energies

MDPI

Article

Assessment of Electromagnetic Fields in Trolleybuses and Electric Buses: A Study of Municipal Transport Company Lublin's Fleet

Paweł A. Mazurek [1,*], Aleksander Chudy [1] and Piotr Hołyszko [2]

[1] Department of Electrical Engineering and Smart Technologies, Faculty of Electrical Engineering and Computer Science, Lublin University of Technology, Nadbystrzycka 38 A, 20-618 Lublin, Poland; a.chudy@pollub.pl

[2] Municipal Transport Company Lublin Ltd., Antoniny Grygowej 56, 20-260 Lublin, Poland; pholyszko@mpk.lublin.pl

* Correspondence: p.mazurek@pollub.pl

Abstract: As electromobility and especially the electrification of public transportation develops, it is necessary to safeguard human health and minimize environmental impact. Electromagnetic fields generated by the current flowing through on-board batteries, installations, converters, propulsion, air conditioning, heating, lighting, or wireless communication systems in these vehicles may pose risks to drivers and passengers. This research investigates electromagnetic fields induced by extreme low-frequency currents and permanent magnets on electric and trolleybuses implanted in Lublin, Poland. The identification of electromagnetic fields concerned an electric bus model and two trolleybus models. A comparative analysis of the results obtained with the permissible limits in the environment was carried out.

Keywords: electromagnetic fields; trolleybuses; electric buses; electric vehicles; EMC analysis; safety assessment

check for updates

Citation: Mazurek, P.A.; Chudy, A.; Hołyszko, P. Assessment of Electromagnetic Fields in Trolleybuses and Electric Buses: A Study of Municipal Transport Company Lublin's Fleet. *Energies* **2024**, *17*, 3412. https://doi.org/10.3390/en17143412

Academic Editor: Andrea Mariscotti

Received: 30 April 2024
Revised: 28 June 2024
Accepted: 4 July 2024
Published: 11 July 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Conventional transportation running on fossil fuel combustion is a major source of CO_2 emissions, toxic particulates, and air pollutants, harming both human health and the environment. Characterized by high energy efficiency and local zero-emission, electric vehicles are now widely recognized as one of the best alternatives to internal combustion vehicles [1,2]. Governments in many countries have implemented policies to promote the development of electromobility. The European Union's goal is to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels to achieve climate neutrality for the continent by 2050. This target was officially included in the 'Fit for 55' package in July 2021 [3].

The implementation of clean electric propulsion is a significant step towards reducing greenhouse gas emissions in the transport sector. One study [4] highlighted the importance of considering the entire lifecycle of electric vehicles, including the production, distribution, and consumption of electricity, to accurately assess their environmental impact. Electric vehicles are often promoted as a cleaner alternative to internal combustion engine vehicles due to their potential to reduce tailpipe emissions. However, the overall greenhouse gas emissions associated with electric vehicles depend significantly on the carbon intensity of the electricity used to charge them. The environmental benefits of electric vehicles vary greatly depending on the energy mix of the electric grid in different countries. To maximize the environmental benefits of clean electric propulsion, it is crucial for policymakers to focus not only on the adoption of electric vehicles but also on the development of cleaner electric generation methods. Increasing the share of renewable energy sources and improving the

efficiency of electric transmission can significantly enhance the greenhouse gas emissions savings from electric vehicles. MPK Lublin has taken a progressive approach towards this issue. Through signed agreements and partnerships, the company ensures that 100% of the energy consumed by their electric buses and trolleybuses comes from renewable energy sources. This commitment significantly enhances the environmental benefits of their electric fleet.

Poland plans for 100% of their new fleet purchased for public transport services to be zero-emission from 2025 in every city with more than 100,000 residents [5]. According to the Act on Electromobility and Alternative Fuels [6], municipalities with a population of more than 50,000 residents are required to take measures to ensure that at least 20% of the vehicles in their bus fleet will be zero-emission buses and those powered by biomethane from 1 January 2025, and this number is to increase to at least 30% from 1 January 2028.

At the end of 2023, according to the Electromobility Counter launched by the Polish Alternative Fuels Association and the Polish Automotive Industry Association, 1185 electric buses were registered in Poland [7]. Public transport using clean electric propulsion is a response to the growing problems of traffic congestion and air pollution in highly urbanized areas. Activities related to the development of electromobility focus on improving the availability of electric urban transport, as the most environmentally friendly form of public transport (promoting the concept of sustainability and improving the environmental awareness of the public). Given the current trend towards electromobility and the desire to reduce the harmful environmental impact of transport modes as much as possible, trolleybuses, in addition to electric buses, are becoming increasingly important.

Additionally, many municipalities are exploring the replacement of existing diesel bus fleets with natural gas buses. Natural gas as an engine fuel has many advantages, including lower costs, lower emissions due to more complete combustion, lower noise, and longer engine life. Compressed natural gas (CNG) and liquefied natural gas (LNG) technologies are mature and commercially available, making them viable options for urban bus fleets. For instance, some European countries have focused on using CNG for urban heavy-duty vehicles such as buses and trucks, seeing significant benefits in terms of reduced CO_2 emissions and improved air quality [8].

Case studies illustrate the practical benefits and challenges of using natural gas as a fuel for public transport. For example, Chamonix, France, has deployed natural gas buses to combat severe air pollution caused by heavy vehicular traffic, improving air quality and reducing emissions in the region [9]. In Poland, there were around 850 buses powered by natural gas on Polish streets by the first quarter of 2022. The adoption of LNG buses in cities like Olsztyn has demonstrated the practical benefits and challenges of this approach [10]. While CNG and LNG buses offer significant environmental and economic benefits, they do not address the electromagnetic field concerns associated with electric propulsion systems. This underscores the importance of this study on electromagnetic fields in trolleybuses and electric buses as part of a comprehensive approach to sustainable urban transport.

The aim of this study is to measure and analyze the values of the strengths of electric and magnetic fields of extremely low-frequency (ELF) and static magnetic fields in electric vehicles operated by the Municipal Transport Company Lublin LTD (MPK Lublin). The presented results are part of a commissioned research project on the identification of electromagnetic fields in the vehicles of the transport company. The scope of this work concerns one electric bus model and two trolleybus models.

The initial part of this article presents information on the research currently being carried out worldwide on electromagnetic emissions from electric vehicles and introduces information on public transport in Lublin and the vehicles selected for this research. Subsequently, the test methodology and measuring equipment are described, test results are presented graphically and tabularly, and an analysis of the results obtained in the context of detecting exceedances of the permissible limits was carried out. This paper concludes with a summary of findings, outlining the current stage of the research.

2. Electromobility and Electromagnetic Fields

In the context of the development of electric bus and trolleybus technology, electromagnetic fields are becoming a topic of increasing importance. As the electrification of public transport continues, the actual assessment of the impact of these fields on human health and the environment becomes crucial. In electric buses and trolleybuses, power electronic converters play a key role. A DC/AC converter converts direct current (DC) from a vehicle's batteries into alternating current (AC) at a specific frequency to power the vehicle's various components. The input terminals of the DC/AC converter are connected to the battery, while through the output terminals, AC current is supplied to the powertrain—the engine and other control units in the vehicles. The converter acts as an intermediary between the power source and the drive train, ensuring that sufficient power is supplied to the drive train. The importance of using an AC/DC converter in the process of charging the battery of an electric vehicle should also be emphasized [11–13].

Electromagnetic fields generated by the current flowing through on-board batteries, installations, converters, propulsion, air conditioning, heating, lighting, or wireless communication systems in these vehicles affect drivers and passengers. These fields can have a variety of consequences, both positive and negative. On the one hand, electric buses and trolleybuses represent a step towards sustainable mobility, reducing harmful emissions into the atmosphere and contributing to improved urban air quality. On the other hand, the electromagnetic fields generated represent an environmental impact and a potential but yet inconclusive risk to human health over a wide spectrum of frequencies from static (DC) fields to gigahertz frequencies.

In the face of such inconclusive potential risks, and in the absence of bus-specific technical regulations, mitigation strategies may be implemented on the safe side to minimize or avoid, whenever feasible, future liabilities to transportation companies and electric trolleybus manufacturers. This is also a relevant aspect of this research. It is therefore important to carry out studies on the identification and impact of electromagnetic fields on living organisms in urban transport and to develop appropriate standards and regulations for the emission of these fields [14]. Despite the issuing of various regulations, there are currently no strict legislative provisions limiting public exposure to low-frequency electromagnetic fields in electric and hybrid vehicles [15]. Currently, there are few studies on passenger exposure to electromagnetic fields in electric vehicles, especially trolleybuses and electric buses. Most of the research concerns exposure to these fields in the context of passenger cars.

A study published in [16] aimed to assess exposure to low-frequency magnetic fields associated with the use of electric vehicles in urban transport. Measurements in different types of vehicles and in the vicinity of charging stations showed that the recorded values were below the limits set by international labor law and International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines. The average RMS values remained below several microteslas, with the highest recorded values reaching 2.6 μT for electric buses and 33 μT for trolleybuses. These results suggest that the use of electric vehicles does not represent a significant source of magnetic field exposure, which may be important for the health of vehicle users and people in their surroundings.

Another study [15] involved measurement procedures carried out in a Mercedes-Benz GLC 350 e 4MATIC plug-in hybrid car. Measurements were made under four different driving conditions: at standstill (idling), in city traffic at 50 km/h, when exceeding 100 km/h, and during braking. The results presented in the paper showed that the magnetic field exposure while traveling in this vehicle remained below the limits set by the ICNIRP.

In [17], an analysis of magnetic field levels in an undisclosed model of an electric vehicle was conducted. The lowest values were observed during charging, with the highest values occurring around the charging station. Magnetic field strengths ranging from 100 to 200 nT were recorded during urban driving, whereas values of 100 to 300 nT were noted on the motorway, with an increase corresponding to higher speeds.

A study of low-frequency magnetic field levels on the rear seat of 10 different passenger electric cars during different driving scenarios was presented in [18]. Measurements from different heights corresponding to the locations of adult and infant heads were used to calculate the induced electric field strength using human anatomical models. The results showed that the measured B-fields on the rear seat were far below the reference levels established by the ICNIRP. Although young children may have been exposed to higher magnetic field strengths, the induced electric field strengths were much lower than in adults due to their body structure.

One article [19] discussed a study of magnetic field exposure in electric and conventional passenger cars, analyzing exposure levels up to 10 MHz. The results showed that exposure near the battery and at the feet during vehicle starting reached up to 20% of the ICNIRP 2010 reference levels but remained below 2% at head height for the front passenger position.

In [20], six passenger cars were analyzed, including three full hybrid vehicles and three mild hybrid vehicles from different manufacturers, manufactured between 2001 and 2010. Measurements were taken while traveling at speeds between 20 and 40 km/h, which showed a noticeable increase in magnetic flux density in the vicinity of the driver's foot. These fields are mainly generated by currents flowing in circuits, motors, and batteries. Measurements were made at different heights in the passenger compartment and during different driving conditions, and the highest values were observed in the foot area, reaching up to 78.8% of the 1998 reference values set by the ICNIRP, especially during braking and acceleration.

Another study [21] on the magnetic field emitted by the drive motors and the power supply system in two passenger cars (electric and hybrid) showed the variability in exposure to electromagnetic fields under different driving conditions. Measurements were made in the frequency range from 40 to 800 Hz, with the highest values recorded mainly in the range up to 300 Hz. The recorded values remained below the limit values specified by Polish occupational health and safety regulations.

In [22], the emphasis was placed on long-term studies of exposure to low-frequency magnetic fields in three passenger electric cars. Measurement results were typically in the range of a few tenths of a microtesla (μT). It was found that both acceleration and braking of the vehicle tended to generate higher μT values. The experimental results showed that changing tires could alter the magnetic field in the vehicle cabin. The study showed that there is a need for regular monitoring of the magnetic field in electric vehicles, especially after major repairs or accidents, in order to protect vehicle occupants from magnetic field exposure.

In [23], researchers examined the potential risk of electromagnetic interference in patients with implanted electronic cardiac devices during the battery charging process of passenger electric cars at fast charging stations. The study involved 130 patients and encompassed a total of 561 charging events, including four electric passenger cars and one experimental vehicle with a charging power of 350 kW. Despite the direct placement of the charging cable over the cardiac devices, no instances of interference were observed. The findings suggested that the use of electric cars with fast chargers by patients with cardiac devices is safe. Nevertheless, caution is advised to avoid prolonged close contact with charging cables.

In 2021, some recent studies also suggested that children exposed to extremely low-frequency magnetic fields of 0.4 μT (or 3.18 A/m) may have a 0.89–4.52 times higher risk of cancer, despite not showing high-intensity relation [24].

3. Public Transportation System in Lublin

The beginnings of transport in Lublin date back to the second half of the 19th century. The basic means of transport then were horse-drawn carriages and horse-drawn omnibuses. However, as early as 1912, the Zborowski Motor Company of Lublin obtained a concession to introduce a regular bus line in Lublin. At that time, a total of three buses were operational.

In 1929, state transport was established under the name, Municipal Buses of the City of Lublin, which is considered to be the beginning of the development of public transport in the city. Since then, through the period of the Second World War, several decades of existence in the socialist system, and years of political transformation of the Polish state, there has been a continuous industrial and civilizational development of the city, including an increase in the population. The last decade has marked a significant breakthrough in Lublin's public transport, advancing it towards modernization. During this time, new buses and trolleybuses were introduced, and upgrades and expansions to the trolleybus traction system were implemented. At present, in terms of a rolling stock structure for line service, MPK Lublin has 355 vehicles. These include 215 buses with internal combustion engines, 40 electric buses, one hydrogen-powered bus, and 100 trolleybuses. Through signed agreements and partnerships, the company ensures that 100% of the energy consumed by their electric buses and trolleybuses comes from renewable energy sources. This commitment significantly enhances the environmental benefits of their electric fleet.

What sets the trolleybus fleet apart is the inclusion of an autonomous energy source in each vehicle. This significantly enhances the availability of electric public transportation, enabling service provision even on route sections lacking access to the overhead line. They are equipped with asynchronous propulsion systems, which are characterized by low electricity consumption, the possibility of recuperating energy and returning it to the grid as a result of vehicular braking, the absence of carbon brush dust, and less operating waste. These systems also offer higher speeds achieved by trolleybuses, greater dynamics during vehicular acceleration and braking, better ride comfort, and lower operating costs with less noise generated by the vehicle [25]. Trolleybuses in Lublin are also equipped with a system, patented by MPK Lublin in cooperation with the Lublin University of Technology, that ensures a continuity of power supply to the auxiliary equipment of the vehicle during travel through insulators installed on the overhead line [26,27].

The most numerous trolleybus model (37 units) in Lublin's fleet is a twelve-meter low-floor Ursus T70116 trolleybus. It is powered by a 175 kW asynchronous traction motor, which was built behind the rear drive axle of the vehicle. The trolleybus is equipped with an autonomous energy source in the form of an NMC-type lithium-ion battery with a total capacity of 34 kWh and a usable capacity of 13.6. kWh. The trolleybus power supply inverter system, together with the current collection system and the autonomous driving system, is built into the roof of the vehicle.

There are also articulated trolleybuses in operation in Lublin. These are Solaris Trollino 18 (27 units) and Ursus CS 18 LFT (15 units). They are powered by a 240 kW asynchronous traction motors, which was built in front of the rear axle of the vehicles. The trolleybuses are equipped with autonomous energy sources in the form of LTO-type lithium-ion batteries with a total capacity of 60 kWh and a usable capacity of 48 kWh. The trolleybus power supply inverter system, together with the current collection system, were built into the roof of the vehicles. Traction battery chargers are located in the rear of the vehicles in the tower housing. Traction batteries were also built into the rear of the trolleybuses, in a tower housing in the case of the Solaris Trollino 18 trolleybus shown in Figure 1, and on the roof in the case of the Ursus CS 18 LFT trolleybus.

A significant part of Lublin's trolleybus fleet consists of Solaris Trollino 12 MB trolleybuses (20 units). They are powered by a 175 kW asynchronous traction motor, which was built in front of the rear drive axle of the vehicle. The trolleybuses are equipped with an autonomous energy source in the form of a series hybrid system, located in the vehicle's tower body, in which an internal combustion engine drives a 100 kW synchronous generator. The vehicles have a 125 L fuel tank, which translates into a range, when powered by the autonomous energy source, of around 250 km. The system of inverters that powers the trolleybuses, together with the power collection system, are built into the roof of the vehicles.



Figure 1. Solaris Trollino 18 in service in Lublin. Credit: © Sławomir Kołodziej.

In terms of catenary, the solutions used in Lublin are among the most modern in the world. The length of the trolleybus catenary network in Lublin is 152 km. It is powered from thirteen traction substations with a capacity of 1.2 MVA to 2.4 MVA. The modern trolleybus network was built in a decentralized system, thus reducing power transmission losses [28]. Traction substations are unmanned, radio-controlled from the Power Dispatch Center. A catenary switch control system called Vetra was implemented at a trolleybus depot in Lublin. In Poland, it is only in Lublin that it is used for trolleybus catenary control, and the way it has been adapted to the trolleybus depot is an element that distinguishes Lublin on a global scale [29]. Currently being implemented in MPK Lublin is a system for the remote control of sectional disconnectors of the overhead line. The control of sectional disconnectors will be carried out through GSM communications and will enable the connection of two power supply sections from neighboring substations in order to increase the recuperation capacity and maintain the continuity of the trolleybus traction power supply. The system is currently in its installation and configuration phase. It will be implemented and operational by the end of 2024.

The experience acquired by MPK Lublin in managing a modern fleet of trolleybuses has led to the integration of electric buses into its service. The electric buses currently operating in Lublin are designed to continuously provide transportation services, facilitated by the provision of suitable charging infrastructure at terminal stops.

A significant portion of the electric buses in operation are Solaris Urbino 12 electric (32 units), which are shown in Figure 2. They are powered by two electric, asynchronous motors of 60 kW each. They were built into the rear axle of the vehicle. The bus is equipped with LTO-type lithium-ion batteries with a total capacity of 4 × 30 kWh. The usable capacity of the battery pack is 94 kWh. Two batteries were mounted in the vehicle's tower body, and the other two were built on the roof over the front axle of the bus. A set of inverters and a pantograph were placed on the roof of the vehicle in the central section. The electric bus charging system includes seven charging points located in the Lublin city area. Each charging point consists of two or four charging stations with a capacity of 450 kW each. The process of charging a vehicle, including its time, depends on the type of vehicle, the on-board battery, and the degree of discharge, and on average this takes 20 min.

The charging system for electric buses at the depot (Figure 3) consists of chargers with an active power of 40 kW to 60 kW. It is possible to connect one vehicle to each charger, with charging processes typically scheduled after the end of the journey, often at night.



Figure 2. Solaris Urbino 12 electric charging on Wróbla Street in Lublin. Credit: © Sławomir Kołodziej.



Figure 3. Stationary electric vehicle charging system at the premises of the MPK Lublin's depot in Lublin. Credit: © Sławomir Kołodziej.

4. Methodology

In order to identify the levels of electromagnetic fields in places accessible to people, measurements of electric field strength E and magnetic field strength H were made using a method based on the vertical measurement axis at heights of 0.3 m to 2 m above the surface where people may have been present. For the purposes of this analysis, the developed test system involved the following steps:

- Identification of the electromagnetic background (vehicle switched off, stationary mode), which allowed for an assessment of how high the field strength levels were due to the operation of the vehicle in relation to the environment and external electromagnetic field sources;
- Identification of electromagnetic field levels during bus operation (vehicle in city traffic, cyclic stops, starts, brakes, continuous driving) during which the vehicle was loaded with lighting, heating, communication systems, etc.;
- Identification of electromagnetic field levels during the charging of the bus's on-board battery using a pantograph;

- Identification of electromagnetic field levels during the charging of the bus's on-board battery using a charger;
- Identification of electromagnetic field levels during trolleybus operation, including measurements during parking and driving in two modes—on-board power and traction power.

This article presents the results of tests conducted with Solaris Urbino 12 electric buses, as well as Solaris Trollino 18 and Ursus T70116 trolleybuses. The tests of the vehicles were carried out over several days, with measurements lasting from the morning hours until the evening. Measurements in stationary mode and stationary charging mode were carried out at the depot of the transportation company. The tests in the driving mode were carried out on the territory of the city of Lublin, driving at speeds resulting from the prevailing urban traffic, and the route for successive vehicles was repeated cyclically.

In order to select the zones where people typically stayed, the space of the vehicle was divided into a cabin (the driver's work zone) and an on-board space in which the vehicle's passengers resided. This analysis focused on the vehicle's passenger zone. In each of these spaces, measurement points were selected in which measurements were made during different states of vehicular operation. Each spatially defined point was a vertical measurement axis. A vertical measurement axis is a vertical line along which a meter probe is moved to determine the maximum levels of electromagnetic fields in the environment. In order to unambiguously locate the vertical measurement axes for each vehicle, their location was plotted on a situational sketch of the vehicle (Figures 4–6).

To assess the consistency of measurements across various vehicles, four measurement levels were established along the vertical axis:

- Floor—zone at a height of 0.2–0.3 m from the vehicle floor;
- Seat—zone at a height of 0.6 m from the vehicle floor;
- Seat handrail—zone at a height of 1.4 m from the vehicle floor;
- Upper handrail—zone at a height of 2 m from the vehicle floor.

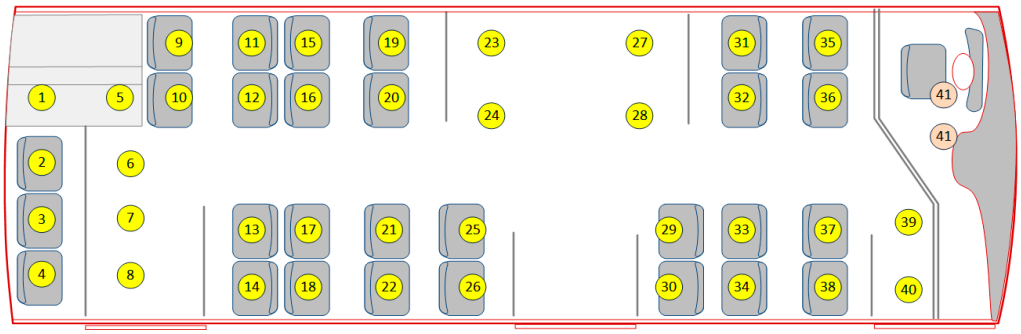


Figure 4. View of measurement points—vertical measurement axes located in the electric Solaris Urbino 12 electric (yellow dots show seats available for passengers, other colors for staff).

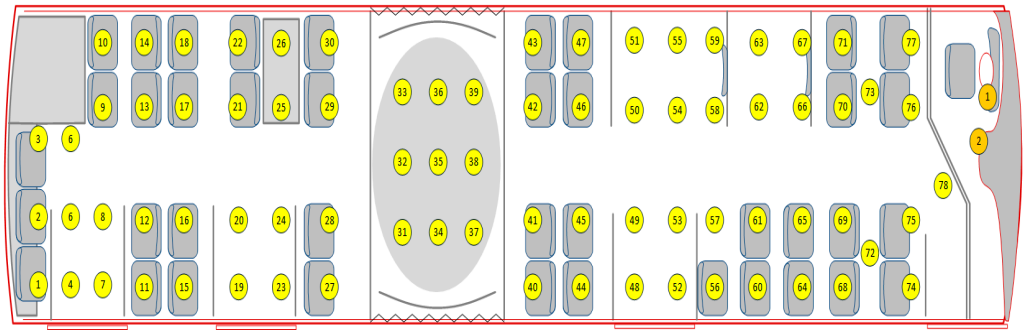


Figure 5. View of measurement points—vertical measurement axes located in the Solaris Trollino 18.

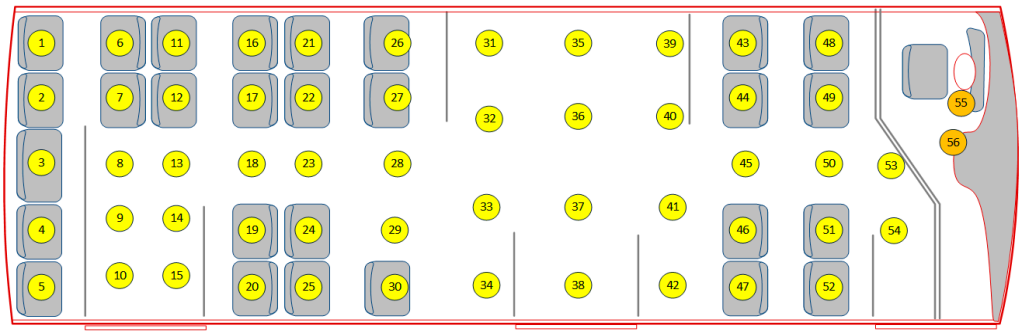


Figure 6. View of measurement points—vertical measurement axes located in the Ursus T70116.

Measurements were conducted in two stages. Initially, a spatial analysis of field component levels was performed at numerous measurement points. The measurements began from points at the rear of the vehicle and progressed towards the front. The subsequent stage involved analyzing changes over time in electric and magnetic field strength values during vehicular operation at selected points, aiming to assess the impact of vehicular acceleration, regenerative braking, and parking on measurement values. The measurement team was equipped with a Maschek ESM-100 H/E Field Meter, a BGM101 Brockhaus Measurements AC/DC magnetic field meter, and a Tenmars 197 AC/DC magnetic field meter. All meters were battery-powered to ensure mobility during measurements. The measurement data were aggregated using dedicated software.

All surface distributions presented in the next section will be based on the measurement points presented in Figures 4–6. The left side represents the rear of the vehicle, while the right side represents the front of the vehicle.

5. Results

5.1. Tests of the Solaris Urbino 12 Electric

The first vehicle tested was a Solaris Urbino 12 electric. Two units were tested, and the results obtained are presented in figures and tables. The first step was to analyze the magnetic and electric field strengths when the vehicle was stationary (representing the electromagnetic background). The identified low levels do not differ significantly from the values obtained outside the vehicle at the bus depot, and the fluctuations in the values may be attributed to the vehicle's geometry, the continuous operation of on-board systems, or external sources. Electric field strengths in the ELF band range from 2 V/m to 18 V/m, while magnetic field strengths in the ELF band ranged from 0.03 A/m to 0.25 A/m.

The next step was to examine the strengths while the bus was traveling through the city. As assumed in the measurement methodology, tests were carried out for four heights, each for 40 points defined in Figure 4. Surface plots were created from the values obtained. All figures in this article depict solely the bus on-board area of the vehicles. Due to the nature of the vehicle's operation—as an electrical object that processed large values of current—the magnetic field strength analyses that were carried out are of particular importance. As an example, the strength levels measured for two heights—the floor and seat level—are presented. Figures 7 and 8 show the magnetic field strengths of the ELF band, and Figure 9, the electric ELF field strengths, respectively. The maximum magnetic field levels were observed in the drive axis area of the bus, where the engines were located. On the other hand, at the floor level, the electric field reached its highest values near the hot air blower.

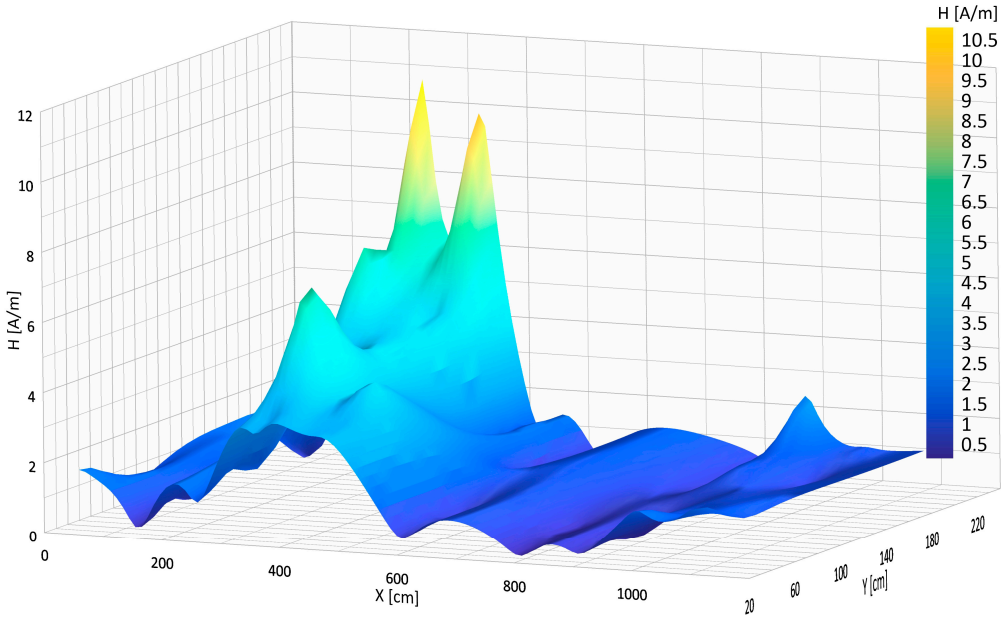


Figure 7. Spatial distribution of magnetic field in the Solaris Urbino 12 electric during urban driving. Measurement height: 0.2–0.3 m.

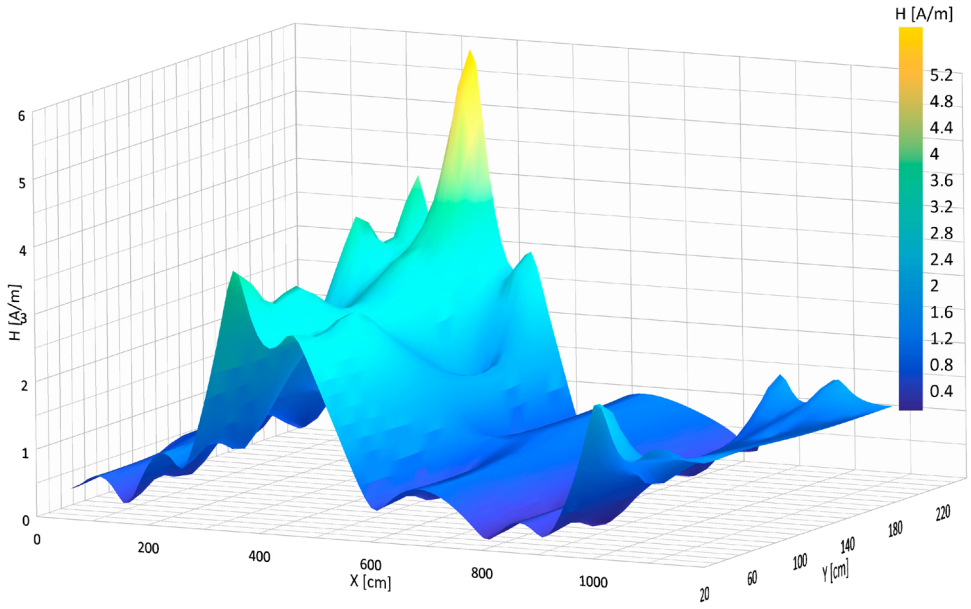


Figure 8. Spatial distribution of magnetic field in the Solaris Urbino 12 electric during urban driving. Measurement height: 0.6 m.

In the next step, the bus was tested during charging. Firstly, a measurement was carried out during fast charging with the pantograph. Measurements were taken at a height of 2 m moving between points 20, 21, 32, and 33 (Figure 4). The measurement started in the zone under the pantograph (points 20–21) and then proceeded to the zone under the traction battery (points 32–33). The measurements were taken by walking in rotation in this zone. A graph illustrating the variation in magnetic field strength during this procedure is presented in Figure 10. The fluctuations in the obtained values result from moving closer to and further away from the key elements of the pantograph system.

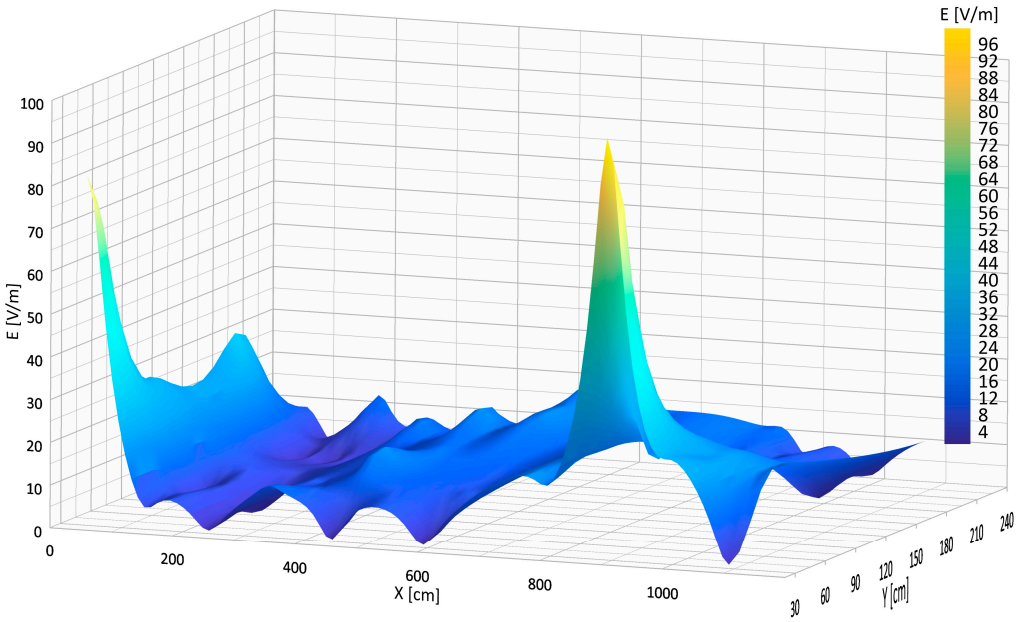


Figure 9. Spatial distribution of electric field in the Solaris Urbino 12 electric during urban driving. Measurement height: 0.2–0.3 m.

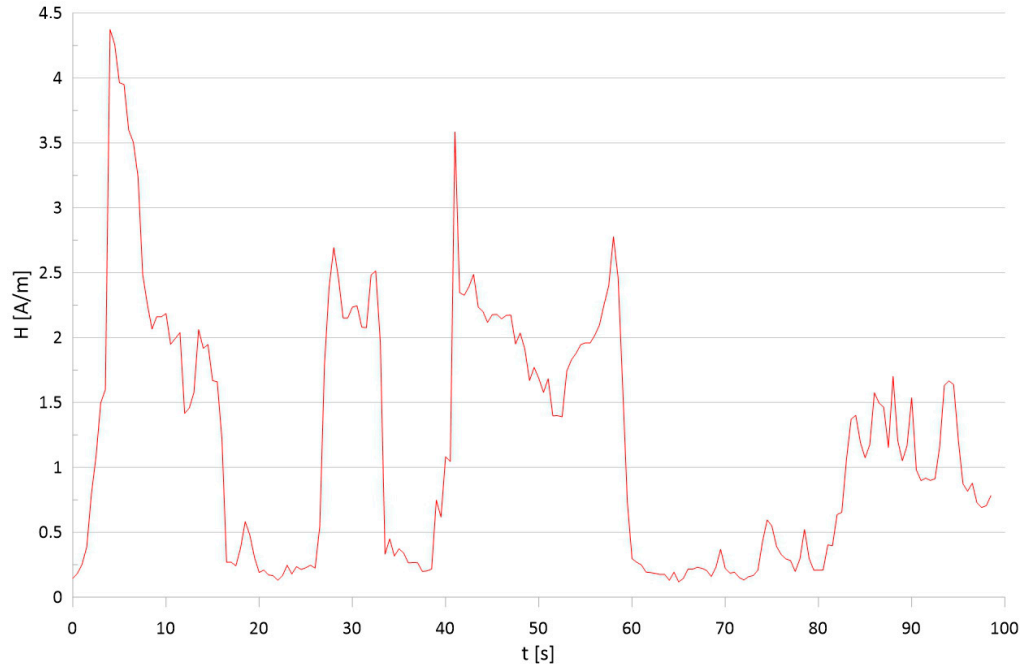


Figure 10. The variation in the magnetic field strength under the pantograph and traction battery zones.

The next stage of this study involved measurements during the electric bus charging using the stationary off-board charger. The vehicle, turned off, stood in the depot area, and measurements were taken at a height of 1.4 m, moving with the meter throughout the entire vehicle, starting from the rear. The entire measurement comprised a double passage of points. Lower magnetic field strength levels were observed compared to pantograph charging, and the selected height was justified by the need to determine the values for the operating personnel performing any preparations for the journey during charging, such as bus cleaning. Figure 11 illustrates the variation in magnetic field strength during off-board charging using the stationary charger at the depot.

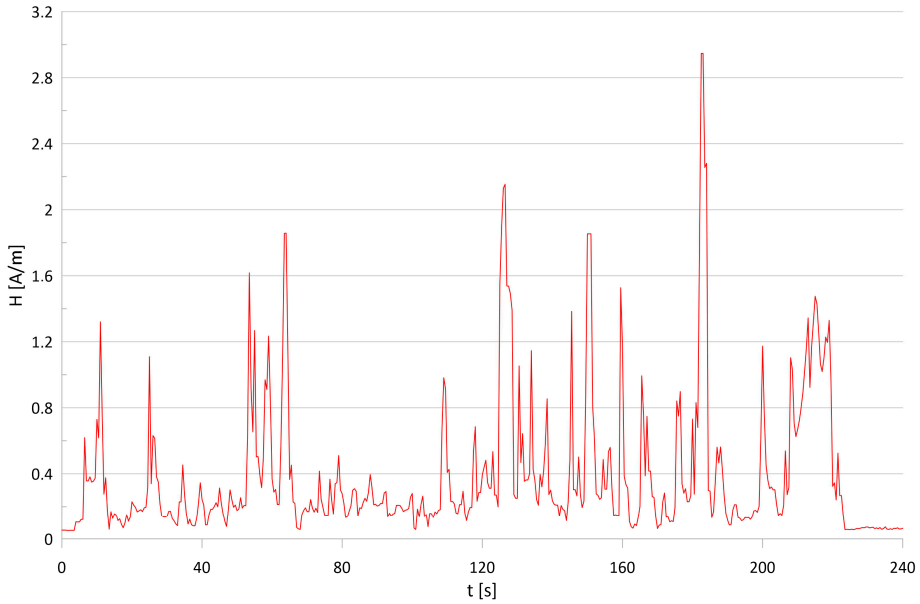


Figure 11. The variation in the magnetic field strength during off-board charging using the stationary charger at the depot.

In parallel with the tests of electric and magnetic field strengths in the ELF band, the strength of the static magnetic field was also measured. Accordingly, the average background value (vehicle off) was 75 A/m, with a measurement range between 23.4 A/m and a maximum of 133 A/m. During driving, the average values of the static magnetic field oscillated around 438 A/m, with the pantograph charging at 497 A/m and with off-board stationary charging at 514 A/m (at the channel with the power supply installation).

The final statistical summary of the tests carried out for the Solaris Urbino 12 electric buses is shown in Table 1. While the graphs show locally dominated zones of high levels of electric and magnetic field strengths, the summary statistics provide a better assessment of the strength levels in relation to the permissible limits.

Table 1. Statistical summary of measured field strengths for the Solaris Urbino 12 electric buses.

	ELF Band During Urban Driving				Static Field (During Urban Driving)
Measurement Height	0.2–0.3 m	0.6 m	1.4 m	2.0 m	
Magnetic Field Strength [A/m]					
Average	1.67	0.91	0.57	0.92	438.4
Median	0.69	0.42	0.34	0.48	463.4
Maximum	16.83	5.96	3.74	6.42	559.9
Electric Field Strength [V/m]					
Average	24.16	16.15	10.57	14.38	N/A
Median	11.57	11.62	6.42	9.01	N/A
Maximum	211.18	112.55	81.42	106.95	N/A

5.2. Tests of the Solaris Trollino 18

The second vehicle tested was a Solaris Trollino 18 trolleybus. Figures 12 and 13 show the spatial distributions of the magnetic and electric field strengths, when the vehicle was stationary (the electromagnetic background). Once again, a low level of magnetic field strength was observed, and while some higher values of electric field strength were noted, they did not significantly differ from the values obtained outside the vehicle, at the depot.

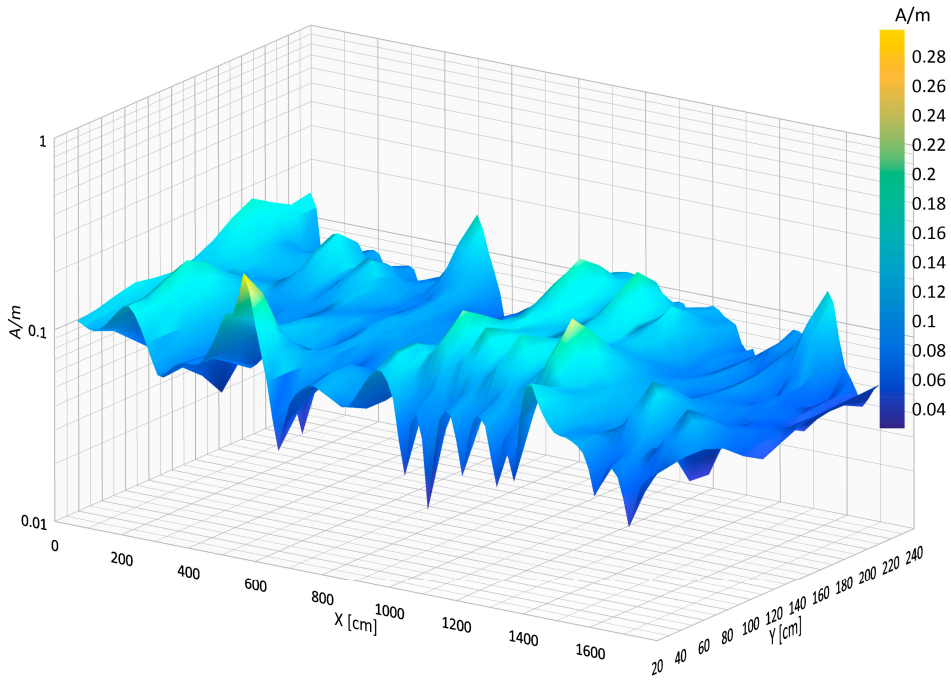


Figure 12. Spatial distribution of magnetic field in the Solaris Trollino 18 during stationary position. Measurement height: 1.40 m.

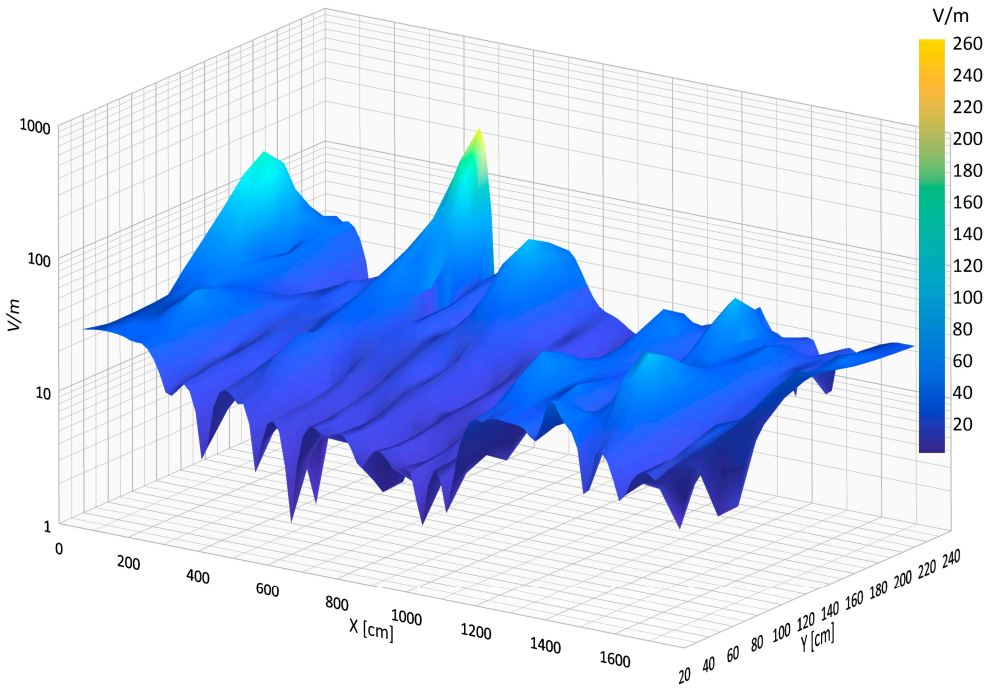


Figure 13. Spatial distribution of electric field in the Solaris Trollino 18 during stationary position. Measurement height: 1.40 m.

Again, the primary focus was on identifying the strengths during urban driving. As outlined in the measurement methodology, surveys were conducted at 78 points for four different heights (see Figure 5). For illustration purposes, the field strengths are depicted in surface plots for two of these heights: the floor level (0.2–0.3 m) and the seat handrail (1.4 m). Magnetic field strengths are shown in Figures 14 and 15, while electric field strengths are depicted in Figures 16 and 17, respectively.

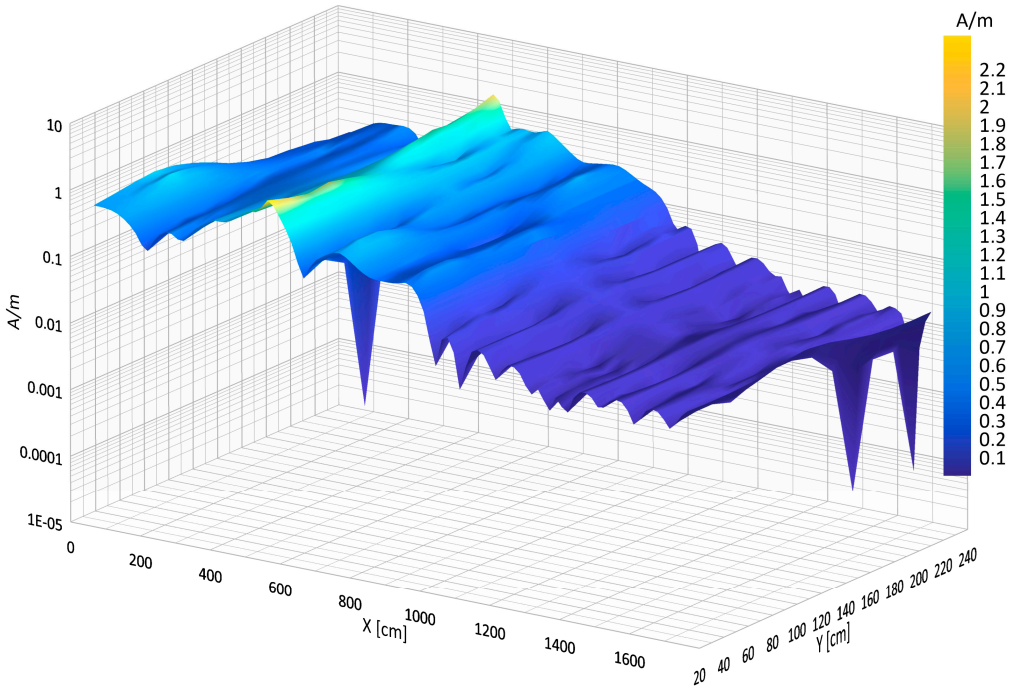


Figure 14. Spatial distribution of magnetic field in the Solaris Trollino 18 during motion. Measurement height: 0.2–0.3 m.

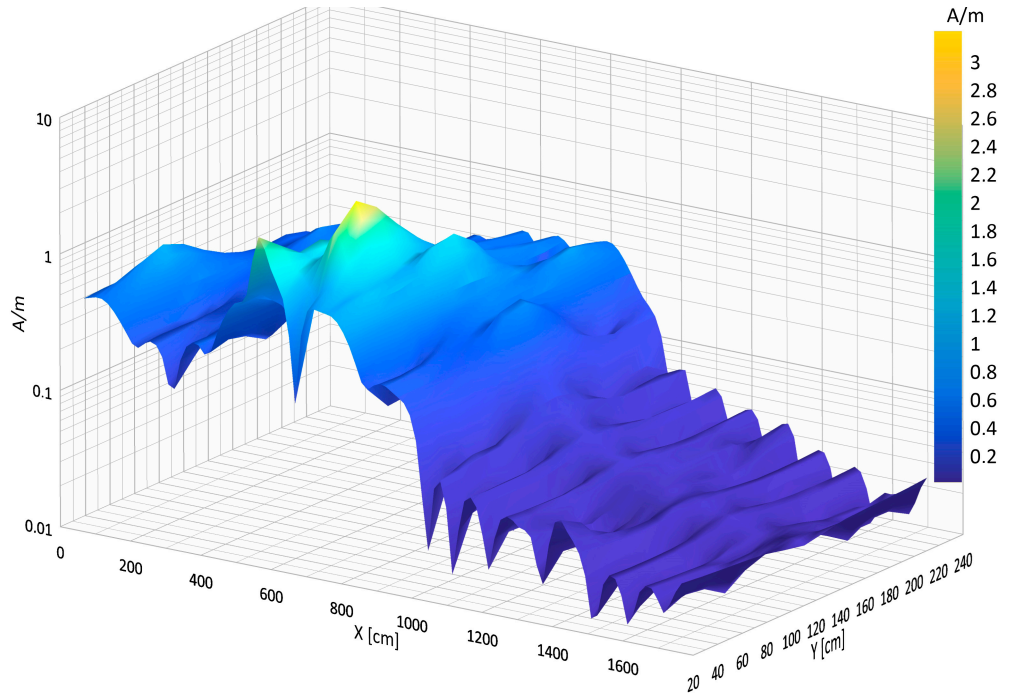


Figure 15. Spatial distribution of magnetic field in the Solaris Trollino 18 during motion. Measurement height: 1.4 m.

Zones with maximum magnetic field strengths (depicted in Figures 14 and 15) were observed in the rear drive axle area of the trolleybus, where the motor was located. The electric field strength, relative to the electric bus, was significantly larger and exhibited a qualitatively similar shape to the magnetic field strength. Also noticeable in the diagrams are the high values of strength of both fields in the area of the articulation (6 m from the

end of the vehicle). In this zone, the on-board installations converge, and the construction of the articulation does not provide as effective shielding as the body.

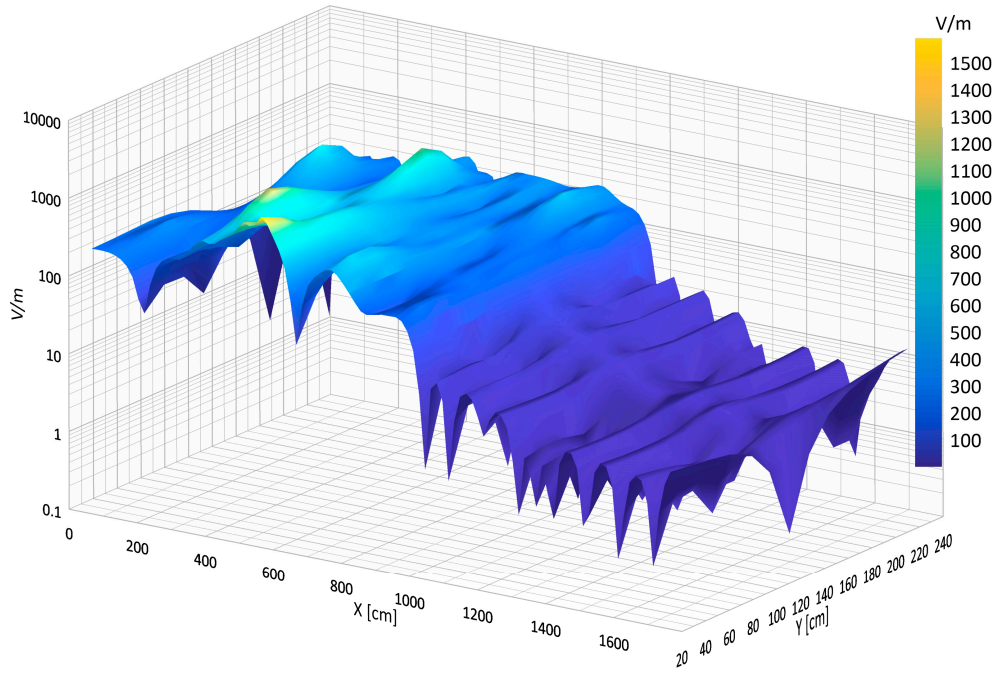


Figure 16. Spatial distribution of electric field in the Solaris Trollino 18 during motion. Measurement height: 0.2–0.3 m.

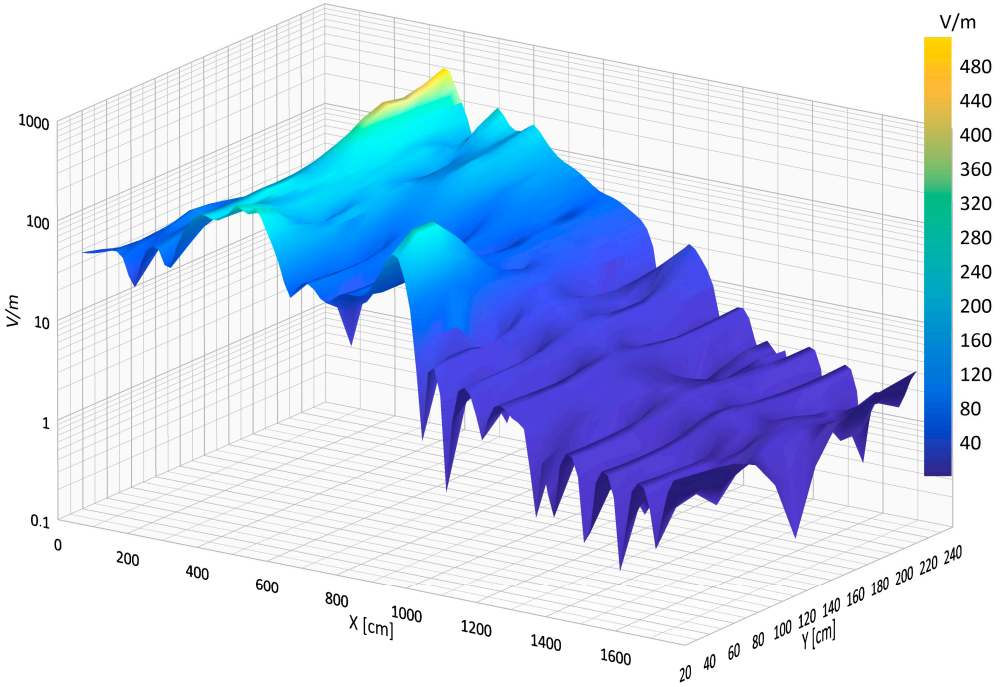


Figure 17. Spatial distribution of electric field in the Solaris Trollino 18 during motion. Measurement height: 1.4 m.

The strength of the static magnetic field was also examined as it was examined previously for the electric bus. Similarly, the average background value (with the vehicle switched off) was found to be 73 A/m, while during driving, the average values of the

static field oscillated around 122 A/m. Static magnetic field strength values ranging from 30 A/m to 246.7 A/m were observed, with no dominant zones.

Furthermore, an additional study was conducted in the area of measurement points 25–26 in Figure 5, which corresponded to the location of the cable duct of the power unit and the motor itself. This involved analyzing changes in the strength of the magnetic field over time, with three positions selected and measurements taken over several minutes at each. The field strength levels were evaluated over time to reflect typical real-world vehicular operating conditions, including regenerative braking, stopping, starting, and uniform driving. The magnetic field strength levels were recorded on both sides of the cable duct during urban driving. Low levels (0.08–1 A/m) were observed when the vehicle was stationary at intersections due to red lights, confirming the principle that no energy consumption by the engine corresponded to no high field strength value. High values of magnetic field strength levels (80–300 A/m) were observed during acceleration and braking maneuvers.

The final statistical summary of the tests carried out for the two Solaris Trollino 18 trolleybuses is shown in Table 2.

Table 2. Statistical summary of measured magnetic and electric field strengths for the Solaris Trollino 18 trolleybuses.

	ELF Band During Urban Driving				ELF Band (Cable Duct)	Static Field (During Urban Driving)
Measurement Height	0.2–0.3 m	0.6 m	1.4 m	2.0 m		
	Magnetic Field Strength [A/m]					
Average	0.398	0.319	0.272	0.78	29.01	122.8
Median	0.07	0.058	0.060	0.1	3.44	119.3
Maximum	4.392	3.326	3.222	11.84	348.1	246.7
	Electric Field Strength [V/m]					
Average	178.14	136.23	54.86	59.08	201.6	N/A
Median	5.64	4.91	7.09	7.92	55.3	N/A
Maximum	1597.52	1091.54	618.49	531.61	4115.4	N/A

5.3. Tests of the Ursus T70116

The third type of vehicle tested was the Ursus T70116 trolleybus, with two units similarly examined. The initial tests involved identifying the electromagnetic background while the vehicle was turned off and stationed at the depot. Once again, low levels of magnetic and electric field strengths were detected, measuring below 2 A/m and 120 V/m, respectively, falling within the typical range observed outside the vehicle at the depot.

During the examination of field strengths in the ELF band, a zone with elevated levels was observed during urban driving. This zone corresponds to the cable duct, situated in the rear pillar of the vehicle structure. This duct carries power from the pantograph system and the on-board battery on the roof to the drive motor located in the rear drive axle of the vehicle. The flow of high currents through this conduit generated the magnetic field observed in this area at various heights (Figures 18 and 19).

More elevated E and H field strengths were observed in the measurement zone at the 2 m level (Figures 19 and 20). This was due to the meters being closer to the roof of the vehicle, where components of the pantograph system, traction battery, energy recuperation systems, and traction resistors were located. The electricity they processed was the source of the measured fields, despite the shielding of this space by a metal roof structure.

The final step was an analysis of the static magnetic field strength. Similarly, the average background value (with the vehicle turned off) was found to be at a low level

of 79 A/m, while during driving, the average values of the static magnetic field strength oscillated around 120 A/m.

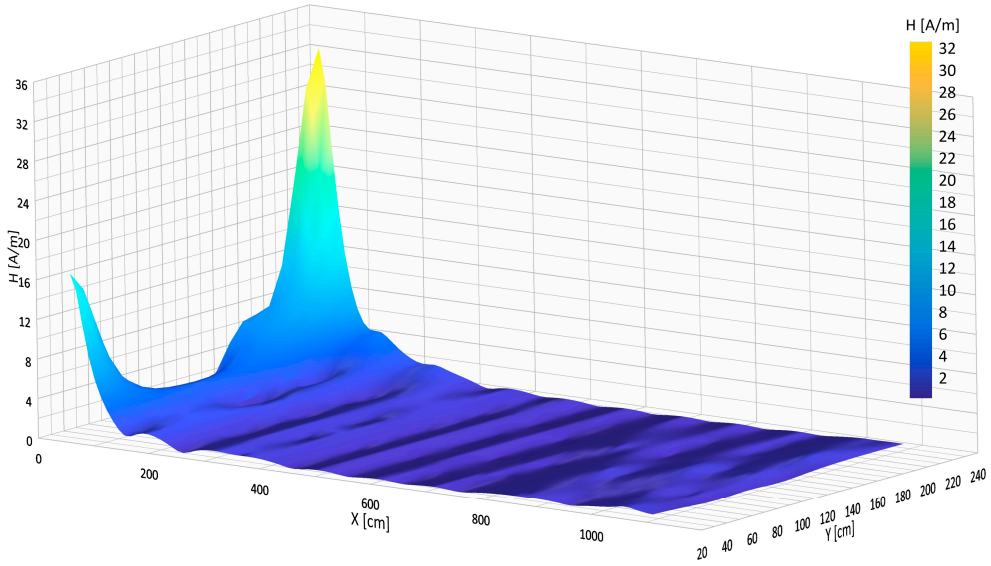


Figure 18. Spatial distribution of magnetic field in the Ursus T70116 during urban driving. Measurement height: 0.6 m.

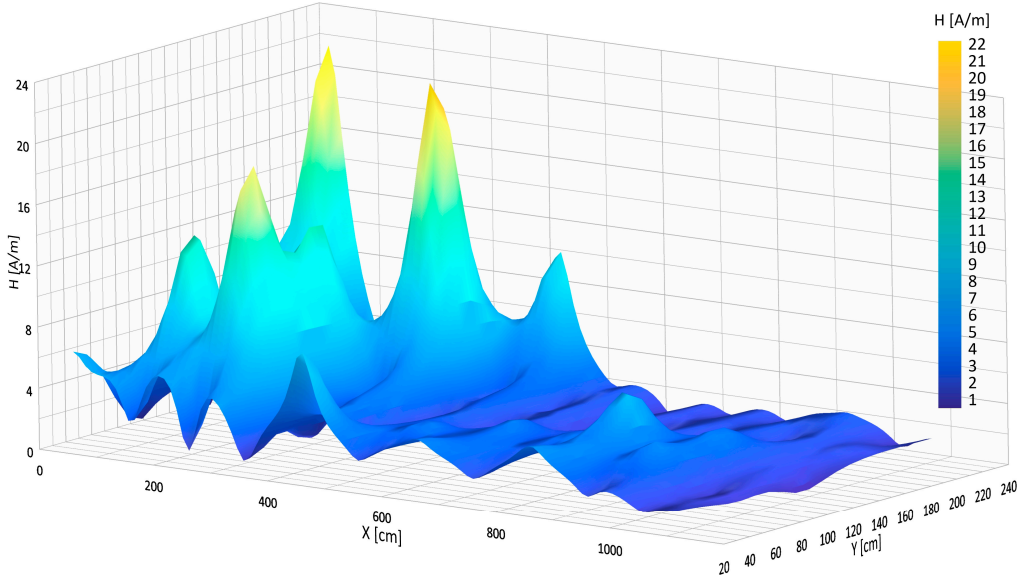


Figure 19. Spatial distribution of magnetic field in the Ursus T70116 during urban driving. Measurement height: 2 m.

As depicted in Figure 18, the segment of the duct cable with the primary wires supplying power to the drive required further analysis. Additional measurements were conducted in this region, with the meter placed in direct contact with the duct and positioned 15 cm away. Measurements were taken over several minutes under typical vehicular operating conditions (including starting from a bus stop, driving in urban areas, and braking using regenerative and standard methods). The highest instantaneous recorded values were 2800 V/m and 200 A/m, respectively. As anticipated, peak values were recorded during periods of high current flow, such as vehicle startup and acceleration.

The final statistical summary of the tests carried out for the two Ursus T70116 trolleybuses is shown in Table 3.

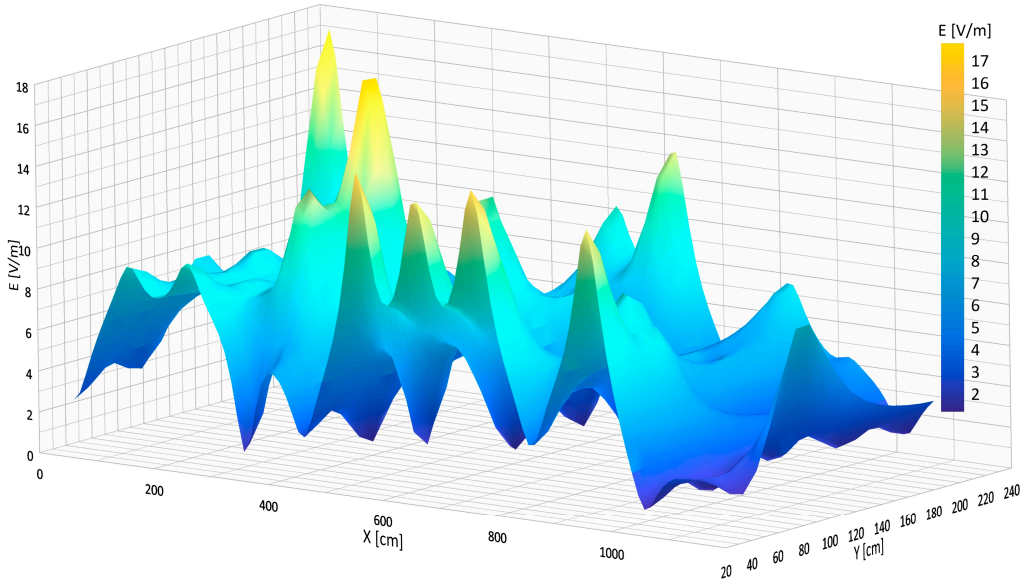


Figure 20. Spatial distribution of electric field in the Ursus T70116 during urban driving. Measurement height: 2 m.

Table 3. Statistical summary of measured magnetic and electric field strengths for the Ursus T70116.

	ELF Band During Urban Driving				ELF Band (Cable Duct)	Static Field (During Urban Driving)
Measurement Height	0.2–0.3 m	0.6 m	1.4 m	2.0 m		
Magnetic Field Strength [A/m]						
Average	0.88	0.65	0.47	0.95	23.19	117.45
Median	0.25	0.25	0.24	0.37	7.19	119.37
Maximum	14.76	8.05	3.75	11.10	201.46	206.90
Electric Field Strength [V/m]						
Average	101.74	80.03	84.91	62.61	N/A	140.68
Median	64.62	40.61	63.88	42.05	N/A	23.88
Maximum	369.45	319.44	317.43	347.54	N/A	2793.26

6. Discussion

The electromagnetic environment around us is the sum total of electromagnetic radiation caused by natural and artificial sources of electromagnetic emission. The value of electromagnetic radiation (of both its components—electrical and magnetic) is influenced by the power of the emitting source, the distance from the source, the frequency of the signal, and the environmental conditions—such as structures that act as screening barriers.

As part of this research, a series of tests were carried out to identify the intensity of electromagnetic radiation in the three types of electric public transport vehicles presented so far in this article.

It was assumed that, for the purposes of this study, the analysis would be carried out in the form of a comparison of the values obtained with the regulations in force in the country, limiting the permissible intensities of electric and magnetic fields in the environment [30,31]. Bearing in mind the need to assess the intensities of the static and extremely low-frequency fields (which arises from the usable signals in on-board installations, power systems, and vehicle drives) as well as the meters used in this study, limits were adopted for the electric static field and in the ELF band of 10,000 V/m, as well as for the magnetic fields of 2500 A/m and 60 A/m, respectively.

For the Solaris Urbino 12 electric, from analyzing all the results collected, including those shown in Figures 7–11 and Table 1, we found the following:

- The average values in terms of static magnetic field strength in relation to the electromagnetic background were higher (by about six times), and the highest values were recorded, during stationary charging at the wire channel, reaching 1200 A/m, even though they nevertheless did not even exceed half of the permissible limit;
- The mean values of the electric field strength in the extremely low-frequency band in relation to the electromagnetic background were several times higher, but did not even exceed one percent of the admissible limit;
- Average values of the magnetic field strength in the extremely low-frequency band in relation to the electromagnetic background were even several times higher, while performing additional, detailed tests in the area of the canal with the main power cables, the intensity increased to values of several hundred A/m, which was several times more than the permissible limit of 60 A/m, and the space with such large fields covered a range of several dozen to several dozen centimeters around the canal, with these such large values observed during the charging of on-board batteries.

For the Solaris Trollino 18 trolleybus, from analyzing all the results collected, including those shown in Figures 12–17 and Table 2, we found the following:

- The average values in terms of static field strength in relation to background were twice as high and statistically the same in most of the passenger areas, with higher values recorded in the vicinity of the power conductor tracks in the articulated vehicle and in the vicinity of the engine, but these did not exceed the permissible limit either;
- The mean values of the electric field strength in the extremely low-frequency band were also two to three times higher than in the background, and in the vicinity of the conductor channel, the strength increased to more than 4 (100 V/m), but no exceedances of the admissible limit were found;
- Average values of magnetic field strength in the extremely low-frequency band in relation to the background were several times higher, but still within the limit, while in the vicinity of the cable duct, the intensity increased to levels of approx. 350 A/m, which exceeded the permissible limit but the registrations of such fields were momentary such that the impact covered only a space of several centimeters.

For trolleybus Ursus T70116, from analyzing all the collected results, including those presented in Figures 18–20 and Table 3, we found the following:

- The average values in terms of permanent magnetic field strength relative to the background were several times higher, but statistically the same as in the previously analyzed vehicles, and did not exceed the permissible limit;
- The mean values of the electric field strength in the extremely low-frequency band compared to the background were higher by a factor of about 4, but did not exceed the permissible limit;
- The mean values of the magnetic field strength in the extremely low-frequency band compared to the background were several times higher, but still within the limit, while in the vicinity of the cable duct, the intensity increased to levels of up to 200 A/m, but the recordings of such fields were momentary and the impact covered only a space of several centimeters.

To summarize the three vehicle types in terms of identified electromagnetic emissions, the highest exposures were found in the conduit area for both buses and trolleybuses. Another zone with elevated values of electric and magnetic strengths was at the rear drive axle with engines.

7. Conclusions

The identification of electric and magnetic field strengths is a necessary measure at a time of increased market demand for electric vehicles. There are public concerns about

electromagnetic effects on people and the environment, to which researchers and vehicle manufacturers must provide a clear response.

The research carried out here is only part of the work to be conducted in this area. Higher-frequency bands should also be considered, as more and more vehicles are using GSM communication, various telecommunication devices, and wireless Internet devices.

Nevertheless, the first step (presented in this paper) is to identify the levels of electric and magnetic field strengths. An analysis of the ELF band and the static field was therefore undertaken at the outset. This is crucial in the context of the currents and voltages used in this type of vehicle.

A detailed analysis of the electric and magnetic fields showed the highest exposures in the areas of the conduit channels and around the drive motor compartments. These are, as expected, locations of elevated electromagnetic emissions. The recorded values exceeding national regulatory limits were in most cases very localized, down to a few centimeters. While the levels may have varied from vehicle to vehicle, the statistical values presented in the tables indicate that the passenger areas in vehicles exhibited low levels of electromagnetic fields, ensuring safety for occupants. Potential (not 100% conclusive) risks for children as indicated by Ref. [24] exist as demonstrated by the measurements. Policy for the improved design of electrical schoolbuses may be needed in the future. More studies are needed in the future.

Author Contributions: Conceptualization, P.A.M. and A.C.; methodology, P.A.M. and A.C.; software, P.A.M.; validation, P.A.M. and A.C.; formal analysis, P.A.M. and A.C.; investigation, P.A.M.; writing—original draft preparation, P.A.M., A.C., and P.H.; writing—review and editing, P.A.M., A.C., and P.H.; visualization, P.A.M.; supervision, P.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Lublin University of Technology (Grant No. FD-20/EE-2/403 and Grant No. FD-20/EE-2/412).

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data is not publicly available because of the contract signed when the study was implemented.

Conflicts of Interest: Author Piotr Hołyszko was employed by the company Municipal Transport Company Lublin Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Sobol, Ł.; Dyjakon, A. The Influence of Power Sources for Charging the Batteries of Electric Cars on CO_2 Emissions during Daily Driving: A Case Study from Poland. *Energies* **2020**, *13*, 4267. [CrossRef]
2. Chudy, A.; Hołyszko, P.; Mazurek, P. Fast Charging of an Electric Bus Fleet and Its Impact on the Power Quality Based on On-Site Measurements. *Energies* **2022**, *15*, 5555. [CrossRef]
3. The European Green Deal. Striving to Be the First Climate-Neutral Continent. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on 12 March 2024).
4. Skrúcaný, T.; Kendra, M.; Stopka, O.; Milojević, S.; Figlus, T.; Csiszár, C. Impact of the Electric Mobility Implementation on the Greenhouse Gases Production in Central European Countries. *Sustainability* **2019**, *11*, 4948. [CrossRef]
5. Ministry of Climate and Environment. Energy Policy of Poland until 2040. Available online: https://www.gov.pl/web/klimat/polityka-energetyczna-polski (accessed on 12 March 2024).
6. The Act on Electromobility and Alternative Fuels of January 11 2018/Ustawa z Dnia 11 Stycznia 2018 r. o Elektromobilności i Paliwach Alternatywnych. Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180000317 (accessed on 12 March 2024).
7. Licznik Elektromobilności: Początek Roku na Plusie w Segmencie Zeroemisyjnego Transportu. Available online: https://pspa.com.pl/2024/informacja/licznik-elektromobilnosci-poczatek-roku-na-plusie-w-segmencie-zeroemisyjnego-transportu/ (accessed on 12 March 2024).
8. Milojevic, S. Sustainable application of natural gas as engine fuel in city buses: Benefit and restrictions. *Istraz. Proj. Privredu* **2017**, *15*, 81–88. [CrossRef]
9. Benefits Of Natural Gas Engines in Transportation. Available online: https://www.cummins.com/news/2022/05/04/benefits-natural-gas-engines-transportation (accessed on 24 June 2024).

10. LNG in Public Transport—Gas-Powered Buses. Available online: https://justtransitionmag.com/lng-in-public-transport-gas-powered-buses/ (accessed on 24 June 2024).
11. Dong, X.; Sun, W.; Lu, M. Evaluation of Electromagnetic Fields in Human Body Exposed to Inverter of Pure Electric Vehicle. *Radiat Prot Dosim.* **2023**, *199*, 216–229. [CrossRef] [PubMed]
12. Chudy, A. Identification and Analysis of the Impact of Electric Vehicle Charging Systems on Power Quality Parameters. Ph.D. Thesis, Lublin University of Technology, Lublin, Poland, 2023.
13. Hołyszko, P. Ensuring the Continuity of Operation of Trolleybus Auxiliary Devices with Overhead Power Supply. Ph.D. Thesis, Lublin University of Technology, Lublin, Poland, 2023.
14. Gajsek, P.; Ravazzani, P.; Grellier, J.; Samaras, T.; Bakos, J.; Thuroczy, G. Review of Studies Concerning Electromagnetic Field (EMF) Exposure Assessment in Europe: Low Frequency Fields (50 Hz–100 kHz). *Int. J. Environ. Res. Public Health* **2016**, *13*, 875. [CrossRef]
15. Wyszkowska, J.; Szczygieł, M.; Trawiński, T. Static Magnetic Field and Extremely Low-Frequency Magnetic Field in Hybrid and Electric Vehicles. *Przegląd Elektrotechniczny* **2020**, *1*, 62–64. [CrossRef]
16. Gryz, K.; Karpowicz, J.; Zradzinski, P. Complex Electromagnetic Issues Associated with the Use of Electric Vehicles in Urban Transportation. *Sensors* **2022**, *22*, 1719. [CrossRef]
17. Garvanova, M.; Garvanov, I.; Ivanov, V.; Borissova, D. Measurement and Estimation of the Magnetic Fields in Electric Vehicles. In Proceedings of the 2022 22nd International Symposium on Electrical Apparatus and Technologies (SIELA), Bourgas, Bulgaria, 1–4 June 2022.
18. Lin, J.; Lu, M.; Wu, T.; Yang, L.; Wu, T. Evaluating Extremely Low Frequency Magnetic Fields in the Rear Seats of the Electric Vehicles. *Radiat. Prot. Dosim.* **2018**, *182*, 190–199. [CrossRef] [PubMed]
19. Vassilev, A.; Ferber, A.; Wehrmann, C.; Pinaud, O.; Schilling, M.; Ruddle, A.R. Magnetic Field Exposure Assessment in Electric Vehicles. *IEEE Trans. Electromagn. Compat.* **2015**, *57*, 35–43. [CrossRef]
20. Karabetsos, E.; Kalampaliki, E.; Koutounidis, D. Testing Hybrid Technology Cars: Static and Extremely Low-Frequency Magnetic Field Measurements. *IEEE Veh. Technol. Mag.* **2014**, *9*, 34–39. [CrossRef]
21. Gryz, K.; Karpowicz, J.; Zradziński, P.; Tokarski, T.; Kapica, Ł. Ekspozycja na pole elektromagnetyczne podczas użytkowania pojazdów samochodowych z napędem elektrycznym lub hybrydowym. *Bezpieczeństwo Pr. Nauka I Prakt.* **2020**, *2020*, 18–21. [CrossRef]
22. Yang, L.; Lu, M.; Lin, J.; Li, C.; Zhang, C.; Lai, Z.; Wu, T. Long-Term Monitoring of Extremely Low Frequency Magnetic Fields in Electric Vehicles. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3765. [CrossRef] [PubMed]
23. Lennerz, C.; Schaarschmidt, C.; Blazek, P.; Knoll, K.; Kottmaier, M.; Reents, T.; Bourier, F.; Lengauer, S.; Popa, M.; Wimbauer, K.; et al. High-power chargers for electric vehicles: Are they safe for patients with pacemakers and defibrillators? *Europace* **2023**, *25*, euad042. [CrossRef] [PubMed]
24. Seomun, G.; Lee, J.; Park, J. Exposure to extremely low-frequency magnetic fields and childhood cancer: A systematic review and meta-analysis. *PLoS ONE* **2021**, *16*, e0251628. [CrossRef] [PubMed]
25. Bartłomiejczyk, M.; Połom, M.; Jakimovska, K. Application of principal component and hierarchical cluster analysis in classifying defects of trolleybuses. *Przegląd Elektrotechniczny* **2013**, *89*, 48–51.
26. Hołyszko, P.; Zieliński, D.; Niewczas, A.; Rymarz, J.; Dębicka, E. Ensuring the Continuity of Power Supply to the On-Board Auxiliary Devices of the Trolleybus through the Recuperation of Kinetic Energy. *Energies* **2021**, *14*, 5035. [CrossRef]
27. Hołyszko, P. Evaluation of methods for ensuring the continuity of work of trolleybus auxiliary. In *Wybrane Zagadnienia z Zakresu Elektrotechniki, Inżynierii Biomedycznej i Budownictwa: Prace Doktorantów Politechniki Lubelskiej*; Lublin University of Technology Publishing House: Lublin, Poland, 2019.
28. Bartłomiejczyk, M.; Hołyszko, P.; Filipek, P. Measurement and Analysis of Transmission Losses in the Supply System of Electrified Transport. *J. Ecol. Eng.* **2016**, *17*, 64–71. [CrossRef] [PubMed]
29. Hołyszko, P. Control of trolleybus traction network switch points based on the functional generation of individual vehicle codes. In *Prace Doktorantów Politechniki Lubelskiej—2020*; Lublin University of Technology Publishing House: Lublin, Poland, 2020.
30. The Regulation of the Minister of Health of 17 December 2019 on Permissible Levels of Electromagnetic Fields in the Environment (Journal of Laws of 2019, Item 2448). Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20190002448 (accessed on 12 March 2024).
31. The Regulation of the Minister of Climate of 17 February 2020 on Ways of Verifying Compliance with the Permissible Levels of Electromagnetic Fields in the Environment (Journal of Laws of 2019, Item 258). Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20200000258 (accessed on 12 March 2024).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.