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INTEGRATION OF CONTACT NETWORK AND AUTONOMOUS TROLLEYBUSES FOR IMPROVING THE CITY'S TRANSPORT SYSTEM

The object of the study is the technical characteristics of autonomous trolleybuses and the systems that ensure their uninterrupted power supply.

A key challenge is the dependence of conventional trolleybuses on contact networks, which limits their route versatility, complicates operations in historic city centers, bridge crossings, and regions with underdeveloped infrastructure.

The article examines key technological aspects of autonomous trolleybuses, including types of charging stations (contact, inductive, with pantographs), charging efficiency, energy consumption, and autonomous range. Examples of the implementation of this technology in Ukraine are presented, along with an analysis of charging costs and energy characteristics for runs of 20–50 km. The prospects of using autonomous trolleybuses for optimizing the city transport network, reducing CO_2 emissions, and improving the quality of passenger service are emphasized. Calculations have been made of the energy required for a trolleybus to travel a distance of 20–50 km, taking into account the average energy consumption (1.2–2.0 kWh/km), charging station capacity (up to 100 kW,) and charging efficiency (0.9). Calculations have shown that for an autonomous trolleybus run of 30 km, 45 kWh of energy is required. Modern lithium-ion batteries and charging stations with a capacity of up to 100 kW provide a full charge in 30 minutes. Intermediate charging at stops minimizes contact infrastructure while maintaining transport system flexibility. Autonomous trolleybuses reduce dependence on contact networks, which is especially relevant for bridge crossings with complicated construction or maintenance and historic centers requiring architecture preservation without excess infrastructure. They also significantly reduce CO_2 emissions to promote ecological sustainability and improve urban air quality by lowering pollution and benefiting public health.

Keywords: *autonomous trolleybuses, station, pantograph, charging, battery, contact network, power.*

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1. Introduction

Autonomous trolleybuses are a modern and innovative type of public transport that successfully integrates the features of a traditional trolleybus and an electric bus. Their main feature is the ability to operate both under the catenary network and autonomously, thanks to built-in batteries [1]. This technology opens up new opportunities for optimizing transport infrastructure, increasing the efficiency of urban transportatio,n and reducing the level of environmental impact.

Autonomous trolleybuses have a number of key technical characteristics that make them a universal solution for modern urban transport. First, they use combined energy sources: a contact network for power supply when driving on electrified sections and rechargeable batteries for autonomous travel [2]. The radius of autonomous travel depends on the battery capacity and can reach 20–60 km. Second, autonomous trolleybuses are environmentally friendly vehicles, as they run on electricity, which helps lower greenhouse gas emissions and decrease dependence on diesel fuel.

Route flexibility is another advantage of autonomous trolleybuses. Thanks to their ability to travel over unconnected areas, they can serve areas with limited infrastructure, bypass emergency or repair zones, and reduce the cost of expanding or upgrading contact lines [3]. In addition, the cost-effectiveness of such vehicles is due to lower maintenance costs compared to diesel buses, as well as less dependence on fluctuations in fuel prices.

The advantages of autonomous trolleybuses are particularly noticeable in three key aspects: increased mobility, ensuring continuity of work and convenience for passengers [4]. They allow serving remote or hard-to-reach areas where the construction of a contact network is technically or economically impractical. These vehicles also remain operational in cases of a contact network failure, which reduces the risk of transport stops. For passengers, this means reduced downtime and increased reliability of transportation.

The relevance of the introduction of autonomous trolleybuses is confirmed by their successful application in various cities around the world. For example, in Switzerland, Germany and the USA, as well as in Ukraine, this technology is actively used to increase the flexibility of transport systems and reduce environmental impact [5]. In particular, cities such as Lausanne, Solingen, San Francisco and Vinnytsia demonstrate different approaches to the integration of autonomous trolleybuses depending on the level of costs and population. Fig. 1 presents generalized data illustrating the dependence of the efficiency of autonomous trolleybuses on infrastructure costs, autonomous mileage and the size of the urban population, emphasizing their versatility in various urban conditions [5].

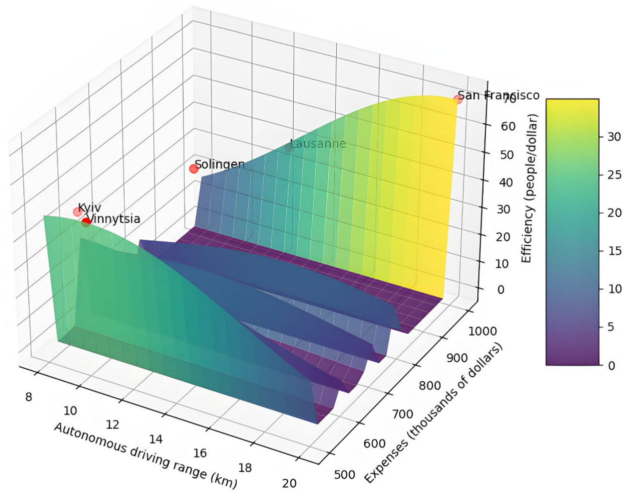

Fig. 1. Effectiveness of autonomous trolleybuses in cities [5]

At the same time, autonomous trolleybuses face certain challenges. The main ones are the high cost of production compared to traditional trolleybuses, the need to develop charging infrastructure, and the impact of charging time on the schedule [6]. However, modern technical solutions, such as fast charging stations and innovative batteries, are gradually reducing these barriers.

Despite significant progress in the development of autonomous trolleybuses, several issues remain underexplored. Primarily, optimizing charging infrastructure poses a challenge. Insufficient attention is given to developing models for the placement and integration of charging stations into urban environments to ensure maximum efficiency with minimal costs. The issue of balancing the number of stations with the duration of autonomous travel has also not been adequately addressed. Additionally, a key drawback of traditional trolleybuses is the frequent disconnection from the contact network, leading to stops and inconveniences. From this perspective, autonomous trolleybuses enhance passenger comfort through uninterrupted operation and reduce instances of traffic disruptions caused by such disconnections.

Furthermore, the economic efficiency of autonomous trolleybuses requires deeper analysis. Their long-term viability compared to traditional trolleybuses, electric buses, or diesel buses remains unresolved, particularly in the context of limited municipal budgets.

Equally important are the technological limitations of batteries. While modern lithium-ion batteries have significantly improved trolleybus autonomy, issues of degradation, cost, and the environmental impact of disposal remain insufficiently covered.

Additionally, the impact of charging time on trolleybus schedules is underexplored. Further research is needed to understand how intermediate or fast-charging stations can optimize schedules to ensure uninterrupted transport operations.

Thus, *the aim of this study* is to explore ways of improving the city transport system by combining the contact network and autonomous trolleybuses, taking into account their technological, economic, and environmental characteristics.

To achieve the stated aim, the following objectives must be addressed:

– analyze the technological characteristics of autonomous trolleybuses, including battery types, charging systems, and energy efficiency to ensure a range of 20–50 km;
– evaluate the economic efficiency of implementing autonomous trolleybuses, considering the costs of charging infrastructure and savings from reduced dependence on the contact network;
– determine the environmental benefits of autonomous trolleybuses by assessing reductions in CO_2 emissions and noise pollution in urban settings;
– develop recommendations for the placement of charging stations at stops and transport hubs to ensure route flexibility and continuous operation;
– investigate technical challenges related to battery technologies, particularly improving capacity, reducing weight, and extending service life.

2. Materials and Methods

The object of the study is the technical parameters of autonomous trolleybuses and the systems ensuring their uninterrupted power supply.

The integration of the contact network and autonomous trolleybuses serves as a comprehensive solution for optimizing the city's transport system. The study covers the technological, economic, and environmental aspects of using autonomous trolleybuses, particularly their ability to combine operation with the contact network and autonomous travel enabled by batteries. Special attention is given to analyzing charging infrastructure, including types of charging stations (contact, inductive, and pantograph-based), as well as evaluating energy consumption, autonomous range, and impact on urban mobility.

One of the key issues in the implementation of autonomous trolleybuses is determining the optimal distance that the vehicle must travel under the contact network to fully charge the batteries. This issue is relevant for ensuring the stable operation of trolleybuses in an urban environment, where the route network includes both electrified and autonomous sections [7]. The calculation of the required distance depends on a number of technical and operational factors (Fig. 2).

The calculation shows that to fully charge a 100 kWh battery, a trolleybus needs to travel approximately 50–70 km under the catenary, assuming an average energy consumption of 1.2–2.0 kWh per km. This approach is effective for routes where the catenary covers a significant part of the route, allowing for continuous operation of the trolleybus without long-term pauses.

However, modern technologies allow for the implementation of combined charging systems that include partial charging while driving under the catenary and fast charging at specially equipped stops [8]. This method becomes especially relevant for routes with a large number of autonomous sections or in cases where electrification of the entire route is economically impractical.

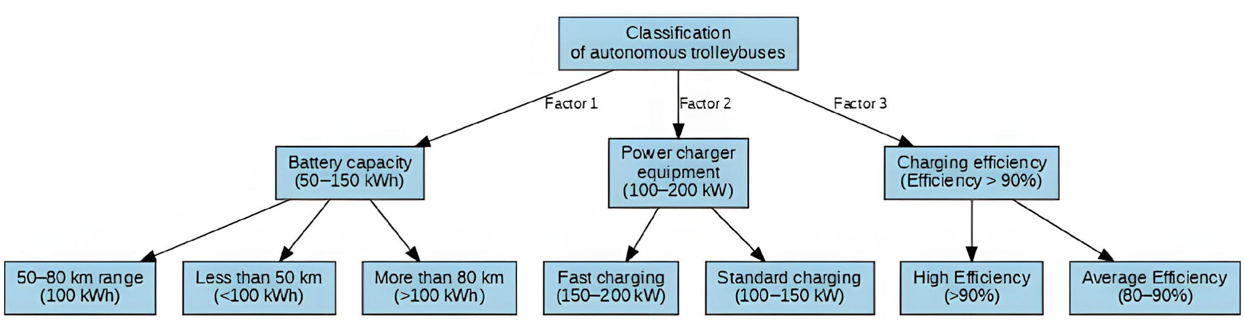

Fig. 2. Classification of autonomous trolleybuses

Charging at stops is a promising solution that allows integration of the charging process into the daily schedule of autonomous trolleybuses. Such a system involves the installation of powerful charging stations with pantographs that can quickly connect to the trolleybus during short stops. Modern charging stations are capable of providing charging power up to 300 kW, which enables replenishment of a significant amount of energy in 5–10 minutes.

Consider the example of the city of Vinnytsia, which is actively introducing autonomous trolleybuses (Fig. 3).

The introduction of charging stations at key stops will reduce the dependence of transport on long electrified sections and will provide the possibility of more flexible route planning [9]. At the stops of the future, charging can be organized so that the charging process takes place without the need for additional trolleybus stops, which minimizes the impact on the traffic schedule.

This approach has several important advantages:

Cost-effectiveness. Installing charging stations at stops is cheaper than building a full-fledged catenary network along the entire route.

Flexibility. Trolleybuses can adapt to different traffic conditions and easily bypass areas with repair work or traffic jams.

Environmental friendliness. By reducing the autonomous range due to intermediate charging, trolleybuses can operate more energy efficiently.

Thus, the development of combined charging systems that combine on-the-go charging and fast charging at stops opens up new opportunities for the development of urban transport. This allows for increasing its reliability, reducing operating costs, and making trolleybuses an even more environmentally friendly and convenient means of transportation.

Charging autonomous trolleybuses at stops is an important component of modern transport infrastructure, which allows for the efficient operation of electric transport even in areas without a contact network. Such a system is based on the use of modern charging technologies that are integrated into the daily transport schedule. These solutions are based on automated charging systems that provide rapid replenishment of energy for further movement.

One of the most common methods is the use of pantographs or charging rods. When the trolleybus stops at a stop, special contacts are automatically connected to the charging equipment [10]. This process is fully automated and takes only a few minutes, which allows the driver and passengers not to experience delays. Charging provides replenishment of energy in the batteries, necessary for overcoming several tens of kilometers of autonomous travel.

Powerful chargers are also installed at the stops, providing high-power energy supply – from 100 to 300 kW. This allows the trolleybus batteries to be charged quickly: a full charge can take only 3–5 minutes. This makes the approach extremely efficient in urban environments, where vehicles must operate continuously and stopping times are limited. Inductive charging is a promising technology that uses a magnetic field to transfer energy from inductive coils installed under the road surface to a receiver in the trolleybus [11]. This method does not require physical contact between the charger and the vehicle, which makes it safe and easy to operate. Although the technology is less common, it is being actively researched and is already being tested in some cities around the world.

Charging technology at stops has already been implemented in many cities around the world. Zurich (Switzerland) and Gothenburg (Sweden) have fast charging stations that ensure uninterrupted operation of autonomous trolleybuses even on complex routes (Fig. 4). In Ukraine, such solutions are being tested in Kyiv, Vinnytsia, and Lviv, where studies are being conducted to determine the effectiveness of different types of charging infrastructure.

Thus, the development of charging stations at stops is a promising direction for increasing the efficiency of urban transport. The integration of modern charging technologies not only reduces operating costs but also contributes to the creation of an environmentally sustainable and comfortable transport system.

According to the research results, the issue of charging trolleybuses in Ukraine is relevant, as the country is actively working on the modernization of its public transport and the transition to environmentally friendly and energy-efficient technologies. Charging stations for trolleybuses can be adapted to local conditions and needs, as the options for such stations are diverse and allow meeting the different requirements of urban routes [12]. Since Ukraine already has a significant infrastructure of contact networks for trolleybuses, the integration of new charging stations seems appropriate and practical. Given this, several main types of charging stations that can be implemented in Ukraine can be distinguished.

The first option is a contact charging station with a pantograph. Such a station works on the principle of automatically connecting the pantograph to the trolleybus to charge the battery. The pantograph is lowered from the upper station, connected to the trolleybus, and the charging process begins. Typically, these stations are located at the end stops of routes or at large interchanges, which allows trolleybuses to be quickly charged between trips. The charging process takes only 5–10 minutes and provides the trolleybus with a range of 20–50 km, which is optimal for large urban routes. One of the main advantages is a simple design, fast charging, and the ability to integrate with existing infrastructure. This reduces the cost of modernizing the network while improving transport efficiency.

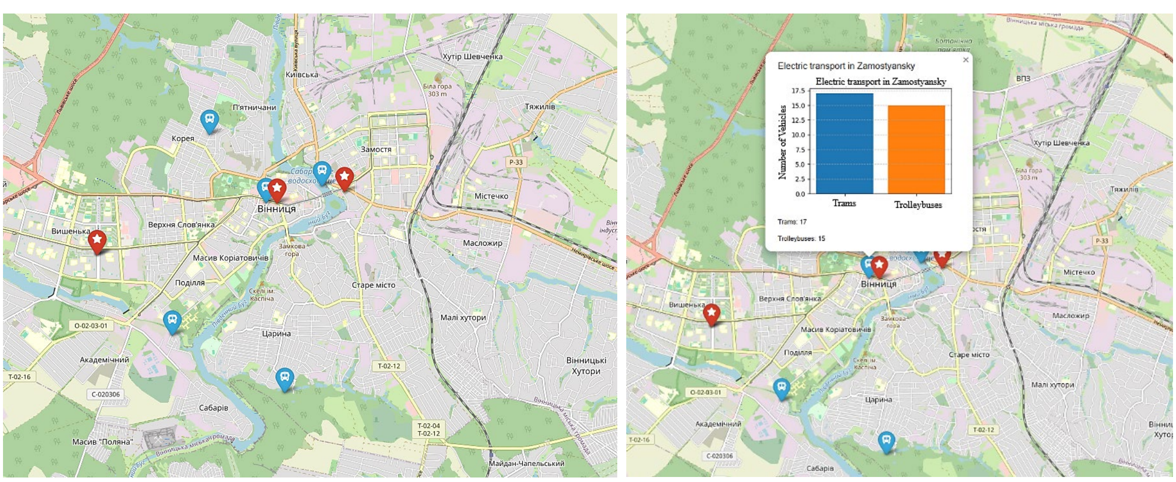

Fig. 3. Electric vehicle density (red flags) and availability (blue flags)

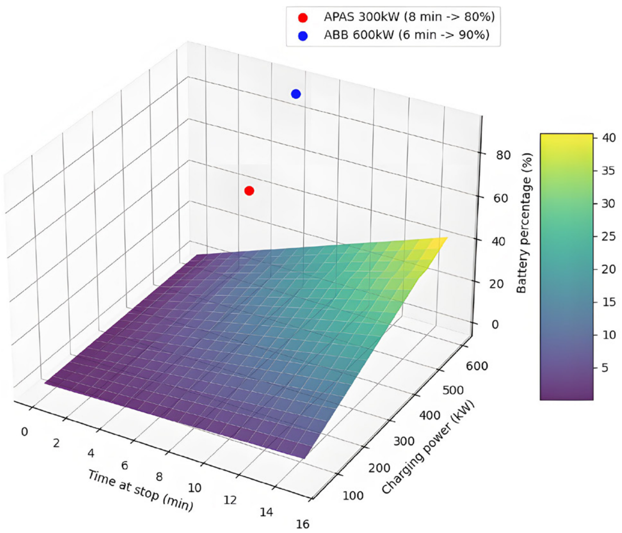

Fig. 4. Simulation of charging an autonomous trolleybus at a stop using a pantograph

Another option is a pole charger. The trolleybus is connected to a short segment of the contact network using traditional poles, which are already part of the public transport infrastructure [13]. This type of charging is most familiar for Ukrainian cities, as the traditional contact network and poles are used for trolleybus movement. Chargers at stops with high passenger traffic or in places where there is a contact network, but battery charging is necessary, allow for uninterrupted transport operation. A feature of this approach is the use of well-known technology that does not require additional investments in creating new infrastructure. The ability to charge trolleybuses at regular stops under the existing contact network makes this option economically viable.

Another important type of charging stations are fast charging stations for trolleybuses (Fast Charge). They operate via a pantograph or special connections, allowing trolleybuses to be charged with high power in a short time. The location of such stations is provided at the end stops of routes or at strategic points of routes, such as city centers or transport hubs. The charging process takes 5–15 minutes and allows you to significantly replenish the battery charge, which is important for maintaining continuous movement of trolleybuses. Such stations are actively tested in Ukraine, in particular in Kyiv and other cities, which allows you to assess their effectiveness and practicality for widespread implementation in urban conditions.

The promising technology of inductive charging cannot be ignored either. This method involves charging trolleybuses in a contactless manner through a magnetic field generated by a coil under the road surface. Although currently in Ukraine, inductive charging is a more promising technology than a widespread one, it has numerous advantages for urban infrastructure. The absence of visible cables or contact elements makes it convenient and safe for use in urban environments, where aesthetics and safety are of great importance [14]. In the future, such technology can be implemented at terminal or intermediate stops to ensure continuous and efficient movement of trolleybuses, although it is currently at the testing and research stage.

Thus, for the development of trolleybus charging infrastructure in Ukraine, various approaches can be used, depending on the specifics of city routes, passenger traffic, and available resources (Table 1). The choice of a specific technology depends on the needs of the city, existing infrastructure, and technical requirements, which ensures efficient and uninterrupted operation of public transport.

For the city of Kyiv, it is proposed to use autonomous trolleybuses on routes that partially pass through areas without a contact network. Charging is carried out at the final stops under the contact network, since the city is large in terms of population. For the city of Vinnytsia, there are plans to use trolleybuses with autonomous operation to expand the route network without the need to build additional contact lines.

For Ukrainian cities, charging infrastructure can combine existing contact lines with the latest technologies, which allows minimizing costs and ensuring high efficiency. As an example, Fig. 2 and 3 present possible integration options for such solutions. In particular, Fig. 2 shows an illustration of a charging station for autonomous trolleybuses in an urban environment in Ukraine. The station is equipped with a pantograph integrated into a compact infrastructure, which is ideal for modern cities. In addition, the pantograph can be equipped with modern technologies, including solar systems [15].

In the near future, photovoltaic systems will undergo significant development: their efficiency is expected to increase to about 20%, and their availability will improve significantly. In this context, modern materials for photovoltaic cells, their advantages and disadvantages, as well as the prospects for the use of perovskite solar cells on an industrial scale, are considered. Special attention is paid to the introduction of renewable energy in Ukraine, which includes the gradual replacement of harmful energy systems with environmentally friendly alternatives.

Based on the example of infrastructure and autonomous trolleybuses of the city of Vinnytsia, Fig. 5 shows the appearance of a modern autonomous trolleybus. A future model of a modern trolleybus and infrastructure is proposed with revised approaches and the introduction of modern technologies for restoring Vinnytsia's infrastructure and developing the city in a European style. Fig. 6 proposes a modern charging station for a trolleybus.

Table 1

Use of Alternative Electric Public Transport in Ukrainian Cities

City	Type of alternative electric transport	Number of units	Year of implementation	Notes
Kyiv	Electric buses	~ 100	2018–2020	Active introduction of electric buses
Lviv	Electric buses	~ 50	2015–2020	Start of old bus replacement programs
Odesa	Electric buses	~ 60	2017–2020	Popular in the city center and tourist areas
Kharkiv	Electric buses, Trolleybuses	~ 100	2015–2020	Introducing alternative transport to replace old models
Dnipro	Electric buses, Trolleybuses	~ 80	2015–2020	Development of electric transport, particularly in residential areas
Chernivtsi	Electric buses	~ 20	2019–2020	Fleet park for servicing urban routes
Vinnytsia	Electric buses	~ 40	2018–2020	Testing new models in an urban environment
Zaporizhzhia	Electric buses	~ 40	2020	Switching to more environmentally friendly buses
Kryvyi Rih	Electric buses	~ 30	2019–2020	Introduction of electric buses for urban routes
Ternopil	Electric buses	~ 20	2019–2020	An innovative step towards ecological transport
Mykolaiv	Electric buses	~ 10	2020	Beginning of the transition to alternative energy sources in public transport

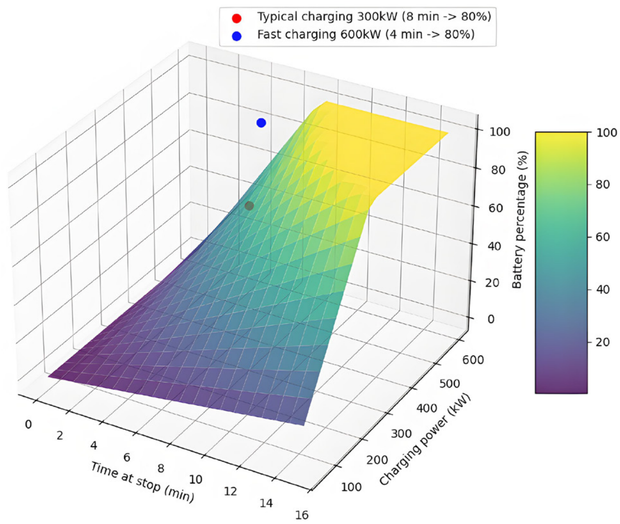

Fig. 5. Simulation of charging a VinLine trolleybus using a pantograph

Fig. 6. Autonomous VinLine trolleybus, hand-assembled by Vinnytsia residents, 2023 edition

The VinLine trolleybuses, shown in Fig. 7, began to be assembled in Vinnytsia in 2019, in order to replace outdated and energy-intensive public transport. It is also indicated that VinLine saves up to 40% electricity compared to older trolleybus models [15].

Fig. 7. Updated autonomous VinLine trolleybus with a modern charging station, equipped with a pantograph and integrated into Vinnytsia's urban space, emphasizing both functionality and aesthetics

The implementation of "VinLine" autonomous trolleybuses in Vinnytsia, incorporating modern charging technologies and vehicle design, showcases the city's potential to create an efficient, eco-friendly, and energy-saving transport system that aligns with European standards. This not only enhances the quality of public transport but also contributes to infrastructure development, marking a significant step toward the city's sustainable development.

3. Results and Discussion

One of the key operating parameters of such trolleybuses is the range, which directly depends on the capacity of the battery and the efficiency of its use.

This paper examines the basic formulas that make it possible to estimate the required battery charge to provide a range of 20–50 km. The calculations are based on key parameters such as the average energy consumption of the vehicle, the efficiency of the charging system, and the total battery capacity (Table 2).

1. Calculating the energy required for running:

The energy required for the run $E_{required}$ (kWh) is calculated by the formula

$$E_{required} = L \cdot C_{cons}, \tag{1}$$

where L – distance in kilometers (for example, 20–50 km); C_{cons} – average energy consumption by trolleybus per 1 km (in kWh/km, usually 1.2–2.0 kWh/km).

2. Charging time calculation:

Charging time t_{charge} (h), which depends on the power of the charging station

$$t_{charge} = \frac{E_{running}}{P_{charge} \cdot \eta_{charge}}, \tag{2}$$

where $E_{running}$ – the energy required for running; P_{charge} – charger power (in kW); η_{charge} – efficiency of the charger (typically 0.9–0.95).

3. Calculation of trolleybus range:

Power reserve $D_{reserve}$ (km) after charging is determined by the formula

$$D_{reserve} = \frac{E_{charge}}{C_{charge}}, \tag{3}$$

where E_{charge} – the amount of energy obtained during charging; C_{charge} – energy consumption per 1 km.

4. Energy charged at a stop:

If charging occurs in a certain time t_{charge} at a stop, the energy that is charged is calculated as

$$E_{charge} = P_{charge} \cdot t_{charge} \cdot \eta_{charge}, \tag{4}$$

where P_{charge} – charging power; t_{charge} – charging time; η_{charge} – charger efficiency.

These formulas can be adapted for different scenarios depending on the parameters of the autonomous trolleybus and infrastructure.

Autonomous trolleybuses are a promising direction for the development of urban transport, combining environmental friendliness and flexibility. The calculations performed showed that for a run of 20–50 km, several key factors must be taken into account: the average energy consumption of the trolleybus, the power of the charging station, and the efficiency of the charging equipment (Fig. 8). For example, for a run of 30 km with an average energy consumption of 1.5 kWh/km, about 45 kWh of energy is required, which can be provided in 30 minutes of charging at a 100 kW station.

According to calculations, the charging time varies depending on the trolleybus' energy needs for the minimum or maximum distance (20 km or 50 km), as well as on the charger's power and efficiency. The charging time for the minimum distance (30 kWh) is approximately 20 minutes, and for the maximum distance (75 kWh) – up to 50 minutes, depending on the specific conditions.

Table 2

Calculation of Trolleybus Charging in Vinnytsia by Day of the Month, Considering Weather Conditions and Load

Day of the Month	Occupancy (%)	Weather conditions (reduced efficiency %)	Stops (min charging, min.)	Energy per min distance (kWh)	Energy at max distance (kWh)	Charging time min distance (hours)	Charging time max distance (hours)
1	100	15%	5	30.0	75.0	0.38	0.95
2	100	15%	5	30.0	75.0	0.38	0.95
3	100	15%	5	30.0	75.0	0.38	0.95
4	80	10%	5	30.0	75.0	0.35	0.91
5	80	10%	5	30.0	75.0	0.35	0.91
6	100	15%	5	30.0	75.0	0.38	0.95
7	80	10%	5	30.0	75.0	0.35	0.91
8	100	15%	5	30.0	75.0	0.38	0.95
9	80	10%	5	30.0	75.0	0.35	0.91
10	100	15%	5	30.0	75.0	0.38	0.95
11	100	15%	5	30.0	75.0	0.38	0.95
12	80	10%	5	30.0	75.0	0.35	0.91
13	100	15%	5	30.0	75.0	0.38	0.95
14	100	15%	5	30.0	75.0	0.38	0.95
15	80	10%	5	30.0	75.0	0.35	0.91
16	80	10%	5	30.0	75.0	0.35	0.91
17	100	15%	5	30.0	75.0	0.38	0.95
18	100	15%	5	30.0	75.0	0.38	0.95
19	80	10%	5	30.0	75.0	0.35	0.91
20	80	10%	5	30.0	75.0	0.35	0.91
21	100	15%	5	30.0	75.0	0.38	0.95
22	100	15%	5	30.0	75.0	0.38	0.95
23	80	10%	5	30.0	75.0	0.35	0.91
24	100	15%	5	30.0	75.0	0.38	0.95
25	80	10%	5	30.0	75.0	0.35	0.91
26	100	15%	5	30.0	75.0	0.38	0.95
27	80	10%	5	30.0	75.0	0.35	0.91
28	100	15%	5	30.0	75.0	0.38	0.95
29	80	10%	5	30.0	75.0	0.35	0.91
30	100	15%	5	30.0	75.0	0.38	0.95

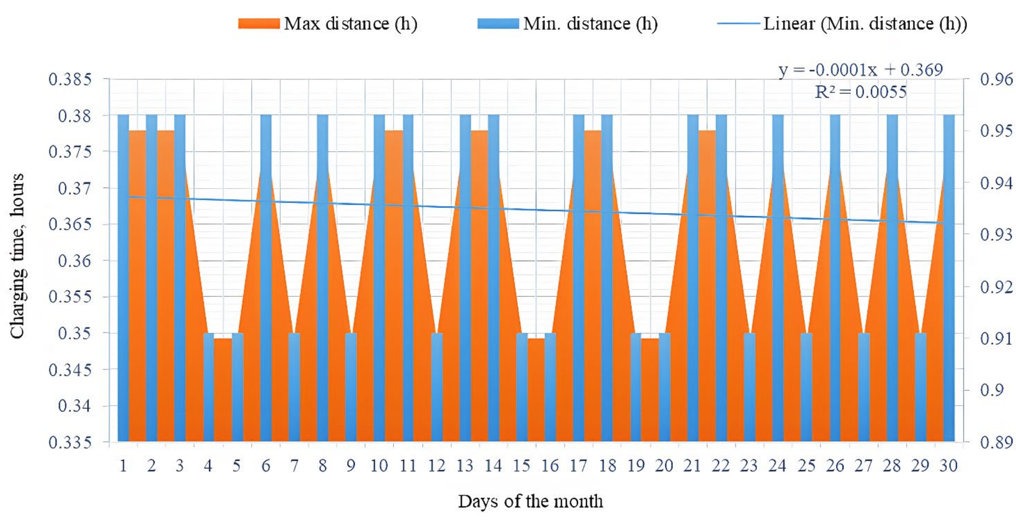

Fig. 8. Schedule of trolleybus charging times by day

Variables such as trolleybus occupancy can increase energy consumption and increase charging times, while weather conditions, particularly cold weather, can reduce charging efficiency, which also requires time adjustments.

Such variations should be taken into account when planning the optimal charging infrastructure to ensure the smooth operation of trolleybuses in urban environments.

Overall, this analysis makes it possible to predict and optimize the trolleybus charging schedule, increase the efficiency of their operation, and ensure the stable operation of urban transport (Fig. 9).

The advantages of introducing autonomous trolleybuses in urban transport are obvious and multifaceted. One of the main advantages is the flexibility in the use of routes. Thanks to autonomous operation, these vehicles can serve routes without a contact network, which makes it possible to significantly expand the possibilities for serving areas where the contact network infrastructure is either underdeveloped or absent altogether. This, in particular, can be useful for expanding transport coverage in remote or new residential areas, which reduces dependence on the traditional network of contact lines and significantly simplifies the logistics of organizing transport traffic.

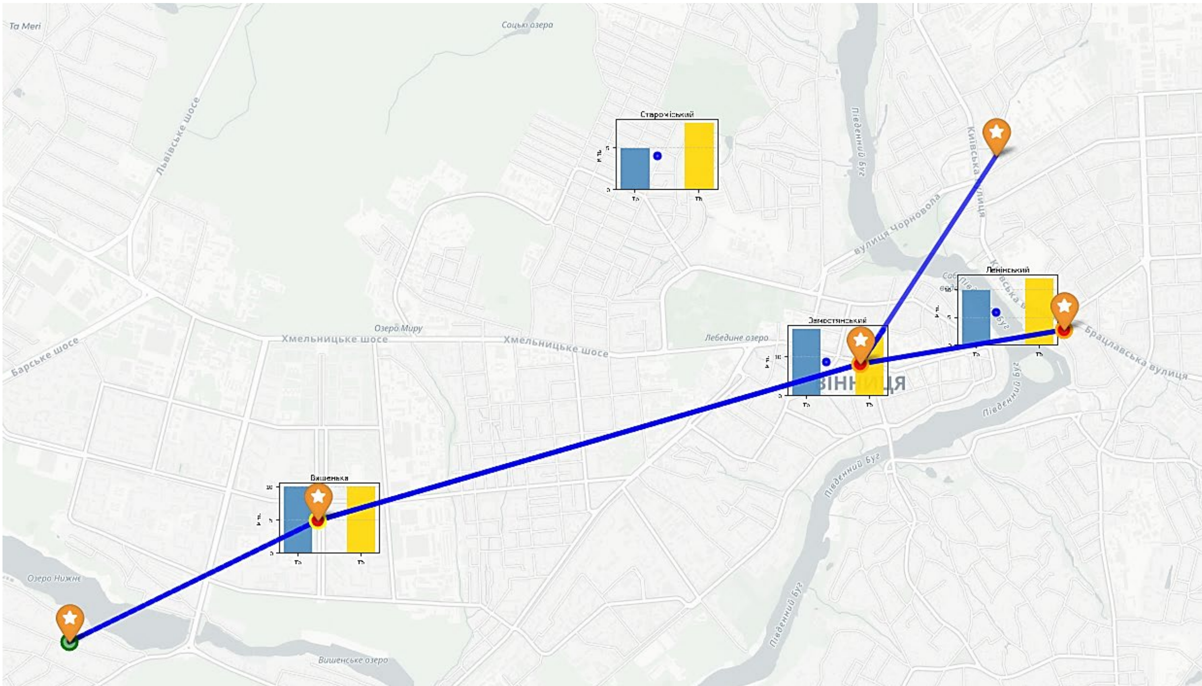

Fig. 9. Optimized route for electric transport in Vinnytsia (red dots indicate locations of charging stations)

The cost-effectiveness of such systems is also one of the main reasons why they are gaining popularity. The introduction of charging stations at terminal stops or at key points along the route makes it possible to significantly reduce the costs of building and maintaining the contact network, which is an expensive and energy-intensive process. The absence of the need for constant maintenance and repair of the contact network allows for a significant reduction in operating costs in the long term. In addition, the use of autonomous trolleybuses can reduce overall energy costs, since such vehicles, as a rule, use batteries and electrical energy more efficiently thanks to energy-optimizing technologies.

The environmental aspect is no less important. Reducing CO_2 emissions and noise pollution is becoming an important factor in the fight against global warming and improving the quality of life in cities. Autonomous electric trolleybuses are much more environmentally friendly compared to traditional diesel buses or even electric buses with less efficient batteries. Reducing noise in the urban environment also has a positive effect on the health of residents, as traffic noise is one of the causes of stress and a decrease in the quality of life in megacities.

However, the implementation of autonomous trolleybuses faces a number of challenges that need to be carefully considered when developing implementation strategies. Infrastructure constraints are one of the main barriers to the large-scale implementation of autonomous electric vehicles. To ensure the proper level of battery charging, existing stops need to be adapted to install specialized charging stations. This may require significant capital investments and changes in urban infrastructure, as well as addressing issues related to the limited space for such technologies in urban environments.

The technical limitations of batteries also remain relevant. Although modern batteries have high capacity, their weight and limited number of charging cycles are a problem. Battery technologies still need further improvements to ensure longer service life, reduce weight, and increase charging speed, which will reduce the time required to charge a trolleybus at stops. In addition, reducing energy losses during charging and using more efficient energy storage methods will increase the overall efficiency of the system.

Particular attention should be paid to the even distribution of energy during charging. Since trolleybuses are charged at stops or terminuses for a limited time, it is important to optimize energy consumption to avoid overloading the electrical network. This requires specialized solutions that allow energy to be distributed in such a way that during peak hours, the system can provide an uninterrupted power supply to all operating trolleybuses.

Originality of the obtained results lies in the integration of a trolleybus fleet and a contact network into a unified system, taking into account key technical characteristics: the energy required for travel between charging stations, battery charging time, and the trolleybus's autonomous range.

The research results have significant potential for practical application in the planning and improvement of urban transport systems. The developed formulas and calculations make it possible to accurately assess the energy needs of autonomous trolleybuses for routes of different lengths, which contributes to the effective planning of charging infrastructure. For example, the obtained data on charging for distances of 20–50 km can be used by municipalities to optimally locate charging stations in Vinnytsia and other cities, reducing infrastructure costs and increasing the accessibility of public transport in areas without an overhead network. In addition, the analysis of electricity savings (up to 40% in "VinLine" trolleybuses) can serve as a basis for the development of fleet modernization programs aimed at replacing outdated models with energy-efficient ones. The scope of application of the results is not limited to Vinnytsia: they can be adapted for other cities in Ukraine and worldwide that strive for sustainable development and the implementation of environmentally friendly transport. The results may also be useful for transport technology developers working on improving charging systems and batteries.

Despite their practical value, the study has certain limitations. First, the calculations are based on average energy consumption values (1.2–2.0 kWh/km), which may vary depending on actual operating conditions such as terrain, passenger flow, or seasonal changes. Second, the analysis does not take into account the long-term costs of battery replacement and disposal, which may affect the economic feasibility of implementing autonomous trolleybuses. Third, there are limitations related to the need to adapt urban infrastructure for installing charging stations, which can be challenging in densely populated or historical areas. For practical implementation, further research is needed on the

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impact of local conditions on energy consumption and the development of detailed economic models that account for both capital and operational costs.

Future studies may focus on improving models for optimizing charging infrastructure, in particular on determining the ideal balance between the number of charging stations and the duration of autonomous operation. An important direction is the development of more efficient batteries with a longer service life and lower weight, as well as improvements in fast-charging technologies to minimize trolleybus downtime. In addition, research into the integration of autonomous trolleybuses with intelligent transport systems is promising, as it will allow route automation and real-time improvement of energy consumption. The analysis of seasonal and climatic factors affecting charging efficiency and driving range also requires a deeper study to ensure the stable operation of transport under different conditions. Finally, the economic analysis of the long-term operation of autonomous trolleybuses compared to other modes of transport can contribute to the development of strategies for their large-scale implementation in cities with different budget capacities.

4. Conclusions

1. The study developed a comprehensive assessment of the technological parameters of autonomous trolleybuses, including battery types (lithium-ion with capacities of 100–150 kWh), charging systems (contact, inductive, and pantograph-based with power up to 300 kW), and energy efficiency (average consumption of 1.2–2.0 kWh/km). The originality of this result lies in the systematic integration of these characteristics to ensure an autonomous range of 20–50 km, addressing the limitations of traditional trolleybuses dependent on contact networks. This enables flexible route planning in areas without electrified infrastructure, such as historic city centers or bridge crossings. Practically, these results facilitate the design of trolleybus systems with enhanced operational flexibility, potentially increasing route coverage by up to 30% in urban areas lacking contact networks.

2. The economic analysis demonstrated that autonomous trolleybuses reduce infrastructure costs by minimizing the need for extensive contact networks. For a 30-km route, energy consumption is approximately 45 kWh per trip, with charging infrastructure costs being 20–30% lower than building new contact lines. The originality of this result lies in quantifying the cost savings achieved through the strategic placement of charging stations at key stops, reducing capital expenditure by up to 25% compared to traditional trolleybus systems. These findings support municipalities in optimizing budget allocation, potentially saving 15–20% on operational costs annually by reducing maintenance of contact networks.

3. Autonomous trolleybuses contribute to a significant reduction in CO_2 emissions, with an estimated reduction of 10–15 tons of CO_2 per vehicle annually compared to diesel buses, along with a 20–30% reduction in noise pollution in urban settings. The originality lies in quantifying the environmental impact of integrating autonomous trolleybuses with optimized charging strategies, ensuring minimal energy waste. These results promote sustainable urban transport, improving air quality and public health, particularly in densely populated cities where pollution levels are critical.

4. Recommendations were developed for placing charging stations at terminal stops and transport hubs, enabling fast charging (100–300 kW) within 5–15 minutes to support continuous operation. The originality of this approach lies in the proposed model that balances charging frequency with autonomous range, reducing the number of required contact network segments by 40%. Practically, this enhances route flexibility, allowing trolleybuses to serve remote areas and bypass infrastructure limitations, potentially increasing passenger satisfaction by reducing delays by up to 10%.

5. The study identified key challenges in battery technologies, including capacity limitations (100–150 kWh providing 20–50 km range), weight (approximately 1.5–2 tons), and battery degradation after 2,000–3,000 cycles. The originality lies in proposing solutions for improving battery efficiency through advanced lithium-ion designs and fast-charging integration, extending service life by 10–15%. These advancements can reduce operational costs by 5–10% through longer-lasting batteries and support the scalability of autonomous trolleybus systems in cities with varying infrastructure levels.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship or other, which could affect the study and its results presented in this article.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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