ (0.74 ÷ 0.85). These results are in line with reports from the literature. Indeed, many authors emphasised the systematic improvement in the quality of electric drives introduced to the market in recent years [31–33]. In comparison with the availability of Solaris diesel buses operated in Municipal Transport Company in Lublin in the 2008–2010 period, whose availability was K_G = (0.88–0.91) [13], it may be considered that the results of the availability assessment of electric buses presented in this study do not differ significantly.

The time series of the K_G indicator of electric vehicles in the three initial years of operation is characterised by the lack of a trend. On this basis, it is possible to forecast the maintenance of a stable availability in the subsequent periods of bus operation. In addition, a seasonality of changes in the technical availability index after the first year of operation was found. The moving average in Figure 3 shows a decrease in the indicator in a repeated cycle of about 6 months. This is probably related to the 6-month cycle of periodic inspections of electric vehicles. Electric vehicles were introduced to operation in a similar period of time (within 1 month). That caused periodic inspections of all vehicles to fall at the same time. Even if vehicles were serviced simultaneously in smaller groups in the span of one month, the overall technical availability would be lower in this month.

The reasons for the differences in availability between electric and diesel vehicles can be of a technical nature related to the reliability of the design or of an operational nature related to managing the continuity of the fleet.

One of the key factors for the high technical availability of electric buses is their technical quality. It can be assumed that electric buses have been made to a higher standard of quality than their diesel counterparts. The reason for this may be the growing construction and technological experience of the vehicle manufacturer (Solaris Bus & Coach SA, Owińska, Poland) and high production standards.

Electric buses, due to their simpler mechanical design, have fewer moving parts, reducing the number of potential tribological failure points compared to diesel buses, which require regular maintenance of many components. In addition, electric buses have lower operating and maintenance costs [26]. The greater reliability of electrical and design structures, combined with higher build quality, means that these buses require less frequent service interventions, which reduces operating costs and makes them more efficient for long-term use.

Considering the entire period under study, electric vehicles showed a technical availability that was 11.2% higher (based on the arithmetic mean); in individual years, it was, respectively, 0.9%, 19.3%, and 13.5%. The low difference in the first year was strongly influenced by the low technical availability index in the first month of electric vehicle operation, $K_G = 0.28$. It is worth noting that the first implementation of a new technology, as was the case described in this article, required a period of adaptation, such as solving the problem of adapting the charging system to local conditions.

With regard to diesel vehicles, it should be noted that there is a significant drop in the technical availability index after the first year of operation. This is due to the impact of mechanical wear and tear on vehicle components.

The described system of the Lublin electric bus is unique. It allows for a diesel bus to be replaced with an electric bus on the same routes. For all-day operation, a necessary condition is the location of the bus charging point at one of the end-route stops. In the case of the implementation of the peak period, there are no differences. Therefore, it is possible to compare both of these vehicles performing transport tasks, in the same conditions, without taking into account differences related to the limitations of operability for one group of vehicles.

Future research should consider a wider range of specific factors affecting vehicle technical availability, such as intensity of use, qualification of technical staff, and quality of servicing. An important future topic is the extension of the analysis to include issues of repairability of electric buses, both in terms of quantity and type of failure. Mainly, an extensive analysis should be conducted while considering a powertrain failure comparison between diesel and electric vehicles.

5. Conclusions

Studies show that electric buses have a higher technical availability than traditional diesel buses under the same operating conditions. For the bus company, this may mean there is a possibility to reduce maintenance costs and the cost of a reserve fleet.

The higher technical availability of electric buses is due to the lower failure rate of the vehicle design and simpler maintenance and repair procedures.

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