The role of public transport network optimization in reducing carbon emissions

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Abstract

During the analysis of passenger transportation in a regional city with a population of less than 1 million registered residents and a developed public transport network, it was found that with the beginning of the pandemic, a decrease in the main indicators of passenger traffic and a slight increase in the volume of emissions of carbon-containing gases into the atmosphere were observed. As a result of the analysis and classification of existing conceptual approaches to the optimization of the organization of public transport networks to reduce carbon emissions, three main approaches were established: prioritization of public transport, hybridization and electrification of vehicles and the implementation of IT monitoring. When researching different types of neural networks, it was proposed to use those that contribute to route optimization and road traffic prediction, namely: recurrent, convolutional, and deep neural networks. After investigating the methods and means of existing conceptual approaches to optimizing the organization of public transport networks to reduce carbon emissions, there is an urgent need to create an attractive alternative to driving in cities, reducing the carbon footprint of public transport and contributing to the sustainable development of cities with the aim of implementation of the concept principles of a smart city.

Keywords

public transport, optimization, reducing carbon emissions, information system

1. Introduction

Every year, the problem of environmental pollution by emissions of carbon-containing compounds into the atmosphere increases with the growth of the population on the planet, the number of vehicles that transport them, and the volume of emissions that these vehicles generate. This problem is acute and sometimes critical in large cities with a multi-million population. Transport, both passenger and freight, is one of the main sources of greenhouse gas emissions, which leads to climate change. As a result, many cities around the world have begun implementing measures to reduce carbon emissions. One of the most effective ways to reduce carbon dioxide emissions in the transport industry is the implementation of the concept of a

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smart city, where one of the key tasks is to reduce carbon emissions by optimizing the network of passenger transport routes. This substantiates the relevance of these studies.

2. Well-known studies on optimizing the public transport network in reducing carbon emissions in a smart city

Scientists from various fields around the world have been working on solving this problem for decades. The work of well-known scientists both in Ukraine and abroad is devoted to the development of the theoretical and methodological foundations of the analysis of passenger transport, the construction of modern information and communication models and tools for optimizing the processes of the organization of passenger transport. The scientists [14-28] whose scientific works caused significant changes in theoretical views and practical approaches to the principles of building passenger transport analysis systems based on the concept of a smart city, should be singled out in the following research.

Boz Y., and Cay T. [14] consider the main characteristics of a smart city and their importance in transforming cities into smart ones and assign a key role to smart passenger transportation services among sustainable city services. Based on the collected information, the authors suggest that cities with a population significantly lower than large metropolises successfully provide services for the transportation of passengers in public transport, which can be linked to the concept of a smart city.

A significant role in the development of smart cities is played by information technologies, which are rapidly developing since the beginning of the 21st century. So, Boreiko O., Teslyuk V. [12, 15], Bushuev S. [12], Vanli T., and Akan T. [16] investigate the tools and means of organizing passenger transportation within the concept of smart cities, where innovations, business complexity, information and communication and transport infrastructure are key factors of a smart city. Lytvyn V. et al [17], and Bublyk M. et al [18] substantiate the ways of implementing the concept of smart specialization to transform both the entire Ukrainian economy, in general, and the transport industry, in particular, into a circular one, where the source of economic income of transport companies is not only the results of their economic activity but also the reduction of emissions into the atmosphere of carbon-containing compounds and waste processing, which pose a threat to all mankind.

Wang H., and Wang Y. [19] consider approaches to smart urban planning, where a critical area of urban development is the development of passenger transportation aimed at creating a sustainable, efficient and livable urban environment. The authors [12] conducted a comprehensive analysis, identifying places with reduced carbon dioxide emissions, optimizing the allocation of resources for economic efficiency and increasing aesthetic appeal for the satisfaction of the community, and also proved the effectiveness of the proposed approach to creating environmentally sustainable, economically efficient and aesthetically attractive urban spaces. Wolniak R. [20], Guenduez A., et al. [21], and Jonek-Kowalska I. [22] study the means of transforming cities into smart ones, where among the basic tools smart transport plays a key role, in which the city authorities can effectively manage transformation and changes in in the context of smart cities, creating new ones, destroying old ones and maintaining effective institutional mechanisms. Dai Y. [11] examines the general basis of the transformation process of a smart city and its transportation system, describes the role of stakeholders for cities at various stages of transformation towards a smart city, singles out both information and scientific and technological technologies as a tool for engaging stakeholders for transformation to a smart city, and also offers four alternative scenarios of transformation to a smart city, where smart passenger transport plays a significant role.

Nguyen, H. et al. [23] explore the essence of the IoT-enabled smart city concept, which consists of many different areas, such as smart transportation, healthcare, and agriculture, where AI advances are most likely to drive adoption growth. Internet of Things. The authors [23 – 25] also presented the concept of a smart city based on the Internet of Things, the prerequisites for its development and its components, where special attention was focused on the study of the latest developments of smart cities with the support of the Internet of Things and breakthroughs with the help of artificial intelligence technologies to highlight the current stage, main trends and outstanding issues of implementation of artificial intelligence-based Internet of Things technologies to create smart cities.

Chen Y., et al. [26], Chen Z., et al. [27], and Chen C., et al. [28] substantiate ways of increasing the environmental and economic efficiency of a smart city, which is achieved through the effects of technology, transport infrastructure, and energy conservation. The authors [26-28] consider the smart city as an accelerator both for increasing economic efficiency and for improving the environment due to the reduction of emissions of carbon-containing compounds into the atmosphere and also prove that the efficiency of a smart city depends on the urban transport structure and the characteristics of its components.

Tang J., et al. [7] investigate the mechanisms of interaction of smart energy and their impact on carbon emissions in smart cities as a single and integrated system, justifying with quantitative estimates the effects of smart energy on carbon emissions in a smart city, proposing to use the approach of synthetic difference in differences and a spatial difference-in-difference approach in models to estimate the impacts of smart energy on carbon emissions in a smart city and demonstrate significant reductions in carbon emissions by accounting for the effects of the spatial distribution of smart energy within a smart city.

Researchers [29 - 32] establish connections between smart cities and sustainable development goals, which are not yet sufficiently studied. A. Sharifi and co-authors [29] identify three main sustainable development goals of SDG 6, SDG 7 and SDG 11, to achieve directed transformation of smart city technologies, even though there is a bias in reporting the benefits of smart cities. The goals of sustainable development have been approved during the last twenty years in the resolutions of international conventions of the UN General Assembly [33], in Ukrainian state programs, resolutions, decrees and national reports [34-38]. The goals of sustainable development such as SDG 6, SDG 7, SDG 11, SDG 12, and SDG 13 [33-38] recognize the fundamental directions of the development of society, among which the provision of access to clean water and proper sanitary conditions, availability and purity of energy, as well as sustainable development of cities and communities, responsible consumption and the fight against climate change. Accordingly, the management of passenger transportation in smart cities is designed to create conditions for improving the quality of living in cities and reducing emissions of carbon-containing compounds into the atmosphere [22, 39-42]. This requires unprecedented efforts in all sectors of society, where the government and business must show partnership to succeed in this process of transformation to smart cities, where access to a clean environment without emissions, discharges and waste is ensured.

The concept of technosoliton was developed as the basis of innovative models for reducing emissions of carbon-containing compounds, which assigns a significant role to the assessment of damage and losses in highly polluting sectors of the economy to determine priorities in all sectors of the economy, social development and environmental protection [8, 43]. Reducing emissions into the atmosphere from the transport system has a significant impact on the formation of a circular economy, improving the quality of life and achieving the goals of sustainable development in smart cities [44 - 47].

Summarizing the research of the problem and the existing methods of developing passenger transportation in smart cities, we see that today, a previously unsolved part of the general problem is the search for effective approaches to optimize the system of organizing public transport networks, which contribute to the reduction of carbon dioxide emissions into the atmosphere for the construction of smart cities. Insufficient attention is also paid to the analysis of passenger transport in cities and the identification of existing problems and prejudices that prevent the introduction of the concept of a smart city into the city's transport system in general, and passenger transport in particular. This indicates the need for scientific research in the indicated direction, namely, the analysis of passenger transportation in cities and the identification of existing effective approaches to optimizing the organization of public transport networks, which contribute to the reduction of carbon dioxide emissions into the atmosphere for the construction of smart cities, which is the goal of this work.

3. Results

Optimizing the system of organizing public transport networks, in general, has a positive effect on improving the economic efficiency and economic results of all transport networks in the settlement, however, this does not mean that this will contribute to the reduction of carbon dioxide emissions into the atmosphere, the achievement of the goals of sustainable development and development of the principles of smart cities.

3.1. The statistics analysis of passenger transportation in a city

For the study of passenger transportation in a regional city with a population of less than 1 million registered residents, data [49] were selected. According to the database [50], passenger transport by public transport was carried out within the city in the amounts shown in Fig. 1. As can be seen from the given graph (Fig. 1), the volume of passenger transportation by public transport has a downward trend. The data are not monitored due to the introduction of martial law [51]. This is due to the introduction of restrictions on the publication of open data during the war. A similar downward trend is observed when studying the dynamics of passenger transportation by bus public transport (Fig. 2), trolleybuses (Fig. 3) and trams (Fig. 4). According to the data of the Main Department of Statistics in the Lviv region [49], an increase in the volume of passenger traffic in electric public transport was observed. The sharp decline in passenger traffic in 2020 is due to quarantine restrictions during the SARS-CoV-2 pandemic.

Table 1 shows data on the number of low-floor vehicles on routes, the share of low-floor cars on routes, the total number of road transport carriers, compensation for repayment of benefits to carriers by road transport, and the average annual cost of travel in communal road transport.

The last update of the vehicle fleet took place in 2019 even before the start of the SARS-CoV-2 pandemic, so we have an increase in the average age of passenger vehicles with each subsequent year, which in 2023 was 13 years.

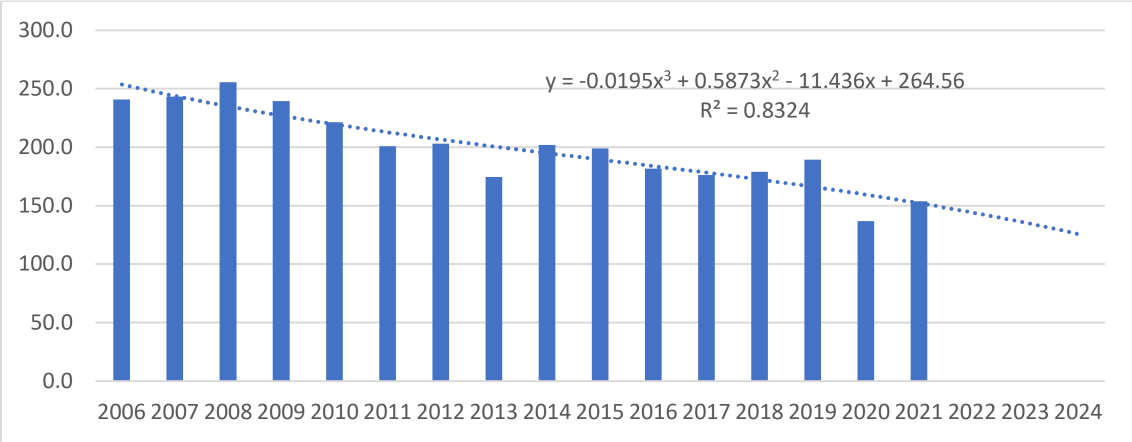

Figure 1: Transportation of passengers by public transport compiled based on materials [49-51].

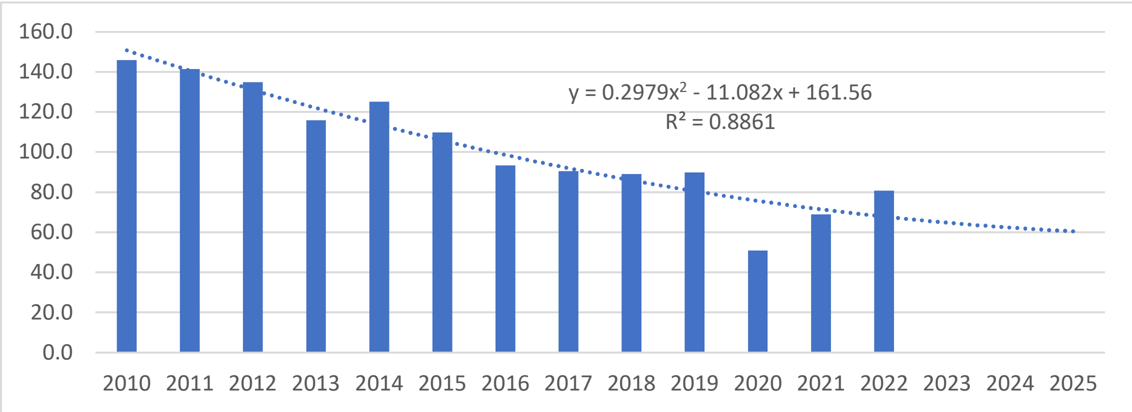

Figure 2: The passenger transportation by bus transport compiled based on materials [49, 52].

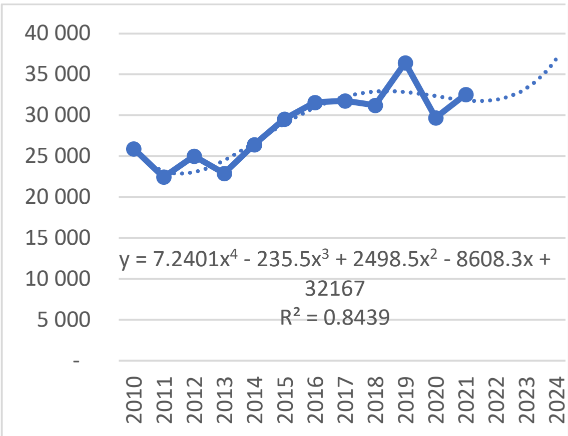

Figure 3: The passenger transportation by trolleybuses [49, 52]

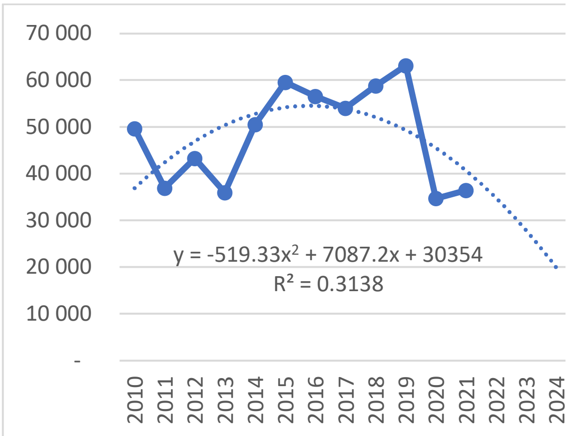

Figure 4: The passenger transportation by trams [49, 52]

Table 1
The main indicators of the passenger transportation by bus transport and their dynamics [52]

Years	Number of low-floor vehicles on routes, units	Share of low-floor cars on routes, %	Total number of road transport carriers, unit	Compensation for repayment of benefits to carriers by road transport, a thousand UAH	Average annual cost of travel in communal road transport, UAH
2010	24	2.86	23	1014.5	1.75
2011	24	2.86	23	802.8	2
2012	138	22.73	5	-	2
2013	138	22.26	5	2491.6	2
2014	118	19.03	5	9011.3	3
2015	80	12.50	5	9250.8	4
2016	143	23.68	5	9850.01	4
2017	137	21.30	5	14989.7	4
2018	130	20.90	5	110368.0	5
2019	237	46.70	5	61313.2	7
2020	240	48.19	5	-	7
2021	240	54.55	5	192465.0	10
2022	194	49.36	5	104336.0	15
2023	222	52.11	5	208263.699	15

The volume of passenger traffic in bus transport in 2021-2022 has almost recovered to the indicators at the beginning of the pandemic, although this is ensured by the increase in the intensity of transportation (increase in the number of flights on the route, overcrowding of transport, etc.). The decrease in the number of vehicles on the routes in 2022 was due to the disabling of vehicles as a result of enemy shelling and their use to evacuate the population from areas of intense hostilities. Therefore, it was decided that such variable data should not be used when forecasting passenger flows, as this would only lead to unreliable results.

Table 2 shows the main indicators of passenger transportation by urban electric transport, including the trams and trolleybuses.

Using the methods of linear and non-linear approximation based on the data given in Fig.1, Fig.2, Fig.3, and Fig. 4, there were interpolated volumes of passenger traffic in public transport, bus transport, and electric transport in Lviv until 2025. The highest determination indicators (R^2 = 0.8324, R^2 = 0.8861, R2= 0.8439 and R2= 0.3138) for passenger transportation by public transport, bus transport, trolleybuses and trams, respectively, have different polynomial functions (1), (2), (3) and (4):

$$y = -0.0195x^3 + 0.5873x^2 - 11.436x + 264.56, \quad (1)$$

$$y == 0.2979x^2 - 11.082x + 161.56, \quad (2)$$

$$y = 7.2401x^4 - 235.5x^3 + 2498.5x^2 - 8608.3x + 32167, \quad (3)$$

$$y = -519.33x^2 + 7087.2x + 30354. \quad (4)$$

Table 2
The main indicators of passenger transportation in urban electric transport and their dynamics [49-52]

Years	Annual need for funds for repayment of benefits to electric transport companies, thousand UAH	Compensation for repayment of benefits to electric transport companies, thousand UAH	Average annual fare in electric transport (tram, trolleybus)
2010	27772.13	48997	1
2011	33800.95	58688.1	1.25
2012	42001.57	65770.2	1.5
2013	35851.66	78664.5	1.5
2014	32540.3	81379	2
2015	32151.3	111674	2
2016	103625.7	29198.04	2
2017	122562.1	50000.0	3
2018	163000.0	55000.0	4.33
2019	277565.8	179070.0	5
2020	206000.0	158939.82	6.5
2021	260000.0	105000.0	7
2022	274925.0	183725.0	8.6
2023	452992.32	322404.3	8.6

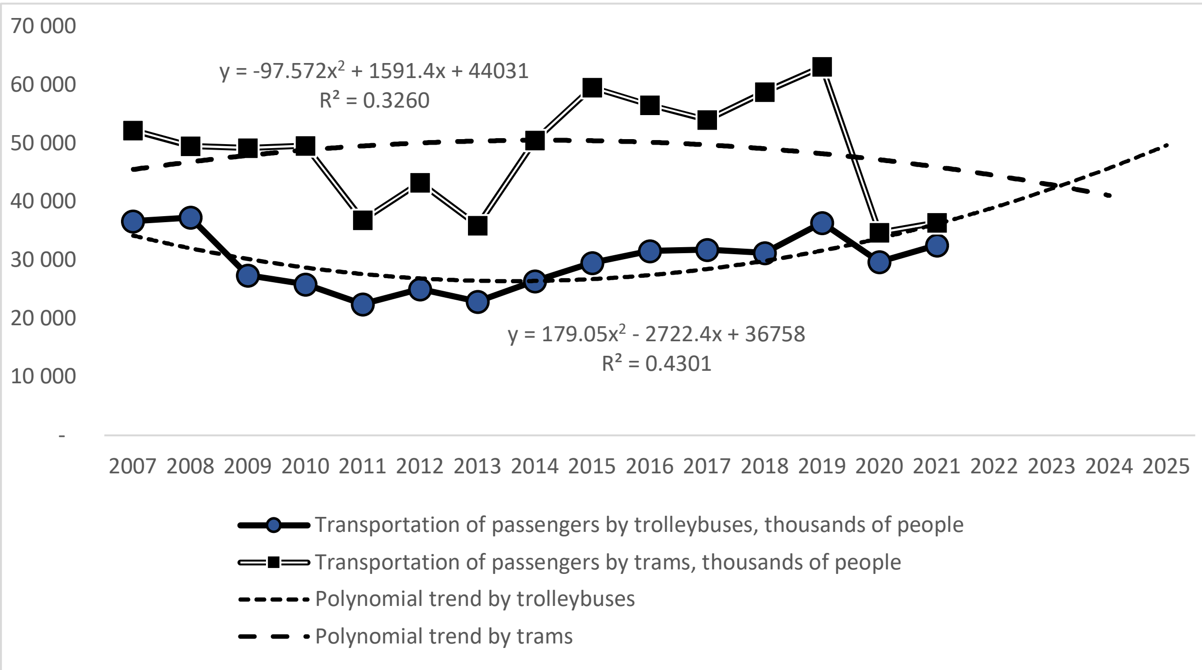

Figure 5: Dynamics of passenger flows in electric transport in Lviv and their calculated values until 2025

The volume of passenger traffic in the electric transport of Lviv during the pandemic in 2021 did not restore its values to the indicators of its beginning (Table 2), although there was an increase in the number of vehicles (there were 3 more trams and 5 trolleybuses running on the routes of Lviv). Quarantine restrictions did affect the operation of electric transport since the passenger flow is ensured not only by the increase in the number of vehicles but primarily by the increase in the number of passengers (who live in the settlement and need to move). Despite the optimism of the obtained values of passenger flows based on the obtained dependencies (achievement in 2023-2024 of the pre-pandemic level of indicators for the volume of passenger transportation by trolleybuses and trams), they are calculated as a result of interpolation of retrospective data, which in no way take into account the decrease in the number of urban populations as a result of the transition the Russian-Ukrainian war into a full-scale phase of intense hostilities on a third of the country's territory, nor the suspension of transport operations during almost constant and frequent air raids, etc. Therefore, the available data sets are incomplete and do not contain sufficient data on factors important for making effective management decisions.

Analyzing the existing datasets on emissions of pollutants into the air from mobile sources in the Lviv region, we can see that the quarantine restrictions in 2020 increased the tendency to their decrease (Fig. 6). Regarding the dynamics of carbon dioxide emissions by mobile sources in the Lviv region, we have two different trends in two periods (ones from 2006 to 2016 and others from 2016 to 2021) (Fig. 7) caused by a change in calculation methods. Thus, since 2006 the methodology has taken into account data on emissions from road, railway, aviation and water transport, to which since 2007 emissions from production equipment (mobile) have been added, and since 2016, the methodology takes into account data on the final use of fuel by bus transport, which are obtained from the energy balance of all Ukraine. Since emissions of carbon dioxide into the atmosphere from mobile sources of pollution in the Lviv region increased with a slight increase in passenger transportation by bus vehicles (Fig. 7), the share of public transport in the total amount of fuel consumed by transport should be taken into account.

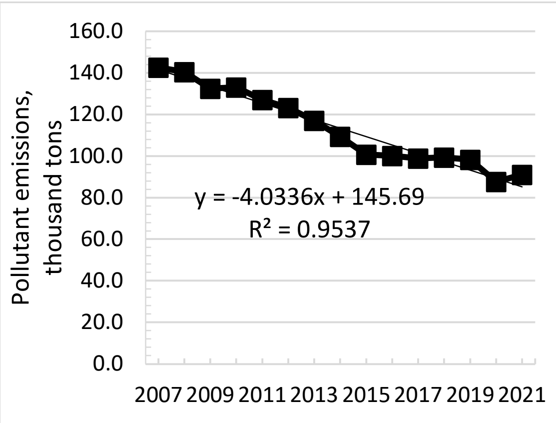

Figure 6: Dynamics of emissions of pollutants into atmospheric air from mobile sources of pollution [49-52]

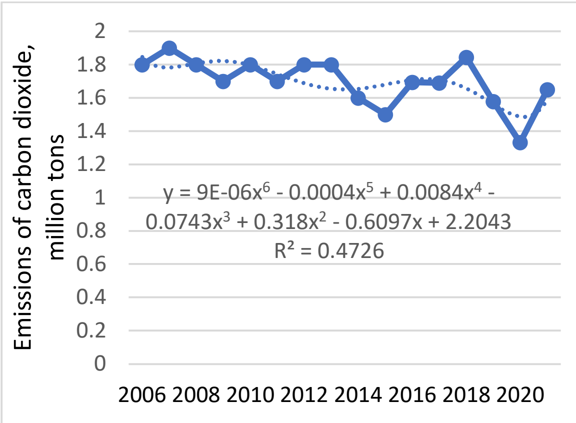

Figure 7: Dynamics of carbon dioxide emissions into atmospheric air from mobile sources of pollution [49-52]

Carbon dioxide emissions by the transport system according to international methods [48, 53-55]. As shown in [9, 56 - 60], light, medium, and heavy vehicles that carry out cargo transportation make up 45% of emissions from the total volume of emissions. The sources of emissions into the atmosphere caused by the operation of the transport system also include passenger cars, minibuses, buses, trolleybuses, trams, funiculars, motorcycles, water, rail and air transport and others. The same share of emissions (44%) is caused by passenger cars. This shortcoming of the automobile market is critical today because according to experts [54], emissions from light trucks will double compared to standard passenger cars in the next 5 years (173 g carbon dioxide per mile vs. 251 g carbon dioxide per mile respectively) [45]. The mobile sources that generate emissions into the atmosphere of carbon-containing compounds also include aviation transportation – 6.8%, transportation by rail transport – 1.9%, water transport – 1.8%, and motorcycles and buses – 1.9% [53]. Therefore, public transport accounts for less than 4.8% of all emissions of carbon-containing compounds into the atmosphere. Based on the data of Fig. 7, it can be calculated that, concerning all emissions, about 83 thousand tons on average are generated by bus vehicles of public transport.

Therefore, the analysis of passenger transportation in a regional city, which is a typical example of a settlement with a population of less than 1 million registered residents and a developed network of public transportation, indicates the need to find effective approaches to reducing atmospheric pollution by carbon-containing compounds by optimizing the organization of public transportation networks based on the concept of smart cities.

3.2. Optimizing the public transport network within the concept of a smart city and its approaches

As a result of the study of the achievements of modern scientific theories, presented in the works of scientists [1-7, 11, 12, 14-31, 42, 61, 62], among the known directions of optimizing public transport network within the concept of a smart city, we will single out three main approaches: 1) giving priority to public transport on the road; 2) transition to electric and hybrid vehicles; 3) implementation of monitoring information technologies (Fig. 8).

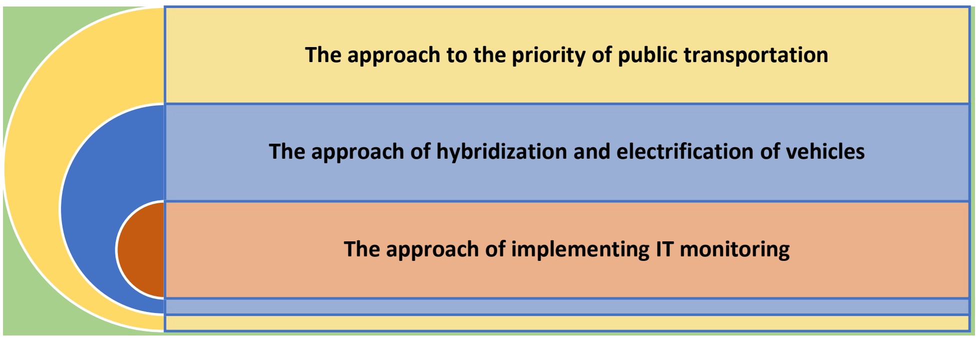

Figure 8: Conceptual directions for optimizing the public transport network within the smart city concept

In the first approach, in a smart city, reducing the number of vehicles on the road is achieved by giving priority to public transport, reducing the attractiveness of its alternative - driving a car. When public transport is faster and more convenient than driving, when public transport is frequent and cheaper, more and more people will use it. Such a problem has recently become more acute with the growth of migration flows in large European cities [63-65]. This streamlining of traffic rules also contributes to sustainable urban development, as it increases the availability of public transport and connects the outskirts of cities to the centre, which in turn reduces the need to own a car and the need for an adequate number of parking spaces. This increases the area for other uses, such as green areas or bike paths [24]. Overall, such a process can help reduce urban sprawl and promote more sustainable models of urban infrastructure development. As a result, this will enable the achievement of sustainable development goals by reducing the number of cars on the road and the associated emissions of carbon oxides into the atmosphere.

According to the second approach, changes in the smart city are focused on the structural transformation of the fleet of vehicles in the direction of increasing the share of electric and hybrid buses, which leads to the optimization of the types of vehicles themselves and can significantly reduce the carbon footprint of public transport. Switching to electric or hybrid buses will significantly reduce carbon dioxide emissions compared to traditional diesel buses.

In the third approach, a key role is played by information technologies that enable real-time tracking of vehicles, monitor traffic on the road, predict the route, and reduce fuel consumption by reducing both the length of routes and the time vehicles are on the road. Such optimization also contributes to reducing the waiting time of passengers for the vehicle and their stay in the vehicle.

We will analyze existing methods and means designed to optimize the functioning of passenger transport systems in smart cities from the point of view of reducing carbon emissions. They include the following (Fig. 9):

1. Intelligent transport systems.
2. Electric vehicles.
3. Transport sharing networks.
4. Smart applications and information systems.
5. Innovative payment systems.
6. Unmanned vehicles.
7. Information boards and announcement systems.
8. Networks of bicycle paths and equipped sidewalks.
9. Environmental monitoring systems.

We will consider in detail each of the methods of optimizing the functioning of the network of passenger transport systems in smart cities from the point of view of reducing carbon emissions (Fig. 9). Each tool has its characteristics and requires specific practical measures for its implementation [2, 7, 11, 15, 16, 19, 21 - 29, 39, 42, 44, 45, 47, 69]. In the process of implementing the concept of a smart city, of course, these tools should be adapted to the specific circumstances and characteristics of the city's transport network to be successful.

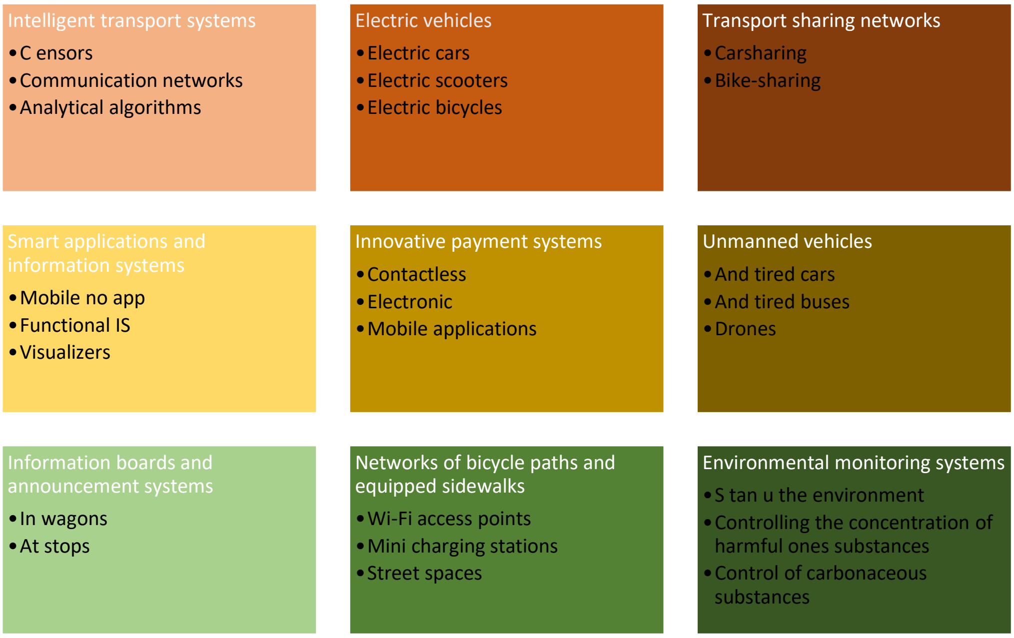

Figure 10: Methods and means of optimization of networks of transport systems of passenger transportation

Intelligent transport systems use various technologies, including sensors, communication networks and analytical algorithms, to ensure optimal management of public transport in the city. Intelligent transport systems make it possible to reduce the waiting time of passengers for public transport as much as possible, simplify payment and ensure safety for passengers.

Electric vehicles include electric cars, electric scooters, and electric bicycles, which ensure zero emissions of harmful substances, minimize fuel costs, and ensure greater environmental friendliness of the entire transportation system of a smart city.

Each country is developing its transport-sharing networks. The most famous in the world are Carsharing and Bike-sharing networks. They provide an opportunity to use the vehicle as needed, instead of owning it, which reduces the costs of its maintenance and contributes to its more efficient use.

Networks of dedicated bicycle lanes and pedestrian-equipped sidewalks in smart cities create a special transport environment where dedicated separated lanes and sidewalks for cyclists and pedestrians ensure safety and convenience for their users.

With the rapid development of information technologies and mobile devices, smart applications and functional information systems have appeared. They help passengers find information about existing routes, the exact time of arrival of transport and the amount and method of payment for services. Smart apps are also equipped with functions to ensure compliance with the schedule, visualize routes and recommend a list of possible routes. This not only increases the efficiency of using public transport but also reduces traffic jams.

Information boards and announcement systems provide passengers with the necessary information about routes, existing schedules and their changes due to traffic delays directly at stops and in vehicles. This contributes positively to the system of effective travel planning and promotes the comfort of passengers during their stay in transport and at stops.

The introduction of information technologies into the banking system contributed to the development of electronic payment systems. Today, it is customary to pay with contactless cards, through mobile applications and other payment systems, which significantly simplifies the process of paying for the use of transport, ensures speed and convenience for passengers, and reduces waiting time at stops and being on the road.

Unmanned vehicles are becoming increasingly popular, including autonomous cars, autonomous buses, and even drones. They are designed to ensure the efficiency and safety of the transport system and to help reduce the number of accidents on the roads, no matter how fantastic it looks.

The spread of the environmental monitoring system in cities provided an opportunity to monitor the state of the environment and to control the concentration of harmful substances in the air that enter there due to emissions of pollutants from transport and various production processes in industry and utilities. The collected information is systematized by environmental inspections and allows leaders of self-government bodies and the public to make relevant and effective management decisions to reduce emissions and improve air quality in cities.

4. Discussion

The analyzed methods and means are only some of those possible methods and means that are designed to optimize the functioning of passenger transport systems in smart cities from the point of view of reducing carbon emissions. Their list was also made taking into account the need to ensure the efficiency and convenience of the transport system for passengers.

4.1. The successful projects of optimizing the public transport network

Having analyzed the modern scientists [53, 57, 60, 61], among the successful projects of optimizing the public transport network, which is used to create smart cities, we will single out the following.

1. Several cities around the world have successfully optimized their public transport network to reduce carbon emissions. For example, in Paris, the city government introduced a new public transport plan that prioritized bus and bike lanes, reducing the number of cars on the road and increasing public transport ridership. This plan resulted in a 14% reduction in carbon emissions from transportation in the city [57].

Another example is the city of Bogotá, which introduced a bus rapid transit (BRT) system that reduced travel time and improved connections in the city. This system reduced carbon dioxide emissions by more than 300,000 tons per year, which is equivalent to taking 60,000 cars off the road [53]. Bogotá's Bus Rapid Transit (BRT) system is one of the most successful public transport network optimization projects in the world.

The system, known as TransMilenio, was first introduced in 2000 and has since expanded to cover more than 112 kilometres of bus-only lanes, serving more than 2.6 million passengers every day [53]. One of the key features of the TransMilenio system is the use of articulated buses that can carry up to 160 passengers at a time. These buses run on dedicated lanes, avoiding traffic jams and reducing travel time for passengers. The system also uses a prepaid smart card system to speed up boarding and reduce delays. TransMilenio has succeeded in reducing carbon emissions in Bogotá. By providing a faster and more efficient public transportation system, the city has reduced the number of cars on the road, resulting in reduced air pollution and greenhouse gas emissions. According to the World Resources Institute, the system cuts carbon emissions by more than 300,000 tons per year, the equivalent of taking 60,000 cars off the road.

In addition to reducing carbon emissions, the TransMilenio system has also had a significant social and economic impact in Bogotá. By improving connectivity and accessibility, the system has increased mobility and economic opportunity for residents, especially those living in low-income areas. The system has also contributed to the revitalization of public spaces, with many bus stations designed to serve as community gathering places. Despite its success, the TransMilenio system has faced some challenges, including peak-hour overcrowding and maintenance issues. However, the city government continues to invest in the system, expanding it to new areas and introducing new technologies to improve performance.

In general, similar to the TransMilenio system in Bogotá is the system of electric Australian transport of the future (Electric Australian Transport Systems) [54], which is a clear example of how optimization of the public transport network can reduce carbon emissions and improve the quality of life of residents. Indeed, this success has inspired governments to implement similar projects in other cities around the world, demonstrating the potential of public transport to play a critical role in addressing climate change and promoting sustainable urban development.

Several route optimization methods can be used to achieve the goal of this work. One of the methods is the use of routing algorithms. These algorithms help to find the shortest route between two points on the map, taking into account various factors such as traffic jams and other obstacles. If such an algorithm is used for every route of public transport in Lviv, it can help solve the problem of delays and reduce the time it takes passengers to move.

Another method is the analysis of data on the use of public transport in Lviv. Collecting data on traffic, passenger flow and delays can help identify the most popular routes and destinations, as well as identify problem areas on the route. This data can be used to optimize routes and plan new routes that will meet passenger needs.

It is also possible to use information technologies to increase the efficiency of public transport. For example, the installation of GPS systems in buses and trolleybuses will allow monitoring of the movement of transport in real-time and provide passengers with accurate information about the time of arrival of the transport at the stop.

Geographic Information Systems (GIS): allow us to determine the shortest route, taking into account various constraints, including road conditions, public transport schedules and other factors.

Passenger flow forecasting systems: allow forecasting of passenger flows at different times of the day and on different routes, which helps improve transport efficiency and reduce waiting time for passengers.

Using data from passengers' smartphones: allows us to monitor the movement of passengers in real time and use this data to optimize transport routes.

Analysis of travel history data: allows us to identify the most popular routes and schedules of public transport, which helps to optimize routes and reduce waiting times for passengers.

The use of smart stops and the "smart regulator" system: allows for the coordination of the movement of various types of transport on the road section, which allows to reduce the downtime of transport.

To optimize the route of each passenger, we can use machine learning algorithms that will work based on real-time traffic data, availability of free seats in transport and other parameters.

For this, the intelligent route optimization system must have access to such data, in particular, provided by GPS trackers in transport, open sources of traffic data and other developed solutions.

In addition, to provide the optimal route for each passenger, the system must take into account his personal preferences. For example, if a passenger wants to get to their destination quickly, the system will offer routes that will allow them to do so. If the passenger is more concerned about the comfort of the trip, the system will offer routes with fewer transfers or with more comfortable transport.

Thus, an intelligent route optimization system should be able to collect, analyze and use a variety of data to solve the problem of providing optimal routes for each public transport passenger in real-time.

If a traffic jam appears on the road or the location of public transport changes, the intelligent system should dynamically correct routes. To do this, it must have access to current information about traffic, congestion and the location of public transport, for example, with the help of GPS modules and a network of sensors placed on the roads.

When the intelligent system receives updated information about the state of the road and the location of public transport, it must decide whether to leave the passenger on the current route or offer an alternative route to reach the goal with maximum speed and comfort.

In case of a traffic jam or a change in the location of public transport, the intelligent system should quickly make calculations and offer the optimal route. Information about traffic jams and other obstacles should be displayed on the board in the cabin of public transport and on the passenger's mobile device so that the passenger can make his choice regarding the optimal route.

4.2. Types of neural networks for optimizing the public transport network

Different types of neural networks can be suitable for the task of improving the process of route optimization and road traffic prediction, depending on the accuracy and speed required for the system [66-70]. Here are some of them:

1. Recurrent Neural Networks (RNN) - These networks are used to work with sequences of data such as time series. They can be useful for predicting road traffic based on historical data.
2. Convolutional Neural Networks (CNN) - These networks are used for image processing, but can also be useful for traffic prediction based on video streams from CCTV cameras.
3. Deep neural networks (DNN) - these networks are used to solve complex problems, such as predicting the routes of complicated urban networks.

Neural networks can be used to predict traffic and optimize routes in real time, ensuring even more accurate and faster operation of the passenger transportation system.

So, the organization of transport systems of passenger transport in smart cities with low CO_2 emissions differs from the usual organization of the passenger transport system in several parameters:

- Use of electric or hybrid vehicles instead of cars with diesel or gasoline engines.
- Using shared transport instead of private transport. For example, big buses instead of small cars. This allows us to reduce the amount of traffic on the roads and reduce traffic jams.
- Using the network of high-speed trams or subways. These passenger transportation systems provide high speed and a level of comfort, thereby becoming an alternative to private transport.
- Use of modern information technologies to optimize routes and monitor traffic flow. This makes it possible to increase the efficiency of the transport system and ensure a quick response to changes in the traffic flow.
- Use of dynamic ticket pricing depending on vehicle load and service demand. This makes it possible to reduce the total cost of transport for users and ensure optimal use of transport.

All these parameters make it possible to improve the level of passenger transportation in smart cities and reduce CO_2 emissions.

Therefore, the use of neural networks contributes to route optimization and road traffic prediction, which is one of the key tasks of optimizing public transport networks with low carbon emissions into the atmosphere within the limits of the smart city concept.

Several route optimization methods can be used to achieve this goal.

1. One of the methods is the use of routing algorithms. These algorithms help to find the shortest route between two points on the map, taking into account various factors such as traffic jams and other obstacles. If such an algorithm is used for every route of public transport in Lviv, it can help to solve the problem of delays and reduce the time of moving passengers.
2. Another method is the analysis of data on the use of public transport in Lviv. Collecting data on traffic, passenger flow and delays can help identify the most popular routes and destinations, as well as identify problem areas on the route. This data can be used to optimize routes and plan new routes that will meet passenger needs.
3. It is also possible to use information technologies to increase the efficiency of public transport. For example, the installation of GPS systems in buses and trolleybuses will allow monitoring of the movement of transport in real-time and provide passengers with accurate information about the time of arrival of the transport at the stop.

Geographic Information Systems (GIS) has allowed us to determine the shortest route, taking into account various constraints, including road conditions, public transport schedules and other factors.

Passenger flow forecasting systems have allowed the forecasting of passenger flows at different times of the day and on different routes, which helps improve transport efficiency and reduce waiting time for passengers.

Using data from passengers' smartphones allows us to monitor the movement of passengers in real time and use this data to optimize transport routes.

Analysis of travel history data allows us to identify the most popular routes and schedules of public transport, which helps to optimize routes and reduce waiting times for passengers.

Using smart stops and the smart regulator system allows us to ensure the coordination of the movement of various types of transport on the road section, which allows for reducing the downtime of transport.

The activity diagram of the intelligent route optimization system for each passenger may include the following stages (Fig. 10):

- Collection of data on traffic and boarding/disembarking passengers at bus stops.
- Data analysis to determine the current road situation and the load on vehicles.
- Determining the most optimal route for each passenger based on their location and destination.
- Calculation of the estimated time of arrival at the destination and development of an individual travel schedule for each passenger.

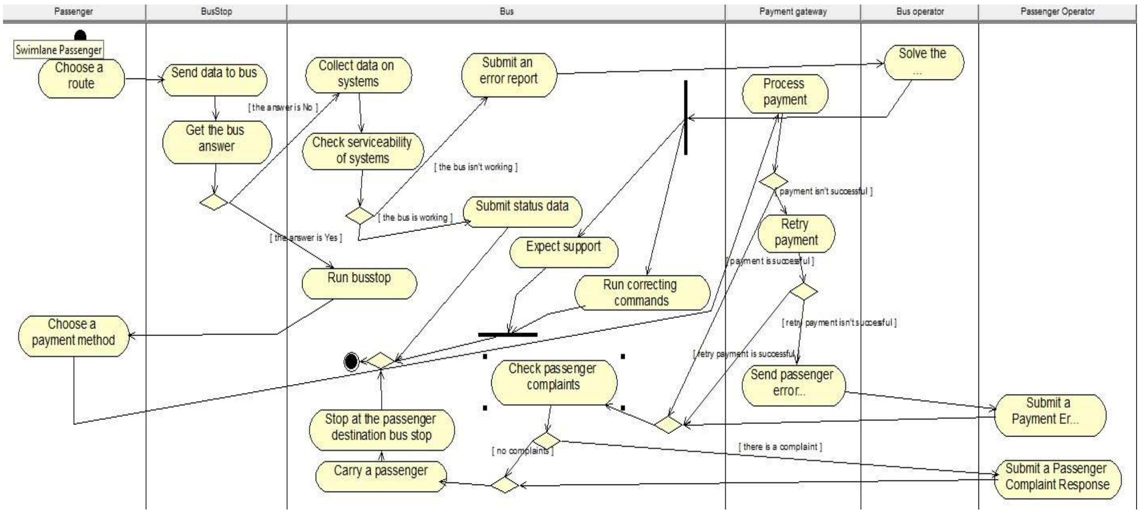

Figure 10: An activity diagram of optimization of networks of transport systems of passenger transportation

- Sending information about the optimal route and travel schedule to the passenger using a mobile application or another form of notification.
- Analysis of data on the execution of the schedule and the current situation on the roads for the correction of the traffic schedule of transport routes.

The system optimizes the route for each passenger:

- The system performs the first optimization iteration, choosing the stop closest to the passenger's starting point and the route to the final stop.
- The system checks the arrival time at the final stop and compares it with the time indicated by the passenger.

- If the arrival time is longer than the one specified by the passenger, the system chooses another route taking into account the traffic schedule and stops that will ensure the arrival on time.
- The system displays the optimal route for each passenger with the specified time of departure and arrival at the final stop.

The system sends optimal routes for each passenger to their mobile devices.

Passengers use the optimal route indicated by the system to move from the starting point to the final point.

The system receives data about the routes used by passengers and analyzes this data for further optimization of routes and planning of traffic schedules.

The system sends data on the use of routes and traffic schedules to the dispatching service for further coordination and planning of transport operations.

After receiving the recommended route, the system notifies the passenger of relevant information, including departure time, route and estimated time of arrival at the destination.

The passenger can confirm the recommended route or request another option.

If the passenger has confirmed the recommended route, information about this is transmitted to the driver of the vehicle or the traffic flow management system.

The driver of the vehicle receives an appropriate message about the recommended route and navigation information to deliver the passenger to the destination.

The system is constantly updated to take into account new data about traffic flow and vehicle schedules, which allows it to offer optimal routes even when traffic conditions change.

The diagram shows the main stages of the system: receiving data from the passenger, finding the optimal route, confirming the passenger's choice of route, and transmitting information about the route to the driver of the vehicle. The diagram also shows that the system is constantly updated to take into account new traffic flow data and provide the most optimal route for each passenger. the priority criteria are the time spent on the road (less is better), the cost of the trip (less is better) and the comfort of the trip (fullness of public transport cabin with passengers). Traffic and congestion are also important to consider. To communicate with the passenger, we can use his mobile device, touch panels in the cabin or other modern devices

The diagram shows the system states and the transition between them. The initial state is waiting for the passenger to enter the current location and destination. After receiving this information, the system goes into the "Analysis of the current situation" state, where it collects and analyzes data about traffic, the location and movement of public transport, the cost of the trip and the occupancy of the cabin.

Based on this data, the system enters the "Route Optimization" state, where it develops the best route based on priority criteria. If the found route meets the passenger's requirements, the system switches to the "Passenger message" state, where it notifies about the optimal route and displays it on the passenger's mobile device, on the board in the public transport cabin or through other modern devices.

If the found route does not suit the passenger, the system switches to the "Edit parameters" state, where the passenger can edit his priority criteria and choose a more suitable route. After that, the system repeats the process of analyzing and optimizing the route and switches to the appropriate state.

If there is a traffic jam on the road or the location of the community changes to optimize the route of each passenger, we can use machine learning algorithms that will work based on real-time traffic data, availability of free seats in transport and other parameters.

For this, the intelligent route optimization system must have access to such data. In particular, data provided by GPS trackers in transport, open traffic data sources and other developed solutions can be used.

In addition, to provide the optimal route for each passenger, the system must take into account his personal preferences. For example, if a passenger wants to get to their destination quickly, the system will offer routes that will allow them to do so. If the passenger is more concerned about the comfort of the trip, the system will offer routes with fewer transfers or with more comfortable transport.

Thus, an intelligent route optimization system should be able to collect, analyze and use a variety of data to solve the problem of providing optimal routes for each public transport passenger in real-time.

If a traffic jam appears on the road or the location of public transport changes, the intelligent system should dynamically correct routes. To do this, it must have access to current information about traffic, congestion and the location of public transport, for example, with the help of GPS modules and a network of sensors placed on the roads.

When the intelligent system receives updated information about the state of the road and the location of public transport, it must decide whether to leave the passenger on the current route or offer an alternative route to reach the goal with maximum speed and comfort.

In case of a traffic jam or a change in the location of public transport, the intelligent system should quickly make calculations and offer the optimal route. Information about traffic jams and other obstacles should be displayed on the board in the cabin of public transport and on the passenger's mobile device so that the passenger can make his choice regarding the optimal route.

In the state diagram, new states are shown as subsets of the Path to Destination state because congestion or a change in the location of traffic can change the optimal route to the destination (Fig. 11).

When the state "Traffic jam" or "Transport location change" is active, the system calculates a new optimal route to the destination based on the current information about traffic and the location of public transport. After that, the system returns to the "Traffic to destination" state and continues to perform its main functions.

The deployment diagram displays the architectural structure of the system and the interaction between its components at the resource level. In the context of optimizing public transport routes, a deployment diagram includes the following components.

The routing server is a component responsible for optimizing routes and sending route information to public transport drivers. This component can be installed on a separate server or in a cloud service.

Database - a component that stores information about routes, schedules and other data used to optimize routes.

A mobile application is a component used by passengers to obtain information about schedules, routes and changes in the movement of public transport.

The driver application is a component used by public transport drivers to obtain information about routes, changes in traffic and other important information.

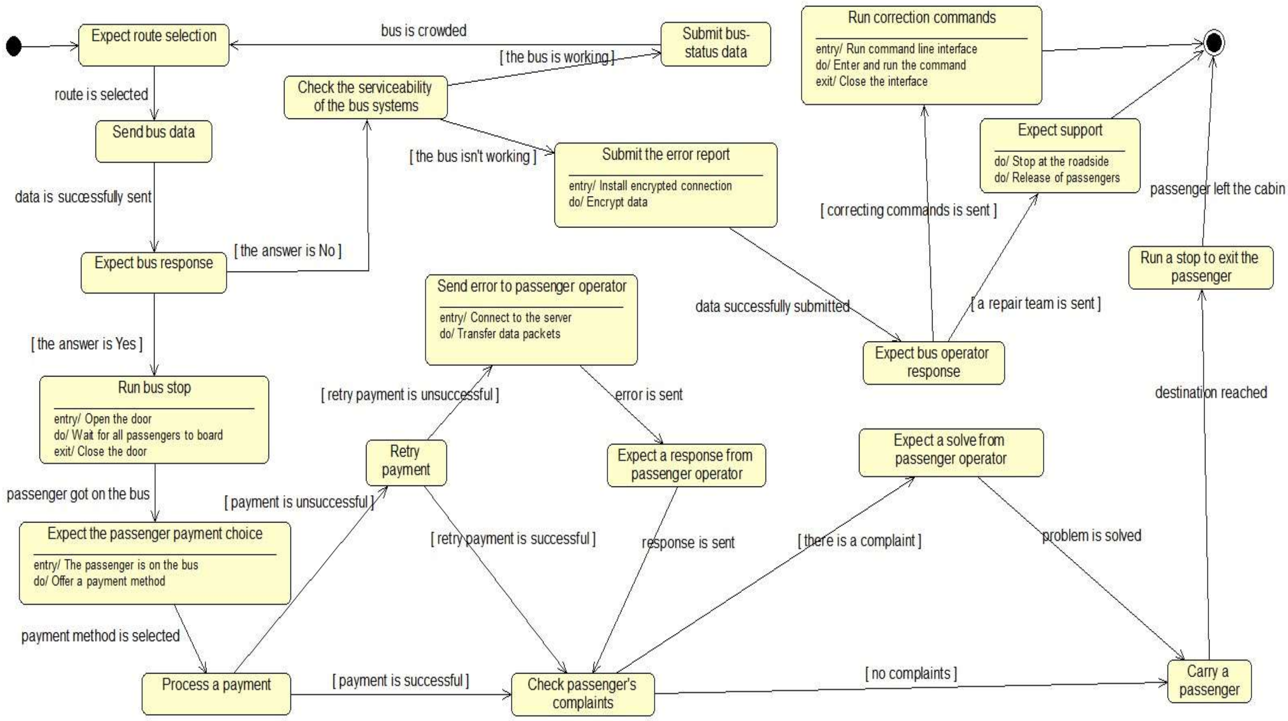

Figure 11: A state diagram of optimization of networks of transport systems of passenger transportation

Traffic sensors are a component that collects data about public transport and transmits it to the routing server to optimize routes.

Internet connection - a component that provides communication between system components and allows data to be transferred between them.

The notification system is a component that is responsible for sending notifications to passengers about changes in the movement of public transport or about delays.

For a deployment diagram, it is necessary to indicate on which physical devices the system is deployed, as well as which external systems interact with this system (Fig.12).

In this case, servers can be deployed on physical devices that ensure the operation of the information system for optimizing public transport routes, as well as sensors that measure public transport traffic indicators. External systems can be a fare payment system, traffic monitoring and traffic congestion control, GPS systems for public transport drivers, etc.

The diagram shows that the route optimization system is deployed on two servers located in different locations in the city. The system interacts with the smartphones of passengers and drivers of public transport, as well as with the fare payment system and the traffic monitoring and traffic jam control system. Public transport drivers use GPS systems that send traffic information to the system to optimize routes. The collected data is analyzed and the system calculates the optimal route for each public vehicle in real-time.

In the diagram, we can also use a neural network (RNN, CNN or DNN) to further improve the process of route optimization and traffic prediction on the road.

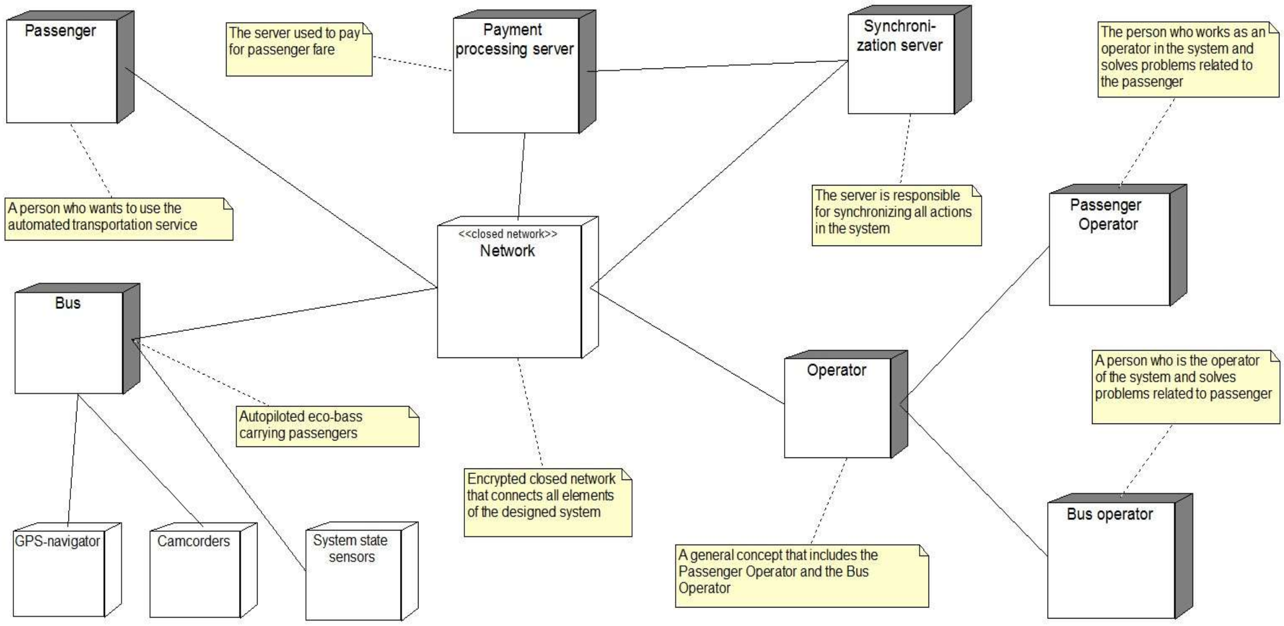

Figure 12: A deployment diagram of optimization of networks of transport systems of passenger transportation

5. Conclusion

As a result of an analysis of passenger transportation in a regional city with a population of less than 1 million registered residents and a developed public transport network, it was found that with the beginning of the pandemic, a decrease in the main indicators of passenger traffic and a slight increase in the volume of emissions of carbon-containing compounds into the atmosphere were observed. As a result of the analysis and classification of existing conceptual approaches to the optimization of the organization of public transport networks to reduce carbon emissions, three main approaches were established: prioritization of public transport, hybridization and electrification of vehicles and the implementation of IT monitoring. During the systematization of existing methods and means designed to optimize the functioning of transport systems of passenger transportation in smart cities, the following groups were substantiated: smart transport systems; electric vehicles; transport sharing networks; smart applications and information systems; innovative payment systems; unmanned vehicles; information boards and announcement systems; networks of bicycle paths and equipped sidewalks; environmental monitoring systems. During the study of successful public transport network optimization projects, it was shown that the success of implementing changes to optimize public transport networks does not depend on the size of cities, but only on the motivation of the participants in the change process (government, business and residents). When defining the existing problems, the prejudices that prevent their implementation were singled out as the most typical obstacle - resistance to changes, the ways of overcoming which are a completed theoretical and practical task. When researching different types of neural networks, it was proposed to use those that contribute to route optimization and road traffic prediction, namely: recurrent, convolutional, and deep neural networks.

Therefore, the optimization of the public transport network plays a crucial role in reducing carbon dioxide emissions in the transport sector. By providing an attractive alternative to driving, reducing the carbon footprint of public transport and promoting sustainable urban development, optimizing the public transport network can help reduce carbon emissions and mitigate the effects of climate change. Successful projects in cities around the world have demonstrated the effectiveness of optimizing the public transport network to reduce carbon emissions, making this strategy critical for governments and cities to fight climate change and improve the quality of life for citizens.

Further research should be directed towards the development of intelligent systems that will contribute to the optimization of public transport networks with low carbon emissions into the atmosphere within the concept of a smart city.

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