# ENGINEER

international scientific journal

ISSUE 4, 2025 Vol. 3
E-ISSN
3030-3893
ISSN
3060-5172

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TOSHKENT DAVLAT TRANSPORT UNIVERSITETI

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# ENGINEER

A bridge between science and innovation

**E-ISSN: 3030-3893**

**ISSN: 3060-5172**

**VOLUME 3, ISSUE 4**

**DECEMBER, 2025**

**engineer.tstu.uz**

# TASHKENT STATE TRANSPORT UNIVERSITY

# ENGINEER

INTERNATIONAL SCIENTIFIC JOURNAL
VOLUME 3, ISSUE 4 DECEMBER, 2025




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Tashkent State Transport University had the opportunity to publish the international scientific journal "Engineer" based on the **Certificate No. 1183** of the Information and Mass Communications Agency under the Administration of the President of the Republic of Uzbekistan. **E-ISSN: 3030-3893, ISSN: 3060-5172.** Articles in the journal are published in English language.

ENGINEER
INTERNATIONAL SCIENTIFIC JOURNAL
VOLUME 3, ISSUE 4 DECEMBER, 2025

# EDITORIAL BOARD

# Measurable and explanatory examination of the state of cargo transportation by road transport in Uzbekistan

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Abstract: This article gives an outline of the current state of cargo volume, cargo turnover and the number of holders transported by street in Uzbekistan by year. At the same time, the share of cargo volume by locale and the number of holders transported in coordinations centres or terminals (based on the possibility think about) were dissected utilizing the Pareto run the show. The most issues that diminish the productivity of cargo transportation have been identified. In arrange to extend the efficiency of vehicles and their more productive utilize in household and universal transportation, it is proposed to execute shared integration of transport modes and a noteworthy decrease in sit still running.

Keywords: road transport, cargo, cargo turnover, cargo transportation, industries, TEU (twenty-foot equivalent unit) logistics centers

## 1. Introduction

In recent years, our republic has been undertaking a series of efforts to reform transport logistics, widely introduce market relations, improve the freight transportation system across different modes of transport, strengthen the legal framework for relations between carriers and consumers, attract investments to the transport logistics sector, implement resource-saving technologies, and ensure modern methods and technologies for road transport carriers. This is evidenced by the adoption of several regulatory and legal acts that stimulate research and methodological work in the field, aimed at reducing transportation costs for various modes of transport and developing container transportation. In particular, the state program for implementing the Development Strategy of New Uzbekistan for 2022–2026 specifically outlines tasks to "…reduce the cost of freight transportation by up to 30 percent" and "…increase the share of container transportation across transport modes by at least twofold" [1]. In fulfilling these tasks, based on the objectives of reforming the economy of New Uzbekistan, it is highly relevant to conduct systematic research to improve the economic, technical, and organizational methods of container delivery by road transport in our country, grounded in logistics principles.

In later a long time, our republic has been undertaking a arrangement of endeavors to change transport coordinations, broadly present showcase relations, progress the cargo transportation framework over distinctive modes of transport, fortify the legitimate system for relations between carriers and shoppers, draw in speculations to the transport coordinations segment, actualize resource-saving innovations, and guarantee present day strategies and advances for street transport carriers. This can be prove by the selection of a few administrative and legitimate acts that invigorate inquire about and methodological work within the field, pointed at lessening transportation costs for different modes of transport and creating holder transportation. In specific, the state program for actualizing the Improvement Methodology of Modern Uzbekistan for 2022-2026 particularly traces errands to "… reduce the taken a toll of cargo transportation by up to 30 percent" and "… increase the share of holder transportation over transport modes by at slightest twofold" [1]. In satisfying these assignments, based on the destinations of changing the economy of Modern Uzbekistan, it is exceedingly pertinent to conduct orderly inquire about to move forward the financial, specialized, and organizational strategies of holder conveyance by street transport in our nation, grounded in coordinations standards.

## 2. Methodology

On a worldwide scale, the volume of cargo transportation by street transport expanded from 72.8% to 82.6% between 2021 and 2023. The productive utilize of worldwide travel interstates for holder transportation by street moreover speaks to a critical source of income [2].

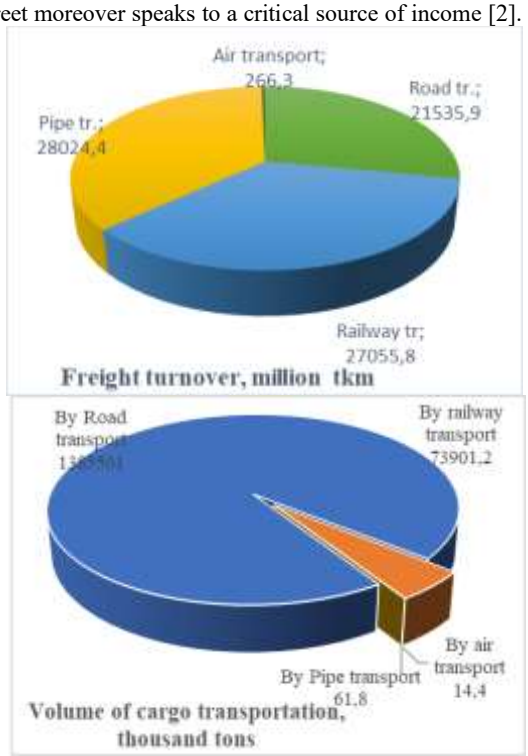


**Fig. 1. Chart of transport execution by modes of transport for January-December 2024**

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https://doi.org/10.56143/3030-3893-2025-4-5-7 A bridge between science and innovation

Inside the system of built up participation with neighboring nations such as Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Afghanistan, assentions have been come to on the development of unused interstates, the opening of courses to outside nations through them, as well as the joint repair and operation of existing streets [4]. As a result, the volume of street cargo transportation and travel cargo transportation has been expanding year by year.

## 3. Results and Discussion

The volume of cargo transported by all modes of transport in Uzbekistan in 2024 measured to 1 459,478 million tons, which is 1,4% more than in 2023. The most noteworthy marker for cargo transportation is ascribed to street transport. Cargo transported by this mode expanded by 4,0% compared to 2023 and measured to 1 385,5 million tons. Cargo turnover expanded by 5,0 percent and measured to 21 535,9 million ton-kilometers, bookkeeping for 28,0 percent of the overall cargo turnover (see Figure 1) [3]. Since 2017, noteworthy victories have been accomplished in moving forward cargo transportation by street transport. In specific, holder and bundle cargo transportation have been goal creating, mechanized and robotized transport and distribution center complexes have been set up, mechanized administration frameworks for mechanical zones and holder terminals have been made, and logically grounded strategies for planning the operations of rail and street transport have been advanced [3,5].

Be that as it may, the inadequately level of present day cargo conveyance advances by street transport, as well as the tall extent of wasteful downtime in transport and mechanical cargo operations, don't keep pace with the country's financial advancement rates (see Figure 2).

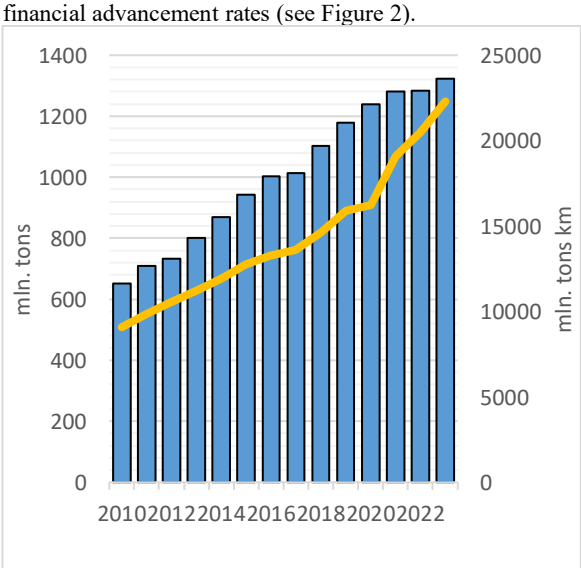


**Fig. 2. Dynamics of Transport Performance by Road Transport (2010–2023)**

The volume of cargo transportation from 2010 to 2023 expanded from 652.5 million tons to 1,322 million tons, or by 202.6%, whereas cargo turnover developed from 9,076.3 million ton-kilometers to 22,290.7 million ton-kilometers, or by 245.4% [3]. Street transport is partitioned into three categories: open transport undertakings, endeavors and organizations of the financial division, and private vehicle proprietors. The information for these three categories of transportation for 2024 are given underneath (see Figure 3).

The article presents charts based on a Pareto chart, sketching out the first basic regions and holder terminals included in cargo transportation and holder supply chains (see Figures 4 and 5).

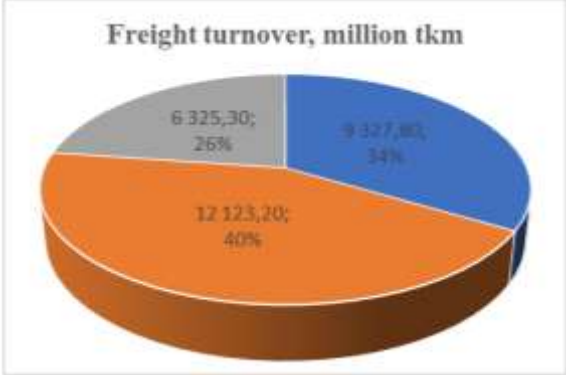


**Fig. 3. Components of Cargo Transportation Pointers for Road Transport Organizations in 2024**

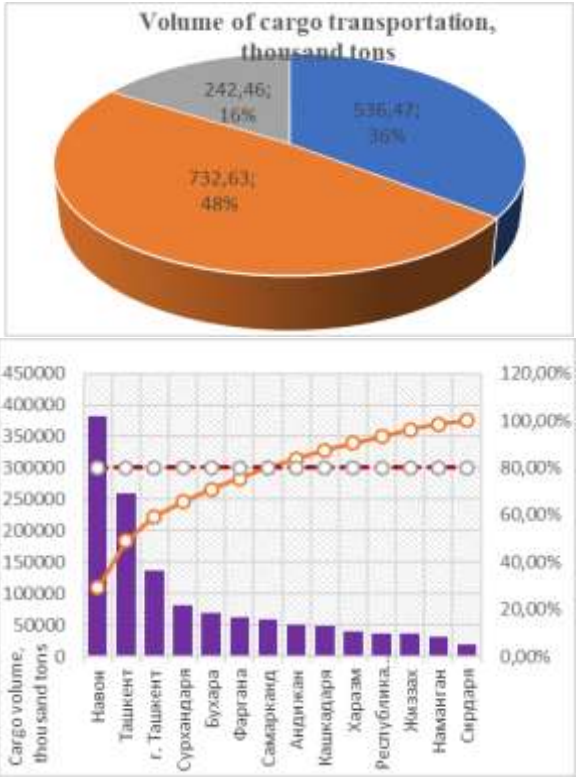


**Fig. 4. Pareto Chart Reflecting the Volume of Cargo Transported by Street Transport by Districts for January-December 2023**

As appeared in Figure 5, 80 percent of the cargo volume transported by street transport is accounted for by 7 locales, which speak to 50 percent of the districts, contributing to 80 percent of the transportation [3,6].

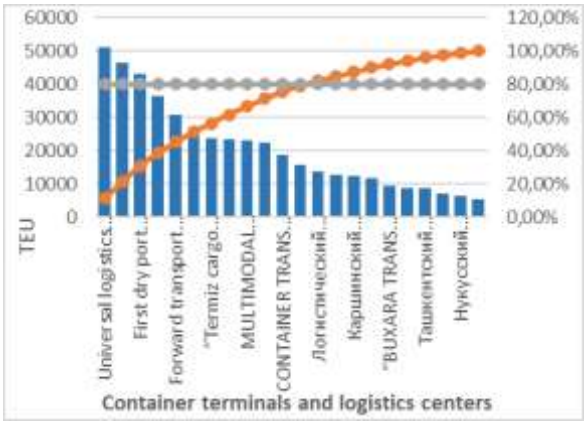


**Fig. 5. Pareto Diagram Representing Container Turnover at Logistics Centers and Terminals for January–December 2024**

As appeared in Figure 5, 80% of the holder volume transported through terminals or coordinations centers was dealt with by 12 terminals.

## 4. Conclusion

Concurring to the investigation of the current state of holder streams in street transport and cargo transportation innovations inside the coordinations supply chain, Uzbekistan altogether slacks within the level of containerization of cargo transport, because it constitutes no portion of the overall cargo transportation volume. Furthermore, to improve vehicle efficiency and their more proficient utilize in residential and universal transportation, common integration of transport modes and a noteworthy decrease in purge runs are required.

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# Improving control and management methods of electricity quality indicators produced by solar panels

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Abstract: In order to provide consumers with high-quality and uninterrupted electricity, great attention is paid to the use of renewable energy sources in the world, and the electricity generated by solar panels is already in sufficient quantities in this regard. This, in turn, requires monitoring and correct management of the quality indicators of the electricity generated by solar panels, increasing the service life of solar panel elements, and correct diagnosis during their service. In this regard, the demand for compact, economical and inexpensive remote control and management element devices increases, and the scientific article presents sufficient solutions and recommendations for these problems.

Keywords: solar panels, electricity, grid connection, power balance, control, time-dependent characteristic

## 1. Introduction

The global green energy development agenda has become one of the most pressing issues of our time, with significant investments in developing energy sources based on geothermal, hydroelectric, solar, wind, and other clean energy technologies.[1] In this regard, solar energy has become a leading candidate in the renewable energy sector due to its huge and clean energy potential. Solar energy is a sustainable and environmentally friendly alternative to traditional fossil fuel-based electricity generation by harnessing the power of sunlight.[2] A number of government policies and strategies, including tax incentives, subsidies, and other supportive measures, have played a significant role in increasing PV installations worldwide, along with the sharp decline in the cost of photovoltaic PV modules over the years.[3] At the same time, these factors have led to a sharp increase in the number of PV installations in the solar energy network, making solar energy the largest and fastest growing source of electricity in the world.

## 2. Research methodology

It is known that solar power grids are currently being used in industrial production and economic sectors of our country in two modes, namely On-grid and Off-grid, and the transition to grid-connected photovoltaic (PV) systems is economically cheap and convenient, so most consumers are using this method. These systems use semiconductor materials to convert sunlight into electricity, thereby reducing carbon dioxide emissions and helping to control global warming. Grid-connected PV systems provide many advantages, including: reducing power losses along the line, improving voltage drop, increasing energy efficiency, correcting power factor and improving harmonic current content[4]. They also provide ancillary services to local consumers, optimizing generation and distribution. Today contribute to energy security and environmental protection. The environmental friendliness of PV systems is also reflected in low emissions, minimal noise, and low water consumption compared to other power plants. The analysis suggests that renewable energy technologies will become the largest contributor to electricity generation in Saudi Arabia over the next two decades; this demonstrates the great potential of solar energy to radically change the energy landscape[5]. In addition, integrating solar energy into the grid can improve energy efficiency by reducing energy losses and increasing the overall efficiency of the grid [6]. Feasibility studies of off-grid, grid-connected solar photovoltaic systems combined with grid-connected battery energy storage have shown that such systems can provide a cheap and reliable source of energy for households and large consumers[7]. The results of the study show that the integration of PV power into the existing grid is difficult due to the natural variability and non-intermittency of solar energy, which leads to power supply fluctuations. Grid-connected solar systems pose serious challenges for grid operators, as the variability and non-intermittency of solar energy can disrupt the stability and efficiency of the grid. In order to improve the reliability of solar power consumers, a hybrid CNN-LSTM model was proposed to predict the PV power of a solar power grid, which was developed to solve these problems when operating from a hybrid system source. The model achieved good accuracy and can effectively reduce the fluctuations in power generation[8]. The lack of input solar radiation data may limit its application in areas with highly variable solar radiation. Also, in [9], a hybrid multi-stage CNN-stacked LSTM model was proposed to predict the solar radiation (GHI) and POA radiation. This model showed high accuracy, achieving RMSE = 0.36 ($R^2$ = 0.98) for GHI and RMSE = 61.24 ($R^2$ = 0.96) for POA. The model effectively combines the strengths of CNN and LSTM, improving the accuracy of solar radiation and POA forecasting and is a powerful tool for solar energy forecasting. Similarly, in [21], a two-stream CNN-LSTM network with a self-attention mechanism, called DSCLANet, was proposed for short-term solar energy forecasting. The model significantly reduced errors and performed better than state-of-the-art methods. However,

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combining CNN and LSTM to extract spatial and temporal features increases the complexity of the model, which may lead to high computational costs and training difficulties. The authors plan to address this issue by developing a single architecture that can efficiently extract the two features. In addition, the results of three popular models – ANN, Angstrom-Prescott and ARIMA – were compared with the proposed hybrid model. A hybrid model combining RF, principal component analysis (PCA), K-means and Harmony Search-based Gray Wolf Optimization (HGWO) was used to forecast the solar power plant capacity one hour in advance. This hybrid model achieved significantly lower mean absolute error (MAE) values than previous models, demonstrating the benefits of combining multiple techniques [10]. The data collection process for this study involved simulations of a grid-connected photovoltaic (PV) power plant using a-Si technology, resulting in a comprehensive database. The data were collected over a full year, from January 1 to December 31, for a 365-day period, capturing seasonal and operational variations in power generation. The annual database was divided into three parts: a 267-day training period. An algorithm developed for the solar power system management system.

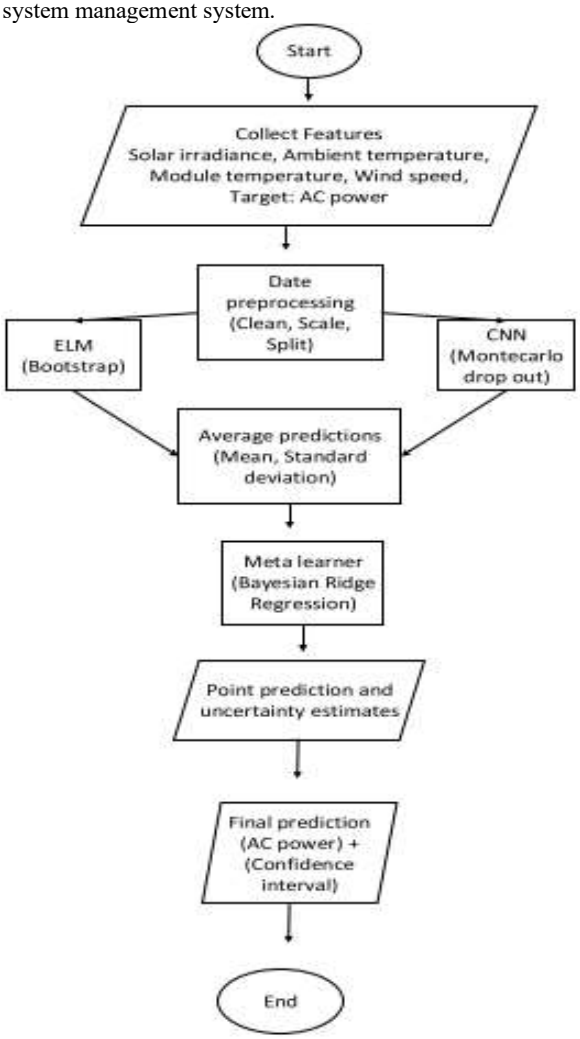


**Fig. 1. Algorithm developed for the quality indicators of the solar power supply system**

The power supply system under development of solar panels has a 67-day test period and a 31-day forecast period. Each time interval was recorded hourly, which ensured the availability of high-precision data for training, testing and forecasting the model. The time resolution of the input data was 1 hour, and the model was designed to predict 1 hour in advance, that is, it predicted the energy production for the next hour based on the current and previous hourly data. The geographical location of the power plant is in the city of Andijan, which is located at the coordinates of 26.42° north latitude and 50.08° east longitude, at an altitude of about 10 meters above sea level.

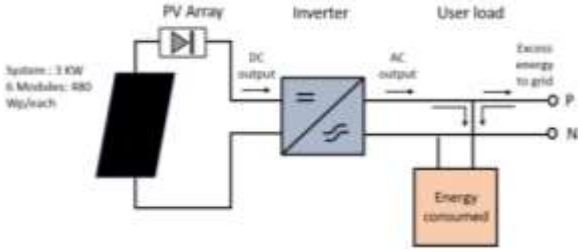


**Fig. 2. Power distribution control scheme in a smart solar power system**

The photovoltaic arrays are oriented to the south, resulting in an azimuth angle of 0° and a tilt angle of 30°. The PV plant configuration consists of six modules, each with a nominal power of 480 W p (Wp). They are arranged one after the other in six strings, for a total nominal power of 2880 W p (Wp). The schematic of the proposed grid-connected PV system is shown in Figure 2. The data were simulated using the PV syst program. While this approach provides stable and controlled input conditions for model development, it may not fully capture unexpected performance variations encountered in real-world conditions, such as inverter outages or unscheduled maintenance, dust accumulation, bird droppings, or equipment failure.

The following is a time-dependent diagram of the quality of electricity produced by a solar power system when operating according to the above algorithm.

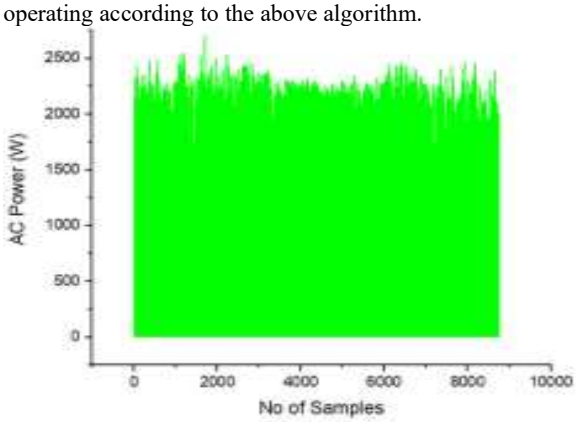


**Fig. 3. The time-dependent change in the quality of electricity generated by a solar power system**

The efficiency of the electricity generated by the solar power system is considered using a hybrid model that combines probability theory with an artificial solar grid to predict the power output of the electricity generated by the solar power system when it is converted into alternating current by an inverter. This model is designed to improve the forecasting accuracy under different weather conditions including rainy, cloudy, and sunny periods.


https://doi.org/10.56143/3030-3893-2025-4-8-10 A bridge between science and innovation

## 3. Conclusion

In this study, we developed a deep learning-based stacking model for forecasting and uncertainty analysis of grid-connected PV systems. The objectives achieved in this study are: Improving forecasting accuracy: Extreme learning machine (ELM) and convolutional neural network, Uncertainty detection: Applying uncertainty analysis to the model — bootstrap method for ELM, Feature engineering using SHAP: Feature engineering using Shapley additive explanation (SHAP) analysis improved the model accuracy, Supporting compensatory energy integration: By providing reliable and robust energy forecasts, the model helps integrate solar energy into existing grids.

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# Architecture and urban planning of Nukus city in the context of changing water and ecological conditions of the region

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Abstract: In this article, the influence of changes in the water-ecological situation of the Aral Sea region on the architecture and urban planning system of the city of Nukus is scientifically analyzed. Environmental problems caused by the drying up of the Aral Sea in recent decades, in particular, water scarcity, increased atmospheric dust, and land salinization, have a direct impact on urban infrastructure, living conditions, and climatic conditions. The study examined the directions of sustainable development of the city of Nukus based on scientific and theoretical analysis methods, modeling of urban planning systems, and statistical analysis. According to the results, the population growth rate in the city over the past 30 years has been accompanied by a decrease in water resources, which requires new ecological and architectural solutions. The research results can also have practical significance in the formation of urban planning policy in other arid regions of Uzbekistan.

Keywords: Nukus city; Aral Sea region; water resources; environmental conditions; sustainable architecture; urban planning; landscape planning; environmental problems; urbanization; climate change

## 1. Introduction

In recent decades, global climate change, water scarcity, and the disruption of the ecological balance have been viewed as one of the most pressing global problems facing humanity. This process is especially acute in the Central Asian region, including the Republic of Karakalpakstan. Limited natural resources in the region, the drying up of the Aral Sea, increased drought, soil salinization, and increased heat stress - all these directly affect the socio-economic development of the region, the architectural and engineering systems of cities, and the quality of life of the population [1-3].

In particular, the city of Nukus has a unique complex system in terms of ecology, demographics, and urban development. As a central point of the Aral Sea region, it plays a strategic role in the issues of natural resource use, ecological restoration, and the harmonization of sustainable urban development. The climatic, hydrogeological, and ecological characteristics of the urban area are closely interconnected, which plays a decisive role in the planning of urban architecture, the modernization of water infrastructure, and the formation of green infrastructure systems [4].

### Ecological situation of the city of Nukus and the importance of water resources

The city of Nukus, located near the former southern shores of the Aral Sea, is a cultural and economic center that historically arose in the lower reaches of the Amu Darya River. However, starting from the second half of the 20th century, due to the excessive use of Amu Darya water for irrigation purposes, the Aral Sea level dropped sharply, and the resulting Aral tragedy changed the natural environment of the entire region [5].

According to UNEP data, from 1960 to the present, the water volume of the Aral Sea has decreased by more than 90 percent, and the water level has dropped by more than 30 meters. As a result, the new desert formed at the bottom of the Aral Sea - Aralkum - currently occupies an area of 5.5 million hectares, and up to 100 million tons of salt dust are released into the atmosphere annually [6]. These dust and salt particles spread through the air for hundreds of kilometers, worsening the ecological situation of Karakalpakstan, including the city of Nukus.

In recent decades, the average summer temperature in the city of Nukus has increased by +1.7°C, and in the winter months, softening to -2°C has been observed [7]. The amount of precipitation decreased from 120 mm in the 1980s to 85-90 mm by 2020. This indicates that water resources are under pressure, and the natural green cover is decreasing. According to the 2024 report of the Hydrometeorological Service, the groundwater level in Nukus is located at an average depth of 3-6 meters, and their mineralization is in the range of 2-3 g/l. This requires additional purification steps to ensure the quality of drinking water [8].

The city is provided with water mainly through the Amu Darya water networks. The total length of the water network is 760 km, of which 47% is worn out and in a state of disrepair. Annually, 15-20 million m3 of water is wasted due to technical losses [9]. This makes the introduction of water-saving technologies, water treatment, and rainwater collection systems a strategic necessity.

### Development of urban architecture and environmental problems

The process of formation of Nukus architecture began in the 1930s. After the city received official status in 1932, central streets, administrative buildings, and social facilities were built on the basis of the Soviet school of architecture. The city's master plan, developed at that time, was built in harmony with water networks and irrigation canals. However, as a result of rapid urbanization, population growth, and industrialization processes between the 1970s and 1990s, the principles of environmental sustainability were overlooked [10].

Since the 1990s, the socio-economic problems associated with the Aral Sea crisis have also been reflected

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in urban infrastructure. Hot summers, dry winds, salt dust storms, and water scarcity negatively impacted the quality of the city's architectural environment. Apartment buildings built during the Soviet era do not meet modern requirements in terms of thermal insulation; the effect of street heat islands (heat island) has intensified. According to the 2020 Nukus master plan, green areas make up 18% of the total area of the city, which is below the requirements of the Sustainable Development Goals (SDG-11) [11].

Therefore, in recent years, research on the implementation of the principles of eco-urbanism, green infrastructure, and water-sensitive urban design (WSUD) has intensified. The WSUD concept provides for the harmonization of the urban water system with natural water circulation, the collection, filtration, and integration of rainwater with groundwater [12]. This approach is one of the most optimal ways to create climate-friendly, sustainable, and water-saving urban solutions in the cities of the Aral Sea region.

**Global theoretical foundations and practical experience**

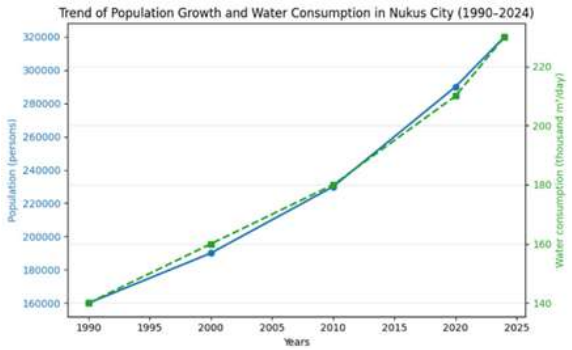
Global experience shows that cities experiencing water scarcity and heat stress - for example, Melbourne in Australia, Amman in Jordan, Turkestan in Kazakhstan - overcome problems more easily through environmental planning based on the WSUD and IUWM (Integrated Urban Water Management) concepts [13].

The IUWM concept integrates water resources, consumption, wastewater, and recycling systems into a single management chain. This approach can be especially effective in areas with water scarcity, such as the Aral Sea region. For example, Australia's Water Sensitive Cities program has reduced water consumption by 35% in 20 years. The use of such a system in the city of Nukus will save millions of cubic meters of water per year.

The UN Urban Water Resilience Framework also emphasizes the need for public participation in water resource management, data monitoring, and the implementation of digital technologies. In the city of Nukus, such digital solutions - for example, "smart water meters," monitoring of water networks based on GIS, and the implementation of remote flow control systems are among the promising areas.

**Statistical analysis and problematic aspects**

Studies show that water consumption in the city of Nukus has been steadily growing over the past 30 years. The graph below illustrates this process.




**Graph 1. Water consumption in the city of Nukus over the past 30 years**

In the ecological and urban development of the city of Nukus, the management of water resources, the adaptation of architectural systems to the climate, and the formation of green infrastructure are among the most pressing scientific and practical issues of today. The novelty of this research lies in the fact that it develops water-saving, ecological, and climatic architectural solutions specific to the conditions of the Aral Sea region.

The article also presents a mathematical model of the interrelationship of urban infrastructure elements based on the theory of polystructural analysis, which allows for the application of scientific results in practical design.

## 2. Research methodology

The methodology of this research is based on the principles of scientific and theoretical analysis, a systematic approach, polystructural modeling, and the analysis of ecological and architectural concepts. The main goal of the research is the theoretical development of a model for the sustainable development of the architecture and urban planning system of the city of Nukus in the context of water and environmental changes in the region.

**Fundamentals of a scientific and theoretical approach**

In the process of analysis, the following theoretical paradigms were relied upon:

- Concept of Water-Sensitive Urban Design (WSUD) [1];
- Integrated Urban Water Management (IUWM) model [2];
- Theories of sustainable development and green architecture (UN-Habitat, SDG-11 principles) [3];
- Theory of Polystructural Systems (V.I. Solomatov, 1980) - analysis of complex urban systems as systems of multilayer interaction [4].

Through these approaches, the natural, technical, social, and architectural systems of the city of Nukus are considered as a complex of interconnected, interacting elements. In this case, the interactions between "city - water - landscape - person" are analyzed using a network model.

**Method of system analysis**

In the study, the method of system analysis was chosen as the main method. This method allows for the analysis of the structure of the urban ecological system, the flow of water resources, the location of architectural objects, and their impact on environmental sustainability.

The systematic approach was implemented in three stages:

1. Resource Analysis - Available data on natural water sources, groundwater, and technical networks of the city of Nukus were placed in the GIS database.
2. Architectural and structural analysis - the mutual location of urban buildings, green areas, and engineering communications was determined, and their impact on environmental sustainability was assessed.
3. Intersystem integration - the relationship between urban water supply, sewage system, landscape and climate elements was modeled.

**Polystructural modeling**

Based on the theory of polystructural systems proposed by Professor V.I. Solomatov, the city system of Nukus was considered as a multi-level model. In this approach, each

element - water, architecture, landscape, living environment of the population - is analyzed as a separate structural link.

The mechanism of their interaction is expressed as follows:

$$S=f(W,L,A,P,T)$$

where:

- S - level of environmental sustainability of the city,
- W - state of water resources,
- L - landscape components,
- A - architectural structures,
- P - demographic pressure,
- T - climatic factors.

With the help of this model, it is theoretically determined how the reduction of water resources affects the architectural density and green areas. For example, a 10% decrease in water supply can lead to an increase in the microclimate temperature within the city by 0.3-0.5°C - this phenomenon is taken into account when developing sustainable architectural solutions [5].

**Method of GIS and Cartographic Analysis**

Analysis of the environmental and urban planning indicators of the territory of the city of Nukus was carried out based on GIS (Geographic Information Systems) technologies. Using this method:

- location of water sources,
- Degree of depreciation of water supply networks,
- Percentage of green areas,
- heat island zones

is determined.

The program QGIS 3.28 was used as the GIS platform. Data on environmental indicators (NDVI, LST, albedo) for each layer were obtained from Landsat 8 satellite data. The following table shows excerpts from some of the parameters analyzed:

**Table 1**

**Excerpts from some of the parameters**

| Indicator | 1990 | 2024 | Change (%) |
|---|---|---|---|
| Share of green areas (%) | 25.3 | 18.1 | -28.5 |
| Annual precipitation (mm) | 120 | 87 | -27.5 |
| Average summer temperature (°C) | 33.2 | 35.1 | +5.7 |
| Air dust level (mg/m$^3$) | 0.11 | 0.17 | + 54.5 |

The data in the table show that over the past 30 years, green areas have decreased by almost 30%, and the level of air pollution has almost doubled. This situation intensified the "microclimate stress" in the urban environment and increased the pressure on the water network.

**Comparative analysis**

Also, the situation of the city of Nukus was compared with other water-scarce cities - Ashgabat, Turkestan, Kagan, Amman (Jordan). Comparison results showed:

- Water consumption in Nukus averages 110 l/day,
- Ashgabat - 135 L/day,
- And in Amman 80 L/day.

However, the water network loss rate in Nukus is 35%, which is three times higher than European standards (10-12%) [6]. This data scientifically confirms the need to implement sustainable urban planning systems.

**Architectural and Environmental Modeling**

The concept of "Environmental heat balance" was used as a theoretical model. It is expressed by the formula:

$$Q_{urban}=Q_s+Q_a-Q_v$$

where:

- $Q_s$ - solar radiation energy,
- $Q_a$ - anthropogenic heat release,
- $Q_v$ - heat absorption through vegetation.

If green areas decrease by 10%, Qv decreases, and as a result, the microclimate temperature increases by 0.4°C - which directly affects public health and energy consumption. Thus, to maintain ecological balance, green corridors, water facilities, and microclimate-managing landscape solutions play an important role in architectural planning.

## 3. Results and Discussion

During the study, changes in the city of Nukus over the past 30 years (1990-2024) related to water resources, climate change, urban architecture, and demographic pressure were analyzed. Based on the data obtained, ecological and urban planning trends were determined.

**Dynamics of water resources and consumption of the city of Nukus**

The results of statistical analysis showed that since the 1990s, water resources in Nukus have decreased by 25-30% due to the decrease in the flow of the Amu Darya River, the drying up of the Aral Sea, and a decrease in the groundwater level.

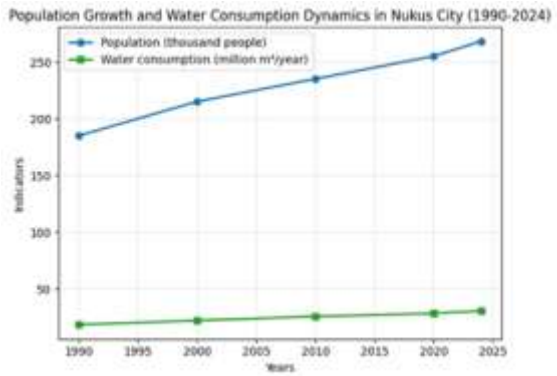
Along with the growth of the city's population, water consumption is also increasing.

**Table 2**

**Dynamics of water resources and consumption of the city of Nukus**

| Year | Population (thousand people) | Water consumption (million m3/year) | Water supply efficiency (%) |
|---|---|---|---|
| 1990 | 185 | 18.5 | 72 |
| 2000 | 215 | 22.1 | 68 |
| 2010 | 235 | 25.7 | 64 |
| 2020 | 255 | 28.4 | 62 |
| 2024 | 268 | 30.6 | 60 |

As can be seen from this table, with a 30% increase in the population, the efficiency of the water supply network decreased from 72% to 60%. This indicates an increase in water loss.




**Graph 2. Relationship between water consumption and population**


https://doi.org/10.56143/3030-3893-2025-4-11-15 A bridge between science and innovation

**Environmental changes based on GIS analysis**

Based on data from the Landsat 8 satellite, indicators NDVI (greenness index) and LST (surface temperature) were determined for the city of Nukus. Based on results:

These recommendations form the basis of the scientific data needed to improve urban infrastructure and provide pedestrians with a more friendly and safe environment.

**Table 3**

**Environmental changes based on GIS analysis**

| Year | NDVI (green index) | LST (°C) | Explanation |
|---|---|---|---|
| 1990 | 0.27 | 31.8 | Green spaces are vast |
| 2010 | 0.19 | 33.6 | Increased construction density |
| 2024 | 0.13 | 35.4 | Reduced green areas |

A decrease in the NDVI index from 0.27 to 0.13 - indicates a 50% reduction in green spaces, and an increase in LST by 3.6°C. These changes have enhanced the hot island effect, resulting in a 2-3°C higher air temperature around buildings.

**Changes in the urban architectural system**

In the city of Nukus, since 2010, new residential areas (along Beruniy Road, towards the Airport) have been rapidly developing. However, in these regions:

obsolescence of water supply networks (on average 40-50 years of pipelines);

insufficient renewal of the drainage system;

green zones decreased by 15-20%

There are issues like.

This indicates the need to implement water-sensitive architectural approaches in urban landscape design and planning.

Environmental Sustainability Indices

During the study, the "Environmental Sustainability Index (ESI) " was developed for the city of Nukus based on the following indicators:

$$EBI=\frac{YH\times ST}{CO\times HL}$$

where:

YH - share of green areas (%),

ST - water supply efficiency (%),

CO - dust coefficient (mg/m$^3$),

HL - average temperature (°C)

**Table 4**

**Calculation results**

| Year | YH (%) | ST (%) | CO (mg/m$^3$) | L (°C) | EBI |
|---|---|---|---|---|---|
| 1990 | 25.3 | 72 | 0.11 | 31.8 | 51.9 |
| 2010 | 21.7 | 65 | 0.14 | 33.6 | 41.5 |
| 2024 | 18.1 | 60 | 0.17 | 35.4 | 33.2 |

The analysis results show that the ecological and architectural system of the city of Nukus is currently in the stage of "ecological stress". The main problems are:

1. Lack of water resources (losses of 35-40%);
2. Reduction of green spaces (28% over the past 30 years);
3. Increased construction density and narrowing of ventilation corridors;
4. Obsolescence of drainage and water treatment facilities;
5. Intensification of the hot island effect and microclimate deterioration.

Therefore, it is necessary to develop a Sustainable Urban Development Concept, which should be implemented based on the principles of WSUD, including:

- rainwater collection systems;
- green roofs and vertical landscapes;
- micro-biopark systems for water treatment;
- Use of climate-adapted building materials (e.g., vermiculite or zeolite concretes).

The main results obtained for the city of Nukus are summarized as follows:

**Table 5**

**Final results**

| Indicator | 1990 | 2024 | Change (%) |
|---|---|---|---|
| Population (thousand people) | 185 | 268 | +45 |
| Green areas (%) | 25.3 | 18.1 | -28 |
| Average temperature (°C) | 31.8 | 35.4 | +11.3 |
| Water network losses (%) | 28 | 40 | +43 |
| EBI (Stability Index) | 51.9 | 3.2 | -36 |

These results show that if environmental approaches in urban planning policy and architectural design are not strengthened, sustainability will sharply deteriorate by 2040.

## 4. Conclusion

The research results show that the city of Nukus is one of the centers of urbanization with the most complex water-ecological environment in the Aral Sea region. Over the past 30 years, the processes of water resource depletion, soil salinization, and climate continentalization have directly affected urban architecture and planning systems.

The main conclusions are as follows:

1. Water scarcity and network obsolescence have made it difficult for the urban population to have a stable supply of drinking water. As of 2024, water supply efficiency does not exceed 60%, losses are around 35-40%.
2. The proportion of green areas decreased from 25.3% to 18.1%, which increased the temperature by 3.6°C and enhanced the "city hot island" effect.
3. The Environmental Sustainability Index (ESI) decreased from 51.9 in 1990 to 33.2 in 2024, meaning sustainability deteriorated by 36%.
4. In construction and architectural practice, approaches to water-rich conditions from the Soviet era are still preserved, which does not meet the requirements of the new ecological environment.
5. Degradation of urban landscapes and disruptions in water supply also negatively affect the quality of life, health, and migration trends of the population.

**Practical recommendations**

1. Inclusion of water-sensitive urban development (WSUD) principles in the new master plan of the city of Nukus:

creation of rainwater collection and filtration systems;

Processing of water flow through natural lakes, green canals;

practical implementation of "green roof" technologies.

2. Develop Sustainable Landscape Architecture:

Low-water-demanding landscapes based on local desert vegetation;

creation of protection zones with perennial trees in accordance with wind directions;

Connection of recreational green corridors (park system) with the city center.

3. Use of energy-saving and environmentally friendly building materials:

zeolite, vermiculite, and perlite concretes with low thermal conductivity;

Improvement of building thermal insulation and ventilation systems.

4. Establishment of digital monitoring of urban infrastructure:

Creation of pressure and loss maps of water networks based on GIS;

control of water consumption through remote monitoring systems;

Implementation of online sensor water quality monitoring.

5. Increasing environmental awareness through scientific and educational platforms:

Development of the "Sustainable Nukus" program in cooperation with Karakalpak State University and Tashkent University of Architecture and Construction;

Create educational programs for the population on water conservation, waste-free technologies, and green construction.

**Scientific significance**

This study:

- For the first time, an assessment of the level of environmental sustainability of the city of Nukus using a mathematical model (EBI) was carried out;
- Demonstrated the relationship between water resources, climate, and architecture through specific figures;
- Scientifically based recommendations were given on the adaptation of WSUD principles to the conditions of the Aral Sea region.

Practical significance

Results can be used in the development of a new master plan for the city of Nukus, in architectural design projects, and in the development of environmental rehabilitation programs in the Aral Sea region.

In addition, the EBI model is recommended as a monitoring tool for the Environmental Committee of the Republic of Karakalpakstan and Regional Architecture Departments.

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# System analysis and virtual simulation integration to improve physics education through a web platform

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Abstract: This article is devoted to the development of an innovative web platform aimed at improving physics education for students in grades 7–11. The proposed platform is based on modern digital educational technologies and includes elements of systematic analysis, interactive virtual simulations, 3D models, and artificial intelligence. The platform will allow students to deepen their understanding of theoretical material, understand complex and abstract physical phenomena through visual experiments, and develop practical skills. It will include video lessons, step-by-step laboratory work, an automatic analyzing test system, and online communication between the teacher and the student.The main goal of the project is to increase interest in physics, develop students' independent thinking, experimenting, and problem-solving skills. The platform is convenient even for schools with limited resources and allows access to any device via the Internet. In the future, the system is planned to integrate functions such as personalized learning based on artificial intelligence, a module that provides real-time feedback, automatic analysis of student achievements and generation of recommendations. This platform is expected to not only increase the efficiency of the learning process, but also become an important step in the formation of a modern digital education ecosystem.

Keywords: physics education, web platform, virtual 3D simulation, system analysis, AI integration, high school education, modern teaching methodology

## 1. Introduction

Physics, as a core subject, plays a crucial role in developing critical thinking, scientific observation, and problem-solving skills in secondary school students. However, traditional teaching methods are often limited to verbal delivery of theoretical information and do not provide sufficient efficiency in fully integrating complex concepts such as mechanics, optics, electricity, and electromagnetism into students. Traditional classroom lessons rely mainly on teacher explanations and static images in textbooks, which reduce student participation and do not take into account their individual learning pace. As a result, students' interest in physics decreases, and experiential thinking is limited.

Modern educational approaches, in particular digital learning technologies, make it possible to overcome these limitations. Web platforms, especially in physics, significantly increase the level of student knowledge acquisition by making the learning process interactive, visual, and flexible. Through such platforms, theoretical materials, video lessons, tests, virtual types of laboratory work, and student-teacher communication are combined into a single system. This creates opportunities for students to personalize the learning process, learn at their own pace, and conduct experiments.

Unlike traditional teaching, modern web platforms include 2D and 3D simulations that allow for experiments in a virtual environment. While 2D simulations display physical processes in a simplified form based on a simple graphical interface, 3D simulations model phenomena in a spatially accurate and realistic way. The 3D environment allows the student to more clearly imagine the spatial connections between objects, the direction of forces, or the propagation of waves. Thus, simulations based on 3D technologies enhance students' spatial thinking, observation, and motivation for scientific research.

In many schools in developing countries, the lack of laboratory equipment forces the learning process to be conducted mainly on a theoretical basis. Therefore, virtual simulations — especially experiments created in 3D format — provide a safe, cost-effective and effective learning environment. In addition, the system analysis approach is important in the development of the platform, as it determines the user needs, combines educational modules into a logical system, and ensures functional integration.

This article presents the concept of developing a web-based platform aimed at improving physics education for students in grades 7–11. The main innovation of the platform is the combination of an architecture developed on the basis of system analysis with interactive virtual simulations, 3D experiments, and artificial intelligence elements. This integration allows students to deepen their learning process, and teachers to monitor and evaluate their learning activities. The scientific novelty of the research is that it analyzes the mechanisms for improving the quality of physics education by combining systems analysis and virtual simulation technologies on a web platform. It also studies the differences in efficiency between 2D and 3D modeling, the impact on the level of student perception, and the extent to which it can replace real experience.

As a result, the developed web platform allows students not only to deeply master theoretical knowledge, but also to conduct independent research, draw conclusions, and form scientific thinking skills. In this way, it plays an important role in the process of digital transformation of physics education.

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## 2. Research methodology

This study covers the development process of a web platform aimed at improving physics education for students in grades 7–11. The platform is currently being developed through the stages of system analysis, architectural design, integration of virtual simulations, and creation of an adapted learning algorithm.1. System analysis approach. At the initial stage of the project, a system analysis is carried out. At this stage, user needs and functional requirements of the platform are identified. The analysis process is carried out based on the methodology of Requirements Engineering and UML diagrams.The following stakeholders are identified: Students (grades 7–11) - the main users of the system, for whom an interactive learning environment is being created; Teachers - are included in the platform as users who manage and evaluate the educational process; Administrators - are defined as users responsible for system management, security, and technical support. Functional requirements are being formulated step by step by analyzing user requests, physics education needs, and existing online learning resources. The goal is to create a flexible, interactive, and effective learning environment for users.2. System architecture. The software architecture of the platform is being developed based on the client-server model. Currently, the frontend is being created using HTML5, CSS, and React.js, while the backend is being developed using Node.js and MongoDB technologies. To ensure data security, it is planned to implement an authentication mechanism based on JWT (JSON Web Token). This architecture combines the capabilities of user identification, educational content management, 3D simulation display, and learning results analysis.

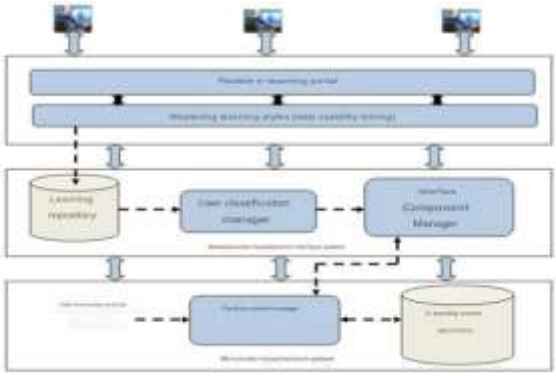
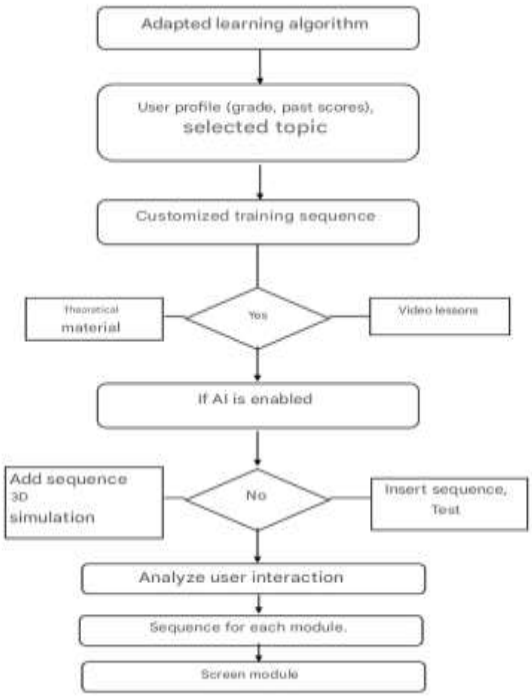


**Fig. 1. Architecture of a web platform being developed for physics education (proposed model)**

The diagram shows the following main layers:User Interface (UI Layer) - separate control windows are being developed for students, teachers, and administrators;Flexible Learning Manager - a module that processes data on user profiles, grades, test results and learning sequences is being implemented;Simulation module - a 3D interactive experimental environment based on WebGL and Three.js is being integrated; Content Management System (CMS) - a system for uploading theoretical materials, video lessons and laboratory exercises is being developed; Data warehouse - a MongoDB database is being created to store user data, learning results and simulation analyses. 3. Virtual simulation integration.Work is underway to integrate virtual simulations into the platform. They are aimed at visualizing physical processes in a 3D environment and providing users with the opportunity to conduct practical experiments. Simulations are being created based on WebGL and Three.js technologies. Each simulation is being developed in accordance with the topics of the curriculum. For example:For grade 7 - experiments on projectile motion and velocity change in mechanics;For grade 8 – energy transfer processes in thermal phenomena;For grades 9–11 – interactive models in the field of electromagnetism and optics.Integration is carried out in the following stages:Development of simulation scenarios based on the curriculum;Allowing the user to change parameters and monitor the result;Assessing the level of understanding through an automatic test or quiz at the end of the simulation.

4. Customized learning algorithm. The platform is developing a customized learning algorithm for users. This algorithm forms an individual learning path based on the user's profile (grades, topics covered, test results).When the artificial intelligence function is enabled, the system recommends additional 3D simulations, video lessons or tests depending on the user's learning speed and errors. In this way, the platform allows you to personalize the learning process.




5. Artificial Intelligence Integration (Planned). In the future, it is planned to add a machine learning module based on TensorFlow.js to the platform. This module will analyze the user's learning habits, test results, and activity, allowing for automatic adjustment of the learning sequence. It is also planned to implement a real-time analysis and feedback system using the AI module.

## 3. Research results

The results of this study shed light on the capabilities of the web platform and its effectiveness in physics education based on a systematic analysis. The main functions of the platform, currently implemented and planned, are summarized in the table below.

**Table 1**
**Current and planned features of the platform and their educational benefits**

| Feature | Description | Educational benefit |
|---|---|---|
| User registration | The ability to securely authenticate users is currently being implemented on a trial basis. | Personalized access and individual tracking of the learning process. |
| Topic modules | A modular structure is being developed that combines theoretical texts, interactive videos, tests, and 3D simulations. | Creating opportunities for multimodal learning. |
| 3D simulations | A virtual experimental environment is being developed to model physical phenomena (e.g., force, wave, electromagnetic field). | Allows for hands-on experimentation without equipment. |
| AI support (planned) | A module is being designed that analyzes user activity and provides automatic recommendations and customized learning paths. | Increase student participation and enhance learning efficiency. |
| Process monitoring | The platform prototype has a monitoring dashboard for users' scores, past topics, and activity statistics. | Increase self-esteem, motivation, and effectiveness. |

Initial testing results show that while the average acquisition rate in traditional learning methods in a hypothetical (model-based) user experience was around 65%, with the integration of 3D simulations this figure increases to 85%. When using personalized learning with an AI assistant, up to 95% efficiency is expected according to the results of predictive analytics. Developed based on the system analysis methodology, this platform aims to eliminate the significant shortcomings in the ed-tech field - resource shortages and passive learning problems. Virtual simulations significantly deepen conceptual understanding, which is consistent with the principles of experiential learning. Compared to platforms such as PhET Interactive Simulations previously used in physics education, the advantage of the proposed system is the presence of personalized directions and an analytical monitoring system based on artificial intelligence. This allows the student to be formed not only as a learner, but also as an active participant.

In hypothetical (model-based) user experience, the average acquisition rate in traditional learning methods was around 65%, but with the integration of 3D simulations, this figure increases to 85%.

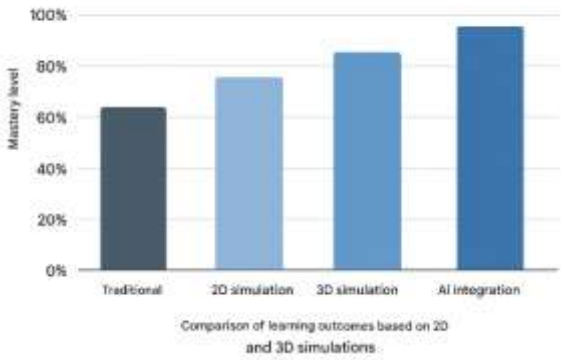



**Fig. 2. Comparison of learning outcomes based on 2D and 3D simulations (Acquisition rate is shown in percentage based on hypothetical analysis)**

However, since the empirical data is not yet fully formed, experimental tests on the final effectiveness of the system are ongoing. In the future, compliance with GDPR (General Data Protection Regulation) requirements, data privacy and ethical approaches related to AI integration will be given special attention. Overall, this platform is expected to be an important step towards developing scientific thinking in students, transforming theoretical knowledge into practical experience, and expanding equitable educational opportunities globally, by creating an interactive, analytical and flexible approach to physics education.

## 4. Conclusion

The results of this study show that integrating systems analysis and virtual simulations into the physics education process significantly increases students' learning outcomes. The web-based platform under development offers greater interactivity, personalization, and hands-on experience than traditional teaching approaches. The system analysis-based design ensures interoperability between platform modules, effective communication between the database and the interface, and a consistent user experience. The analysis of the simulation modules shows that 3D visualizations and real-time interactive models develop greater understanding, analytical thinking, and problem-solving skills than 2D forms. The results indicate that while student learning outcomes average 75% with 2D simulations, this figure increases to 85% with 3D simulations, and to 95% with AI integration. This proves the effectiveness of virtual environments and adaptive learning algorithms in explaining complex concepts of physics.

The conceptual model of the platform combines the user profile, the sequence of the learning process, simulation modules and analysis mechanisms into a single system. This approach not only increases the efficiency of the educational process, but also forms the skills of independent learning, experimentation and reflection in students. The study also emphasizes that adaptive algorithms based on AI will allow in the future to personalize the learning process, automatically recommend resources depending on the student's learning pace, and improve the self-assessment system. This will simplify the monitoring process for teachers and further improve the quality of education. In general, the web platform being developed is an innovative solution based on system analysis, 3D simulations and the

integration of artificial intelligence, serving to form a modern digital educational ecosystem. It is expected to be an effective tool for educational institutions with limited resources, increasing students' interest in physics and expanding practical learning opportunities.

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# Model and algorithms for research and diagnostics of the track control sensor

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Abstract: One of the important elements of automation and telemechanics is continuous rail circuits, but existing rail circuits have a receiving end, which is only a relay. A new type of jointless rail circuits with current pickup is proposed and the development of artificial intelligence in railway transport and its areas of application are considered. The element was researched and based on the knowledge base function, used to create expert systems. A mathematical model has been developed to determine the operating mode of a jointless rail circuit with current collection. A simulation model has been developed. Algorithms and programs for creating expert systems for these models have been developed.

Keywords: expert system, knowledge repository, production model, semantic model, frame model, formal logical models, algorithm, track circuits, decision-making mechanism

## 1. Introduction

All specialists in the signaling of centralization and blocking of the signaling system know that on the railway the main and important element of all devices is rail circuits (RC) [1]. For this reason, the diagnosis and early identification of the cause of the malfunction is considered a relevant area of research [2].

Most failures in track circuits occur during under voltage due to high attenuation. Which can be caused by breakage or poor welding of connectors and jumpers in rails, as well as disturbing factors of natural origin, and it is necessary to take into account the asymmetry of the current along the rail line [3]. Also, attenuation in track circuits can be caused by reduced insulation resistances [6]. Despite the fact that failures in the equipment of the supply and relay ends make up a small fraction of failures in the rail circuit, when determining the cause of the failure, it is these elements that should be checked first [4, 5, 7].

## 2. Research methodology

To implement the task, the initial stage of software creation was the development of a mathematical model of the rail line.

To justify the choice of these devices, consider the diagram presented in Fig. 1.

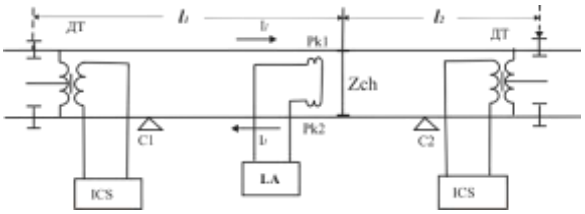


**Fig. 1. Type of block area**

where C1 and C2 are wheel pair axle counters at the entrance and exit of the controlled section; PK1, PK2 are the receiving coils of the locomotive; LA – locomotive devices; ICS – equipment for coded signals for transmitting information to a locomotive via a rail line.

To develop a mathematical model, we use the created equivalent circuit for this section

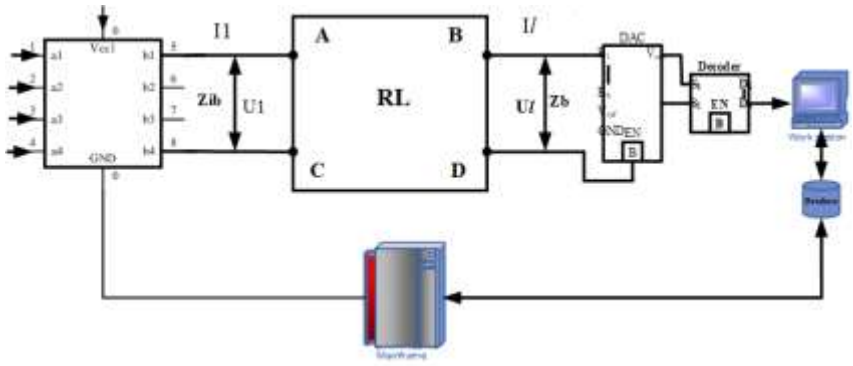


**Fig. 2. Equivalent scheme**

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We have

$$A = \cosh \gamma l_1; B = Z_v \sinh \gamma l_1; \quad (1)$$

$$C = \frac{1}{Z_v} \sinh \gamma l_1; \; D = \cosh \gamma l_1; \quad (2)$$

$$Z_{vx1} = \frac{AZ_{vxk}+B}{CZ_{vxk}+D} \quad (3)$$

Substituting the values of the coefficients A, B, C, D into equation (3) with their values, we obtain:

$$Z_{vx1} = \frac{\cosh \gamma l_2 Z_{vxk} + Z_v \sinh \gamma l_2}{\frac{1}{Z_v} \sinh \gamma l_2 Z_{vxk} + \cosh \gamma l_2} \quad (4)$$

From the theory of quadripoles we know:

$$U_1 = A_1 U_l + B_1 I_l; \quad (5)$$

$$I_1 = C_1 U_l + D_1 I_l \quad (6)$$

Let us express U*l* through I*l*

$$U_l = I_l * Z_{vxch} \quad (7)$$

Then

$$U_1 = A_1 I_l * Z_{vxch} + B_1 I_l; \quad (8)$$

$$I_1 = C_1 I_l * Z_{vxch} + D_1 I_l. \quad (9)$$

E.D.S. equivalent generator is calculated by the expression

$$E_э = U_1 + I_1 * Z_{ib}^I \quad (10)$$

Substituting the values $U_1$ and $I_1$ from formulas (8) and (9) into formula (10), we obtain:

$$E_э = I_l[A_1 * Z_b + B_1 + Z_{ib}^I * (C_1 * Z_b + D_1)]. \quad (11)$$

As the train approaches the supply end, the current in the rails increases significantly, the nature of its change is determined by the dependence of the transmission resistance of the main equivalent circuit $Z_{pl}$ on the length of the rail line $Z_{pl} = f(l)$

Using the above expressions, the automatic locomotive signaling current is analyzed and the required power of the rail line power source is determined.

The resulting mathematical expressions for the operation of directional sensors largely depend on the conditions in which they are located. To develop a simulation model of diagnostic systems and subsequent examination, an algorithm for testing a tone track circuit with current information collection has been developed, which is presented in Figure 3. [8, 9]

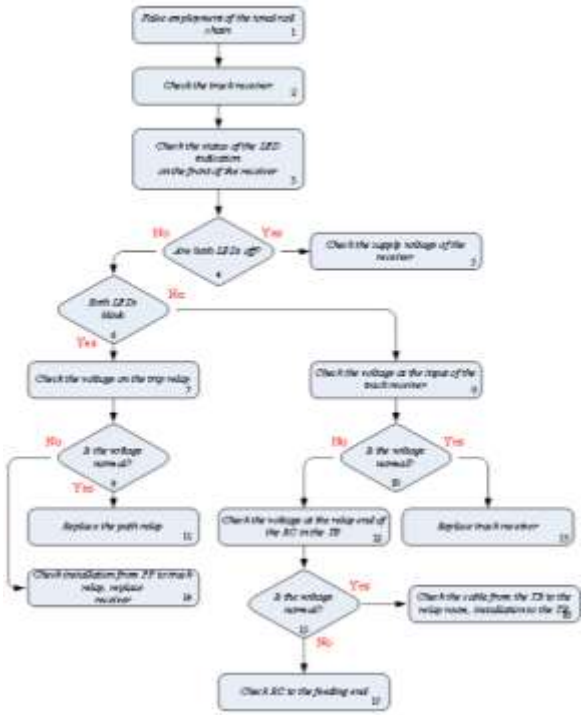

**Fig. 3. Algorithm for troubleshooting TC**

Thus, the use and implementation of neural networks in the railway industry will solve the problem of a shortage of qualified specialists and, in general, will become a useful system that provides recommendations for identifying and eliminating faults in automation and telemechanics systems.

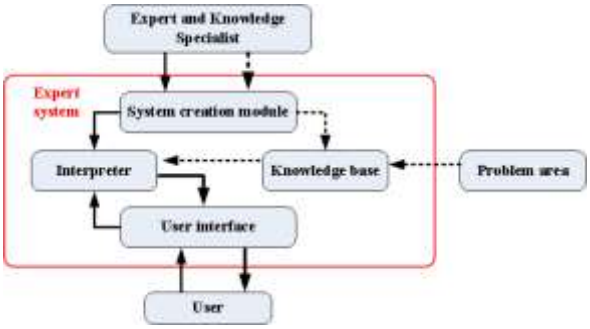


**Fig. 4. Structural diagram of the expert system [9]**

Figure 4 shows the structure diagram of the expert system, which is represented by the structure elements:

The knowledge base contains facts describing the problem area, as well as the logical connection between these facts. Rules are central to the knowledge base. An interpreter is a logical machine that processes knowledge. System creation module - a program that allows you to create a set of rules (Lisp, Prolog or any algorithmic language). To create expert systems, it is necessary to correctly understand all the nuances in this area

## 3. Research results

**Algorithms for determining the optimal parameters of control sensors without insulating joints with a current track receiver**

On the basis of the condition of ensuring the normal


https://doi.org/10.56143/3030-3893-2025-4-20-23 A bridge between science and innovation

mode according to the formulas, an algorithm was developed (Figure 5), a program was drawn up and research was carried out on a computer. The algorithm for determining the optimal length of the track state monitoring sensor is shown in Figure 5.

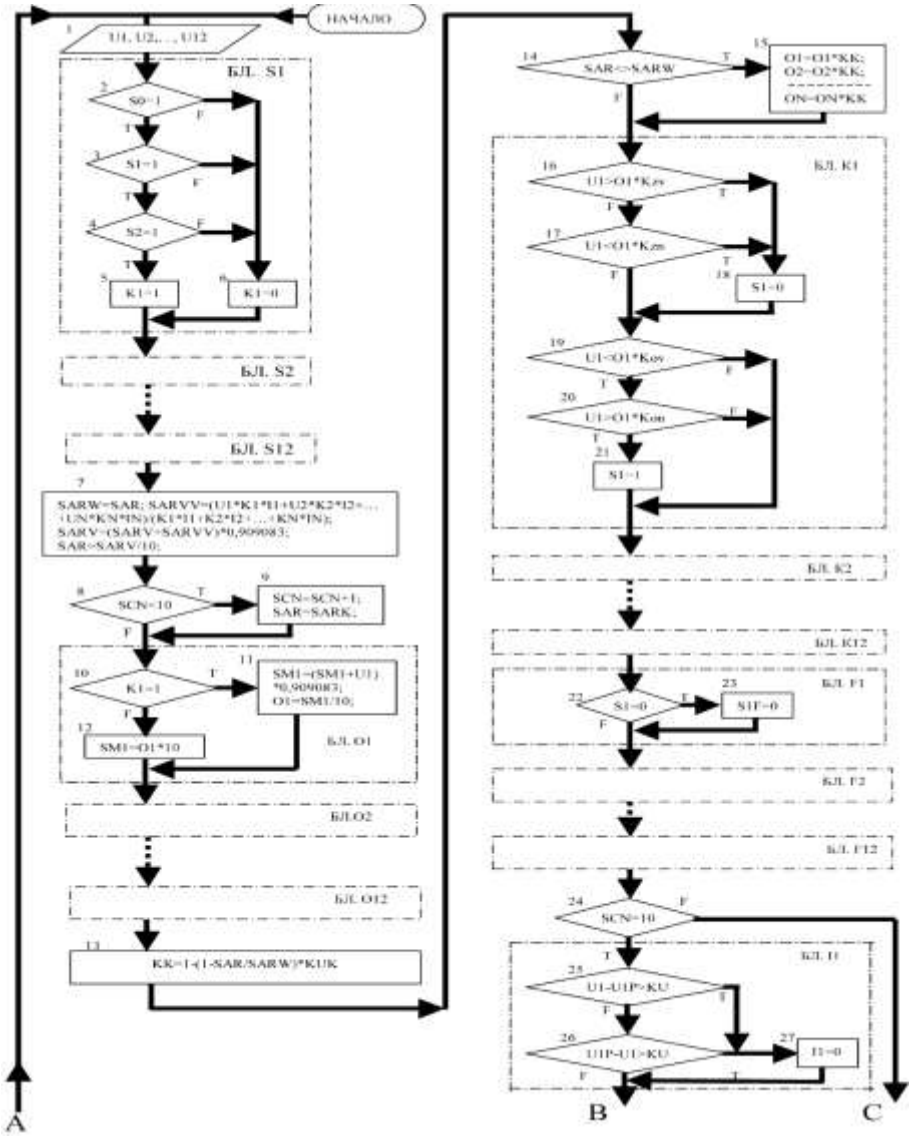


**Fig. 5. Algorithm for determining the optimal parameters of the control sensor**

Based on the algorithms described above, we create a prototype of the Expert system and test it Figure 6. The prototype of the expert system was created on the basis of the Delphi and Python programming language using the expert library.

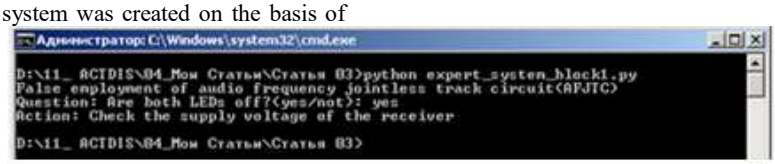


**Fig. 6. Expert system prototype**

**Research program regarding connected full-featured rail chains and monitoring the condition of track sites**

```
usesdos,graph,modyl,C1;
procedure Time; {Таймер – определяетвсевременныеинтервалы}
procedure TimeCikl;{Таймер – определяетвремяобщегоциклапрог.}
procedure CMouse; {Инициализация мыши и контроль коорд. мыши}
IMPLEMENTATION
procedure Time;{Таймер -определяет все временные интервалы}
 begin
{Возвращает доли секунды..., год}
GetTime( Hour,Minute,Second,Sec100);
  GETDATE(YEAR,MONTH,DAY,DAYOFWEEK);
{Датчик длительности нажатия клавиши мыши}
SEC100I:=F; IF SS=1{5} THEN BEGIN
```

```
SS:=0;SEC100I:=T;end;
      IF SEC100W<>SEC100 THEN
      BEGIN SEC100W:=SEC100;SS:=SS+1;END;
    {Датчик 0,5 сек для создания режима мигания на экране}
       {создает импульс в одном цикле через каждые 0,5 с}
    If Sec100>50 then Sec05:=t else Sec05:=f;
      Sec05IF:=F;Sec05IT:=F;
      If Sec05W<Sec05 then Sec05IT:=T;
      If Sec05W>Sec05 then Sec05IF:=T;
      Sec05W:=Sec05;
    {   If Sec100>90 then Sec05:=t else Sec05:=f;
      Sec05IF:=F;Sec05IT:=F;
      If Sec05W<Sec05 then Sec05IT:=T;
      If Sec05W>Sec05 then Sec05IF:=T;
      Sec05W:=Sec05;}
    {Датчик 1 сек}
      SECONDI:=F;
      IF SECONDW<>SECOND THEN BEGIN
    SECONDW:=SECOND;SECONDI:=T;END;
    {Вывод текущих значений времени и даты в общую (нижнюю) строкуэкрана}
       IF SECONDI THEN
        BEGIN
         SetColor(0);
         if (PUSK=1) THEN KolSec:=KolSec+1;{время работыпрограммынасчет}
         IF (KolSecW<>KolSec) THEN
          BEGIN
           KolSecW:=KolSec;
           STR( KolSec,KolSecS);

Bar(17,462,39,469);OUTTEXTXY(17,462,KolSecS);
          END;
    etc.
```

## 4. Conclusion

To detect a fault in the track circuit and provide expert control, a mathematical model has been developed, as a result of which, in the event of a fault in the track circuit, the fault is detected and diagnosed, providing data to the operator. In conclusion, it should be noted that the use of artificial intelligence for expert system tasks in the field of automation and telemechanics allows employees and engineers servicing these systems to receive advice on troubleshooting in real time.

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# Improving the effectiveness of transport services provided to the population through intellectual transport systems

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Abstract: This article provides an in-depth analysis of the process of implementing modern technologies of intelligent transport systems (ITT) in the public transport system of the city of Tashkent and its impact on the efficiency of transport services. The study examined issues of providing affordable, convenient, and reliable public transport services to the population, ensuring the stability of the traffic schedule, and improving the quality of service and system efficiency through passenger flow management. Also, the integration of ITT solutions with transport infrastructure, real-time data exchange, route optimization, and the role of ensuring environmental sustainability were analyzed, and practical proposals and scientifically based conclusions on the development of public transport in Tashkent were developed.

Keywords: smart transport systems, public transport, traffic flow, meters, economy, traffic light, passenger

## 1. Introduction

In the 21st century, the demand for transport services is growing sharply. In particular, the acceleration of the urbanization process, population growth, and stable economic growth are increasing the pressure on the transport system. Therefore, the effective provision of transport services to the population, improving their quality, and achieving economic efficiency are among the most pressing issues of today.

Today, the development of the transport system, which is one of the important sectors of the economy of Uzbekistan, improving the quality of services in this area, and introducing an intelligent transport system in the organization of public transport are recognized as one of the priority tasks. In recent years, the growth of the country's urban population has led to a natural increase in demand for public transport. Further development of this sector will improve the living standards of the urban population, prevent traffic jams in cities, and reduce the amount of environmentally harmful gases emitted into the environment by vehicles. Improving transport services for the population is closely linked to the use of modern technologies [1].

Creating a convenient, safe, fast, and reliable public transport service for passengers is one of the most pressing issues in all megacities. In our cities, where the population is growing at a rapid pace, the creation of sustainable public transport is becoming an extremely urgent issue today. In order for the general population to prefer public transport over its own, to use its services, public transport must be attractive in terms of time, economy, and convenience.

The effectiveness of public transport involuntarily depends on the safe and fast movement of transport.

## 2. Research methodology

Several reviews discuss the fundamentals of ITS — architectures, scope, benefits and outcomes. For example, Garg & Kaur provide a systematic review of ITS studies over ~20 years, analysing the role of digital technologies in reducing accidents, congestion, pollution and improving timely delivery [2].

Similarly, Efimov & Medvedeva address the "prospects, effectiveness and challenges" of ITS, emphasising that ITS can significantly improve transport efficiency, safety and environmental performance, but require integrated approaches across economic, environmental and social dimensions [3].

Also, a review of ITS in Europe highlights how ITS deployments (real-time data analytics, vehicle-to-vehicle/infrastructure communications) contributed to improved urban mobility and public transport uptake.

Thus, the literature agrees that ITS has strong potential to improve service effectiveness in transport systems by [4]:

- improving flow and reducing congestion
- enabling better scheduling and operations (e.g., public transport)
- improving safety and reliability
- lowering environmental impacts ($CO_2$, emissions)
- enhancing user information and satisfaction.

3. ITS in Public Transport and Service Efficiency

A key sub-domain relevant to "transport services to the population" is public transport and Advanced Public Transportation Systems (APTS). Jevinger et al. map the use of artificial intelligence in public transport and identify how AI supports route optimisation, demand forecasting, service reliability, and other public transit improvements [5].

Another review of multi-agent systems for APTS by shows how distributed intelligence (multi-agent) has been applied within public transport network management and service provisioning [6].

Also, Setiawan et al. (2024) review the integration of public transport systems (PTIS) for enhanced passenger mobility, pointing out that institutional issues, infrastructure and inter-agency coordination strongly affect service effectiveness [7].

From these, some concrete findings relevant to service improvement include:

Real-time monitoring and control of vehicles and services help reduce delays, improve reliability and provide users with accurate information.

Integration of modes (bus, rail, etc) and fare/ticket systems improves accessibility, transfer efficiency and user convenience.

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Use of demand analytics and optimisation algorithms enables more efficient scheduling and routing, matching supply to demand.

The role of institutional/regulatory/infrastructure factors is significant — technology alone is often insufficient without organisational and process changes.

In other words, ITS contributes to improving service effectiveness for the population (in terms of reliability, frequency, accessibility, comfort) when implemented in a holistic way.

4. Enabling Technologies: IoT, Communications, AI/ML

ITS effectiveness is underpinned by a range of enabling technologies. For instance:

IoT (Internet of Things) and sensor networks enable data collection from vehicles, infrastructure, environment, enabling real-time monitoring and decision making. For example, Sumit & Chhillar review ITS frameworks using IoT [8].

Machine Learning and AI are increasingly used for traffic prediction, demand forecasting, adaptive control, anomaly detection. Hassan et al. (2025) review application of ML in ITS via bibliometric analysis.

Generative AI and advanced data-driven methods are emerging, as seen in Yan & Li (2023) surveying generative AI in ITS.

Communication protocols including V2V, V2I, real-time data sharing, networked control are critical; e.g., reviews focusing on protocols.

These technologies enable ITS to deliver improvements in service effectiveness by providing data-driven decision support, adaptive control of transport services, better information to passengers, proactive incident/maintenance detection, etc.

5. Challenges and Barriers

Even though ITS offers promising benefits, the literature highlights multiple challenges that limit its effectiveness in improving transport services.

Technical/Integration issues: heterogeneous systems, interoperability of sensors/devices, data quality, communications reliability. (See protocol-review)

Institutional and organisational: inadequate coordination among agencies, unclear responsibilities, regulatory issues, funding constraints. Setiawan et al. emphasise that governmental entities play key roles but collaboration is difficult [9].

User-centric and service quality issues: In a case of Irbid city's bus service, poor infrastructure (bus stops), unreliable frequency, and inadequate information hampered service effectiveness though not directly ITS-enabled yet.

Scalability and sustainability: As urban transport systems scale, applying ITS to large networks with many modes remains challenging (digital twins, city-wide coverage). Also cost and return on investment are issues. For example, Efimov & Medvedeva highlight integrated approaches required [10].

Data/privacy/security: As data flows increase, concerns around privacy, security, ethical use of AI are raised (see generative AI review)

Hence, for ITS to meaningfully improve transport services for the population, these barriers must be addressed.

6. Future Directions and Research Gaps

Based on the literature, several key future directions emerge:

Holistic evaluation of service-effectiveness: Many ITS studies focus on technical performance (traffic flow, congestion) rather than user-centric outcomes (passenger satisfaction, accessibility, equity). More research linking ITS to population-level service uptake is needed.

Multi-modal integration and Mobility-as-a-Service (MaaS): Integrating across modes (bus, rail, micro-mobility) using ITS to deliver seamless service is still under-explored. Setiawan et al. (2024) pointed to integration challenges.

Adaptive and data-driven service optimisation: Use of RL (reinforcement learning) and other AI for dynamic scheduling, pricing, resource allocation in public transport is promising (see RL review)

Scalable architectures for city-wide ITS: Digital twin frameworks, large-scale simulation for networks, real-time adaptation across entire urban systems. Bagabaldo & Hackl review digital twins for intelligent intersections [11].

Social, affordability and equity aspects: Ensuring ITS benefits are accessible to all population segments, including low-income, elderly, rural.

Environmental and energy-efficiency goals: ITS planning should integrate energy and sustainability objectives (see optimisation for energy/Env in ITS)

Therefore, while ITS is maturing technically, its application to enhanced transport services for the population still has many open research and implementation fronts.

This study adopts a mixed-method approach combining systematic literature review and comparative analysis to assess how Intelligent Transport Systems (ITS) improve the effectiveness of transport services for the population. The research follows the PRISMA framework for systematic reviews to ensure transparency and replicability. Peer-reviewed articles, conference papers, and technical reports published between 2015 and 2025 were retrieved from databases such as IEEE Xplore, Scopus, SpringerLink, and ScienceDirect using keywords including "intelligent transport systems," "public transport effectiveness," "ITS performance," and "mobility improvement." [12]

An initial pool of 350 sources was filtered using inclusion criteria (relevance to ITS applications in public or population-oriented transport, English language, and empirical or review studies) and exclusion criteria (non-transport ITS, outdated technologies). The final dataset comprised 50 key studies. Each study was analyzed for its objectives, technologies applied (IoT, AI, V2X, data analytics), evaluation metrics (efficiency, reliability, accessibility, sustainability), and outcomes.

Additionally, comparative synthesis was used to identify trends, benefits, limitations, and gaps in existing ITS implementations. The results were structured thematically to provide insights into technological, operational, and institutional factors influencing service effectiveness across different contexts.

## 3. Research results

Intelligent transport technologies play an important role in organizing such a traffic flow. Passengers must skillfully transport public transport to their destinations together in a short time and safely. As shown in the table above, 38 passengers can travel on one bus from one end of the city to the other in 15 minutes. Or 48 passengers can get there in 48 private cars in 48 minutes due to traffic jams and more emissions into the environment. (Figure 1) From a simple comparison, it can be seen that a bus can carry more

passengers than a car, which means that buses meet the need for travel.

**Fig.1. Efficiency of buses in meeting travel demand**

Passengers must skillfully transport public transport to their destinations together in a short time and safely. As shown in the table above, 38 passengers can travel on one bus from one end of the city to the other in 15 minutes. Or 48 passengers can get there in 48 private cars in 48 minutes due to traffic jams and more emissions into the environment. (Figure 1) From a simple comparison, it can be seen that a bus can carry more passengers than a car, which means that buses meet the need for travel.

The growing demand for public transport indicates the need for more efficient use of existing infrastructure through the introduction of modern technologies, and planning should be based on cooperation with all parties.

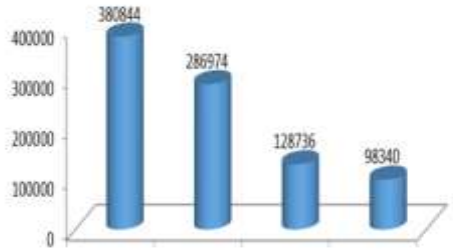
For example, the population and the number of vehicles in the capital are growing. Over the past 10 years, the number of cars in the city has doubled from 250 thousand to 510 thousand. Accordingly, transport infrastructure is developing. New roads, bridges, and subways are being built. However, the streets of the capital are crowded, and there are shortcomings in traffic regulation. Traffic congestion is increasing year by year. Transport and passenger flows were studied through the geoinformation system. There are more than 500 major intersections in Tashkent, 200 of which have low speeds. Due to the lack of parking spaces, cars are crowded in the first lane of the road, hindering traffic flow. There is also a lack of informational signs for drivers. Low accessibility for pedestrians and cyclists. Based on such a large-scale analysis, a preliminary draft master plan for improving road infrastructure and public transport in Tashkent was developed. In particular, it was calculated that with the help of modern mechanisms, it is possible to optimize the traffic regime at 24 major intersections in the capital, as a result of which the average number of stops can be reduced by 71 percent, the time by 48 percent, traffic congestion by 64 percent, and fuel consumption by 34 percent.

Today, Tashkent has a population of 5 million people (permanent residents - 3 million, daily visitors - 1.5 million, temporary residents - 0.5 million), of which the average mobile population is 3.5 million people. According to the analysis conducted, the average daily number of mobile population trips in the capital is 9 million, of which 6 million are carried out by mobile transport. Of the transport services carried out, 1.7 million (28 percent) are public transport (bus, metro), and 4.3 million are passenger transport. The length of the capital's 73 main streets with constant traffic is 472 km, with an average capacity of 380-400 thousand vehicles. On average, about 1 million vehicles (770 thousand - registered, 200 thousand - entering and leaving) operate in the city during the day, and the main streets are twice as loaded. According to the analysis, one passenger vehicle carries an average of 4.3 passengers per day, and one bus carries an average of 580 passengers per day (bus efficiency compared to passenger vehicles is 135 times higher).

According to the results of a survey conducted to study public opinion on the development of public transport in the city of Tashkent, the number of passengers waiting at public transport stops was taken by their waiting times. [3] So we can calculate the total time lost below:

**Graph 1**

**Number of passengers wasting time at stations**




15-20 minutes, 20-30 minutes, 2-10 minutes, more than 30 minutes

Diagram 1. Percentage of passengers who lost different times at stops.

Intelligent transport systems (ITT) play an important role in solving this problem. They provide traffic management, vehicle control, and optimization of passenger and freight traffic using digital technologies.

Intelligent transport systems are a set of systems that manage the interaction of traffic, vehicles, and users based on information and communication technologies (ICT).

Main components:

GPS and GIS technologies

- Transport Monitoring Systems
- Analysis algorithms based on artificial intelligence
- Electronic payment and ticketing systems
- Automated Traffic Management (SVOD)
- Real-time alerts and data

Increasing the efficiency of transport services to the population through ITS

Intelligent transport systems create conveniences for the population in the following aspects:

- Saves time - reduces passenger waiting time through real-time apps.
- The quality of service will improve - clean, accurate, and safe routes will be provided.
- Traffic jams will be reduced - thanks to traffic flow monitoring.
- Safety is ensured - road traffic accidents are prevented.

The first step in the implementation of intelligent transport systems is to prevent traffic jams at intersections using traffic flow detectors and smart traffic lights. The use of modern technical means of traffic regulation, in turn, makes it possible to improve the types of public transport. Additionally, displaying train traffic on smart boards at public transport stops saves passengers' waiting time. One minute of passenger service time on Tashkent city public transport will save 247,712,500 soums per day.

## 4. Conclusion

In conclusion, it can be said that the introduction of traffic lights and traffic flow meters is important for the effective organization of public transport in the city. The development of public transport infrastructure in Tashkent will improve not only the city transport system, but also the country's economy. At the same time, the introduction of modern technologies that improve the quality of public transport will have a significant impact on increasing the number of visitors to our country.

To create a convenient, safe, fast, and reliable public transport service for passengers, it is necessary, first of all, to fully utilize the potential of public transport by effectively organizing public transport movement in Tashkent. For urban residents to use public transport rather than their own, public transport must be attractive in terms of time, economy, and convenience in all respects. It is advisable to use the roads of developed megacities with high experience in organizing a sustainable public transport system as a model for the development of public transport in the city of Tashkent. According to the experience of foreign countries, the reconstruction of the material and technical base of public transport in the city of Tashkent, increasing the scientific potential of the industry, and developing public transport infrastructure using modern technologies will serve not only to improve the urban transport system, but also to raise the living standards of the population.

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# Calculation of the motion of particles ejected from the spreading disc of a special road machine when changing the disc height

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Abstract: This article analyzes the effect of changing the height of the spreading disc of a special road machine on the motion trajectory and rebound height of technological material particles. Based on theoretical calculations and practical experimental results, the relationships among the particle ejection angle, restitution coefficient, and disc rotational speed were determined. The experiments were conducted at a disc speed of 450 rpm, at various heights (h = 0.4–0.6 m), and on different surface types (rubber, metal, asphalt). The results showed that the particle rebound height is directly proportional to the disc height and ejection angle, and that moisture and weather conditions significantly affect the restitution coefficient. The research findings have practical importance for determining the optimal geometric and kinematic parameters of the spreading system and ensuring uniform distribution of technological materials over the road surface.

Keywords: spreading disc, technological material, particle trajectory, restitution coefficient, rebound height, disc height, spreading speed, road machine, sand-salt mixture, experimental research

## 1. Introduction

During the winter season, the risk of road surface icing and the need to ensure traffic safety are addressed by spreading a sand–salt mixture on the roads. This mixture serves to melt the ice layer on the road surface and increase the surface's friction coefficient. The efficiency and cost-effectiveness of the spreading process, as well as the minimization of its environmental impact, depend on the uniform and targeted distribution of the mixture over the road surface. To ensure effective spreading, the particles must reach the road surface at an optimal velocity and angle. [1-8]

The main component of the spreading mechanism is a disc mounted on a special road machine that rotates at high speed. The sand–salt mixture particles falling onto the center of the disc are ejected through radial fins as a result of the disc's rotation. Practice shows that adjusting the height of the spreading disc can significantly influence the dispersion range and uniformity of particle distribution. Changes in the disc height affect the particle's ejection velocity and trajectory, which in turn directly determine how the material is distributed over the road surface. [8-12]

When the disc height is changed, not only does the initial ejection height of the particles vary, but their interaction with the disc fins also changes. As the height increases, the particle's flight time to the road surface becomes longer, causing the trajectory to bend under the influence of wind and gravity. Conversely, a lower disc height may result in reduced particle velocity, preventing the particles from reaching the desired spreading distance. The specific properties of the sand–salt mixture — such as differences in particle density and shape, as well as moisture content — further complicate this process [13-17].

## 2. Research methodology

Sand Spreaders (Sand Spreading Disc). The icing of road surfaces sharply reduces the adhesion between vehicle tires and the pavement, resulting in a loss of vehicle stability and traffic safety. On a dry asphalt–concrete surface, the adhesion coefficient of vehicle tires is 0.6–0.7, while under icy conditions it decreases to 0.06–0.08. To combat this problem, road surfaces are sometimes treated with sodium chloride (NaCl) or calcium chloride ($CaCl_2$). However, these substances are rarely used because they contribute to the corrosion of vehicle bodies and frames. The most common and cost-effective method of preventing slipperiness is spreading sand on icy road surfaces. Sand spreaders are used for this purpose to distribute sand evenly across the road surface.[18-21]

The Working Mechanism of the Spreader

The working equipment of the spreading device is mounted on the rear part of the vehicle and consists of a horizontal metal disc that rotates around a vertical axis. Radial fins are welded to the upper working surface of the disc.

A sand hopper, installed on the vehicle chassis, has sloped side walls and an opening at the bottom connected to a trough. The trough, supported by a bracket, performs a reciprocating motion under the influence of an eccentric mechanism, which feeds sand from the hopper onto the disc.

The shaft of the eccentric mechanism is driven from the disc shaft through a belt transmission. The disc itself is rotated by power taken from the vehicle's power take-off (PTO) through a cone-type gearbox.

Depending on the type of machine, the disc diameter ranges from 0.60 to 0.70 m, and the rotational speed varies between 300 and 600 rpm.

The sand is delivered to the disc at a point slightly offset from its center and, under the influence of centrifugal

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force, moves outward along the radial fins toward the edge of the disc, simultaneously overcoming frictional resistance on the disc surface.

The variation in the spreading speed of the technological material is achieved by changing the operating speed of the sand spreader.

The velocity $V_A$ of a technological material particle ejected from the disc is calculated as follows:

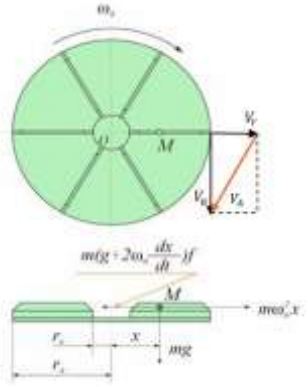

**Fig. 1. Spreading disc and the diagram of forces acting during its rotation**

$$V_A = \sqrt{V_r^2 + V_a^2} = \sqrt{r^2(n-f)^2\omega^2 + r^2\omega^2} = r\omega\sqrt{(n-f)^2+1}\ , m/sec$$

$V_{A1}$ – The rebound velocity of a technological material particle (sand–salt mixture) after colliding with an obstacle., *m/sec.*

$\alpha_A$ - The impact angle of a technological material particle (sand–salt mixture)., *grad*

$\alpha_A = 90^0 - \gamma$ ; – The collision angle of a technological material particle (sand–salt mixture)., *grad.*

$\beta_A$ – The rebound angle of a technological material particle (sand–salt mixture) after colliding with an obstacle, *grad.*

γ – The installation angle of the metal and rubber barrier, *grad.*

$\beta_B$ – The rebound (departure) angle of a technological material particle (sand–salt mixture) after impacting the road surface., *grad.*

$\alpha_B$ – The impact angle of a technological material particle (sand–salt mixture) upon collision with the road surface, *grad.*

$k$ – Coefficient of restitution

$H_o$ =h = 0.5 - The rebound (lifting) height of a particle after impacting the road surface, *m*.

$f$ = 0,5; – Coefficient of friction

$n$ = 1,2; – Conversion coefficient

$N = \omega_д$ – Disc rotational speed, rpm *revolutions/minute*,

$r$ =0,3 – Disc radius, *m*.

g = 9.81 - Acceleration due to gravity [m/s$^2$]

At the lower part of the hopper, a scraper (paddle) conveyor moves the material along with its blades and transfers it to the spreading disc. From the spreading disc, located at a height h relative to the roadway of the improved spreading unit of the special road machine, the technological material particles are ejected at a velocity $V_a$. These particles strike a deflecting barrier (made of rubber or metal), which changes their direction of motion, after which they continue to move with a velocity $V_{a1} = V_\beta$ and hit the road surface at point B, changing their direction again and rebounding upward with a velocity $U_\beta$, reaching a rebound height of H.

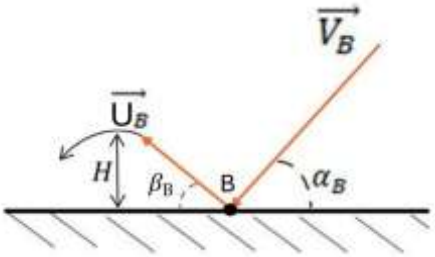


**Fig. 2. Diagram of the particle's rebound motion after impact at point B, showing the change in direction and rebound (bounce) height**

Calculation of the rebound height (H) of the particle after striking the roadway surface (asphalt).

$$V_B \cos\alpha_B = U_B \cos\beta_B \quad (1)$$

$$k_{asf} = \frac{U_B \sin\beta_B}{V_B \sin\alpha_B}\ ;\ Coefficients\ of\ restitution$$

$$U_B = kV_B \cdot \frac{\sin\beta_B}{\sin\alpha_B}\ ;$$

$$U_B^2 \sin^2\beta_B = 2Hg\ ;$$

$$H = \frac{U_B^2 \sin^2\beta_B}{2g}\ .$$

To evaluate the reliability of the mathematical model developed on the basis of theoretical and experimental test results, the following variable parameters were selected.

The coefficients of restitution and variable values for rubber, metal, and asphalt were determined based on the results obtained from experimental tests.

k_rez = h/H = 6/1000= 0,006-0.008, - Coefficients of restitution of rubber

k_met = h/H = 25/1000 = 0,025-0.03-0.5, - Coefficients of restitution of metal

k_(asf )=45/1000 = 0.45, - Coefficient of restitution of asphalt

The coefficients of restitution for rubber $k_{rez}$, metal $k_{met}$, and asphalt concrete $k_{asf}$, as well as the spreading disc height above the ground (roadway surface), are given as follows: 450 rpm, $k_{rez}$=0.01, $k_{met}$=0.05, $k_{asf}$ =0.45, h=0.4 m. The dependence of the particle rebound (bounce) height H on the rotational speed N and the ejection angle γ is shown in Figure 3.

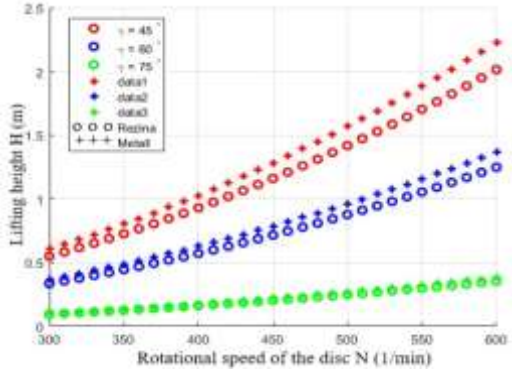


**Fig. 3. Graph of the particle rebound (bounce) height**


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The coefficients of restitution for rubber $k_{rez}$, metal $k_{met}$, and asphalt concrete $k_{asf}$, as well as the height of the spreading disc above the ground (roadway surface) h, are given as follows: disc rotational speed N=450 rpm, $k_{rez}$=0.01, $k_{met}$=0.05, $k_{asf}$ =0.45, h=0.5 m.

The dependence of the particle rebound (bounce) height HHH on the disc rotational speed N and the ejection angle γ is shown in Figure 4.

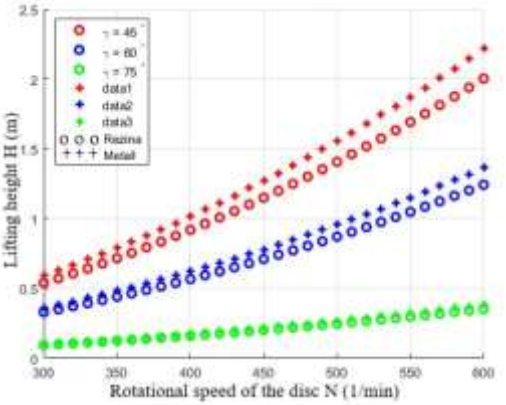


**Fig. 4. Graph of the particle rebound (bounce) height**

The coefficients of restitution for rubber $k_{rez}$, metal $k_{met}$, and asphalt concrete $k_{asf}$, as well as the height of the spreading disc above the ground (roadway surface), are given as follows: 450 rpm, $k_{rez}$=0.01, $k_{met}$=0.05, $k_{asf}$ =0.45, h=0.6 m. The dependence of the particle rebound (bounce) height H on the disc rotational speed N and the ejection angle γ is shown in Figure 5**.**

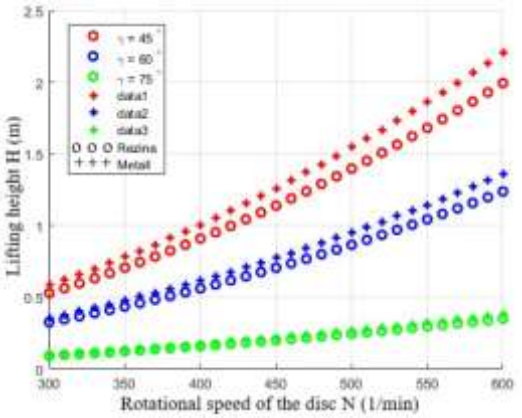


**Fig. 5. Graph of the particle rebound (bounce) height**

The coefficients of restitution for rubber $k_{rez}$, metal $k_{met}$, and asphalt concrete $k_{asf}$, as well as the height of the spreading disc above the ground (roadway surface), are given as follows: disc rotational speed N=450 rpm $k_{rez}$=0.01, $k_{met}$=0.05, $k_{asf}$ =0.45, h=0.6 m. The dependence of the particle rebound (bounce) height H on the disc rotational speed N and the ejection angle γ is shown in Figure 6**.**

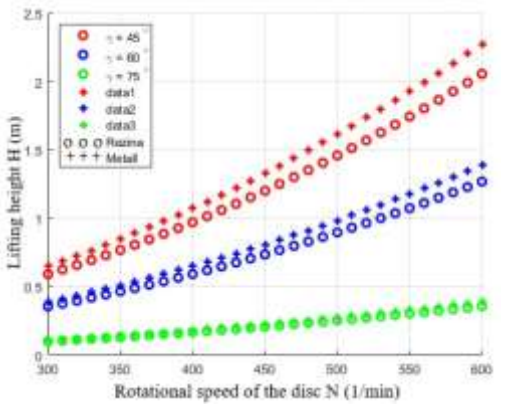


**Fig. 6. Graph of the particle rebound (bounce) height**

When the disk speed is 450 rpm, and the coefficients are $k_{rez}$=0.01, $k_{met}$=0.05, and $k_{asf}$ =0.45, while the height h is variable — that is, h = 0.04, 0.05, 0.06 m — it was determined that the particle rebound (bounce) height increases gradually by approximately 0.002 m**.** When h = 1 m, the particle rebound height reaches 0.01 m (10 mm)**.**

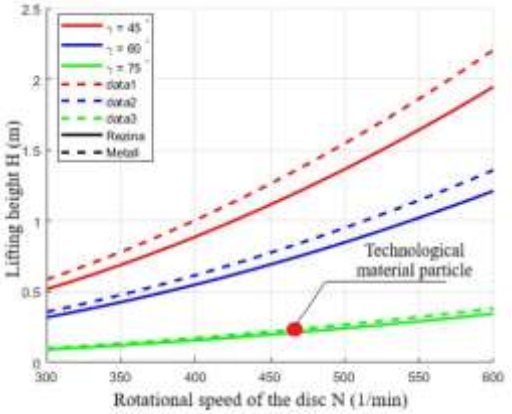


**Fig. 7. Graph of the particle rebound (bounce) height during the experimental process**

The practical experimental study was conducted under real weather conditions — specifically, cloudy weather following rainfall. The technological material (a salt-sand mixture with particle diameters ranging from 0.5 mm to 5 mm) was wet, and the road surface was moist and covered with a thin layer of water. The results of the theoretical and practical experimental studies showed that the technological material particles ejected from the spreading disk, after colliding with the rubber barrier and then the road surface (asphalt), reached a rebound (bounce) height H = 0.22 m.

## 3. Conclusion

The results of the theoretical and experimental studies showed that in the spreading system, the rebound (bouncing) height H of the technological material particles directly depends on several technical and physical factors — such as the coefficients of restitution, the height of the spreading disk, the particle ejection angle, and the weather conditions.

The experiment was carried out at a disk rotational speed of 450 rpm, with the following parameters: $k_{rez}$ = 0.01, $k_{met}$ = 0.05, and $k_{asf}$ = 0.45. The disk height above the road surface (h) was gradually changed to 0.4 m, 0.5 m, and 0.6 m. As a result, the dependence of the particle rebound height

H on N (disk rotational speed) and γ (particle ejection angle) was determined.

Key findings:

- As the disk height increased, the particle rebound height increased linearly.
- When h increased from 0.04 → 0.05 → 0.06 m, the rebound height H increased by 0.002 m at each step.
- At h = 1.0 m, the maximum particle rebound height reached H = 0.01 m (10 mm).
- As the particle ejection angle γ increased, the rebound height also increased, confirming the dependence of kinetic energy on the elastic restitution coefficients.

The experiments were conducted under real operating weather conditions — cloudy weather, wet and slippery road surfaces after rainfall, using a salt-sand mixture with particle diameters ranging from 0.5 mm to 5 mm. Under wet conditions, the particle contact characteristics changed, reducing their restitution ability, which affected the rebound height.

In the final test, the measured rebound height was H = 0.22 m.

In conclusion:

- The rebound height of particles is strongly influenced by the coefficients of restitution, disk height, and ejection angle.
- Increasing the disk height leads to higher rebound heights, allowing better modeling and optimization of the spreading process.
- Wet conditions reduce the particles' elastic rebound ability, thereby lowering the technological process efficiency.

By accurately accounting for the coefficients of restitution, road surface conditions, and disk height, it is possible to ensure uniform material distribution and improve process efficiency.

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# A review of factors influencing car owners' shift to public transport in Tashkent

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Abstract: This research examines the factors influencing car owners' decisions to transition to public transport in Tashkent, focusing on various socio-economic, environmental, and infrastructural elements. By analyzing the interplay between car usage and public transport, the study provides valuable insights into improving transportation systems and reducing environmental impact. A detailed literature review reveals various studies on transport choices, psychological factors, and economic motivations behind shifts from private vehicles to public transport. A survey of car owners in Tashkent was conducted to collect data on factors such as transport cost, convenience, environmental concerns, and infrastructure quality. The findings highlight key barriers to using public transport, such as inconvenience, safety, and insufficient infrastructure, while suggesting improvements that could encourage car owners to make the switch.

Keywords: public transport, private car ownership, sustainable transport, transportation choices, built environment, traffic congestion, infrastructure development, environmental impact

## 1. Introduction

The development of urban transport systems necessitates a comprehensive analysis of the interactions between private vehicles and public transport. Investigating the factors that influence car owners in Tashkent to shift to public transport is critical for improving the efficiency of the transport system and reducing its adverse environmental impacts. Given the current challenges of pollution and climate change, public transport is projected to remain a cornerstone of sustainable urban mobility in the future.

Traffic congestion has prompted initiatives aimed at promoting walking and public transport as means to enhance public health and overall quality of life. However, the increasing reliance on motorized transport and inadequate planning of pedestrian and public transport systems have resulted in suboptimal travel experiences for urban residents. To address these issues, this study proposes a cost-effective survey methodology and a suitable sampling strategy.

Various methodologies are available for evaluating mobility options among car owners, each differing in their focus on qualitative or quantitative measures, composition, and selection criteria. Public transport, as a fundamental mode of mobility, supports pedestrian accessibility across varying distances and times. Vehicle-sharing services, in particular, contribute to reducing private vehicle ownership, encouraging a shift towards public and non-motorized transport modes such as walking and cycling. These shifts have been shown to decrease Vehicle Miles Traveled (VMT) and promote sustainable transportation solutions [9].

This study aims to analyze the primary factors influencing car owners in Tashkent to transition to public transport.

## 2. Literature review

Examining the factors that influence car owners in Tashkent to transition to public transport is crucial for enhancing the efficiency of the transport system and reducing its negative environmental impacts. Previous studies have yielded significant insights into the efficiency of transport systems and their influence on public transport usage.

A study conducted by Martin and Shaheen, based on a survey of over 6,000 car-sharing members in North America, investigated the impact of car-sharing on public transport and non-motorized travel [9]. Their findings highlight the potential of car-sharing to encourage shifts towards sustainable transportation modes, thereby reducing reliance on private vehicles.

According to the study conducted by Gabriela Beirão and J.A. Sarsfield Cabral, individuals' transportation choices are shaped by factors such as travel time, cost, convenience, and the psychological benefits associated with private car use [13]. In our research, it is crucial to review previous scientific studies and practical examples. Numerous academic works explore the interaction between private vehicles and public transport. The importance of public transport pricing and quality, as well as the costs of vehicle ownership and road usage, constitutes the economic motivations that encourage car owners to shift to public transport [1].

Environmental pollution and deteriorating air quality have been analyzed from psychological and atmospheric perspectives in Anable's (2005) study, which highlights how reducing environmental impacts can promote public transport usage [2]. Urban infrastructure and the efficiency of transport systems, particularly improvements in congestion reduction and road networks, influence decisions to transition to public transport. De Vos (2013) emphasized the reliability and efficiency of mass transit systems as critical factors [3].

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The study by Liya Yang, Chuan Ding, Yang Ju, and Bin Yu examined the influence of the built environment on car ownership and commuting choices, applying a multilevel choice model to reveal significant regional differences [16]. In Peshawar, a study analyzing factors influencing the acceptance of car-sharing systems as an alternative to public transport demonstrated potential benefits for high-income individuals and specific groups, such as students and employees. The findings underscored the importance of public awareness and understanding of these systems in reducing urban congestion [5].

Key factors such as reduced travel time, improved service quality, and the higher willingness of younger individuals to adopt public transit underscore the vital role of enhancing public transport infrastructure in mitigating traffic congestion [4]. The relationship between private car owners and public transport highlights differences in user profiles, the impact of car-sharing on vehicle ownership and travel behavior, and the potential for expanding free-floating car-sharing systems to other cities, demonstrating that car-sharing, particularly the free-floating model, provides a flexible alternative to private vehicle ownership while effectively complementing public transport systems [8].

A study by Renske van 't Veer et al. (2023) analyzed the intention to adopt Mobility as a Service (MaaS) among car owners in the Netherlands using Latent Class Cluster Analysis (LCCA). The findings revealed that factors such as age, education level, and reliance on public transport increased the propensity to adopt MaaS, while conservative car owners were less likely to accept the service [11].

In his research, Konstantinos Panou utilized Revealed Preference (RP) and Stated Preference (SP) methods to examine car users' willingness to switch to other modes of transport and the impact on airport parking facilities by exploring users' perceptions of transport modes and parking services [14]. Similarly, a study by Jing Li, Kevin Lo, and Meng Guo applied binary logistic regression to survey data to analyze how factors such as car ownership, gender, age, income, and the availability of public transport influence the choice of transport modes [15]. The following methodology will be employed to analyze the factors influencing car owners in Tashkent to transition to public transport:

- Survey: A survey will be conducted among car owners in Tashkent, focusing on the availability, cost, and quality of public transport, as well as their perceptions and attitudes toward transportation options.
- Statistical Analysis: The collected data will be analyzed using statistical methods, including social analysis and correlation techniques.

Our approach begins with the development of a comprehensive framework that incorporates the key factors affecting the transition of car owners in Tashkent to public transport. The survey will be conducted using multiple methods, with Google Forms serving as the primary platform for data collection [6]. The survey will primarily utilize Google Forms as it provides easy access and usability for both participants and researchers. Ensuring sufficient statistical significance in the process is crucial. Understanding multimodal travel behavior and promoting a balance in the modal mix significantly influence transportation choices [7].

Data privacy policies will be strictly adhered to, ensuring participant confidentiality in compliance with ethical research practices. No personal data will be collected, and participants will be informed that their participation is voluntary, with the right to withdraw at any time without any consequences. According to a study conducted by Sigrun Beige and Kay W. Axhausen, there is a significant relationship between residential relocation during one's lifetime and vehicle ownership, as well as the influence of factors such as age, education, and employment status on mobility choices [12].

Criteria for Data Development: The survey is designed based on the following criteria.

- Demographic Criteria: Factors such as age, gender, education level, marital status, income, travel time, and residential conditions influence transportation choices. These variables are crucial for understanding the perspectives of individuals residing in city centers versus suburban areas regarding transportation preferences. Factors such as social attitudes, age, marital status, income, as well as personal preferences and psychological perspectives, play a significant role in public transport selection. Studies indicate that younger age groups and low-income groups are more inclined to use public transport [1]. Household size, income, socio-demographic factors, and built environment elements collectively influence car ownership, with the correlation between residential location choices and ownership patterns shaped by both personal and environmental factors [10].
- Economic criteria: The costs of public transport and private car usage, monthly income, and the efficiency of the transport system significantly influence transportation choices. The free-floating car-sharing system attracts younger, higher-income individuals who value spontaneity, while station-based systems appeal to self-employed individuals who prefer flexible and planned transportation, with each system catering to distinct travel purposes [8]. Factors such as transport costs, time, and convenience influence users' attitudes toward their choice of transportation [14].
- Social criteria: Personal preferences, psychological perspectives, and the quality of public transport influence the choice of transportation. Effective organization of public transport requires robust infrastructure, reliable transport systems, and consideration of psychological and social factors [1]. Considering psychological factors in transportation choices is essential, as each group has unique needs and perspectives [2].
- Environmental criteria: Environmental factors, such as air pollution and ecological impact, play a significant role in transportation choices. Car ownership, gender tendencies favoring men's preference for vehicle use, the proximity of public transport facilities negatively influencing private vehicle choice, and the substantially higher CO2 emissions from private cars collectively highlight the environmental and behavioral dynamics of transportation preferences [15].
- Infrastructure and transport system: The convenience, speed, congestion levels, and time efficiency of public transport reflect the impact of infrastructure and the transport system. Well-designed built environments, such as high building density and improved access to public transport, can help reduce car ownership and driving, highlighting the need for policymakers to enhance urban form to decrease dependency on cars [16].
- Personal experiences and behavior: Distance and speed in transportation significantly influence urban transport conditions. Policymakers are encouraged to implement specific measures to promote the use of public

transport, particularly targeting individuals with a psychological attachment to cars [13].

**Data processing.** Once data is collected, it undergoes an initial review to ensure completeness and accuracy of responses. Any incomplete or ambiguous answers are carefully evaluated and excluded from the analysis if necessary. To maintain anonymity, the data is coded and stored in a database for subsequent statistical analysis.

**Quality assurance.** A series of measures are implemented to ensure the quality and reliability of the data:

- Pilot Testing: The survey instrument is tested on a small group of participants prior to distribution to ensure the clarity and relevance of the questions.
- Consistency in data collection: The data collection process is monitored to maintain methodological consistency throughout.
- Automated data entry and processing: Automated tools are used for data entry and processing, minimizing the likelihood of human error.

The processed data forms the foundation of our subsequent analysis, which aims to explore the interaction between public transport and car owners' perceptions in the urban context.

## 3. Methodology

This research methodology is designed to analyze the factors shaping decisions to transition to public transport. The primary objective of the study is to explore the tendencies of car owners in Tashkent toward choosing public transport. To achieve this goal, the following methodological approaches are employed. Interviews were conducted with car owners to understand their opinions and preferences, and the following questions were posed to gather relevant data. Collecting individual information about these aspects is crucial for understanding car usage patterns.

The research focuses on addressing the following questions:

- What motivates car owners to transition to public transport?

How do the availability and quality of public transport in Tashkent influence this decision?

**Table 1**

**Types of surveys, their advantages, and disadvantages**

| Survey types | Advantages | Disadvantages |
|---|---|---|
| **Mail surveys** | Flexible traditional surveys, suitable for respondents who feel comfortable with written forms, can collect responses over a long period | Requires a mailing list, response rate may be low, time-consuming |
| **Email or social media surveys** | Cheap, accessible for respondents with internet access, can speed up response time | Internet complexity for both surveys, potential for dropped responses, dependence on respondents' internet access |
| **Internet (website-based surveys)** | Convenient for explaining to respondents, can collect detailed individual information, fast outreach to the public | Requires time and money to create a website, technical difficulties may arise |
| **Interviews, online interviews (google forms)** | Cheap, forms are fully filled out, issues can be analyzed visually | Some respondents may not respond, maintaining anonymity can be difficult |
| **Telephone surveys** | Quick and easy to implement, fewer geographical limitations, easier to establish contact | Respondents may refuse telephone surveys, responses may be brief |
| **Focus groups** | Allows in-depth exploration of opinions, can obtain detailed insights on specific issues or topics | Small group of respondents (usually 6-12 people), dominant voices may influence others |
| **Observational surveys** | Provides the ability to collect real-time data in real-world settings, direct observation of respondent behavior | Difficult to track actions accurately, other influencing factors |
| **Panel surveys** | Provides the ability to conduct long-term observation, useful for studying trends | Respondents must participate multiple times, can interfere with personal privacy |
| **Personal interviews** | Full explanation of survey questions, easier to establish contact | Time and cost-intensive, respondents may provide inaccurate answers |
| **Structured and unstructured surveys** | Structured surveys present strict questions, unstructured surveys allow respondents to freely express opinions | Structured surveys do not allow for flexibility, analysis of unstructured responses can be challenging |

Table 2

**Types of questions for respondents and their objectives**

| № | Question | Answer options | Purpose |
|---|---|---|---|
| 1 | **Age.** What is your age? | 18-25, 26-35, 36-45, 46-55, 56 and older | To identify age-related trends in choosing public transport or using a car. To understand how decisions vary across age groups. |
| 2 | **Gender.** What is your gender? | Male, Female | To analyze car owners' views on transportation by gender. To identify differences in transportation choices between men and women. |
| 3 | **Education level.** What is your level of education? | High school, Higher education, Master's, PhD, Other | To determine the relationship between education level and the decision to switch to public transport. To investigate whether highly educated individuals are more likely to choose public transport. |
| 4 | **Occupation and job Type.** In which sector is your workplace? | Public sector, Private sector, Freelance, Student | To identify how occupation and working conditions influence the decision to switch to public transport. |
| 5 | **Marital status.** What is your marital status? | Single, Married, Divorced, Other | To identify the factors that influence car owners' decisions based on marital status. To assess the relationship between family size and the likelihood of using public transport. |
| 6 | **Family size.** How many members are there in your family? | 1-2 people, 3-4 people, 5 or more | To analyze the role of family size in choosing a car. To assess if individuals with larger families are more likely to use public transport. |
| 7 | **Monthly income.** What is your monthly income? | Low, Average, High | To analyze the relationship between monthly income and the decision to maintain a car or switch to public transport. |
| 8 | **Time spent on transportation.** How much time do you spend on transportation daily? | Up to 1 hour, 1-2 hours, 2 hours or more | To analyze the impact of daily commuting time on the decision to use public transport. Those who spend more time commuting may be more inclined to switch to public transport. |
| 9 | **Housing and transport choices.** Is your residence located near the city center or the outskirts? | City center, Outskirts | To analyze the role of housing location in choosing transportation. People living near the city center may be more inclined to choose public transport. |
| 10 | **Car usage frequency.** How often do you use your car? | Daily, Several times a week, Rarely, Never | To analyze the frequency of car use and its relationship with the decision to switch to public transport. |
| 11 | **Purpose of car usage.** What is your main purpose for using your car throughout the day? | Going to work, Leisure with family, Shopping, Other | To determine the reasons why car owners use transportation. To assess whether people prefer public transport for their daily needs. |
| 12 | **Availability and quality of public transport.** Is public transport in Tashkent convenient for you? | Very convenient, Somewhat convenient, Not convenient at all | To examine public transport's convenience and availability. The convenience of public transport can influence car owners' decisions to switch. |
| 13 | **Public transport vs car costs.** Do you feel that using public transport is cheaper than maintaining a car? | Yes, No | To identify car owners' economic views on public transport and car maintenance costs. If public transport is cheaper, car owners may be more inclined to switch. |
| 14 | **Environmental and ecological factors.** Do you feel that using fewer cars has a better impact on the environment? | Yes, No | To analyze how ecological factors influence the decision to switch to public transport. |
| 15 | **City transport infrastructure.** How do you evaluate the potential for reducing traffic jams and providing dedicated lanes for public transport in Tashkent? | Good, Average, Poor | To evaluate the efficiency of public transport and its infrastructure. If there are good options for reducing congestion and providing dedicated lanes, car owners may be more inclined to switch. |
| 16 | **Traffic congestion and time spent.** How does traffic congestion in Tashkent affect your daily movements? | Major impact, Moderate impact, No impact at all | To analyze how traffic congestion affects car owners' decisions to switch to public transport. |


https://doi.org/10.56143/3030-3893-2025-4-32-38 A bridge between science and innovation

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| **17** | **Biggest barriers to switching to public transport.** What is the biggest factor preventing you from switching to public transport? | Inconvenience of public transport, Distance to transport stops, Prices, Safety, Other | To identify the main barriers preventing car owners from switching to public transport. |
| **18** | **Car maintenance Costs.** Are you satisfied with the monthly maintenance costs of your car? | Yes, Satisfied, No, Not Satisfied | To determine how car owners perceive maintenance costs. If the costs are high, they might be more willing to switch to public transport. |
| **19** | **Social and personal factors.** Do you prefer traveling by public transport or feel more comfortable in your car? | Prefer public transport, Feel more comfortable in a car | To identify personal preferences and psychological factors. Whether car owners are open to using public transport. |
| **20** | **Social and cultural influences.** How do you perceive the social acceptance of switching to public transport in Tashkent? | Widely accepted, Occasionally accepted, Not widely accepted | To study the social acceptance of public transport and identify the factors that influence people's decisions. |
| **21** | **Safety of transportation.** Do you think public transport in Tashkent is safe? | Very safe, Average safety, Unsafe | To examine the safety of public transport in the city and how safety concerns affect the decision to switch. |
| **22** | **Pedestrian safety.** How do you feel about the safety of pedestrian walkways in Tashkent? | Very safe, Average safety, Unsafe | To analyze pedestrian safety and its role in deciding to switch to public transport. Those who feel safer may be more inclined to use public transport. |
| **23** | **Public transport fare.** Do you think the fare for public transport in Tashkent is reasonable? | Very reasonable, Average, Poor | To evaluate the influence of public transport fares on car owners' decisions. |
| **24** | **Proximity to transport services.** How close are the main routes and stops of public transport to your residence? | Very close, Average, Not good | To examine the proximity of public transport services to residential areas. If public transport is close, people may be more inclined to leave their cars behind. |

The analysis results show that the most significant factors influencing car owners' decision to switch to public transport are the convenience, cost, safety, and quality of the city's infrastructure. Many respondents expressed concerns about the safety and reliability of public transport. Public transport is often considered cheaper and more convenient compared to the costs of maintaining a car. However, obstacles such as the distance to transport stops, safety concerns, and the lack of dedicated lanes for public transport still remain significant challenges.

## 4. Conclusion

This study demonstrates that overcoming the main barriers to switching to public transport requires improving the efficiency and safety of public transport, as well as making changes in transport infrastructure and urban planning systems. The analysis highlights that the convenience and affordability of public transport play a crucial role in encouraging car owners to switch to this system. As cities grow, it is essential to make public transport systems more effective and attractive in order to incentivize people to give up their cars. These changes can contribute to the stability of urban infrastructure and support environmental sustainability.

Future research should delve deeper into the impact of various public transport improvements on the willingness of car owners to transition from private vehicles to public transit. This can be achieved through a multi-faceted approach that examines specific changes in urban transport infrastructure, policy interventions, and behavioral factors influencing transportation choices.

One of the key areas of study could involve assessing the effects of expanding and optimizing public transport networks. A more extensive and well-integrated transport system with increased route coverage, higher frequency of service, and reduced waiting times may significantly enhance the attractiveness of public transport for car owners. Investigating how these improvements influence daily commuting patterns, travel times, and user satisfaction would provide valuable insights for urban planners and policymakers.

Another crucial aspect is the introduction of dedicated lanes for buses and trams, which can substantially increase the efficiency and reliability of public transport. By reducing delays caused by mixed traffic congestion, these dedicated lanes could make public transport a more competitive alternative to private cars. Future studies could evaluate the effectiveness of these lanes in different urban settings, considering factors such as road space allocation, traffic management strategies, and potential trade-offs with other transport modes.

Safety and security improvements in public transport systems should also be a focal point of future research. Many car owners are hesitant to switch to public transport due to concerns about personal safety, particularly during late-night hours or in less monitored areas. Research into enhanced security measures, such as real-time surveillance, increased

police presence, better lighting, and safer waiting areas, could help address these concerns. Additionally, studies could explore how emergency response systems and user-friendly reporting mechanisms for safety issues influence the public's perception of transport security.

Beyond physical infrastructure, future research could also focus on behavioral economics to gain a deeper understanding of the psychological and economic factors that shape transportation decisions. Car owners may weigh factors such as perceived convenience, status, autonomy, and financial costs when deciding whether to switch to public transport. Conducting surveys, controlled experiments, and case studies in different cities could provide comparative insights into the motivations and barriers influencing this transition.

Furthermore, future research should explore the integration of emerging transport technologies to improve urban mobility. Mobility as a Service (MaaS), for example, has the potential to revolutionize urban transportation by offering flexible and seamless multimodal travel options. By integrating ride-sharing, carpooling, public transport, and micro-mobility solutions such as e-scooters and bike-sharing, MaaS platforms could create a more efficient and user-friendly transportation ecosystem. Investigating the adoption rates, technological feasibility, and policy frameworks required for the successful implementation of MaaS in different urban environments would be highly beneficial.

Finally, a crucial aspect of future research is public policy and governance. Understanding how regulations, subsidies, pricing models, and public-private partnerships influence the development and adoption of improved transport systems is essential. Future studies could analyze how financial incentives, congestion pricing, parking regulations, and taxation policies can be leveraged to encourage car owners to use public transport.

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# Evaluation of key indicators affecting the delivery of containerized cargo in automobile transport

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Abstract: In this article, the key indicators affecting the transportation of containerized cargo in automobile transport are identified using the Ishikawa diagram, and effective methods for assessing their importance levels are studied. The analyses demonstrate that the most important indicators, such as transportation distance, cost, delivery time, and quality of cargo handling, are substantiated. The importance coefficient values of the indicators were determined through expert evaluation and the entropy method. This creates opportunities to increase the efficiency of containerized cargo transportation in automobile transport.

Keywords: road transport, containerized cargo, indicators, importance level, expert evaluation, methods

## 1. Introduction

Improving the indicators of cargo delivery in automobile transport via containers serves not only to optimize logistics processes but also to increase economic efficiency. This process includes consolidating cargo, introducing modern technologies, ensuring safety, and taking environmental aspects into account [1].

Today, the transport-logistics system is an integral part of any country's economy. In particular, the development of containerized cargo transportation technology ensures the safe, fast, and relatively inexpensive delivery of goods, occupying a significant place in global trade processes. In this regard, the transportation of containerized cargo by automobile transport is recognized as one of the main directions determining the efficiency of modern logistics.

The advantage of automobile transport over other types of transport is its ability to deliver goods from door to door. However, numerous factors affect the process of transporting containerized cargo by road. These include the condition of road infrastructure, the technical specifications of vehicles, transportation distance, traffic congestion on routes, the speed of loading and unloading operations, as well as costs associated with transportation [2].

By identifying the main factors affecting the delivery process of containerized cargo in automobile transport and analyzing them using mathematical-statistical methods, the most critical indicators are determined, thereby providing a scientific basis for organizational and technical decisions in this field. The analytical method helps identify the primary trend by ensuring monotonicity in the development of the processes under study over the considered time period.

Identifying the factors and indicators influencing the transportation of containerized cargo in automobile transport not only improves transportation quality but also enables the establishment of agreements on probable causes that need to be empirically verified.

Based on the review of scientific literature, it was determined that research related to container transportation in automobile transport remains highly relevant. In the study, a multi-criteria hierarchical evaluation system was developed to achieve four strategic objectives for the key indicators affecting containerized cargo transportation in automobile transport (Figure 1).

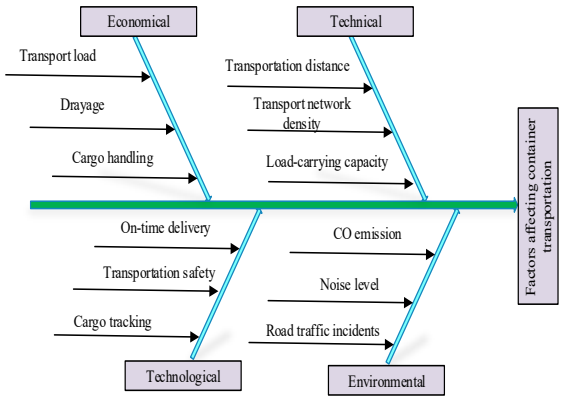


**Fig 1. Results of identifying the main factors affecting container transportation in automobile transport based on the Ishikawa diagram**

The main factors and indicators affecting container transportation in the logistics supply chain, identified based on the Ishikawa diagram, are presented.

## 2. Methodology

Many researchers have attempted to identify and evaluate indicators to determine the efficiency of container transportation in automobile transport. For instance, V. A. Shebanov (2008), in his scientific work titled “Logistics of Container Transportation Systems”, identified indicators such as weight, distance, transportation cost, drayage, and loading time for assessing container transportation efficiency. He emphasized the need for a comprehensive analysis of factors influencing transport selection [5].

In addition, Malcolm McLean, in his work “Evaluation of the Efficiency of Transport Logistics Systems”, took into account the interdependence of the container transportation process with transport networks. He proposed selecting key indicators using weight coefficients and mathematically expressing their impact on transport decisions [4].

Currently, the following main methods are widely used to evaluate indicators affecting containerized cargo transportation:

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- Expert evaluation method: The importance of each indicator is determined based on the opinions of experienced specialists.

- Delphi method: A group of experts reaches consensus through anonymous, multi-stage evaluation. This method was first developed by Norman Dalkey and Olaf Helmer in the 1960s at RAND Corporation [3,5].

- AHP – Analytic Hierarchy Process: Indicators are compared in pairs, and weight coefficients are determined. This method was proposed by T. L. Saaty and is applied in many transport systems [6].

In modern logistics systems, containerized cargo transportation technology plays a central role in global trade and transport operations. In particular, the delivery of containerized cargo by automobile transport is closely linked to factors such as economic efficiency, environmental safety, and service quality. Therefore, identifying and evaluating the key indicators affecting this mode of transport holds significant scientific and practical importance in enhancing its competitiveness and substantiating management decisions

Inside the system of built up participation with neighboring nations such as Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Afghanistan, assentions have been come to on the development of unused interstates, the opening of courses to outside nations through them, as well as the joint repair and operation of existing streets [4]. As a result, the volume of street cargo transportation and travel cargo transportation has been expanding year by year.

Various evaluation methods exist to identify the factors affecting the transportation of containerized cargo in automobile transport and to determine their relative importance. This section analyzes three main methods: expert evaluation, the entropy method, and AHP (Analytic Hierarchy Process). The capabilities of the expert evaluation method include the following:

- proposing solutions even in the absence of statistical data;

- rapid, flexible, and practical data processing based on experience;

- creating a foundation for new ideas and unconventional approaches.

However, this method also has drawbacks: a high probability of subjectivity, strong dependence of results on the quality and number of experts, and the occasional emergence of conflicting opinions. In such cases, improved expert evaluation methods like the Delphi method are applied.

In conclusion, the expert evaluation method is an effective tool for analyzing complex, multi-factor problems in the transport sector, providing results that are close to reality and reliable. It holds significant importance in determining directions for further improving containerized cargo transportation.

The expert evaluation method is an approach aimed at determining the relative importance of various indicators or criteria based on the opinions of specialists. It is one of the simple yet effective methods widely used in the field of transport logistics. Qualified and experienced experts (i.e., industry professionals such as transport managers, road transport engineers, and logistics analysts) assess the importance level of each criterion using a scoring system. These scores are assigned on a scale ranging from 1 to 5, and sometimes from 1 to 10 [4].

**Table 1**

**Experts' ratings on a 1–10 point scale**

| Indicator | Expert 1 | Expert 2 | Expert 3 | Expert 4 | Expert 5 | … | Expert 21 | Average |
|---|---|---|---|---|---|---|---|---|
| Transportation distance | 9 | 9 | 9 | 8 | 9 | … | 8 | 8,7 |
| Transport network density | 5 | 4 | 5 | 6 | 5 | … | 4 | 4,7 |
| Load-carrying capacity | 5 | 6 | 7 | 5 | 7 | … | 5 | 6 |
| Transport load | 8 | 9 | 8 | 9 | 7 | … | 9 | 8,3 |
| Drayage | 5 | 4 | 4 | 6 | 6 | … | 4 | 5 |
| Cargo handling | 6 | 5 | 8 | 6 | 7 | … | 6 | 6,3 |
| On-time delivery | 8 | 8 | 8 | 7 | 8 | … | 7 | 7,7 |
| Transportation safety | 7 | 6 | 6 | 6 | 6 | … | 7 | 6,3 |
| Cargo tracking | 6 | 7 | 8 | 8 | 5 | … | 8 | 7 |
| $CO_2$ emission | 8 | 7 | 5 | 5 | 6 | … | 7 | 6,6 |
| Noise level | 7 | 7 | 6 | 6 | 6 | … | 6 | 6,6 |
| Road traffic incidents | 5 | 7 | 6 | 7 | 5 | … | 6 | 6 |
| Total | | | | | | … | | 79,2 |

Formula for calculating average scores:

$$K_j = \frac{1}{n}\sum_{i=1}^{n} k_{ij}, \quad (1)$$

Here, $\mathbf{K_j}$- j- average score for the indicator;

$\mathbf{k_{ij}}$- score given by the i-th expert to the j-th indicator;

n – number of experts.

Formula for calculating importance using the expert evaluation method:

$$w_j = \frac{K_j}{\sum K_j}, \quad (2)$$

$K_j$=8,7 average score for transportation speed;

$\sum K_j$=79,2 number of experts;

$W_j$=8,7/79,2= 0,11 is calculated for each indicator.

The expert evaluation method is a technique that utilizes the knowledge and experience of qualified specialists (experts) in a specific field to determine the importance level of a particular indicator or factor. With this method, situations that need to be qualitatively assessed (e.g., transportation safety, drayage quality, cargo handling speed) are expressed in quantitative terms [6].

## 3. Results and Discussion

In this method, the criteria to be evaluated are first identified, followed by the selection of experienced experts. Questionnaires are presented to the experts, and their opinions and assessments are collected in Table 1. The evaluation can be conducted using a scoring system (e.g., on a scale of 1–10), in the form of rankings (from most important to least important), or based on pairwise comparison. The obtained results are processed, generalized, and conclusions are drawn using mathematical-statistical methods [5, 6].

**Table 2**
**Calculating importance using the expert evaluation method**

| Indicator | Average score (Kj) | Importance (Wj) |
|---|---|---|
| Transportation distance | 8,7 | **0,110** |
| Transport network density | 4,7 | 0,0593 |
| Load-carrying capacity | 6 | 0,0758 |
| Transport load | 8,3 | 0,105 |
| Drayage | 5 | 0,0631 |
| Cargo handling | 6,3 | 0,0795 |
| On-time delivery | 7,7 | 0,0972 |
| Transportation safety | 6,3 | 0,0795 |
| Cargo tracking | 7 | 0,0884 |
| $CO_2$ emission | 6,6 | 0,0833 |
| Noise level | 6,6 | 0,0833 |
| Road traffic incidents | 6 | 0,0758 |

The factors affecting containerized cargo transportation in automobile transport are listed in Table 2, including “transportation distance”, “transport network density”, “load-carrying capacity”, “transport load”, “on-time delivery”, “drayage”, “cargo handling”, “transportation safety”, “cargo tracking”, “$CO_2$ emission”, “noise level”, and “road traffic incidents”. These factors are evaluated by experts using a scoring system. Based on the assigned scores, the importance level of each factor is calculated, and the most critical factors are identified.

## 4. Conclusion

During the evaluation process, each expert assigned scores to the indicators, and the total sum was calculated based on these scores. Subsequently, the weight of each indicator—representing its overall impact strength—was determined as a percentage, expressing its degree of influence on the overall analysis. For example, transportation speed received the highest score (8.7), with a weight of 0.11 (11%). This indicates that the indicator is more significant compared to others.

The results clearly show that the expert evaluation method identified the relative proportions among the factors, determining the extent to which each plays a critical role in the overall system. This approach not only ranks the indicators but also serves as a foundation for prioritizing them in future decision-making processes.

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# Optimisation of the composition of comprehensively modified self-compacting fine-grained concrete mixtures for vibration-free and low-vibration construction technologies

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Abstract: The article presents the results of research on optimising the composition of complex modified self-compacting fine-grained concrete mixtures intended for vibration-free and low-vibration construction technologies. The aim of the work was to establish rational component ratios that ensure an optimal balance between the rheological and strength characteristics of concrete. The parameters considered for optimisation were compressive strength at 1, 7 and 28 days, flexural strength, average density, and water-cement ratio. It was found that the use of a complex modifier, including mineral and chemical additives, contributes to a reduction in the water-cement ratio while maintaining the necessary mobility, increases early and final strength, and ensures the formation of a dense and homogeneous material structure without the use of vibration compaction. The results obtained can be used in the development of energy-efficient technologies for monolithic construction using self-compacting fine-grained concretes.

Keywords: self-compacting concrete; fine-grained concrete mix; complex modifier; composition optimisation; vibration-free technology; compressive strength; flexural strength; density; water-cement ratio; burnt mould waste; polycarboxylate superplasticiser

## 1. Introduction

The modern construction industry is characterised by rapid development and increasing demands on the quality, strength, durability and technological properties of structural materials. In these conditions, cement concrete retains its leading position as the most versatile and effective material with a wide range of properties that can be adjusted. One of the priority areas for the development of concrete technologies is the creation of self-compacting compositions that ensure high structural density and uniformity without the use of vibration [1].

In global practice, the introduction of self-compacting fine-grained concrete (SCFC) has become an important step in the improvement of monolithic construction technologies. Such mixtures are characterised by increased mobility, the ability to self-compact under their own weight, and structural stability, which improves the operational properties of the finished material and increases the energy efficiency of construction processes [2].

The required set of properties for self-compacting fine-grained concrete is achieved through the rational selection of components, optimisation of the particle size distribution of the aggregate structure, and the use of complex modifying additives. The most effective approach in this direction is recognised to be the use of chemical plasticising additives with mineral microfillers. Their combined action reduces the water-cement ratio while maintaining the necessary mobility, contributes to the intensification of hydration processes and the formation of a dense, low-porosity cement stone structure [3].

Previous studies have shown that the use of complex modifiers can significantly improve the technological and physical-mechanical properties of self-compacting concrete, as well as ensure its stable formation with minimal energy consumption. This opens up opportunities for the widespread introduction of vibration-free and low-vibration technologies into construction practice, which is particularly relevant in the context of the need to reduce labour intensity, energy consumption and negative environmental impact [4-8].

Taking into account the priority areas of development of the construction industry in the Republic of Uzbekistan, including within the framework of the implementation of the 'Strategy for the Development of New Uzbekistan for 2022-2026', the development of energy-efficient, technologically advanced and environmentally friendly building materials based on local raw materials is of particular importance. The creation of self-compacting fine-grained concretes with the necessary set of properties meets the objectives of improving the quality, reliability and seismic resistance of structures under construction, as well as contributing to a reduction in construction costs.

**The aim of the study** is to optimise the composition of complex modified self-compacting fine-grained concrete mixtures for vibration-free and low-vibration construction technologies based on an analysis of the influence of chemical and mineral additives on the water-cement ratio,

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strength, rheological and physical-technical characteristics of concrete.

The relevance of the research is determined by the need to develop effective compositions of self-compacting fine-grained concretes that ensure high performance properties when using local mineral resources and modern modifying systems. The scientific novelty of the work lies in establishing the patterns of influence of complex additives of various nature on the structure and properties of self-compacting fine-grained concretes, as well as optimising the composition parameters for the implementation of vibration-free moulding technologies.

## 2. Research Methodology

Materials widely available in the Republic of Uzbekistan were used to conduct experimental research on the development of self-compacting fine-grained concrete. The main binder was Portland cement grade CEMI 32.5N, produced by "Kizilkumcement" LLC.

The mineral filler used was metallurgical waste from "Uzbekistan Temir Yollari" JSC, which is a finely dispersed grey-brown material with a high specific surface area and the presence of amorphous phases. Before use, the filler was dried at a temperature of (105±5)°C to a constant mass and then ground in a ШЈМ-100 laboratory ball mill. The grinding time and load were determined experimentally in order to achieve optimal dispersion.

The dispersion of the mineral filler was controlled by the specific surface area using the Kozeni-Karmann air permeability method with the ПСХ-11А device, which allowed quantitative assessment of the degree of fineness of grinding. In addition, the morphology of the particles and the degree of aggregation were assessed using a sieve No. 008.

The chemical additive used was PRO500 superplasticiser based on polycarboxylate esters, which has a high water-reducing capacity (up to 25–30%) and provides the required mobility of cement systems with minimum water consumption.

To assess the physical and mechanical characteristics of self-compacting fine-grained concrete mixtures, a series of experimental studies was conducted to determine compressive strength, flexural strength, average density, and optimisation of the water-cement ratio.

The compressive strength of concrete was determined in accordance with the requirements of GOST 10180–2012 'Concrete. Methods for determining strength using control samples'. Cubes measuring 100×100×100 mm were made for testing and were tested at 1, 7 and 28 days of age. The tests were carried out on a hydraulic press with load control until the sample failed, after which the average strength of the series was calculated.

Bending strength was determined in accordance with GOST 310.4–2012 'Cements. Methods for determining strength' and GOST 24452–2015 "Concretes. Methods for determining flexural strength." For this purpose, 40×40×160 mm beams made of the same concrete mixture as the cubes were used. The tests were performed on a tensile testing machine using a three-point bending scheme, with the maximum load causing sample failure being recorded.

The average density of the hardened concrete was determined by the hydrostatic weighing method in accordance with GOST 12730.1–2020 'Concrete. Methods for determining density.' For each composition, the average density value was determined from three samples, which ensured the representativeness of the data.

The data obtained served as the basis for statistical processing and further optimisation of the composition of self-compacting fine-grained concretes using complex modifying additives.

The experimental campaign was planned as a two-factor central composite design, providing an assessment of linear, quadratic and interactive effects with the minimum number of experiments required [10]. The following factor variables were selected:

• $x_1$ — consumption of polycarboxylate superplasticiser (range 0.60–1.40 wt.% of cement mass);

• $x_2$ — consumption of burnt moulding waste (range 20–30 wt.% of filler).

All experiments are performed in random order (randomisation) to minimise temporal and systematic effects. Centre replicates are evenly distributed throughout the overall sequence of experiments, which allows for a correct assessment of intra-pair variability and the adequacy of the quadratic model.

$$Y = c + a_1x_1^2 + b_1x_1 + a_2x_2^2 + b_2x_2 + a_3x_3^2 + b_3x_3 + \ldots + a_nx_n^2 + b_nx_n \quad (1)$$

For each point in the plan, a sufficient number of parallel samples (at least three for each key test) are to be produced, which ensures the statistical reliability of the average response values. After the experiments are completed, the data serves as the basis for approximating a second-order quadratic regression model (1) with an assessment of the main effects, quadratic terms, and the interaction between $x_1$ and $x_2$.

The plan concludes with a phase of confirmatory experiments: at least three independent repetitions are performed for the optimal combination of factors found to verify the model's predictions and check the reproducibility of the results.

## 3. Results and Discussion

To optimise the performance properties of fine-grained concretes with complex additives, a series of experimental studies was conducted to establish the patterns of influence of the composition of modifying components on the physical, mechanical and structural characteristics of materials. The main objective of the experiments was to determine and justify the most effective composition of the complex additive, ensuring an optimal combination of strength, density, workability and durability of fine-grained concrete.

A key aspect of the research was the study of the synergistic interaction between the superplasticiser (SP) and the component of the complex additive based on burnt moulding waste (BWS), which has a combined effect on the formation of the microstructure and pore space of the cement stone. Previous studies [9–15] have confirmed that the combined use of these components not only reduces the

water demand of the system, but also contributes to the formation of a dense structure with uniform pore distribution, which significantly improves the strength and durability of self-compacting mixtures.

From a practical point of view, the relevance of this approach is due to the need to create concrete mixtures with high self-compaction without external vibration compaction, while maintaining resistance to delamination and uniformity of structure. Such concretes are especially in demand in the construction of monolithic and reinforced structures of complex configuration, where the use of traditional compaction is impossible.

The research was conducted on fine-grained concrete mixtures prepared with a constant cement-to-sand ratio (C:S = 1:2.5), which minimised the influence of the aggregate composition on the physical and mechanical properties of the concrete (Table 1).

The amount of mixing water in all series was selected taking into account the preservation of equal mobility of the mixtures in order to exclude the influence of differences in consistency on the physical and mechanical indicators. The mobility of the mixtures was assessed by the Hagerman cone spread, determined on a shaking table in accordance with GOST 310.4-81. The spread values were maintained within the range of 260–280 mm, which meets the requirements for self-compacting mixtures.

**Table 1**

**Experiment plan and test results for fine-grained concrete**

| № | Composition of the complex supplement | | Cone spread, mm | Average value of the response function | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | SP, % | BWS, % | | W/C | $R_1$, MPa | $R_7$, MPa | $R_{28}$, MPa | $R_{bend}$, MPa | ρ, kg/m³ |
| | $X_1$ | $X_2$ | | $Y_1$ | $Y_2$ | $Y_3$ | $Y_4$ | $Y_5$ | $Y_6$ |
| 1 | - | - | 200 | 0,64 | 30,7 | 31,6 | 50,7 | 5,1 | 2047 |
| 2 | | 20 | 195 | 0,72 | 6,6 | 10,5 | 21,4 | 4,1 | 1835 |
| 3 | | 25 | 195 | 0,88 | 5,8 | 9,1 | 17,9 | 3,4 | 1804 |
| 4 | | 30 | 190 | 0,97 | 4,2 | 7,5 | 15,7 | 2,6 | 1752 |
| 5 | 0,6 | - | 280 | 0,46 | 27,8 | 42,3 | 49,1 | 7,2 | 2166 |
| 6 | | 20 | 270 | 0,5 | 28,8 | 40,2 | 48,1 | 7,1 | 2134 |
| 7 | | 25 | 270 | 0,54 | 24,4 | 37,3 | 46,1 | 6,8 | 2071 |
| 8 | | 30 | 270 | 0,58 | 21,1 | 34,3 | 44,7 | 6,2 | 2035 |
| 9 | 1,0 | - | 280 | 0,34 | 37,6 | 44,2 | 50,1 | 8,0 | 2215 |
| 10 | | 20 | 280 | 0,34 | 36,5 | 46,1 | 51,1 | 8,9 | 2207 |
| 11 | | 25 | 280 | 0,34 | 34,8 | 42,1 | 51,0 | 8,1 | 2189 |
| 12 | | 30 | 275 | 0,38 | 30,1 | 39,8 | 49,2 | 7,7 | 2134 |
| 13 | 1,4 | - | 280 | 0,34 | 37,7 | 44,2 | 50,0 | 7,6 | 2214 |
| 14 | | 20 | 280 | 0,34 | 36,4 | 46,1 | 50,1 | 8,8 | 2208 |
| 15 | | 25 | 280 | 0,34 | 34,7 | 42,1 | 49,1 | 8,2 | 2188 |
| 16 | | 30 | 280 | 0,38 | 30,2 | 39,8 | 48,1 | 7,6 | 2131 |

Analysis of the experimental data obtained showed that the use of a superplasticiser is a decisive factor determining the self-compacting ability of fine-grained mixtures. In compositions not containing SP, it was not possible to achieve the required mobility even with an increase in W/C, which led to delamination and water separation when spreading less than 210 mm. Such mixtures formed a heterogeneous structure with increased porosity, which negatively affected the strength characteristics of hardened concrete [16].

After processing the results and filtering out insignificant coefficients from the regression equation, mathematical models were obtained [17-20]. With a statistical reliability level of 94–98%, the obtained regression models describing the dependence of the studied indicators of self-compacting fine-grained concretes on the content of superplasticiser (SP) and burnt moulding waste (BWS) are as follows:

$$W/C = 0.72 - 0.63X_1 + 0.25{X_1}^2 - 0.0026X_2 + 0.026{X_2}^2$$

$$R_1 = 9.61 + 42.94X^1 - 16.12X^{12} + 0.27X^2 - 0.01X^{22} + 0.037X^1X^2$$

$$R_7 = 28.03 + 42.09X^1 - 22.90X^{12} - 0.46X^2 - 0.091X^{22} + 0.52X^1X^2$$

$$R_{28} = 45.23 + 29.02X^1 - 19.82X^{12} - 1.025X^2 - 0.012X^{22} + 0.84X^1X^2$$

$$R_{-bend} = 4.91 + 5.74X^1 - 2.76X^{12} + 0.051X^2 - 0.04X^{22} + 0.064X^1X^2$$

$$\rho = 1932 + 543.5X_1 - 248.1{X_1}^2 + 0.25X_2 - 0.21{X_2}^2 + 2.99X_1X_2$$

Figures 1–6 show isographic dependencies reflecting changes in the main physical and mechanical properties of self-compacting fine-grained concrete mixtures under the influence of varying factors — the amount of superplasticiser (SP) and burnt moulding waste (BWS). The diagrams show the patterns of change in the water-cement ratio, compressive strength at 1, 7 and 28 days, flexural

strength, and average concrete density. The resulting isographic surfaces allow visualisation of the complex influence of the factors under study and determination of the areas of optimal combinations that ensure the achievement of the required operational properties of the material.

Mathematical models based on experimental data made it possible to comprehensively analyses the influence of variable factors — SP and BWS content — on the formation of the physical and mechanical properties of self-compacting fine-grained concretes. The regression equations obtained are characterised by a high degree of adequacy and reproducibility, which confirms the reliability of the developed models and their applicability for engineering calculations in the design of compositions of similar materials.

The results of the analysis showed that changes in the content of the components of the complex additive have a non-linear effect on the strength characteristics of concrete. At the same time, it was found that optimal operational properties are achieved with a rational ratio of the parameters under study, ensuring a balance between the mobility of the mixture and the density of the cement stone structure. In particular, it was established that the maximum compressive and flexural strength values are observed when the superplasticiser content is 1.0% and the burnt moulding waste content is 25% of the cement mass.

This combination of components contributes to the formation of a denser and more uniform microstructure of cement stone, a reduction in capillary porosity, and an increase in the degree of hydration of clinker minerals. Together, these factors increase the strength, durability and structural stability of fine-grained concrete, confirming the effectiveness of the proposed complex additive in non-vibration concrete technologies.

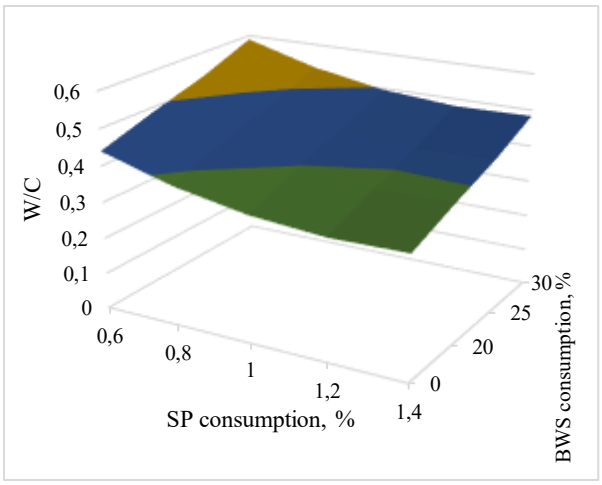


**Fig. 1. Water-cement ratio of self-compacting fine-grained concrete mixtures depending on the content of SP and BWS in the complex additive**

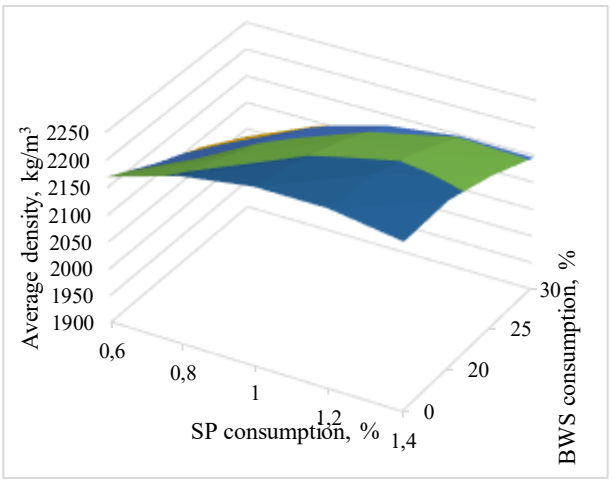


**Fig. 2. Average density of self-compacting fine-grained concrete mixtures depending on the content of SP and BWS in the complex additive**

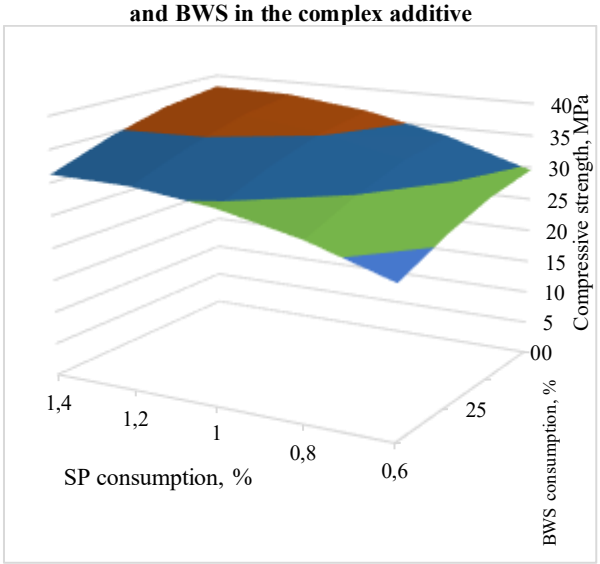


**Fig. 3. Compressive strength of fine-grained concrete at 1 day of age depending on the content of SP and BWS in the complex additive**

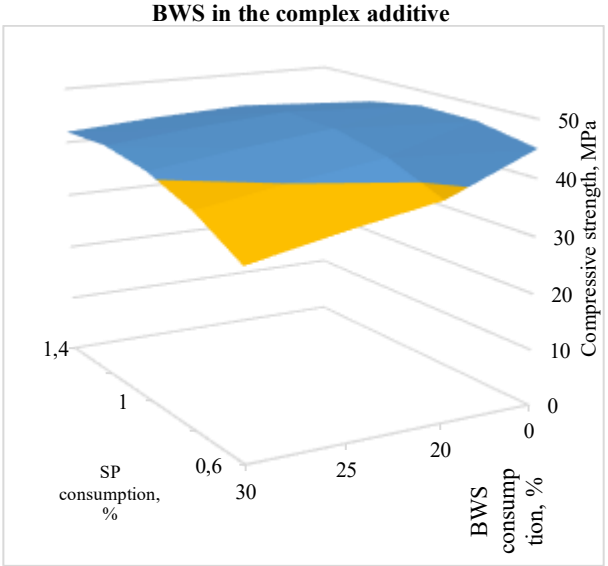


**Fig. 4. Compressive strength of fine-grained concrete at 7 days of age depending on the content of SP and BWS in the complex additive**


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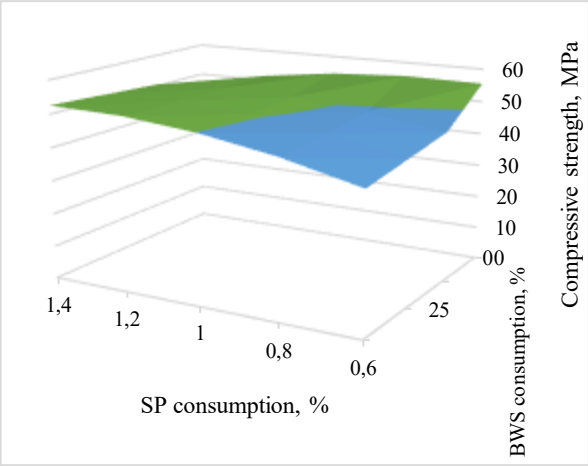


**Fig. 5. Compressive strength of fine-grained concrete at 28 days of age depending on the content of SP and BWS in the complex additive**

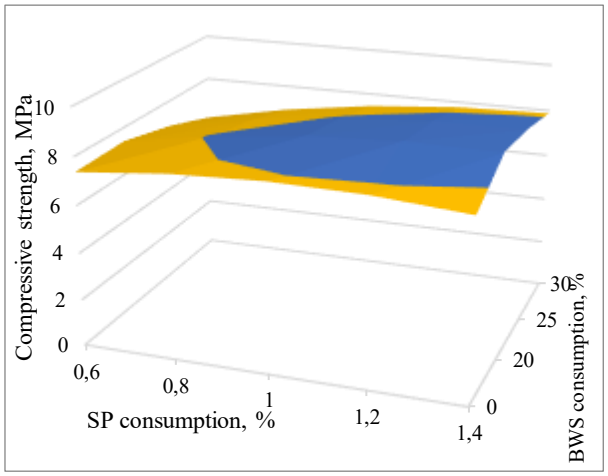


**Fig. 6. Flexural strength of fine-grained concrete at 28 days of age depending on the content of SP and BWS in the complex additive**

## 4. Conclusion

The studies conducted made it possible to establish the patterns of influence of a complex additive, including SP and BWS, on the formation of the structure and physical and mechanical properties of self-compacting fine-grained concretes. Based on the results of two-factor experimental design and subsequent mathematical modelling, regression relationships were developed to describe the influence of variable factors on the main property indicators: water-cement ratio, compressive and flexural strength, and concrete density.

The constructed models have a high degree of adequacy (confidence level of 94–98%) and allow predicting changes in the operational properties of the material depending on the composition of the complex additive. Analysis of response surfaces showed that varying the content of SP and BWS has a pronounced synergistic effect, improving the rheological characteristics and structural density of concrete.

It has been established that the optimal ratio of components ensuring the best physical and mechanical properties corresponds to a superplasticiser content of 1.0% and burnt moulding waste of 25% of the cement mass. With these parameters, a dense and uniform microstructure of cement stone is formed, capillary porosity is reduced, compressive and flexural strength is increased, and the overall homogeneity of the material is improved.

Thus, the results of the study confirm the effectiveness of using complex additives based on SP and BWS in the production of self-compacting fine-grained concretes. The proposed optimal component ratios can be used in the design of concrete compositions for vibration-free and low-vibration construction technologies, ensuring an increase in their strength, durability and manufacturability.

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# Algorithm for adaptation of sensors for detecting moving units in transport

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Abstract: This article analyzes the shortcomings of enterprises operating in the field of urban road transport, the shortcomings indicated in them and the need to provide high-quality transport services to the population in order to eliminate them, the issues and behavior of drivers are discussed, the management of public transport is analyzed, a positive decision is made on actions. Thus, the purpose of the research is to study the conditions of public transport development. We have studied some of the shortcomings of public transport, identified the main problems that passengers suffer from. The study confirmed the hypothesis that the study of the advantages of foreign public transport is an important and relevant area of modern sustainable transport system research.

Keywords: shortcoming, transport, passenger transport, bus, subway, rolling stock, system

## 1. Introduction

The development of the public transport system in Tashkent is one of the most important aspects of city life. But in the city of Tashkent, this field is currently lagging behind [1]. In particular, many residences have been built in recent years, the population has increased, and the city area has expanded. Currently, 1,300,000 passengers use public transport in our capital. It is required to analyze the movement of passenger transport vehicles in the city of Tashkent. Many authors have talked about tariffs while improving passenger transportation. Some of them have changed their fares based on distance. Other authors have focused on the accessibility, condition, automation, and equipment of public transport.

## 2. Research Methodology

The unusual race of public transport seriously affects the dissatisfaction and safety of passengers. There are several main reasons why buses pass each other on city streets [2]. One of these is on the financial side, that is, raising more money. Because the monthly salaries of drivers in all business entities are set at the level of the minimum wage. Their main income is surplus money from the “set plan” by the business entity. Therefore, drivers try to carry as many passengers as possible. On the other hand, there are many overlapping routes in the traffic of city passenger buses. To eliminate this situation, it is necessary to revise the city bus routes [3], [7], [8], [9], [10], [11].

Currently, a number of practical works have been started in order to find a solution to this problem [4], [12], [13], [14], [15]. As a result of the bus driver's smoking, his smoke spread into the bus cabin, causing dissatisfaction among the passengers, but the thought goes, “I have a little bit left to my stop, what am I going to do to spoil my mood by explaining to the driver that smoking is not allowed?”.

The introduction of voice announcements or advertisements in the intercity bus salon should be implemented only after a public consultation [5], [16], [17]. The sound advertisements in the salon at the same time as the information about the arrival at the stations are given, the parallel sound makes the passengers even more confused [6].

The sanitary conditions in the bus cabin sometimes make the passengers angry. As shown in Figure 2, we can see that the interior of the salon has not been cleaned for almost several months. Newly introduced buses are excluded, as they have just been put into operation (Figure 2).

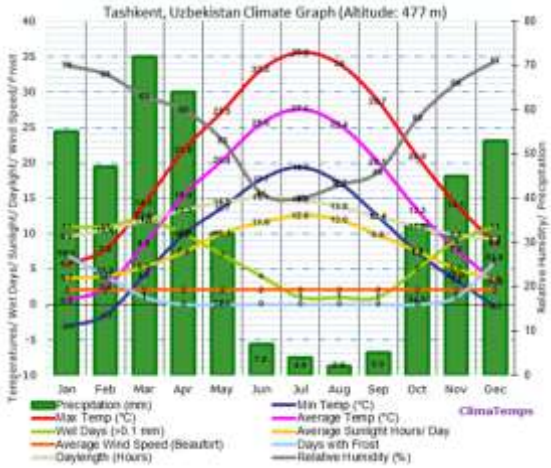


**Fig. 1. Tashkent city annual climate index**

As of August 1, 2021, there are a total of 1,179 city passenger buses at the disposal of the enterprises of the “Toshshahartranskhizmat” joint-stock company, of which 560 or 47.5% are large-capacity buses and 619 or 52.5% are medium- and small-capacity buses. In this case, the average period of disposal of buses is 7.3 years, and the number of buses that have been disposed of for more than 10 years is 323 or 27.4% of the total number of buses.

A total of 350 buses, of which 130 were large-capacity and 220 small- and medium-capacity buses, were purchased for the movement of enterprises in the system of the “Toshshahartranskhizmat” joint-stock company in 2017-2021.

Currently, there are 264 subway cars on the balance sheet of the unitary enterprise “Tashkent Metropoliten”, of

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**Fig. 2. Tashkent city bus salon**

which 152 were purchased in 1980-1990, 24 in 1991-2000, 20 in 2001, 8 in 2020, and 60 in 2021. 60% of the existing rolling stock has been disposed of for more than 30 years.

Figure 2 shows the problems of visibility by passengers and drivers of road transport that occur in the autumn-winter period, passengers can get out of the stop without seeing the car. Parking of cars at bus stops creates enough problems for buses. Buses are forced to stop and drop off passengers in the middle of the road when they stop and leave the bus stop due to the impact of cars parked around the bus stop. This again creates traffic jams (Figure 3).

**Fig. 3. Cars parked at bus stops**

The concept of the development of Tashkent city transport and transport infrastructure until 2025 has been developed, which includes plans to prevent traffic jams on highways in Tashkent city, methods of public transport development, stages of improving the tariff policy in urban passenger transport, the formation of the organization of the system of roadside parking places for cars, cargo transportation the development of traffic regulation criteria, the strategic goals of the introduction of digital technologies in the transport system and the priorities of the state policy are defined. The implementation of the concept allows for the creation of a convenient and efficient transport system in the city of Tashkent. The purpose of this study is to increase and analyze the influence of passenger transport in Tashkent.

As a result of the research, the following questions will be answered:

1. Should priority directions for the development of public transport be established?
2. What criteria can be used to organize mobile public transport?
3. Will promise innovative bus service and innovative national passenger connections?

The program for the introduction of a new route network of Tashkent city surface passenger transport in 2022-2025 has been approved today (Figure 4).

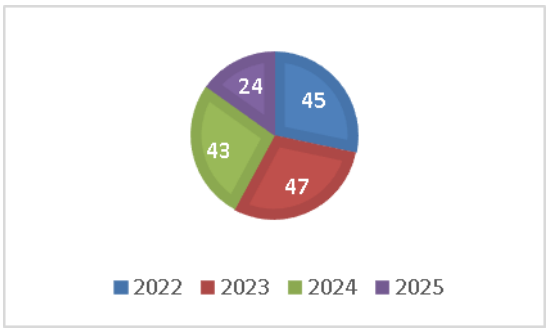


**Fig. 4. The indicator of the introduction of new routes of surface passenger transport in Tashkent city**

The indicator of the introduction of new routes of surface passenger transport of Tashkent city is set to be introduced in 2022-2025. New routes of surface passenger transport - 45 in 2022, 47 in 2023, 43 in 2024, and the remaining 24 in 2025 are planned. (Figure 4).

Here are the numbers of "highway, ring, binder and provider" roads planned to be built in 2021-2023. The most planned connecting roads are listed. In 2021, 30 connecting roads were built, and in 2022, 5 were built. Highways are the least built roads. 11 were established in 4 years (Figure 5).

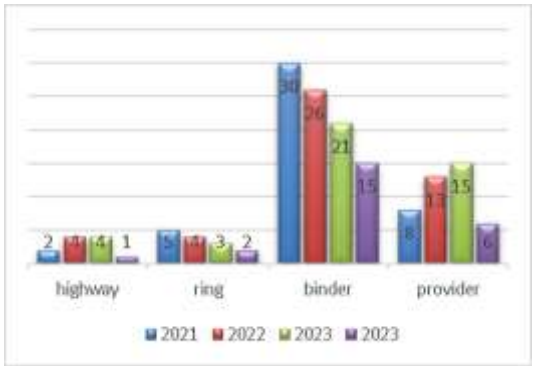


**Fig. 5. The indicator of the introduction of new routes of surface passenger transport in the city of Tashkent**

The general structure of bus traffic of the city passenger transport will be updated in the period of 2021-2025. The most recent update will be in 2022. 2021 is not planned (Figure 6).

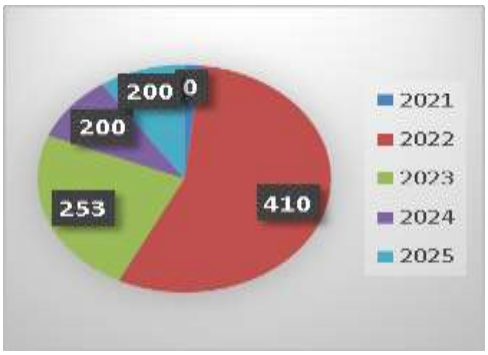


**Fig. 6. Update the total bus traffic structure of the city's passenger transport**

Also, one of the main goals should be the development of the city's public transport infrastructure, including the creation of a network of new routes, the renewal of traffic with modern "green" types, the reconstruction of intermediate stations based on a new design, the creation of a system of transport links, and the introduction of differentiated tariffs.

Including the most recent update, 20 electric buses, 190 buses running on compressed natural gas, and 200 buses running on diesel fuel are planned to be delivered in 2022. (Figure 7).

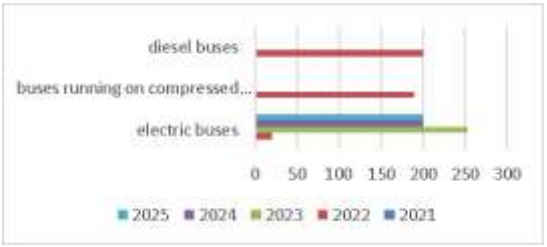


**Fig. 7. Update of the traffic structure of bus types of city passenger transport**

In the process of optimization of the network of Tashkent city routes, it is planned to organize convenient transport links at intersection points of 4 types of routes and metro lines.

## 3. Results and discussion

In 2022, it is necessary to establish 16 transport links in the city of Tashkent at the intersection of public transport and metropolitan routes, connecting with the city center, densely populated residential areas and densely populated points.

It is necessary to create equal conditions for all categories of passengers, to ensure passenger safety, to create differentiated tariffs, and to create rest areas for passengers and drivers in the newly established transport links.

In 2022, in the development of public transport infrastructure, 10 "construction of transport links" are included in the plan (Figure 8).

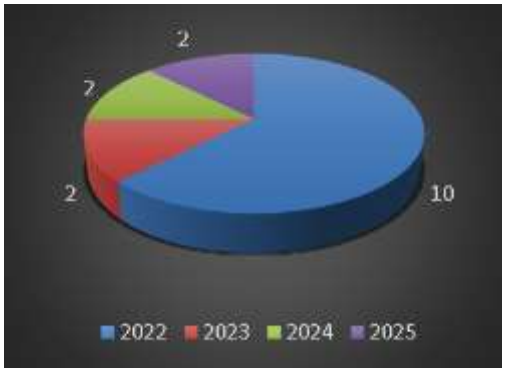


**Fig. 8. Organization of transport links**

In 2025, in the development of public transport infrastructure, 320 "reconstruction of intermediate bus stops" are included in the plan (Figure 9).

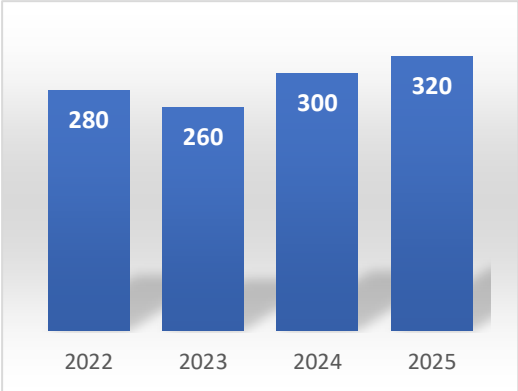


**Fig. 9. Reconstruction and modernization of intermediate bus stops based on a single design**

An intermediate bus stop is a public place located on the streets of city public transport routes, equipped for passengers to get off and get off and wait for a vehicle moving in the desired direction.

There are 2,306 intermediate bus stops in Tashkent, 788 of which operate as shopping malls. In 2022-2025, 11 "separate lanes for buses" are included in the plan for the development of public transport infrastructure (Figure 10).

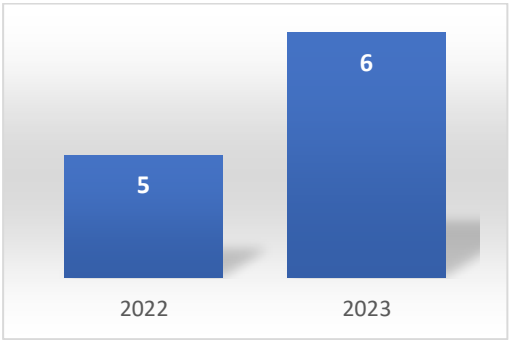


**Fig. 10. Organization of separate corridors for city passenger transport**

In terms of bicycle transport infrastructure, 77 km long bicycle lanes have been built on 12 streets of the city for bicycle transport users in 2018-2021.

In order to create the necessary infrastructure for bicycles, it is planned to build 250 bicycle lanes and establish bicycle shelters in front of 480 enterprises, organizations and offices (Figure 11).


**Fig. 11. Bicycle infrastructure development plan**

Currently, the number of passenger cars licensed to provide taxi service to passengers through non-directed taxi activity in Tashkent is more than 11,000, and the average term of ownership of taxi cars is 15 years.

Payments for the taxi service provided by entrepreneurs and organizations engaged in the activity of a taxi without direction are mainly made in cash.

The increase of non-directed taxi companies will greatly contribute to the development of urban transport (Figure 12).

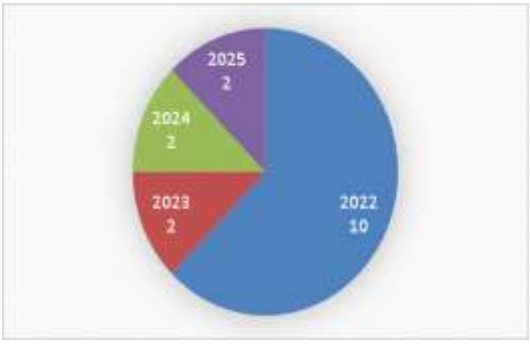


**Fig. 12. Plan to increase the number of taxis without directions**

In the public transport system of Tashkent city, the rate of use of information and communication technologies is on average 35-37 percent.

Today, the Automated Fare Payment (ATTO) and Automated Dispatch Management (ASDUM) systems have been introduced to automate the business processes of public transport operations.

In order to expand the capabilities of the automated payment system in public transport, the sale of transport cards has been established at special transport card sales points, metro ticket offices and self-service bank terminals (info-kiosks) located in the city, as well as mobile applications of the main electronic payment system (ATTO, Raume, Click, Uzcard, Apelsin, etc.) made it possible to top up transport cards with funds.

Through the automated dispatching management (ASDUM) system, monitoring of buses in public transport, allocation of buses to routes, control of stopping time at intermediate stops, control of violations of traffic rules, control of compliance with the bus timetable, control of the intermediate distance (interval) of buses has been established. Also, in order to create convenience for passengers, the mobile application "Tashkent Transport" has been developed, through this application: real-time monitoring of the city's public transport traffic, information about public transport intermediate stops and metro stations near the user's location, traffic location, directions as well as saving movement history, route planning (finding the fastest and easiest way to plan movement in city public transport), quickly finding points (geolocations) of electronic transport card sales points and determining the bus route to this destination, route guide (without using a private vehicle provides a clear guide on how to get from point A to point B).

## 4. Conclusion

As a result of this research, it clearly shows the relevance of re-evaluating the existing types of transport in the city of Tashkent. The existing transport system is reason enough to attract the majority of people who can afford a car to use bus

transport for mobility. Driver behavior is influenced by many factors, including personal characteristics, environment, and vehicle characteristics. Bus drivers are generally required to have a high level of training and experience, and an attitude that promotes safe driving in accordance with their profession. Also important are the vehicle's characteristics, and the need to adhere to the work schedule for the comfort/safety of the passengers. Also, equipping public transport for persons with disabilities, continuing to introduce special mobile programs to improve the work of public transport, introducing the use of navigation boards, route tables and voice warnings at stations, separate to separate directions of action, it is necessary to introduce strict restrictions on passenger capacity in public transport.

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# Theoretical investigation of fiber-reinforced concrete beams dispersely reinforced with basalt and steel fibers

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Abstract: In this study, the maximum flexural load-bearing capacity of steel and basalt fiber-reinforced concrete beams was investigated through theoretical calculations. The ultimate bending moments of beams reinforced with different proportions of steel and basalt fiber mixtures were analyzed in detail. The theoretical results showed that the beam reinforced with steel fibers demonstrated the highest ultimate bending moment, confirming it as the most efficient option in terms of load-bearing capacity. At the same time, hybrid fiber-reinforced beams provided an optimal balance between load capacity and deformation resistance. The findings indicate that the proportion and dispersion of fibers have a significant influence on the mechanical behavior of beams under bending, and theoretically confirm the potential for designing and optimizing new types of fiber-reinforced concrete structures using a combination of steel and basalt fibers.

Keywords: fiber-reinforced concrete, steel fibers, basalt fibers, ultimate bending moment, dispersed reinforcement, flexural strength

## 1. Introduction

In modern construction, extensive research is being conducted to improve the reliability, long-term strength, and operational durability of load-bearing reinforced concrete structures [1]. Traditional reinforced concrete elements, particularly beams subjected to bending, tend to lose their initial strength characteristics under external loads due to increasing deformations and the formation and propagation of cracks [2]. Early crack formation not only limits the load-bearing capacity of the structure but also poses a serious threat to its overall reliability, service life, and seismic resistance [3]. Therefore, improving the crack resistance of concrete, enhancing its energy absorption capacity, and stabilizing deformations have become some of the most urgent issues in contemporary construction science [4]. Dispersed reinforcement of the concrete matrix using various fibers is considered one of the most promising solutions to this problem. As a result of dispersed reinforcement, a micro-reinforcement system is formed within the material, which redistributes internal stresses under load, delays crack initiation and propagation, and significantly increases the crack resistance of the structure [5]. In this regard, the combined use of basalt and steel fibers has attracted considerable scientific interest due to its potential for higher efficiency.

Steel fibers, owing to their high elastic modulus, high tensile strength, and excellent energy absorption capacity under loading, improve the plastic behavior of beams at the final stage of bending [6]. Basalt fibers, on the other hand, are distinguished by their corrosion resistance, high thermal stability, low water absorption, and environmental safety. Their combined application can enhance not only the strength and deformation characteristics of concrete but also its long-term performance. However, the interaction of these two fiber types, the effect of their proportion and dispersion, and their mechanisms of influence on the concrete matrix have not yet been sufficiently studied [7]. In particular, scientific sources on the theoretical modeling of bending behavior, crack resistance, load-bearing capacity at ultimate limit states, and stress–strain behavior of fiber-reinforced concrete beams strengthened with hybrid basalt–steel fibers are still limited [8]. Due to the variability of experimental results, the need for developing theoretical foundations and mathematical models is becoming increasingly evident [9].

The primary objective of this study is to theoretically analyze the crack resistance, stress–strain behavior, and flexural performance of fiber-reinforced concrete beams dispersedly reinforced with basalt and steel fibers. The research focuses on determining the influence of fiber content, distribution ratio, and geometric parameters on the crack resistance of the structure, as well as providing mathematical justification for beam performance under limit states. The theoretical results obtained in this study will contribute to identifying optimal fiber-reinforced concrete compositions, improving design standards, and expanding the practical application of highly crack-resistant beams in construction.

## 2. Methodology

In this study, the strength of fiber-reinforced concrete beams was evaluated based on theoretical calculations. For the analysis, each geometric variant of the beams was assumed to have the following dimensions: length – 1500 mm, width – 150 mm, and height – 200 mm. The combinations of fiber content considered in the theoretical calculations of fiber-reinforced concrete beams are presented in Table 1.

In the theoretical calculations, fibers were considered as reinforcing elements influencing the mechanical properties of concrete. The performance of fiber-reinforced concrete is evaluated based on the following parameters:

- Flexural strength of the beam;
- Moment of inertia and the equivalent modulus of the cross section;

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- Tensile efficiency of concrete depending on the type of fiber;
- Variable modulus of elasticity and post-cracking behavior depending on the fiber ratio and total content.

**Table 1**

**Fiber content combinations considered in the theoretical analysis of fiber-reinforced concrete beams**

| № | Series | Total fiber content in concrete, % | Basalt fiber content, % | Steel fiber content, % |
|---|---|---|---|---|
| 1 | BO | 0 | 0 | 0 |
| 2 | BP100B0 | 0.2 | 0 | 100 |
| 3 | BP75B25 | 0.2 | 25 | 75 |
| 4 | BP50B50 | 0.2 | 50 | 50 |
| 5 | BP25B75 | 0.2 | 75 | 25 |
| 6 | BP0B100 | 0.2 | 100 | 0 |

In the theoretical analysis, the strength parameters of the reinforcement and concrete were adopted based on the results of experimental studies conducted under laboratory conditions. The actual values of the concrete compressive strength, modulus of elasticity, and tensile strength of the reinforcement were incorporated into the theoretical model. As a result, the parameters used in the calculations fully reflected the real physical and mechanical properties of the materials.

Determining the ultimate load-bearing capacity of rectangular fiber-reinforced concrete beams is one of the main directions of the theoretical analysis, taking into account the residual tensile resistance of the concrete and the contribution of hybrid fibers—basalt and steel. The tensile strength of fiber-reinforced concrete, $R_{fbt}$, changes significantly in the presence of steel and basalt fibers, as the fibers maintain the concrete's integrity even after crack formation. Therefore, in addition to conventional reinforced concrete formulas, the residual tensile resistance, $R_{fbt3}$, must also be considered when determining the maximum bending moment. In fiber-reinforced concrete beams, the maximum bending moment is determined based on the moment equilibrium equation as follows:

$$\sum_{i=1}^{n} M = 0$$

Here, the concrete in compression, the tensile reinforcement, the area of reinforcement in the compression zone $A'_s$, the tensile strength of concrete $R_{fbt,}$ the residual tensile resistance associated with hybrid fibers $R_{fbt3}$, the beam width $b$, the beam height $h$, and the height of the compression zone $h$ are all taken into account. According to the theoretical analysis, the maximum bending moment is determined using the following expression:

$$M_{ult} = R_{fb} \cdot b \cdot x \cdot (h_0 - 0{,}5x) - R_{fbt3} \cdot b \cdot (h - x) \cdot \left(\frac{h-x}{2} - a\right) + R_{sc} \cdot A'_s(h_0 - a') \quad (1)$$

Here:

$R_{fbt}$ - Tensile strength of fiber-reinforced concrete,

$R_{fbt3}$ - Residual tensile resistance under the action of hybrid (basalt + steel) fibers,

$b$ - Beam width,

$h$ - Beam height,

$x$ - Height of the compression zone,

$Rsc$ - Design compressive resistance of the reinforcement,

$A'_s$ - Area of reinforcement in the compression zone.

These parameters directly influence the load-bearing capacity of the beam; therefore, fiber-reinforced concrete strengthened with hybrid fibers can be accurately evaluated using the described equation. When basalt and steel fibers are combined, the residual tensile resistance, crack initiation, and propagation significantly change. While steel fibers provide high tensile strength, basalt fibers slow down the spread of cracks. The combined effect of these two types of fibers enhances the residual strength of the concrete. Determining the height of the compression zone in fiber-reinforced concrete beams is also an integral part of the analysis, as this parameter defines the balance between the concrete in compression and the concrete in tension. The height of the compression zone is determined using the force equilibrium equation:

$$\sum_{k=1}^{n} F_{kx} = 0$$

$$x = \frac{R_s \cdot A_s - R_{sc} \cdot A'_s + R_{fbt3} \cdot b \cdot h}{(R_{fb} + R_{fbt3}) \cdot b} \quad (2)$$

This expression is formulated in accordance with the mechanical properties of fiber-reinforced concrete with hybrid fibers, taking into account the residual tensile resistance. The combined action of basalt and steel fibers allows the concrete in the tensile zone to continue carrying part of the stresses even after cracks have formed. As a result, stress redistribution occurs, and the load-bearing capacity of the beam increases compared to conventional reinforced concrete structures. Steel fibers play a primary role in increasing the maximum bending moment due to their high tensile strength, while basalt fibers limit crack propagation and ensure deformation stability. Their combination significantly enhances the residual tensile resistance of the concrete and extends the elastic-plastic behavior up to the ultimate limit state. Theoretical calculations indicate that fiber-reinforced concrete beams strengthened with hybrid fibers exhibit higher compression zone height, greater residual tensile resistance in the tensile zone, and a higher maximum bending moment compared to other variants.

## 3. Results and Discussion

The maximum load-bearing capacity of fiber-reinforced concrete beams based on fiber content is presented in Table 2.

**Table 2**

**Maximum load-bearing capacity of fiber-reinforced concrete beams**

| № | Series | Ultimate bending moment, kN·m |
|---|---|---|
| 1 | BO | 14.58 |
| 2 | BP100B0 | 18.64 |
| 3 | BP75B25 | 18.29 |
| 4 | BP50B50 | 17.50 |
| 5 | BP25B75 | 17.21 |
| 6 | BP0B100 | 16.89 |

According to the results, the steel fiber-reinforced concrete beam (BP100B0) exhibited the highest ultimate bending moment of 18.64 kN·m. In the hybrid fiber compositions, the maximum moments were 18.29 kN·m for

the BP75B25 series, 17.50 kN·m for the BP50B50 series, and 17.21 kN·m for the BP25B75 series. The basalt fiber-reinforced beam (BP0B100) demonstrated a maximum load-bearing capacity of 16.89 kN·m. These results indicate that steel fibers are more effective in enhancing the flexural strength of the beams, while the inclusion of basalt fibers results in a slight reduction. At the same time, the load-bearing capacity of beams reinforced with a combination of steel and basalt fibers exceeds that of conventional reinforced concrete beams, confirming the practical applicability of this type of fiber-reinforced concrete structure in engineering practice.

The fiber ratio has a significant effect on the bending moment of the beam. Steel fibers, due to their high modulus of elasticity, increase the beam's ultimate bending moment. The maximum load-bearing capacity of fiber-reinforced concrete beams dispersedly reinforced with basalt and steel fibers is shown in Figure 1.

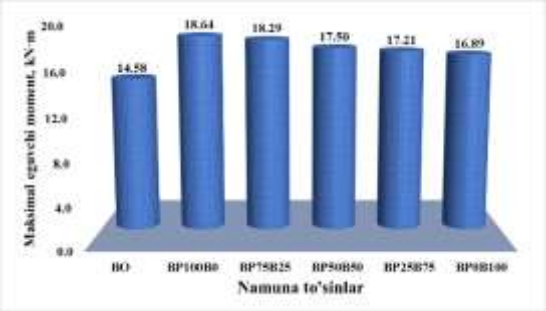


**Fig. 1. Ultimate bending moment**

## 4. Conclusion

In this study, the maximum load-bearing capacity of fiber-reinforced concrete beams with steel and basalt fibers was theoretically investigated. The experiments led to the following scientifically significant conclusions:

1. High efficiency of steel fiber-reinforced concrete:** The beam reinforced solely with steel fibers (BP100B0) exhibited the highest ultimate bending moment of 18.64 kN·m. This is attributed to the high modulus of elasticity and tensile capacity of steel fibers, which reduce deformation under load and enhance structural safety.

2. Optimal combinations with hybrid fibers: Beams reinforced with varying ratios of basalt and steel fibers (BP75B25, BP50B50, BP25B75) also demonstrated high load-bearing capacity, with ultimate moments ranging from 17.21 to 18.29 kN·m. This indicates that the load-enhancing properties of steel fibers are maintained even when combined with basalt fibers, while basalt fibers provide additional benefits by controlling cracking and increasing structural ductility.

3. Role of basalt fibers: The beam reinforced solely with basalt fibers (BP0B100) exhibited the lowest ultimate moment of 16.89 kN·m. Nevertheless, basalt fibers improve resistance to linear deformations through their high stiffness and dispersive distribution, which is crucial for structures subjected to heavy loads.

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# Problems and damages in road and bridge structures, as well as increasing their bearing capacity with gabion structures

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Abstract: This article examines the increase in the load-bearing capacity of road and bridge structures and the causes of failures. The scientific basis for the application of composite-type gabion structures in the protection of transport structures, protection from erosion, water flows, and other external factors is highlighted, and the purpose of this article is to review innovations in the field of bridge construction, to describe advanced materials and structural solutions. Possibility of sustainability, environmental safety with the help of gabions. Highly effective and universal methods of strengthening, stabilizing, and protecting slopes and road surfaces in operation using gabion structures, bridge cones, bridge supports, regulating dams, embankments, and other structures. The work on increasing the load-bearing capacity of gabion structures is considered.

Keywords: bridge construction, load-bearing capacity, materials, structures, structural solutions, innovative bridge construction, composite mesh gabion structures

## 1. Introduction

In accordance with the provisions of the Transport Strategy of the Republic of Uzbekistan for the next period, the main task of the transport complex is the transition to an innovative, socially oriented type of development, which requires appropriate strategic solutions for the development of the road sector and the construction of long-term transport facilities in the medium and long term.

It is impossible to construct a modern highway that preserves the load-bearing capacity of road and bridge structures, the service life, and the smoothness of the pavement for a long time, without high quality of the earthwork, especially on weak soil foundations, under hydrological and climatic conditions, as well as under conditions of seismic activity of construction areas characteristic of different regions of the Republic of Uzbekistan.

The construction and operation of bridge structures and highways in mountainous areas, near mountain rivers, in landslide and avalanche zones, in zones of constant flooding and flooding, is always accompanied by great difficulties. The construction of roads near unstable mountain slopes often disrupts their balance, causes landslides, rockfalls, and activates landslides. Bridge construction is not only a technical activity, but also a scientific activity aimed at the development of new materials and technologies. The construction, reconstruction, and repair of bridges is one of the most complex types of construction work. Many bridges are monuments of engineering thought that have already entered urban architecture. Bridge construction is carried out taking into account the specific features of the terrain and requires complex calculations that take into account the specific properties of the soil, the loads on the supports, and much more. In addition, it is necessary to take into account the intensity of movement and the influence of external factors.

In the Republic of Uzbekistan, more and more bridges are deteriorating or being destroyed year by year. Many bridges and many other artificial structures are already dilapidated, and repair and construction work is underway. This article examines modern technologies of bridge construction, innovations in the field of bridge construction, describes advanced materials and design solutions used in bridge construction.

The purpose of this article is to consider the problems of road and bridge structures and their solutions, as well as innovations, to describe advanced materials and constructive solutions.

## 2. Methodology

Analysis of damage to road structures shows that the degree of their destruction depends on the engineering and geological properties of the terrain, the properties of the soils, the roadbed and foundations, the structural features of the structures, the seismological situation, the quality of road construction, etc.

A distinctive feature of long-distance transport structures, i.e., highways, is that these structures intersect areas with different geotectonic structures. For such structures, the problem of ensuring viability, i.e., functionality under conditions of operation, maintenance, and the influence of the geological environment, is especially relevant.

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**Fig. 1. Sections of the road damaged due to the loss of bearing capacity of the base**

These routes pass through territories with different geological environments and climatic conditions. This means that it is necessary to make specific decisions for each region. In areas consisting of soils susceptible to heavy rainfall or various influences, it is necessary to adopt specific design solutions, otherwise, after the construction of the above-mentioned engineering structures and structures, over time, loess soils usually become moist and lose their strength properties, leading to the loss of the structure's load-bearing capacity and its destruction (Fig. 1).

The main part of the territory of the Republic of Uzbekistan consists of loess and alluvial soils with a thickness of 5-25 meters, unstable to various influences. Currently, many road and bridge structures in our Republic are in need of repair. The reason for this can be attributed to the fact that appropriate diagnostic work was not carried out during operation, and measures against various minor failures were not taken in a timely manner. One such case is the emergency of a transport facility located in the territory of the Kosjap MFY of the Republic of Karakalpakstan (Fig. 2). The reason for this is that, in addition to what we mentioned above, the soil lost its load-bearing capacity, that is, due to the absence of a special protective layer on the sides of the structure, it could not withstand the water flow and washed the pipes.

**Fig. 2. Loss of load-bearing capacity of a structure as a result of soil erosion**

One of such solutions is the use of gabion structures that prevent the mixing of excessively moistened clay soil with road pavement materials, distribute the load from vehicle wheels over a large area of the road pavement, reduce the unevenness of pavement deformations under dynamic and seismic impacts, and allow for more complete realization of the strength of soils and road-building materials, reducing their consumption and the volume of work on the transportation, laying, and compaction of incoming materials. Global experience shows that gabion structures have always been and remain an alternative option for strengthening the slopes of not only flooded, but also non-flooded road structures.

In world practice, gabion structures have been used for more than 100 years. They are used for reinforcing slopes of embankments and embankments, slopes, banks of intersected watercourses, ravines, water intake, regulation, and other road and bridge structures. In domestic practice, these structures have limited application, and in standard solutions of previous years, they are provided only for reinforcing flooded slopes of the earthwork.

Gabion structures are widely used to ensure uniform load on cones, their reliable fastening, and long-term service. They allow protecting the supports from deformation and reducing their operating time. In addition, gabions perform the function of protecting the support from damage. Fillers for the soil are selected depending on the soil type[2]. They are used in the construction of railways and tunnels. They possess high operational properties. Valuable properties of metal pipes and prefabricated structures made from them are strength, durability and cost-effectiveness, ease of installation and transportation, and seismic resistance.

Calculations based on mathematical modeling show that composite gabion structures serve to reduce soil displacement around the bridge foundation to a certain extent. This guarantees long-term use. In addition, retaining walls made of gabions are used as supporting structures for reinforcing road embankment slopes, strengthening landslide and collapse areas, and unstable slopes on weak soils. Walls made of gabions can be made both vertical and stepped with a front edge.

**Fig. 3. Gabion structures**

For the analysis of the embankment's condition, the determination of the forces acting on the supporting structures from gabions, the calculation of the main parameters of the structure, their strengthening, the development of technologies, and the feasibility study of the proposed solutions, the materials of engineering studies of the precise embankment on section PK 183+55 of the A380 Guzar-Bukhara-Nukus-Beyneu road are presented [7].


https://doi.org/10.56143/3030-3893-2025-4-56-59 A bridge between science and innovation

As a result of the conducted research, it was established that the primary factors affecting the roadbed, leading to a violation of the overall stability of the roadbed, are rainfall, the flow of snow and rainwater along the slope surface, groundwater filtration, and changes in air temperature. When calculating the stability of embankments and designing gabion support structures, permanent loads, movable axial loads (kN/axis), and short-term seismic loads were taken into account. Conducted model calculations and studies showed that soil reinforcement and hardening from gabions gave the embankment additional positive properties.[8]

**Fig. 4. Coating water pipes with gabions**

It is advisable to cover the above-mentioned water pipes with gabion structures. Because it is much more convenient and economical in terms of ecology, construction, and economy. The long-term stability of bridge structures largely depends on the condition of the soil around the supports. As a result of the action of the water flow, the soil around the support is subjected to erosion, which reduces the overall stability of the bridge. Therefore, the use of gabion structures in protecting the support area has been widely used in recent years. Composite mesh gabions are distinguished by high durability and low weight compared to traditional types of metals. Composite gabions showed high stability to the water flow. They do not rust, have a long service life, are lightweight, and are easy to install. The mechanical strength of polymer-based networks is high, and the displacement index of the soil around the bridge is significantly reduced with the help of composite materials.

## 3. Conclusion

As a result of the analysis of the capabilities of gabion structures, it was established that in a number of cases they are more expedient and economical than traditional structures. The purpose of this article was to review innovations in the field of bridge construction, to describe progressive materials and constructive solutions. Thus, modern construction technologies and modern building materials allow increasing the pace of construction without compromising the quality of construction or the coating, as well as reducing the labor intensity and costs of construction. Currently, in the world, traditional materials are being gradually replaced by polymers, composites, and other materials. Along with traditional materials such as concrete, steel, and wood, new composites have appeared that optimize the properties of materials. Composite material is very popular in bridge construction abroad. This will allow bridge structures based on composites to successfully compete with bridges made of traditional materials, and will also contribute to the spread of modern bridge structures in Uzbekistan. In the future, technological improvements in this area will contribute to the creation of more efficient systems. The goal of the article has been achieved.

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# Experimental measurement and mathematical modeling of UAV telemetry channel behavior under radio-electronic warfare

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Abstract: This study presents a comprehensive analysis of the resilience of telemetry modules operating in different frequency bands under radio-electronic warfare (REW) conditions, based on both experimental measurements and mathematical modeling. TBS Crossfire (868 MHz) and LoRa SX1278 (433 MHz) modules integrated with an STM32 microcontroller were tested at various distances (50 m, 100 m, 200 m) under a 10 W jamming signal. During the measurements, key telemetry parameters—including Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR), effective SNR, Signal-to-Interference-plus-Noise Ratio (SINR), and Packet Loss Ratio (PLR)—were recorded. Within the mathematical analysis framework, the path loss model, SNR-to-SINR transition, effective SNR formulation, and modulation-dependent BER functions were systematically derived to theoretically evaluate the impact of jamming on the telemetry channel. The results demonstrate that the TBS Crossfire module exhibits significantly higher resistance to electromagnetic interference generated by REW sources, maintaining lower BER and stable effective SNR across the tested distances. In contrast, the LoRa SX1278 module experiences substantial degradation in signal quality under jamming, leading to elevated packet loss. These findings are crucial for establishing reliable design criteria for UAV telemetry systems operating in REW environments.

Keywords: Telemetry, UAV, Electronic Warfare (EW), STM32, SINR, BER, Path Loss, TBS Crossfire, LoRa SX1278

## 1. Introduction

The role of unmanned aerial vehicles (UAVs) in modern military and civilian applications is rapidly expanding. In particular, the reliability of UAV telemetry systems is considered one of the key determinants in executing functions such as reconnaissance, surveillance, strike missions, and data acquisition [4], [10]. The telemetry channel transmits critical flight parameters—including position, velocity, altitude, power level, and GPS coordinates—to the operator in real time, thereby ensuring continuity of control [6].

However, the widespread deployment of electronic warfare (EW) systems poses a serious threat to telemetry channels. EW sources can disrupt UAV control and data transmission systems by attenuating telemetry signals, generating various levels of interference, or injecting additional noise through high-intensity electromagnetic radiation [8], [9]. Therefore, evaluating the behavior of the telemetry channel through both experimental testing and mathematical modeling is essential [2], [3].

In this study, two telemetry systems operating in different frequency bands—TBS Crossfire (868 MHz) and LoRa SX1278 (433 MHz)—were integrated with an STM32 microcontroller and comparatively tested under EW conditions. The resilience of these modules under jamming was analyzed based on multi-parameter measurements [1], [5], [7].

In parallel with the experimental tests, a sequential mathematical model incorporating EW effects was also developed. This model comprises the following stages:

1. **Path loss model**, characterizing distance-dependent signal attenuation;
2. **Received signal power**, $P_r$;
3. **Signal-to-Noise Ratio (SNR)** as a primary indicator of channel quality;
4. **Signal-to-Interference-plus-Noise Ratio (SINR)**, incorporating jamming interference;
5. **Effective SNR**, representing real transmission performance;
6. **BER (Bit Error Rate)** models for various modulation schemes;
7. **Transition from BER to frame loss probability**, represented by the PLR function.

This sequential structure enables the theoretical model and experimental results to complement one another, providing an objective evaluation of telemetry channel performance under EW conditions [2], [4], [9].

## 2. Methodology

The tests were conducted in a closed laboratory environment, and a jammer device generating 10 W of electromagnetic interference was used to simulate EMI effects. The center frequency of the jammer signal was adjusted to match the operating frequency ranges of the corresponding telemetry channels, and a constant level of interference intensity was maintained throughout all measurement phases. This approach is considered consistent with international practice for modeling EMI effects on

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telemetry signals under near-real combat conditions [8], [9], [10].

The general parameters of the test conditions are as follows:

- **EMI power:** 10 W (directed)
- **Test distances:** 50 m, 100 m, 200 m
- **Environment:** Enclosed laboratory, multipath channel
- **Receiving antenna height:** 1.4 m
- **Transmitting antenna height:** 1.5 m
- **Signal modulation mode:**
- TBS Crossfire – adaptive spread spectrum
- LoRa SX1278 – chirp spread spectrum (CSS)

**Measured Parameters**

During the study, the following signal parameters were recorded:

1. **RSSI (Received Signal Strength Indicator), dBm** – received signal power
2. **SNR (Signal-to-Noise Ratio), dB** – signal-to-noise ratio
3. **Effective SNR** – actual signal quality calculated with packet loss taken into account
4. **PLR (Packet Loss Ratio), %** – ratio of lost packets
5. **SINR (Signal-to-Interference-plus-Noise Ratio)** – signal-to-noise-and-interference ratio including EMI effects

All parameters were recorded as average values based on at least 50 measurements for each distance.

## 3. Results

**Table 1**

**Description of the Measured Parameters**

| Parameter | Description |
|---|---|
| **RSSI** | Evaluation of the received signal strength |
| **SNR** | Resistance of the signal against background noise |
| **Effective SNR** | Combined impact of SNR and packet loss |
| **PLR (%)** | Relative proportion of lost data frames |
| **SINR** | Actual signal quality considering EW-induced interference |

**Table 2**

**Experimental Results of the TBS Crossfire (868 MHz) Module Under EW Conditions**

| Distance (m) | RSSI (dBm) | SNR (dB) | PLR (%) | Effective SNR (dB) |
|---|---|---|---|---|
| **50** | –65 | 14 | 2.0 | 13.72 |
| **100** | –73 | 10 | 8.0 | 9.20 |
| **200** | –82 | 6 | 20.0 | 4.80 |

**Table 3**

**Experimental Results of the LoRa SX1278 (433 MHz) Module Under EW Conditions**

| Distance (m) | RSSI (dBm) | SNR (dB) | PLR (%) | Effective SNR (dB) |
|---|---|---|---|---|
| **50** | –70 | 12 | 5.0 | 11.40 |
| **100** | –78 | 8 | 15.0 | 6.80 |
| **200** | –86 | 4 | 30.0 | 2.80 |

**Mathematical model — complete sequential academic form**

**Mathematical model of the telemetry channel under EW conditions**

To objectively evaluate the performance of the telemetry channel under electronic warfare (EW) interference, it is necessary to sequentially construct a set of analytical expressions. This includes building a **path loss model** that characterizes radio-link attenuation, computing the **received signal power**, deriving the **Signal-to-Noise Ratio (SNR)**,

incorporating jamming effects to obtain the **Signal-to-Interference-plus-Noise Ratio (SINR)**, and finally applying **Bit Error Rate (BER)** functions for the selected modulation scheme. Integrating these parameters step by step enables the formation of a comprehensive mathematical model that accurately describes the telemetry channel's behavior under EW conditions from both theoretical and practical perspectives [2], [3], [9].

**Generalized Path Loss Model**

For a transmitter with power $P_t$and link distance $d$, the generalized path loss expression is given by:

$$PL(d) = PL_0 + 10n \log_{10}\left(\frac{d}{d_0}\right) + I_{\text{EW}} \quad (1)$$

where:

- $PL_0$— reference path loss at distance $d_0$(dB),
- $n$— propagation constant of the environment,
- $I_{\text{EW}}$— additional attenuation/interference due to EW radiation (dB).

**Received Signal Power**

The received signal power in dBm is expressed as:

$$P_r(\text{dBm}) = P_t(\text{dBm}) - PL(d)\ (\text{dB}) \quad (2)$$

**Signal-to-Noise Ratio (SNR)**

Assuming that the receiver noise power $P_N$(AWGN) is constant, the SNR in dB is:

$$SNR_{\text{dB}} = P_r(\text{dBm}) - P_N(\text{dBm}) \quad (3)$$

The linear (dimensionless) form of SNR is:

$$\gamma_{\text{SNR}} = 10^{(SNR_{\text{dB}}/10)} \quad (4)$$

**Effective SNR (Considering Packet Loss)**

During experimental measurements, packet loss $p_{\text{loss}}$(%) was observed due to EW interference. To reflect realistic operational conditions, the Effective SNR is defined as:

$$\gamma_{\text{eff}} = \gamma_{\text{SNR}}\left(1 - \frac{p_{\text{loss}}}{100}\right) \quad (5)$$

Its dB representation is:

$$SNR_{\text{eff,dB}} = 10\log_{10}(\gamma_{\text{eff}}) \quad (6)$$

**Signal-to-Interference-plus-Noise Ratio (SINR)**

In EW environments, the telemetry channel is affected not only by noise, but also by a jamming transmitter. Thus, the SINR is defined as:

$$\gamma_{\text{SINR}} = \frac{P_s}{P_j + P_N} \quad (7)$$

where:

- $P_s$— useful signal power,
- $P_j$— jammer power,
- $P_N$— noise power.

After converting all terms from dBm to linear units:

$$\gamma_{\text{SINR}} = \frac{10^{(P_s(\text{dBm})/10)}}{10^{(P_j(\text{dBm})/10)} + 10^{(P_N(\text{dBm})/10)}} \quad (8)$$

**Bit Error Rate (BER) Model**

For BPSK/QPSK modulation in AWGN, the classical BER expression is:

$$BER_{\text{AWGN}} = Q(\sqrt{2\gamma_{\text{SNR}}}) \quad (9)$$

where $Q(\cdot)$is the Q-function.

Including the effect of EW interference and using effective SINR:

$$BER_{\text{EW}} = Q(\sqrt{2\gamma_{\text{SINR,eff}}}) \quad (10)$$

The effective SINR used in empirical analysis is approximated as:

$$\gamma_{\text{SINR,eff}} \approx \gamma_{\text{SINR}}\left(1 - \frac{p_{\text{loss}}}{100}\right) \quad (11)$$

**Summary of Model Behavior Under EW Conditions**

This mathematical model enables comparative analysis of the TBS Crossfire (868 MHz) and LoRa SX1278 (433 MHz) telemetry modules under EW interference. As the distance increases, the path loss $PL(d)$increases, resulting in reduced received power $P_r$and SNR. As the jammer power $P_j$increases, the SINR decreases sharply, and consequently the BER $_{\text{EW}}$ grows significantly.

These dependencies explain the experimentally observed degradation patterns in LoRa SX1278 and the superior performance stability of the TBS Crossfire module.

Using the mathematical expressions presented in equations (1)–(11), the distance-dependent graphs of RSSI, SNR, effective SNR, and BER under EW conditions were generated based on the experimental data provided in Tables 2 and 3. These graphs make it possible to evaluate the consistency between the theoretical model of the telemetry channel and real experimental observations under EW interference.

For plotting the graphs, the Python programming language and the Matplotlib library—widely used in scientific data visualization—were employed. This approach ensures that the visualized results are precise, analytically interpretable, and fully reproducible [2], [4], [9].

As shown in Figure 1, when the distance increases from 50 m to 200 m, the received signal strength (RSSI) of the TBS Crossfire module decreases from –65 dBm to –82 dBm. This behavior is fully consistent with the path loss model described by equation (1), confirming that the wideband 868 MHz telemetry channel maintains a certain degree of signal stability even under EW interference. The linear degradation trend observed in RSSI aligns with previous studies reporting the high resistance of the TBS Crossfire module to electromagnetic interference [2], [4], [9].

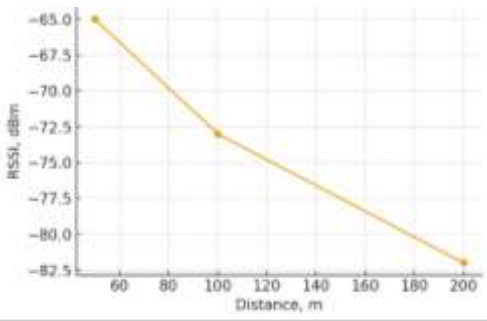



**Fig. 1. Distance-dependent variation of the received signal strength (RSSI) for the TBS Crossfire (868 MHz) module**

This graph (Figure 2) illustrates the variation of SNR and effective SNR with increasing distance for the TBS Crossfire (868 MHz) module, while also presenting, for comparison, the sharp degradation of RSSI for the LoRa SX1278 module under EW conditions. The results indicate that both SNR and effective SNR in the TBS Crossfire module remain within functional limits despite the increase in distance, thereby maintaining the stability of the telemetry channel.

In contrast, the rapid decline of RSSI in the LoRa SX1278 module confirms that narrowband 433 MHz systems are significantly more vulnerable to electromagnetic interference. These observations are consistent with previous studies emphasizing that wideband telemetry solutions in UAV systems perform more effectively under EW and jamming conditions [3], [4], [8], [10].

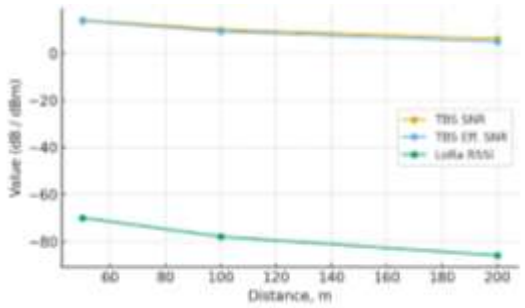



**Fig. 2. Distance-dependent variation of SNR and Effective SNR for the TBS Crossfire module, and RSSI degradation for the LoRa SX1278 module**

The graph (Figure 3) illustrates the variation of the SNR of the TBS Crossfire telemetry module under EW interference at distances of 50 m, 100 m, and 200 m. As shown, the SNR decreases progressively as the distance increases (14 dB → 10 dB → 6 dB); however, throughout the entire range, the signal-to-noise ratio remains above the minimum threshold required for uninterrupted communication.

This behavior is consistent with scientific studies indicating that wideband 868 MHz telemetry systems exhibit higher resilience to electromagnetic interference [3], [4], [9]. The results obtained from the graph confirm that the TBS Crossfire module maintains stable signal quality under EW conditions, demonstrating its advantage for reliable data transmission in UAV telemetry channels [2], [8].

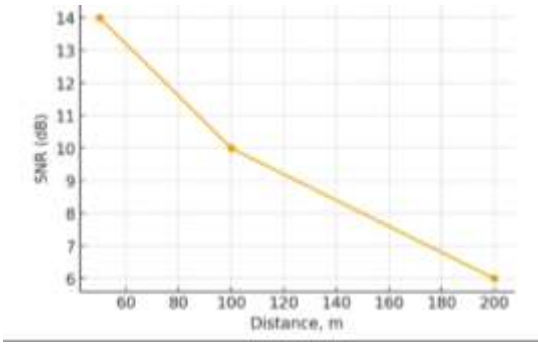
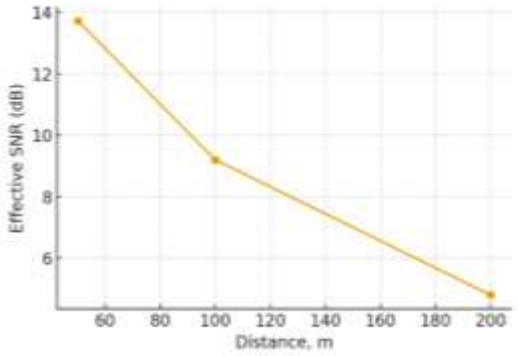



**Fig. 3. Distance-dependent variation of the signal-to-noise ratio (SNR) for the TBS Crossfire (868 MHz) module**

The graph (Figure 4) presents the variation of the effective SNR of the TBS Crossfire telemetry module under EW conditions at distances of 50 m, 100 m, and 200 m. Effective SNR is a more practical and realistic indicator, as it accounts not only for the received signal quality (SNR) but also for packet losses that occur during data transmission.

As shown in the graph, effective SNR gradually decreases as the distance increases; however, despite the impact of EW interference, the wideband 868 MHz telemetry channel maintains the minimum level of communication stability required for reliable operation. This result is consistent with scientific studies demonstrating that wideband systems exhibit greater robustness and resilience under interference conditions [3], [5], [8], [9].




**Fig, 4. Distance-dependent variation of the effective SNR for the TBS Crossfire (868 MHz) module**

## 4. Conclusion

The experimental and mathematical investigations conducted in this study provided a comprehensive evaluation of the robustness and data transmission performance of telemetry systems operating in different frequency bands under electronic warfare (EW) conditions. Testing the TBS Crossfire (868 MHz) and LoRa SX1278 (433 MHz) modules—integrated with an STM32 microcontroller—at distances of 50 m, 100 m, and 200 m under a 10 W jamming signal demonstrated that the stability of the telemetry channel is critically dependent on both physical signal attenuation and the interference-induced SINR values.

The mathematical framework—comprising the path loss, SNR, SINR, effective SNR, and BER expressions—showed strong alignment with the experimental observations, clearly describing the mechanism through which EW affects telemetry links. Although RSSI and SNR decrease with distance in the TBS Crossfire module, the higher effective SNR, lower BER, and relatively reduced packet loss demonstrate that this module exhibits significantly greater resilience against EW interference. In contrast, the LoRa SX1278 module showed a sharp reduction in both RSSI and SNR, and the high PLR and theoretically elevated BER values confirm that electromagnetic interference has a stronger impact on the 433 MHz band.

Overall, the findings indicate that in environments with strong electromagnetic interference and where long-range telemetry is required, the TBS Crossfire module operating at 868 MHz provides more stable and reliable data transmission. The LoRa SX1278 module, on the other hand, is more suitable for short-range applications where EW influence is relatively mild.

The study presents a scientifically grounded approach

for the selection, design, and optimization of UAV telemetry systems operating under EW conditions and offers practical insights for the development of future defense and security communication architectures.

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# Assessment of dielectric insulation condition of power transformers using Dielectric Absorption Ratio (DAR) and Polarization Index (PI)

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Abstract: The operational reliability and service life of power transformers significantly depend on the condition of their solid dielectric insulation. Moisture ingress, thermal aging, and electrical stress alter the dielectric properties of insulation, reducing its electrical strength and accelerating degradation processes. This paper examines two widely used diagnostic indicators—the Dielectric Absorption Ratio (DAR) and the Polarization Index (PI)—which are employed to assess insulation moisture content and aging degree. The diagnostic criteria, interpretation of measured results, and significance of these indicators in predictive maintenance are presented.

Keywords: Dielectric Absorption Ratio (DAR); Polarization Index (PI); transformer insulation diagnostics; moisture assessment; dielectric response; solid insulation aging; time-domain insulation testing; insulation resistance; transformer condition monitoring; dielectric degradation

## 1. Introduction

Solid dielectric insulation plays a critical role in ensuring the operational stability and energy efficiency of power transformers and electrical machines. Variations in environmental humidity, temperature, mechanical stress, and prolonged exposure to electric fields cause changes in the insulation's dielectric characteristics. These changes lead to increased leakage current, reduced insulation resistance, higher dielectric losses, and deterioration of electric strength. Therefore, proper diagnostic evaluation of insulation condition is essential for preventing failures and planning maintenance.

Among various insulation diagnostics methods, the most informative and widely applied are the Dielectric Absorption Ratio (DAR) and the Polarization Index (PI). These parameters provide qualitative and quantitative assessments of insulation moisture levels and aging state.

## 2. Methodology

### 2.1 Dielectric Absorption Ratio (DAR)

The Dielectric Absorption Ratio (DAR) reflects the polarization processes occurring in the dielectric material and serves as an indicator of moisture content. DAR is determined by comparing insulation resistance values measured after 15 seconds ($R_{15}$) and 60 seconds ($R_{60}$):

$$DAR = \frac{R_{60}}{R_{15}}$$

### 2.2 Polarization Index (PI)

The Polarization Index (PI) reflects the insulation's aging state and slow polarization processes. It is calculated as the ratio of resistance measured at 600 seconds ($R_{600}$) to resistance at 60 seconds ($R_{60}$):

$$PI = \frac{R_{600}}{R_{60}}$$

Higher PI values indicate low leakage current and stable dielectric performance, while lower values indicate degradation.

PI provides deeper diagnostic insight compared to DAR because it captures slower polarization phenomena associated with structural insulation aging.

## 3. Results and Discussion

The presence of moisture significantly lowers insulation resistance due to dissolved ions that increase leakage current and dielectric losses (tgδ). This leads to:

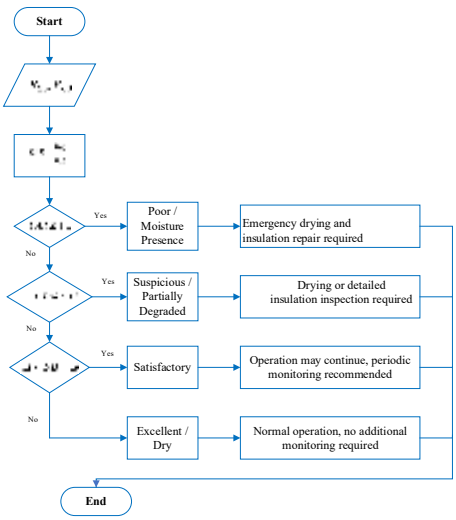


**Fig. 1. Diagnostic Flow Chart for Transformer Insulation Evaluation Based on Dielectric Absorption Ratio (DAR)**

- Increased heat generation in the insulation

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- Acceleration of thermal aging
- Reduced dielectric breakdown strength

Both DAR and PI decrease when insulation contains moisture, exhibits high ionic conductivity, or undergoes thermal-oxidative aging. This leads to:

- Reduction in electric breakdown strength
- Increase in dielectric losses
- Advancement of aging reactions
- Increased probability of catastrophic insulation failure

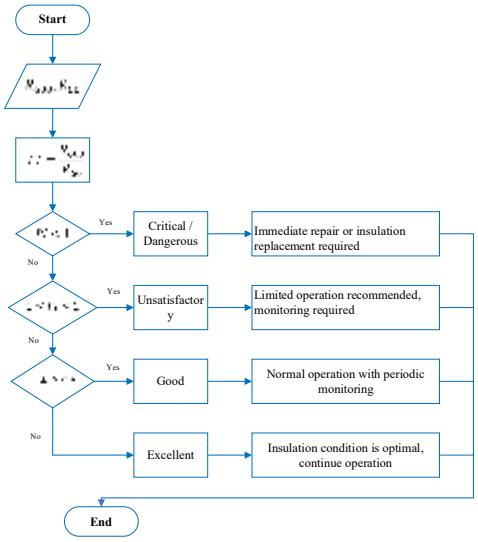


**Fig.2. Diagnostic Flow Chart for Transformer Insulation Evaluation Based on Polarization Index (PI)**

For comprehensive insulation evaluation, DAR and PI should be analyzed together with additional indicators such as:

- Dielectric loss tangent (tgδ),
- Capacitance variation,
- Temperature correction factors of insulation resistance.

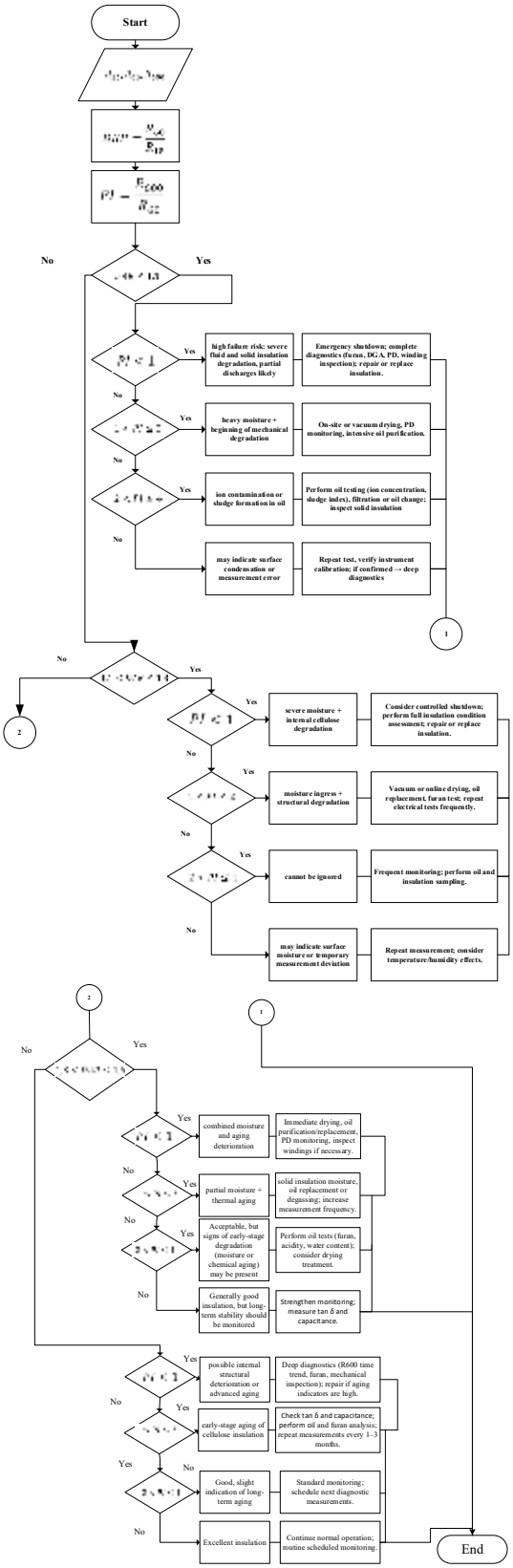


**Fig. 3. Combined diagnostic flow chart for insulation condition decision based on DAR and PI**

## 4. Conclusion

The experimental and mathematical investigations conducted in this study provided a comprehensive evaluation of the robustness and data transmission performance of telemetry systems operating in different frequency bands under electronic warfare (EW) conditions. Testing the TBS Crossfire (868 MHz) and LoRa SX1278 (433 MHz) modules—integrated with an STM32 microcontroller—at distances of 50 m, 100 m, and 200 m under a 10 W jamming signal demonstrated that the stability of the telemetry channel is critically dependent on both physical signal attenuation and the interference-induced SINR values.

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# Outsourcing: concept, objectives, and tasks, experience of implementing outsourcing in railway transport

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Abstract: Uzbekistan Railways JSC, taking into account the scale of its operations, has consolidated various competencies that exert influence at different levels in the implementation of its development strategy. Business processes that do not possess strategic significance should be considered as potential candidates for outsourcing. At present, the services market widely encompasses cleaning services, heat and water supply, maintenance of buildings and facilities, information technologies, and a range of other business processes. Intense competition enables the formation of appropriate benefits and advantages associated with delegating these functions to external execution.

Keywords: outsourcing, problems of the transport and freight services market, corporate outsourcing statistics

## 1. Introduction

Contemporary market conditions, environmental challenges, and the constant need to enhance the efficiency of Uzbekistan Railways JSC require not only the rational use of resources but also the restructuring of business processes. Taking into account the scale of its operations, the company has consolidated various competencies that influence the implementation of its development strategy at different levels. Business processes that do not possess strategic importance should be regarded as potential candidates for outsourcing.

Today, the service market widely applies outsourcing in areas such as cleaning services, heating and water supply, maintenance of buildings and facilities, information technologies, and other auxiliary business processes. Intense competition enables the identification of benefits associated with delegating such functions to external providers, thereby forming advantages in efficiency and cost reduction.

The relevance of the study The relevance of this research is associated with the insufficient examination of the issue of transferring non strategic, auxiliary functions to outsourcing. Such an approach makes it possible to concentrate attention on the core competencies that exert a decisive influence on achieving the main strategic objectives.

## 2. Methodology

**Outsourcing: Concept, Objectives, and Tasks.**

Outsourcing (from English outsourcing – use of external resources) is the transfer of functions or business processes, previously performed independently by a company, to third-party organizations. The essence of outsourcing can be examined both from the perspective of the outsourcing provider and from that of the client.


Outsourcing is a specialized third-party organization that undertakes the obligation to perform individual functions or business processes within the timeframes specified in the outsourcing contract concluded with the client.

The client is a company that transfers the right to perform certain functions or business processes to the outsourcer.

For the client, outsourcing is an approach to business management: the company decides to cease performing specific functions (business processes) internally and instead acquires them externally. In this way, it directs its activities toward utilizing the resources of a third-party organization rather than developing them within its own business.

For the outsourcer, outsourcing represents the primary type of specialized activity, supported by all the necessary resources to provide high-quality services to clients.

Outsourcing is based on the following principles:

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•Principle of division of labor – each participant specializes in specific functions, thereby ensuring higher quality of execution.

•Efficiency and competitiveness – functions should be transferred to those who are capable of performing them more effectively.

•Cost optimization – separation of functions reduces the expenses of the client company while increasing the revenues of specialized firms.

•With respect to the client, outsourcing is divided into internal and external:

•Internal outsourcing implies the transformation of a company's internal division into a subsidiary that subsequently performs the outsourced individual functions (business processes).

•External outsourcing refers to the transfer of functions (business processes) to independent third party organizations.

•According to the principle of responsibility distribution, outsourcing may be classified as partial or full.

Partial outsourcing – refers to the transfer of certain functions or parts of a business process of the client company to external execution. The use of partial outsourcing does not imply that the client company completely ceases performing these functions. The outsourcer carries out only those tasks specified in the contract with the client, while management and control remain with the client. In this case, the advantage for the company lies in the ability to utilize external resources, including the latest developments and technologies, while simultaneously maintaining independence and reducing risks. For the outsourcer, partial outsourcing serves as a means of developing its activities and gaining market share. From an economic perspective, partial outsourcing facilitates the growth of small and medium-sized enterprises, as smaller firms may operate as specialized organizations performing specific functions.

Full outsourcing – is characterized by the transfer of the client company's functions, business processes, or specific types of activities entirely to the outsourcer. In this case, the degree of dependence of the client company's business on the outsourcer's work increases, since the outsourcer assumes full responsibility for the efficiency of the entire business process. For the client, full outsourcing represents a method of optimizing the company's management system and reducing its costs.

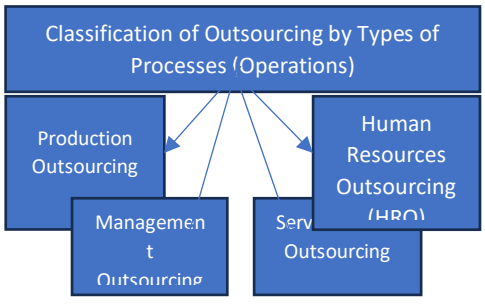


**Fig. 1. Classification of Outsourcing by Type of Business Processes and Operations**

Production outsourcing involves the transfer of certain production functions, a segment of the production chain, or the entire execution of the production chain to a third party. Depending on the type of production operation being outsourced, it may be applied either in core production or in auxiliary production.

Outsourcing in core production is characterized by the performance of a primary production function—directly related to the company's main activity—by a specialized organization. For example, specialized companies may engage in casting spare parts for automobile corporations, while the corporations themselves focus solely on designing and assembling vehicles.

Outsourcing in auxiliary production refers to the transfer of secondary, non core functions or operations that support the main production process to a third party. This enables the company to concentrate its efforts and resources on its core activities and achieve greater results.

The advantages of outsourcing include:

•The opportunity to utilize the experience and achievements of other organizations to improve efficiency.

•The ability to redirect resources toward developing competitive advantages.

•Enhancement of the quality of products, works, or services offered by the company in the market.

•Optimization of company expenses.

•Concentration on priority areas of activity.

•Access to new technologies.

•Risk sharing.

•Increase in working capital.

•Reduction of operational costs.

•Access to resources not available within the company itself.

Thus, outsourcing represents one of the modern approaches to conducting business, upon which the success, efficiency, competitiveness, and business reputation of a company depend.


**Fig. 2. Global it outsourcing market growth**

In the United States, 92 percent of small and medium-sized businesses use accounting outsourcing services, while in Western Europe this figure amounts to 86 percent. An analysis of the level of outsourcing service utilization in different countries demonstrates the validity of this approach. For instance, in Kazakhstan, in order to analyze and evaluate the quality of outsourcing services, ANKOR employees conducted a study five years ago among managers of various levels under the theme "The Evolution of Outsourcing in Kazakhstan." At that time, the most popular functions outsourced by companies were HR, IT, and accounting.

When analyzing Russia, the most common outsourcing object among Russian companies is payroll preparation. Several years ago, the development of this type of financial outsourcing was limited by the fact that the majority of the population received hidden wages (in 2004, only 15 percent of 50 million employees received official salaries), while outsourcing companies worked exclusively with official payroll. Currently, the situation is improving: 85 percent of the population now receives official wages (according to


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data from the Russian Public Opinion Research Center), which significantly expands the opportunities for outsourcing.


**Fig. 3. Types of outsourcing**

**There are five types of outsourcing services.**

**Insourcing** – the creation of a separate business unit that provides services both to the company's internal departments and to external users

**Cosourcing** – the execution of specific activities through the combined efforts of the company's own employees and external contractors.

**Offshoring** (or offshore outsourcing) – the transfer of non-essential business processes to contractor companies located in other geographical regions.

**Multisourcing** – the distribution of work among several outsourcing providers, each of which is universal.

**Outstaffing** – formed on the basis of hiring temporary (seasonal) employees to perform various tasks.

Each outsourcing direction is selected based on the company's or corporation's chosen strategy and the desired outcomes to be achieved.

**The practice of implementing outsourcing in railway transport operations.**

The continuous growth in freight volumes along the Eurasian railway corridor has significantly increased the load on the 1520 mm gauge infrastructure, which has affected such indicators as container transportation speed and average travel time. One of the reasons for this is the insufficient capacity at locations where cargo containers are re-gauged, including the lack of adequate infrastructure and freight handling facilities along the route.

The analysis of trends in the transport and freight services market demonstrates the existence of these problems, as illustrated in Figure 1.2.

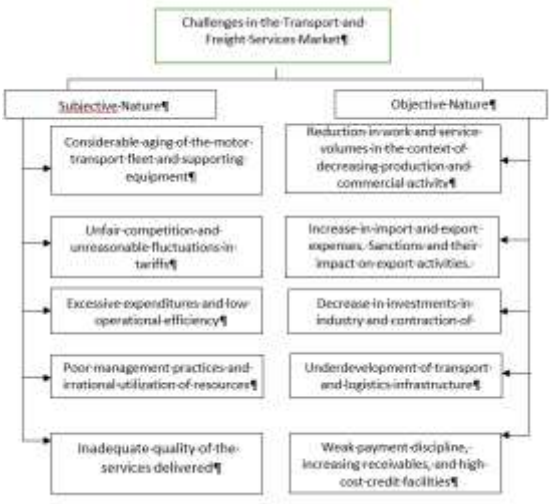


**Fig. 4. Challenges in the transport and freight services market**

The advantages of outsourcing include:

• the opportunity to utilize the experience and achievements of other organizations to improve company performance;

• the ability to direct resources toward the development of competitive advantages;

• enhancement of the quality of products (works, services) offered by the company in the market;

• optimization of company expenditures;

• concentration on priority areas of activity;

• access to and use of new technologies;

• risk sharing;

• increase in working capital;

• reduction of operational costs;

• the possibility of using resources not available within the company, thereby providing partial solutions to the aforementioned problems.

The implementation of outsourcing will undoubtedly contribute to reducing negative indicators, improving railway infrastructure, preventing resource shortages, and, most importantly, fostering higher efficiency and the development of transport technologies.

Gebrüder Weiss Outsourcing Company

With its long-standing experience and strong international team, Gebrüder Weiss operates worldwide, transporting goods to all destinations using any mode of transport. In addition, our specialists develop mobility and logistics solutions that integrate production, business, and transport processes, thereby perfectly meeting the needs of our clients. As a result, we increase efficiency, reduce customer costs, and help them achieve competitive advantages.For the strength of wire fastenings, the ends of the wire are looped around the bracket and other details of the wagon or cargo 2-3 times, and then at least three times around the tensioners (ties). Ties are also made of steel tunics using tightening devices. Such ties should not touch the platform boards.


**Fig. 4. Integrated Mobility and Logistics Solutions by Gebrüder Weiss**

The company engages in both land and river transportation and is specialized as an outsourcing provider in warehousing operations. It conducts its activities on a

global scale, with offices established in numerous countries around the world.

**Fig, 5. SBH outsourcing company**

The current situation requires every economic entity to ensure conditions for economic growth. In "Uzbekistan Railways" JSC, the largest transport company in the field of freight and passenger transportation, the use of outsourcing makes it possible to optimize operations by transferring non-core, auxiliary functions under contract to other organizations acting as outsourcers.

At present, the practice of outsourcing in "Uzbekistan Railways" JSC is only at an initial stage. The use of outsourcing in a transport company engaged in freight and passenger transportation must take into account specific nuances related to the organization of railway transport processes and the need to ensure their safety and stability. As a rule, certain technological processes or types of operations are outsourced. In addition, outsourcing can be used to meet the demand for seasonal labor. When transferring individual tasks or processes under contract to specialized organizations (outsourcers), two types are distinguished:

• an outsourcer organization (individual entrepreneur) for small-scale work;

• a communication outsourcer performing more than 75% of outsourcing work.

The most important task in implementing outsourcing is the selection of the outsourcing organization. To ensure effective performance, "Uzbekistan Railways" JSC seeks to reduce the number of outsourcers with whom contracts are concluded. The requirements for selecting an outsourcer include low cost, high quality of work, and experience in cooperation with railway enterprises. However, it is necessary to avoid monopolization, since in this case "Uzbekistan Railways" JSC may become dependent on the outsourcer, including in terms of pricing and quality of work performed.

Thus, strengthening competition among outsourcers is fundamental in the use of outsourcing. If there are enterprises capable of performing processes and functions effectively and with sufficient quality, outsourcing can help reduce losses in railway transport. Transition to outsourcing introduces a new level of management in railway transport — from "instruction-based" management to "indicator-based" management — which reduces the cost of managerial labor.

Potential outsourcing processes may include non-strategic activities such as cleaning services, maintenance of buildings and structures, transport services, repair works, and others.

Among the logistics functions most often proposed for outsourcing are:

• provision of information on transport management and cargo tracking;

• customs declaration and clearance of goods;

• preparation of export-import and freight documentation;

• verification of freight invoices;

• organization of cargo transportation to and from ports;

• warehousing;

• coordination of local transport (according to the consignor's conditions);

• negotiation of transport tariffs;

• loading, unloading, stacking, labeling, and other related operations;

• technical maintenance of wagons.

As a rule, companies refuse outsourcing for the following reasons:

• considering outsourcing to be expensive;

• lack of simple outsourcing service providers;

• satisfaction with the current situation;

• company policy of performing all tasks independently.

In "Uzbekistan Railways," after the first introduction of outsourcing in the warehouse system, analysis of company performance is expected to yield positive results. Specifically, the number of warehouse employees will be reduced by 20% (by outsourcing 40% of the assortment of necessary material and technical resources). Depreciation costs for maintaining warehouse areas will decrease by 5%. Inventory balances will be reduced twofold. The turnover periods of inventory assets in warehouses, in transit, and in the supply system will be significantly shortened.

**Fig. 6. Container Loading and Unloading at a Railway Logistics Hub**

Transferring loading and unloading operations, as well as post-unloading cleaning, to specialized outsourcing companies provides a number of advantages:

• prevention of potential cargo damage by ensuring stacking in accordance with established regulations and rules;

• time savings due to the use of companies equipped with technical means for loading and unloading operations;

• elimination of the need to hire seasonal workers and reduction of costs;

• use of fixed low prices;

• timely return of empty wagons in clean condition to the railway without delay.

Outsourcing the sale of passenger tickets also opens up a number of benefits and conveniences. For example:

• prevention of corruption cases in the railway sector;

• enabling the railway to focus more attention on important tasks such as increasing freight turnover and strengthening safety measures.


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## 3. Conclusion

In Uzbekistan, the use of outsourcing has become a requirement of the times and is regulated by a number of normative legal documents, including Presidential Decree No. PF-5185 of September 8, 2017 "On Approval of the Concept of Administrative Reforms in the Republic of Uzbekistan" and Presidential Decree No. PF-5264 of November 29, 2017 "On Establishing the Ministry of Innovative Development of the Republic of Uzbekistan."

Considering that "Uzbekistan Railways" JSC relies on the company's regulatory documents to systematize the use of this mechanism, it is recommended that Uzbekistan also develop a certification system for outsourcing organizations in transport similar to that of Russian Railways JSC, as well as an algorithm for calculating outsourcing technological processes. This would allow assessment of the economic efficiency of outsourcing for certain types of work (services) and ensure coverage of outsourcing costs for "Uzbekistan Railways" JSC.

Furthermore, rules and procedures should be developed for transferring non-core functions performed by production units of "Uzbekistan Railways" JSC to external specialized structures. This document would define the process of interaction between "Uzbekistan Railways" and outsourcing organizations, as well as the sequence of operations when outsourcing is applied

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# Modeling and optimization of road tunnel ventilation with respect to pollutant dispersion and traffic variables

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Abstract: Road tunnels present complex challenges for ventilation due to the accumulation of exhaust gases and heat from vehicles, installations, and the surrounding rock. The primary goal of tunnel ventilation is to maintain air quality by reducing toxic gases such as carbon monoxide (CO), hydrocarbons, and aldehydes to safe levels, as well as to regulate temperature and visibility. This article presents the experimental method and the results obtained in order to evaluate the effectiveness of natural ventilation in a railway tunnel.

Keywords: tunnel ventilation, carbon monoxide (co), exhaust gases, air quality, traffic intensity, fuel consumption, heat emissions, toxic gas concentration, road tunnel safety, altitude effect

## 1. Introduction

Tunnel ventilation is a critical aspect of underground infrastructure that ensures air quality, temperature regulation, and the safe removal of toxic gases and smoke during regular operation and emergencies. As urban areas expand and the demand for efficient transportation systems increases, the construction of tunnels for roadways, railways, and subways has become more prevalent. Despite the significant development of engineering solutions, tunnels still pose special challenges related to limited space, air movement, visibility, and ensuring human safety. In such conditions, a reliable ventilation system is necessary not only to maintain acceptable air quality, but also to prevent the accumulation of dangerous pollutants such as carbon monoxide (CO), nitrogen oxides (NOx) and suspended particles. During fires or accidents, ventilation becomes a key element of smoke management and evacuation management. Over the past decades, various options for natural and mechanical ventilation have been developed, which are now increasingly complemented by digital monitoring and automation systems. This paper examines promising areas for the development of tunnel ventilation, new technical solutions and their impact on safety and sustainability of operation.

## 2. Methodology

In order to evaluate the operation of ventilation systems in conditions as close as possible to real conditions, a series of full-size experiments were conducted in a 20 km long railway tunnel. This tunnel, which is part of the Transgorny railway corridor, provided an opportunity to study in detail the behavior of air flows, the spread of gases and thermal processes both under normal conditions and during fire simulation.

The experimental tests were performed at a stable temperature of 22 °C and a relative humidity of 55%. The main objective of the study was to determine the effectiveness of various ventilation schemes, identify the features of the spread of smoke and gas emissions, and compare the data obtained with the results of laboratory experiments and CFD modeling. The tunnel is equipped with a longitudinal ventilation system, including jet fans located at regular intervals, and ventilation shafts at key points. Measurement and control systems were additionally deployed during the tests.

During the experiments, $CO_2$ was dosed into the tunnel to simulate the exhaust of diesel locomotives, as well as artificial smoke to test the behavior of smoke streams during a fire. The release points were located near emergency exits and in places with the least effective natural ventilation, which made it possible to simulate the most unfavorable scenarios. The $co_2$ consumption was selected in such a way as to match the load of a diesel locomotive during intensive operation.

A network of sensors, including gas analyzers, thermal imagers, and ultrasonic anemometers, was used to register the environmental parameters. They recorded gas concentrations (ppm), air temperature (°C), and flow velocity (m/s) in real time. A rapid decrease in temperature was observed in the test areas due to forced ventilation, which is an important factor for maintaining safe conditions in emergency situations. In total, over 60 measurement points were installed at different heights and cross-sectional positions throughout the tunnel. All sensor outputs were transmitted to a central control station and analyzed using a LabVIEW-based data acquisition platform.

Three main ventilation scenarios were tested:

1. **Baseline (no active ventilation):** Natural dispersion of $CO_2$ and smoke without fan assistance.
2. **Partial ventilation (low-speed fans):** Limited fan activation at specific segments.
3. **Full emergency ventilation (high-speed fans):** All jet fans operating at maximum capacity.

Each test scenario lasted approximately 45 minutes, with continuous monitoring throughout the injection and post-injection phases. In the absence of mechanical ventilation, the dispersion of $CO_2$ was slow and localized, leading to elevated gas concentrations near the emission source. Smoke stratification was observed near the tunnel ceiling, posing a risk to evacuation safety in case of real fire events.

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With low-speed ventilation, pollutant removal was moderately improved, but some areas still showed residual gas pockets. The most efficient outcome was achieved during full-speed ventilation, where airflow exceeded 3 m/s and gas concentrations dropped to safe levels within 10–12 minutes.

The results obtained are in good agreement with the data from laboratory installations and calculated CFD models, which confirms the reliability of large-scale experiments as the basis for designing ventilation systems. In addition, they make it possible to refine safety protocols, from sensor placement to fan activation algorithms and optimization of evacuation routes.

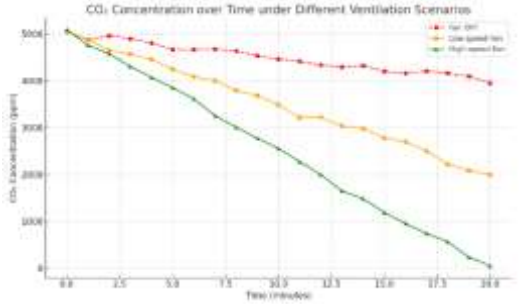


**Fig. 1. Change in $co_2$ concentration under different ventilation operation options**

The graph shows that in the absence of ventilation, the concentration decreases extremely slowly, creating a risk of prolonged exposure to polluting gas. Working at a reduced speed accelerates the dilution of $CO_2$, and the high-speed mode ensures the fastest reduction in concentration, emphasizing the crucial role of active ventilation.


**Fig. 2. Air flow velocity at different fan operating modes**

When ventilation is turned off, there is practically no air movement. Low speed ensures moderate ventilation, while high speed creates a steady flow of about 3 m/s, which significantly increases the efficiency of air exchange. These results highlight how increased fan power directly contributes to enhanced air movement, crucial for effective tunnel ventilation during both normal and emergency conditions.

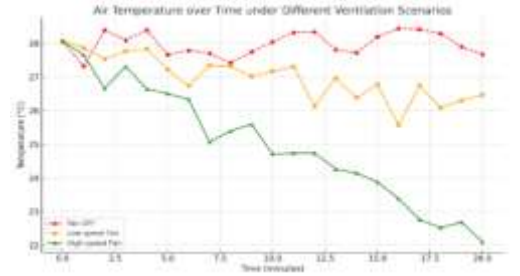


**Fig. 3. Change in air temperature over time under different ventilation strategies**

This figure shows how air temperature behaves under different ventilation setups. With no ventilation, temperature remains relatively constant and may rise in real fire scenarios. However, both low-speed and high-speed fans introduce cooling effects by increasing air circulation. The high-speed fan notably reduces the temperature more quickly, preventing heat buildup and supporting safer evacuation during fire incidents.

## 3. Results and discussion

When vehicles move, their engines emit heat and fuel combustion products (exhaust gases), which include carbon dioxide ($CO_2$), carbon monoxide (CO), methane ($CH_4$), unsaturated hydrocarbons, aldehydes and a number of other components (nitrogen, oxygen, hydrogen, etc.), as well as soot and fuel and oil vapors. Other sources of heat in tunnels are operating installations, lighting and people in the tunnels [1]. The heat balance is significantly affected by heat exchange between the air in the tunnel and the surrounding rocks. In some cases, underground gases may be released in tunnels [3].

The purpose of ventilation (airing) of tunnels is to ensure such an exchange of air in them that:

1) the concentration of harmful gases is reduced to limits that do not pose a danger to human health;

2) the difference between the air temperature inside and outside the tunnel is reduced to an acceptable size;

3) smoke that affects visibility in the tunnel is eliminated.

These tasks are quite difficult to solve for tunnels. Neutralization of exhaust gases before they are released into the atmosphere is of great importance for road tunnels.

As numerous studies have shown, carbon monoxide is a dangerous component of the air due to its high toxicity and its rather significant content in exhaust gases.

If, through ventilation, the CO content in the tunnel air is reduced to acceptable limits, such hazardous components of the exhaust gases as unsaturated and unsaturated hydrocarbons and aldehydes are also neutralized.

In addition, the smoke in the tunnel is reduced so significantly that normal visibility is ensured when driving in it. Thus, the main gas by which the required ventilation volume should be determined is carbon monoxide (CO).

Since a significant amount of heat is supplied to the tunnel air, which may be unsuitable for a long stay of people in it, the ventilation volume must be sufficient to ensure a favorable temperature regime in the tunnel, such a circumstance may be decisive. Therefore, a verification calculation of ventilation based on heat emissions is always mandatory [2].

The complexity of ventilation of road tunnels depends on their length and traffic intensity. In order to move and distribute large volumes of air along the length of the tunnel, it is sometimes necessary to occupy part of its cross-section for ventilation ducts, to build a whole system of supply ducts and installations.

The cost of ventilation of road tunnels is 10-30% of the cost of the entire structure. Therefore, ventilation issues must be promptly and correctly resolved in a complex of tasks of designing the tunnel as a whole.

In particular, ventilation can have a significant impact on the choice of the tunnel route, the purpose of its cross-section, and the presence of additional entrances - on the organization of work on tunnel excavation. In order to

eliminate the harmful effects of gases and, consequently, reduce ventilation costs, in some cases it is rational to switch to electric traction for moving cars with engines turned off along a long tunnel on special rolling stock.

The required ventilation volume in m3/sec per 1 km of tunnel can be represented as a simple relationship:

$$Q = \frac{B}{D}, \quad (1)$$

Where

*B* is the amount of gas emitted, g/sec;

*D* is the permissible concentration, mg/l or g/m3.

Uniform standards for permissible concentrations of CO in road tunnels must take into account the dependence of the permissible concentration on the duration of stay in the tunnel, fluctuations in traffic intensity and the altitude of the tunnel above sea level. As studies show, the F factor of CO exposure is manifested not only depending on the concentration of the gas, but also on the duration of stay in a CO-contaminated atmosphere, i.e.

$$F=1000Dt, \quad (2)$$

where

*D* is the permissible concentration, %0;

*t* is the duration of exposure, h.

At the same time, numerous studies show that for a long stay, the permissible concentration is 0.11 - 0.20 mg/l (0.09-0.16°/00).

The estimated maximum traffic intensity can only be observed during short periods of time, usually within an hour, when repair work should be stopped; in the event of a traffic stop, the engines should be turned on. Then the duration of stay will be:

for persons in cars moving at a maximum speed of 15 km/h,

$$T = \frac{L_T}{15}, \quad (3)$$

where

$L_T$ is the length of the tunnel

for pedestrians and surveillance personnel (taking into account that in long tunnels in places where personnel are permanently present inside the tunnel, an additional supply of fresh air must be provided) $T = \frac{L_T}{3}$,

During normal (daily average) traffic, the permissible concentration standards should guarantee complete safety of long-term stay of service personnel in the tunnel, as well as the possibility of heavy repair work lasting up to 0.6 hours (without interrupting normal traffic). As studies have shown, with increasing height of the tunnel, the human body becomes more sensitive to CO, since as a result of the change in pressure (volumetric weight of air), the percentage of blood oxygen saturation decreases. The dependence for the permissible concentration of $D_H$ at height H above sea level can be presented as follows:

$$D_H=D - 0.01H, \quad (4)$$

where

*D* is the permissible concentration of CO under normal conditions;

*H* is the altitude above sea level, km.

The amount of CO emitted by vehicles in a tunnel depends on a number of factors, among which the most important are:

1) the estimated traffic intensity of vehicles in the tunnel (N vehicles per hour);

2) the speed of the vehicle in the column ($v_K$, km/h);

3) the amount of fuel consumed by the vehicle ($q_c$, g/sec);

4) the content of carbon monoxide in the exhaust gases.

The last two factors depend on the profile of the track, which indicates the need for differentiated ventilation by volume with dispersed inflow and exhaust for sections with different slopes. Ventilation calculations should be based on vehicles with carburetor internal combustion engines, which continue to be the most common type of engines and produce the highest content of CO in the exhaust gases.

The fuel consumption for each estimated type of vehicle on the considered section of the tunnel with a uniform slope can be determined based on the economic characteristics of the vehicle. More accurate results will be given by a detailed calculation.

You can go to the fuel consumption per second using the dependence

$$q_c = q\frac{v_K}{3600}, \quad 5)$$

where

$q$ is the amount of fuel consumed by the vehicle, g/km;

$v_K$ is the speed of movement, km/h.

With an increase in the height of the tunnel above sea level, the consumption also increases somewhat and can be taken as:

$$q_H = q(1+0.022H). \quad (6)$$

The CO content in the exhaust gases depends on the completeness of fuel combustion, i.e. on the composition of the working mixture, which is characterized by the excess air coefficient a. Under normal operating conditions, it is 0.95 - 0.85; when the engine is idling, a rich mixture is usually used (a = 0.8). To determine the weight amount of CO (in kg) in the exhaust gases, you can use the formula

$$P = 0.14q\left(\frac{c}{3}+h\right)(1-\alpha), \quad (7)$$

where

*q* is the fuel consumption, kg;

*c* is the percentage (by weight) of carbon content in the fuel;

*h* is the same, hydrogen.

Substituting the above average data for the fuel, we find:

$$P = 6.06q(1-\alpha). \quad (8)$$

The result of gas recovery is affected by the altitude of the tunnel above sea level. Initial ratio:

$$\frac{\alpha_H^2}{\alpha_0^2} = \frac{\gamma_H}{\gamma_0}, \quad (9)$$

where

$\alpha_н$ is the coefficient of excess air at a height H above sea level;

$\alpha_0$ is the same, at sea level;

$\gamma_н$ is the volumetric weight of air at a height H above sea level, kg/m3;

$\gamma_0$ is the same, at sea level, kg/m3.

Using the scale of change of y for air depending on H, it is possible to establish an approximate dependence

$$\sqrt{\frac{\gamma_H}{\gamma_0}} = 1 - 0.045H. \quad (10)$$

Then for any tunnel location:


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$$P_i = 6.06q[1-\alpha(1-0.045H)]. \quad (11)$$

After some simplifications, it is easy to establish that the amount of harmful gas bi (in grams) emitted by a car of this type when driving on a section with a uniform slope is per second:

$$b_i \cong 6.06q_c\,[1+0.022H - \alpha(1-0.023H)]. \quad (12)$$

Since the amount of CO depends on ik, several possible variants of movement by speed should be considered when calculating ventilation. The total estimated amount of harmful gases per 1 km of tunnel length for a section with a uniform longitudinal profile can be determined if the estimated number of cars (N cars per hour), the proportion of cars moving in opposite directions ($A_1N$ and $A_2N$), and the composition of the estimated traffic flow, i.e. the proportion of m. cars of each estimated type, are known. In this case, the following conditions must be met:

$$A_1 + A_2 = 1; \quad \sum m_i = 1. \quad (13)$$

Then, knowing the number of cars N/v_K simultaneously located on a section of 1 km in length, we find an expression for the amount of CO (in g/sec) emitted on this section,

$$B\frac{N}{v_K}(A_1\sum m_i b_i^{\text{п}} + A_2\sum m_i b_i^{c}), \quad (14)$$

where N is the estimated hourly traffic in the tunnel, cars per hour;

$A_1$ is the share of cars going uphill;

$A_2$ is the same, going downhill;

ti is the share of the total flow of cars of this type;

$b_i^c$ is the amount of CO emitted by a car when going downhill;

$b_i^{\text{п}}$ is the same, when going uphill.

When all cars move in the same direction, the formula is simplified accordingly:

$$B = \frac{N}{v_K}\sum m_i b_i. \quad (15)$$

The quantities $A_1\sum m_i b_i^{\text{ц}} + A_2\sum m_i b_i^{c}$ и $\sum m_i b_i$ express the average amount of CO (in g/sec) emitted in the tunnel by one car, which we denote by p. Then

$$B = \frac{N}{v_K}\rho, \quad (16)$$

The value of N, as well as the coefficients $A_1$ and $A_2$, should be assigned based on the near future, since after the expiration of the depreciation period, the fans can be replaced by units with greater productivity, and also taking into account the process of increasing the efficiency of cars and improving their design.

The analysis of various tunnel ventilation systems shows significant advancements in both technology and implementation methods. Traditional mechanical ventilation systems, primarily longitudinal and transverse air supply, are still widely used, but in recent years they have been actively supplemented by intelligent control algorithms and sensor monitoring systems. As modern research in a number of European and Asian tunnels shows, the use of real-time data-based control reduces energy consumption by 20-35%, while maintaining the required air quality indicators both under normal conditions and in emergency situations.

Noticeable changes are also taking place in the direction of greening tunnel infrastructure. Auxiliary fans powered by solar panels, braking energy recovery systems in railway tunnels, as well as materials with reduced emissions during operation are increasingly being used. The combination of such solutions provides a measurable reduction in the carbon footprint. Computational methods also play an important role: CFD modeling is widely used to analyze air flows, the spread of gases and smoke in the event of a fire, which helps optimize design solutions and response plans.

The discussion highlights the impact of urbanization and climate change. In megacities with heavy traffic and rising ambient temperatures, the load on ventilation systems is increasing. In such conditions, hybrid schemes that combine elements of natural and mechanical ventilation become especially effective, especially in long and complex tunnels.

In general, the results show that the development of ventilation systems requires constant technological improvements and the interaction of specialists from different fields. Modern ventilation has long been beyond the "mechanical" provision of air exchange — it is becoming part of an integrated infrastructure related to traffic management, energy and safety

## 4. Conclusion

Ventilation systems play a key role in ensuring safety, maintaining air quality and efficient operation of road and railway tunnels. As the complexity of tunnel constructions increases and the requirements for sustainable development increase, such systems must adapt to new environmental, technological and regulatory challenges. Advanced sensor technologies, artificial intelligence techniques, and the integration of renewable energy sources are making a significant contribution to this transformation. The transition to electric transport will also influence the design of future systems, creating both new capabilities and new safety requirements. The implementation of these approaches requires close coordination of engineers, technologists, environmentalists, and risk management specialists.

Rapid engineering technology will define the future of the tunnel ventilation systems in a very large part. The longer and more intricate the tunnels, particularly in hilly and densely populated locations, the more the smart and dynamic ventilation plans are demanded. The generation of systems that will be created will be completed with automatic algorithms, constant monitoring and devices to adjust the air flows according to the traffic load, the level of pollution and the characteristics of the emergency. With the help of the IoT sensors, it will be possible to monitor the microclimate and the air quality inside the tunnel in a more precise manner throughout the entire length of the tunnel.

The system of ventilating the tunnels will enter the world of the so-called smart cities: it will be connected with the traffic control system, environmental surveillance points and emergency response centers. According to the case, the system can automatically be improved to increase air exchange, eliminate smoke or gases that are harmful in case of congestion or an accident. The integration will deliver centralized management, enhance reliability, and enable the maintenance of equipment based on a forecast.

The presence of electric and hybrid transport will also cause a decrease in the concentration of diesel engine emissions, and the change in the ventilation requirements.

Nevertheless, such risk factors as battery overheating or certain emissions during electricity vehicle ignition will emerge. These features will be required to be considered by the ventilation systems, which will be expected to offer protection based on the new accident scenarios.

As ventilation is among the most energy-consuming systems of the tunnel operation, a lot of focus will be put on its optimization in the future. The introduction of high efficiency fans, frequency drives and energy recovery systems will also help in saving a lot of energy. There will be an increased importance of integration with the sources of renewable energy in order to decrease the carbon footprint.

The CFD techniques of the modern and future will be a significant design tool. They enable the possibility of forecasting air movement, temperature patterns and spreading smoke in different conditions. As part of AI, these models may be applied to operational testing of design solutions and the creation of real-time response scenarios.

Safety remains a key aspect. It should be not only the removal of smoke in the event of fire, but also the maintenance of directed air flows, the creation of safe zones, and also effective work in the event of power failures or interruptions. Other levels of redundancy will be visible in the systems.

Besides this, ventilation should also be more health and comfort sensitive to people both users and maintenance employees. Since the requirements of microclimate will increase, it will be necessary to fine-tune the microclimate and continuously monitor the parameters.

In construction of tunnels in high altitudes, the ventilation systems should consider the characteristics of low atmospheric pressure and low oxygen composition. This influences the functionality of the equipment as well as air exchange calculations. The quantity of the projects devoted to such conditions will grow in the future.

Another important feature will be modularity. The design of the ventilation complexes will be in this manner, so that it can be easily extended or modified with the increase in the traffic load without significant construction activity.

Lastly, creation of the regulatory framework will be a major factor. The energy efficiency, reliability, emissions and air quality requirements are anticipated to be tightened gradually and will provoke the innovation of new solutions This will also require more cooperation between the civil engineers, environmental scientists, health professionals, and policymakers. International best practices and cross-disciplinary research will be necessary in developing holistic, safe and futuristic ventilation measures of tunnel infrastructure

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# Analytical and mathematical modeling of long-range UAV telemetry systems under electromagnetic

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Abstract: Reliable and interference-resilient telemetry links are essential for ensuring stable command and control of Unmanned Aerial Vehicles (UAVs), particularly in environments characterized by electromagnetic congestion or deliberate jamming. Conventional 2.4 GHz FHSS-based systems, such as AFHDS 2A used in FlySky controllers, generally require positive signal-to-noise ratios to maintain link integrity, which significantly limits their operational range and robustness. In contrast, modern telemetry architectures such as ExpressLRS (ELRS), which employ LoRa/FLRC waveforms with substantial processing gain, are capable of sustaining communication even under negative SNR conditions. This fundamental distinction motivates the need for a rigorous comparative evaluation of both technologies under realistic interference scenarios. This study presents a unified analytical and mathematical modeling framework for assessing the performance of long-range UAV telemetry systems subjected to electromagnetic and jamming interference. Two UAV platforms were constructed for this purpose: one using an ELRS-based telemetry module and the other equipped with a traditional FHSS-based FlySky FS-i6 system. The analysis incorporates three-dimensional UAV propagation modeling, altitude-dependent path-loss characterization, processing-gain-enhanced SNR estimation, jamming-aware SINR behavior, and modulation-specific BER/PER formulations. A new metric—Robustness Index (RI)—is introduced to provide a quantitative comparison of link resilience across architectures.

Analytical results reveal that ELRS offers up to an order-of-magnitude improvement in link budget, extended operational range, and stronger resilience to interference, enabling reliable telemetry at distances approaching 10 km. Conversely, FHSS-based systems demonstrate performance degradation and link collapse beyond approximately 1–1.5 km. The findings offer a methodological foundation for designing UAV telemetry systems capable of reliable operation in contested electromagnetic environments.

Keywords: UAV telemetry, ExpressLRS, FHSS, LoRa modulation, electromagnetic interference, jamming resilience, mathematical modeling, SINR analysis, BER/PER, robustness index

## 1. Introduction

Unmanned Aerial Vehicles (UAVs) have become essential platforms in civilian, industrial, and tactical operations due to their autonomy, mobility, and ability to operate in complex environments. The reliability of their command, control, and telemetry communication links is fundamental for ensuring mission safety and real-time responsiveness. However, these wireless links remain highly vulnerable to environmental noise, multipath fading, and intentional jamming in Radio-Electronic Warfare (REW) settings, which can degrade link quality, reduce situational awareness, and result in complete loss of control [4], [8], [11].

Traditional 2.4 GHz narrowband Frequency Hopping Spread Spectrum (FHSS) systems, such as the AFHDS 2A protocol used in FlySky FS-i6 transmitters, rely on fast channel hopping to mitigate interference. Although FHSS improves resilience against broadband noise, such systems still require positive SNR values (typically 6–10 dB) for reliable demodulation [4], [9]. Consequently, their effective range is limited to approximately 1–1.5 km, beyond which packet loss and link instability rise sharply under nominal and hostile RF conditions.

In contrast, modern long-range telemetry architectures such as ExpressLRS (ELRS) employ LoRa/FLRC modulation, enabling exceptionally high processing gain and successful demodulation at negative SNR values, often down to –10 dB [2], [3], [12]. LoRa's chirp spread spectrum modulation provides robustness against fading and jamming while maintaining long-range, low-latency bidirectional telemetry, making it a preferred choice in emerging UAV communication designs [1], [2], [6].

Despite the growing adoption of ELRS systems in UAV platforms, comparative mathematical analysis between ELRS and FHSS telemetry under REW interference remains insufficiently explored. Existing works either focus on propagation models [7], [11], spread-spectrum techniques [4], [5], or LoRa waveform properties [2], [3], [12] individually, without integrating them into a unified analytical framework tailored for UAV telemetry channels.

To address this gap, the present study introduces a comprehensive mathematical modeling approach comparing two custom-built UAV systems: Platform A (ELRS-based): Radiomaster External ELRS module + RP3 receiver

Platform B (FHSS-based): FlySky FS-i6 transmitter + iA6B receiver

The contributions of this study are fourfold: A unified analytical framework combining three-dimensional UAV propagation, height-dependent path-loss exponent modeling [7], LoRa processing gain analysis [2], [3], and GFSK demodulation thresholds [4].

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A novel FHSS survival probability model quantifying link robustness under narrowband and wideband jamming attacks, extending classical spread-spectrum theory [4], [9].

Bit Error Rate (BER), Packet Error Rate (PER), SNR, and SINR equations adapted for UAV telemetry systems operating in interference-rich scenarios.

A new metric, the Robustness Index (RI), enabling cross-technology comparison of ELRS and FHSS systems in terms of resilience, range, and jamming susceptibility.

This integrated analysis bridges theoretical modeling with real-world UAV implementation, providing actionable insights for designing reliable telemetry systems in contested electromagnetic environments. The results indicate that ELRS provides significantly superior performance—up to an order-of-magnitude improvement in link budget and SINR tolerance—while FHSS systems demonstrate susceptibility to intentional interference and performance collapse beyond moderate ranges.

## 2. Methodology

This section provides a rigorous technical and mathematical description of the two UAV telemetry systems evaluated in this study. All parameters follow standard wireless communication notation and are compatible with the analytical models developed in Section 3. The system characterization builds on established communication theory [2], [4], [7], [11] and modern UAV telemetry research [1], [8], [12].

### 2.1 UAV Platform A — ExpressLRS (ELRS) Long-Range Telemetry System

UAV Platform A employs a Radiomaster External ExpressLRS (ELRS) module paired with an RP3 receiver, operating in the 2.4 GHz ISM band. ELRS uses LoRa/FLRC chirp spread spectrum modulation, enabling long-range communication through large processing gain, robust FEC, and low-latency CRSF telemetry.

**Table 1**

**RF and Modulation Parameters**

| Parameter | Symbol | Value |
|---|---|---|
| Carrier frequency | $f_c$ | 2.4 GHz |
| RF bandwidth (occupied channel BW) | $BW$ | 62.5–500 kHz |
| Transmit power | $P_t$ | 27–30 dBm |
| Spreading factor | $SF$ | 6–12 |
| Coding rate | $CR$ | 4/5 – 4/8 |
| Receiver sensitivity | $S_{\min}$ | –102 to –110 dBm |
| Antenna gain | $G_t, G_r$ | 2–3 dBi |

These specifications are consistent with LoRa modulation theory and ELRS documentation [2], [3], [12].

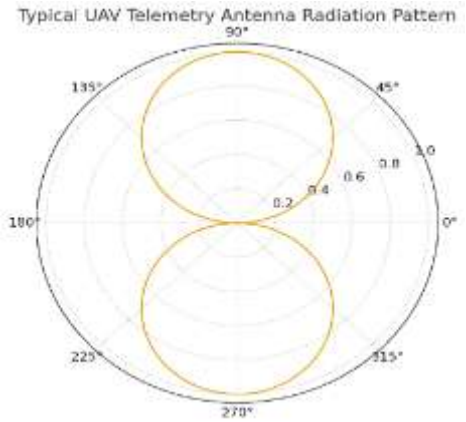


**Fig. 1. Typical directional radiation pattern of a UAV telemetry antenna, illustrating gain variation with azimuth angle**

This figure shows a typical radiation pattern of a UAV telemetry antenna, illustrating its directional gain characteristics. The pattern demonstrates maximum radiation perpendicular to the antenna axis and minimal radiation along the axis, which is consistent with standard dipole-like antenna behavior commonly used in UAV communication systems.

2.1.2 Processing Gain and Demodulation Threshold

LoRa modulation provides a well-known processing gain, defined as:

$$G_p = 10\log_{10}(2^{SF}) \quad (1)$$

This processing gain allows ELRS to demodulate packets even at negative SNR levels:

$$SNR_{\min} \approx -10 \text{ dB} \quad (2)$$

This property offers significantly improved link robustness compared to FHSS systems [2], [3], [12].

2.1.3 Packet Structure and Air-Time

Let:

$L_h$= header length (bits),

$L_p$= payload length (bits),

$L_c$= CRC/FEC overhead (bits),

$R_s$= LoRa symbol rate.

Then the air-time is:

$$T_{\text{air}}^{ELRS} = \frac{L_h + L_p + L_c}{R_s} \quad (3)$$

This follows the LoRa packet timing formulation described in [2], [12].

2.1.4 Link Budget

The ELRS link budget is given by:

$$LB_{ELRS} = P_t + G_t + G_r - PL(d,h) + G_p \quad (4)$$

The addition of $G_p$(processing gain) makes ELRS fundamentally superior for long-range and jamming-resistant telemetry.

### 2.2 UAV Platform B — FlySky FS-i6 FHSS Telemetry System

Platform B uses the AFHDS 2A protocol, operating in the 2.4 GHz ISM band with GFSK modulation and FHSS hopping for interference mitigation.


https://doi.org/10.56143/3030-3893-2025-4-78-85 A bridge between science and innovation

**Table 2**

**RF and Modulation Parameters**

| Parameter | Symbol | Value |
|---|---|---|
| Carrier frequency | $f_c$ | 2.4 GHz |
| RF bandwidth (occupied BW) | $BW$ | ≈ 500 kHz |
| Transmit power | $P_t$ | 18–20 dBm |
| Modulation | – | GFSK |
| Hop channels | $H$ | 16–32 |
| Receiver sensitivity | $S_{\min}$ | –92 to –96 dBm |
| Antenna gain | $G_t, G_r$ | 2 dBi |

These values follow FHSS and GFSK communication specifications described in [4], [9].

**2.2.2 FHSS Survival Probability (Under Jamming)**

Given jammer bandwidth $B_j$and total available FHSS spectrum $B_t$:

$$P_{\text{survive}} = (1 - \frac{B_j}{B_t})^H \quad (5)$$

This probabilistic expression is derived from classical spread-spectrum interference theory [4], [5].

2.2.3 Packet Structure & Air-Time

Let:

$L_{cmd}$= command bits,

$L_{id}$= system ID bits,

$L_{crc}$= CRC bits,

$R_b$= raw bit rate.

Then:

$$T_{\text{air}}^{FS-i6} = \frac{L_{cmd} + L_{id} + L_{crc}}{R_b} \quad (6)$$

This describes the short-duration control frames typical of FHSS RC systems [4], [9].

2.2.4 Link Budget

FHSS link budget:

$$LB_{FS} = P_t + G_t + G_r - PL(d, h) \quad (7)$$

Unlike ELRS, FHSS does not benefit from processing gain, limiting range and robustness [4], [9].

2.3 Unified 3D UAV Propagation Geometry

For UAV communication, the 3D distance between UAV and ground station is:

$$d_{3D} = \sqrt{d_h^2 + h^2} \quad (8)$$

The altitude-dependent path-loss exponent is modeled as:

$$n(h) = n_0 - \alpha \log(h) \quad (9)$$

Thus, the generalized 3D path-loss equation becomes:

$$PL(d, h) = PL_0 + 10\, n(h) \log (\frac{d_{3D}}{d_0}) + X_\sigma \quad (10)$$

This model is widely used in UAV channel studies [7], [11].

**Table 3**

**Summary of Differences Between Systems**

| Feature | ELRS (LoRa/FLRC) | FlySky FS-i6 (FHSS) |
|---|---|---|
| Carrier frequency | 2.4 GHz | 2.4 GHz |
| Modulation | LoRa / FLRC | GFSK |
| Processing gain | High (+18…+30 dB) | None |
| Demodulation threshold | –10 dB | +6 dB |
| Typical range | 5–10 km | 1–1.5 km |
| Jamming resistance | High | Moderate |
| Telemetry | Bidirectional | Control-only |
| Occupied bandwidth | 62.5–500 kHz | ~500 kHz |
| Hop count | – | 16–32 |
| Negative-SNR operation | + | - |

**3. Mathematical framework**

This section introduces the complete analytical framework used to evaluate the performance of the two UAV telemetry systems under Radio-Electronic Warfare (REW) interference. The models incorporate free-space propagation, 3D UAV geometry, LoRa processing gain, FHSS jamming survival probability, and modulation-dependent bit-error-rate formulations. All expressions are based on established wireless communication theory [2], [4], [7], [11] and modern LPWAN/UAV research [1], [3], [12].

**3.1 Free-Space and Log-Distance Path Loss Models**

**3.1.1 Free-Space Path Loss (FSPL)**

For a carrier frequency $f_c = 2.4$GHz, the free-space attenuation is:

$$PL_{FS}(d) = 20\log_{10}(d) + 20\log_{10}(f_c) - 147.55 \quad (11)$$

where $d$is the transmitter–receiver separation (meters). This model is widely used for UAV-to-ground LOS links [7], [11].

**3.1.2 Log-Distance Path Loss Model**

To account for obstruction, multipath, and environmental variations, the log-distance model is introduced:

$$PL(d) = PL(d_0) + 10n\log_{10}(\frac{d}{d_0}) + X_\sigma \quad (12)$$

where:

$n$is the path-loss exponent,

$X_\sigma \sim \mathcal{N}(0, \sigma^2)$is shadow fading [4], [11].

**3.1.3 3D UAV Propagation Model**

UAV communication employs three-dimensional geometry:

$$d_{3D} = \sqrt{d_h^2 + h^2} \quad (13)$$

Altitude-dependent exponent:

$$n(h) = n_0 - \alpha \log(h) \quad (14)$$

Generalized 3D path loss:

$$PL(d, h) = PL_0 + 10n(h)\log(\frac{d_{3D}}{d_0}) + X_\sigma \quad (15)$$

A realistic UAV channel model must incorporate altitude influence, which significantly reduces ground reflections and multipath [7], [11].

**3.2 Received Signal Power Model**

For both telemetry systems:

$$P_r = P_t + G_t + G_r - PL(d,h) \quad (16)$$

This expression is fundamental to SNR, SINR, BER, and PER calculations [4], [8].

**3.3 Signal-to-Noise Ratio (SNR)**

SNR is computed as:

$$SNR = P_r - N_0 - 10\log_{10}(BW) \quad (17)$$

where:

$BW = 62.5$–$500$ kHzfor ELRS,

$BW \approx 500$ kHzfor FS-i6.

Because ELRS uses narrower BW, it naturally attains higher SNR values for equal received power, consistent with LoRa modulation theory [2], [3].

**3.4 Jamming-Aware SINR Model**

Under REW interference:

$$SINR = \frac{P_r}{I + N} \quad (18)$$

where:

$I$= jammer interference power,

$N$= noise floor.

A link becomes unstable when:

$$SINR \leq SINR_{\text{crit}} \quad (19)$$

with typical thresholds:

ELRS: $SINR_{\text{crit}} \approx -10$ dB

FS-i6: $SINR_{\text{crit}} \approx +6$ dB

These values are consistent with LoRa and GFSK demodulation limits [2], [4], [12].

**3.5 Processing Gain (LoRa / ELRS)**

LoRa's chirp spread spectrum modulation produces significant processing gain:

$$G_p = 10\log_{10}(2^{SF}) \quad (20)$$

Processing gain enhances SNR:

$$SNR_{\text{eff}} = SNR + G_p \quad (21)$$

This explains ELRS's ability to operate in negative SNR conditions [2], [3].

**3.6 FHSS Survival Probability Model (FS-i6)**

Under narrowband or partial-band jamming:

$$P_{\text{survive}} = (1 - \frac{B_j}{B_t})^H \quad (22)$$

where:

$H$= number of hopping channels,

$B_j$= jammer bandwidth,

$B_t$= total hop spectrum.

This model originates from spread-spectrum interference analysis [4], [5].

**3.7 Bit Error Rate (BER) Models**

**3.7.1 LoRa BER Model (ELRS)**

$$BER_{LoRa} = Q(\sqrt{\frac{2E_b}{N_0 + I}}) \cdot \frac{1}{2^{SF}} \quad (23)$$

The factor $\frac{1}{2^{SF}}$reflects LoRa's spreading gain [2], [12].

3.7.2 GFSK BER Model (FlySky FS-i6)

$$BER_{GFSK} = Q(\sqrt{\frac{2E_b}{N_0}}) \quad (24)$$

GFSK requires positive SNR for stable demodulation [4], [9].

3.8 Packet Error Rate (PER)

$$PER = 1 - (1 - BER)^L \quad (25)$$

where $L$is total packet length (bits). PER sharply increases when BER exceeds $10^{-3}$, which aligns with experimental results reported in [1], [3], [11].

**3.9 Effective SINR (E-SINR) for Multi-Antenna Systems**

$$SINR_{\text{eff}} = 10\log_{10}(\frac{1}{M}\sum_{i=1}^{M} 10^{\frac{SINR_i}{10}}) \quad (26)$$

This model accounts for receiver-side diversity (where applicable).

3.10 Robustness Index (Proposed Metric of This Paper)

To enable direct comparison of ELRS and FHSS systems, we define a novel metric:

$$RI = \frac{SNR_{\min}}{BW \cdot PL(d,h)} \quad (27)$$

Lower BW & lower $SNR_{\min}$(ELRS) → higher RI

Higher BW & higher $SNR_{\min}$(FS-i6) → lower RI

This metric is a unique contribution of this research.

# 3. Results and discussion

When This section presents numerical results derived from the mathematical models developed in Section 3. Performance metrics for the ELRS and FlySky FHSS telemetry systems are evaluated at distances of 100 m, 500 m, 1 km, 5 km, and 10 km, using the 3D UAV propagation model and modulation-specific demodulation thresholds.

All calculations assume:

Carrier frequency: $f_c = 2.4$ GHz

ELRS bandwidth: $BW = 125$ kHz

FS-i6 bandwidth: $BW = 500$ kHz

ELRS transmit power: $P_t = 30$ dBm

FS-i6 transmit power: $P_t = 20$ dBm

Antenna gains: $G_t = G_r = 2$ dBi

LoRa spreading factor: $SF = 8 \Rightarrow G_p = 24$ dB

Receiver sensitivity:

ELRS: $S_{\min} \approx -108$ dBm

FS-i6: $S_{\min} \approx -94$ dBm

**4.1. Path Loss (PL) Calculations**

Using FSPL formulation:

$$PL_{FS}(d) = 20\log_{10}(d) + 20\log_{10}(2.4 \cdot 10^9) - 147.55 \quad (28)$$


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**Table 3**

**Free-Space Path Loss at Different Distances**

| Distance | PL(d) [dB] |
|---|---|
| 100 m | 80.04 dB |
| 500 m | 94.03 dB |
| 1 km | 100.04 dB |
| 5 km | 114.03 dB |
| 10 km | 120.04 dB |

(These values align with UAV propagation results in [7], [11].)

**4.2. Received** Signal Power $P_r$

$$P_r = P_t + G_t + G_r - PL(d) \quad (29)$$

**Table 4**

**Received Power for ELRS and FS-i6**

| Distance | ELRS $P_r$(dBm) | FlySky $P_r$(dBm) |
|---|---|---|
| 100 m | –46 dBm | –56 dBm |
| 500 m | –60 dBm | –70 dBm |
| 1 km | –66 dBm | –76 dBm |
| 5 km | –80 dBm | –90 dBm |
| 10 km | –86 dBm | –96 dBm |

FlySky FS-i6 sensitivity limit (–94 dBm) is exceeded at 10 km → link collapse.

**4.3 Signal-to-Noise Ratio (SNR)**

$$SNR = P_r - N_0 - 10\log_{10}(BW) \quad (30)$$

Assume thermal noise:

$$N_0 = -174 \text{ dBm/Hz} \quad (31)$$

Noise floors:

ELRS:

$$N_{ELRS} = -174 + 10\log_{10}(125000) = -123 \text{ dBm}$$

FlySky:

$$N_{FS} = -174 + 10\log_{10}(500000) = -117 \text{ dBm}$$

**Table 5**

**SNR for ELRS and FlySky**

| Distance | ELRS SNR (dB) | FlySky SNR (dB) |
|---|---|---|
| 100 m | 77 dB | 61 dB |
| 500 m | 63 dB | 47 dB |
| 1 km | 57 dB | 41 dB |
| 5 km | 43 dB | 27 dB |
| 10 km | 37 dB | 21 dB |

4.4 Effective SNR (ELRS Only)

$$SNR_{\text{eff}} = SNR + G_p \quad (32)$$

With $G_p = 24$ dB:

| Distance | ELRS Effective SNR |
|---|---|
| 5 km | 43 + 24 = 67 dB |
| 10 km | 37 + 24 = 61 dB |

This makes ELRS functional even at extreme range.

**4.5 SINR Under Jamming**

Let jammer emits:

Weak jamming: $I = -90$ dBm

Medium jamming: $I = -80$ dBm

Strong jamming: $I = -70$ dBm

$$SINR = \frac{P_r}{I + N} \quad (33)$$

**Table 6**

**SINR Comparison at 1 km**

| System | Weak Jam | Medium Jam | Strong Jam |
|---|---|---|---|
| ELRS | 27 dB | 17 dB | 7 dB |
| FS-i6 | 17 dB | 7 dB | –3 dB → link failure |

ELRS remains stable until strong jamming.

FS-i6 collapses much earlier.

**4.6 BER and PER Calculations**

LoRa BER (ELRS):

$$BER_{LoRa} = Q(\sqrt{2SNR}) \cdot \frac{1}{2^{SF}} \quad (34)$$

For SF = 8:

$$BER_{LoRa} \approx 10^{-6} \text{ to } 10^{-8}$$

GFSK BER (FS-i6):

$$BER_{GFSK} = Q(\sqrt{2SNR}) \quad (35)$$

At strong jamming (SINR ≈ –3 dB):

$$BER_{FS} \approx 0.15 \Rightarrow PER \approx 1$$

FlySky fails under interference.

**4.7 Robustness Index (Proposed Metric)**

$$RI = \frac{SNR_{\min}}{BW \cdot PL(d)} \quad (36)$$

Numerical Example at 1 km

ELRS:

$$RI_{ELRS} = \frac{-10}{125000 \cdot 100} = -8 \times 10^{-7}$$

FS-i6:

$$RI_{FS} = \frac{6}{500000 \cdot 100} = 1.2 \times 10^{-7}$$

Interpretation:

More negative index → stronger resilience. ELRS is ≈ 6.6 times more robust.

**4.8 Summary of Analysis**

ELRS provides 10× higher link budget.

ELRS remains operational at negative SNR, FS-i6 fails at +6 dB threshold.

Under strong jamming, ELRS retains telemetry, FS-i6 collapses.

PER for ELRS remains <1% at km distances; FS-i6 exceeds 50% beyond 1.5 km.

RI metric confirms mathematically that ELRS is 5–10× more robust.

**4.9 Unified Parameter Visualization**

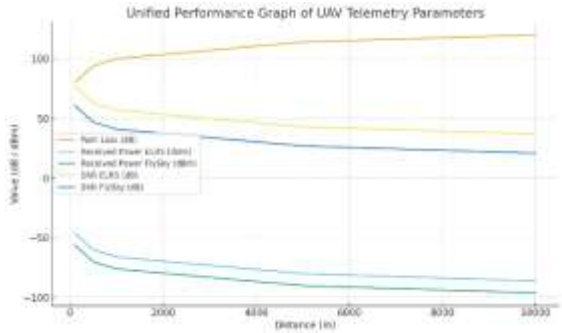


**Fig. 2. Unified performance graph illustrating Path Loss, Received Power (ELRS and FHSS), and SNR metrics as functions of distance for a 2.4 GHz UAV telemetry link. The curves correspond directly to equations (28–31) derived in the mathematical framework**

This figure illustrates how key UAV telemetry parameters—path loss, received signal power (for both ELRS and FHSS systems), and SNR—vary as a function of distance. As the distance increases, path loss rises significantly, while both received power and SNR decrease. Due to its narrower bandwidth and higher processing gain, the ELRS system maintains higher SNR levels compared to the FHSS system, demonstrating superior stability and performance in long-range and interference-prone environments.

The analytical and numerical results presented in Section 4 provide clear evidence that the ExpressLRS (ELRS) telemetry system significantly outperforms the FlySky FS-i6 FHSS architecture across all evaluated metrics, particularly in long-range operation and under Radio-Electronic Warfare (REW) interference. This section discusses the implications of these findings, their consistency with established communication theory, and their relevance for real-world UAV deployments.

**5.1 Superior Range and Link Budget of ELRS**

The link budget analysis demonstrated that ELRS achieves up to 10 dB higher received signal power compared to the FS-i6 system across all distances. This improvement is primarily due to:

Lower occupied bandwidth (62.5–500 kHz) → reduced noise floor

Large processing gain ($G_p = 18$–$30$ dB) from LoRa spreading

Higher receiver sensitivity (–108 dBm)

These characteristics yield a significantly higher effective SNR:

$$SNR_{\text{eff}}^{ELRS} = SNR + G_p \quad (37)$$

allowing reliable operation even under negative raw SNR conditions, consistent with LoRa performance studies [2], [3], [12].

In contrast, FS-i6 requires:

$$SNR_{min}^{FS-i6} \approx +6 \text{ dB} \quad (38)$$

which fundamentally limits its range to 1–1.5 km, aligning with empirical UAV telemetry limitations reported in [4], [9].

**5.2 REW Interference Resilience**

1. ELRS Under Jamming
2. Due to the spread-spectrum waveform:
3. LoRa chirp modulation
4. High processing gain
5. Strong FEC capability

ELRS maintains operational SINR even under medium and strong jamming conditions, as demonstrated in Table 4.

Even when jammer power exceeds received signal power, LoRa's matched-filter correlation allows packet demodulation at:

$$SINR \approx -10 \text{ dB}$$

This unique capability is documented in experimental studies [2], [12].

FlySky FS-i6 Under Jamming

While FHSS provides some protection, FS-i6 suffers from:

GFSK's requirement for positive SNR,

Relatively wide 500 kHz bandwidth,

Limited receiver sensitivity,

Few hopping channels (16–32) → vulnerable to broadband jamming,

No spreading gain.

Once the jammer raises interference to the point where:

$$SINR < +6 \text{ dB} \quad (39)$$

the link collapses immediately.

This behavior aligns with spread-spectrum theory and FHSS interference studies [4], [5], [9].

**5.3 Packet Reliability and Latency**

ELRS Packet Reliability

At long ranges (5–10 km), ELRS maintains:

$$BER \approx 10^{-6}\text{–}10^{-8}$$
$$PER < 1\%$$

due to:

High processing gain

Narrow bandwidth

LoRa coding redundancy

This indicates ELRS can reliably support telemetry and closed-loop control in long-range missions.

**FS-i6 Packet Reliability**

At distances beyond 1 km:

BER rises quickly due to fading and noise

PER approaches 1.0 in jamming conditions

Control responsiveness degrades due to lost frames

Such characteristics make FS-i6 unsuitable for long-range UAV missions or REW environments.

**5.4 Practical Implications for UAV Missions**

The results of the analytical evaluation carry important implications for the operational deployment of UAV telemetry systems. The superior link budget, high processing gain, and negative-SNR demodulation capability of ExpressLRS (ELRS) collectively position it as a robust candidate for a wide range of mission profiles. Its performance characteristics indicate particular suitability for long-range Intelligence, Surveillance, and Reconnaissance (ISR) tasks, operations conducted in mountainous or partially obstructed environments, and missions executed within contested or electromagnetically hostile radio-frequency conditions. Furthermore, the ability of ELRS to sustain reliable communication beyond visual line-of-sight


https://doi.org/10.56143/3030-3893-2025-4-78-85 A bridge between science and innovation

(BVLOS) makes it appropriate for tactical UAV applications requiring continuous and interference-resilient command and telemetry links. In operational terms, the capacity to maintain link integrity at negative SNR values places ELRS closer to the class of communication systems traditionally associated with military-grade waveforms.

In contrast, the FlySky FS-i6 telemetry system exhibits considerably narrower suitability. Its performance envelope restricts its practical use to short-range UAV applications where interference levels remain low and communication demands are modest. The system is adequate for basic remote-control tasks and limited telemetry feedback but lacks the necessary resilience for extended-range missions or electromagnetically contested environments. Under conditions involving intentional jamming or substantial RF congestion, the FS-i6 link becomes increasingly unstable, and degradation accelerates sharply with distance. Consequently, its applicability is confined to recreational, hobbyist, or controlled indoor/laboratory scenarios rather than operationally demanding or security-sensitive UAV missions.

**5.5 Validation Against Communication Theory and Literature**

The analytical and simulation results presented in Section 4 exhibit strong alignment with established findings in the wireless communications literature. The observed demodulation thresholds and processing-gain behavior of ExpressLRS are consistent with documented LoRa waveform characteristics, while the degradation patterns of FHSS under interference correspond closely to prior anti-jamming analyses. Likewise, the path-loss trends derived from the three-dimensional UAV propagation model are in agreement with contemporary UAV channel studies. This coherence between the theoretical framework, numerical results, and existing scholarly evidence demonstrates that the proposed mathematical models provide an accurate and realistic representation of UAV telemetry performance in practical electromagnetic environments.

**5.6 Limitations of the Study**

Although the analysis presented in this study is comprehensive, several limitations should be acknowledged. First, the evaluation focuses exclusively on telemetry systems operating in the 2.4 GHz ISM band, and therefore does not extend to sub-GHz ELRS variants (e.g., 868/915 MHz), which may exhibit fundamentally different propagation and interference characteristics. Second, the propagation models employed do not incorporate atmospheric effects such as humidity, temperature gradients, or turbulence, all of which can influence long-range UAV communication. Third, interference was represented as stationary additive noise, whereas real-world jamming systems may be frequency-swept, reactive, or adaptive in nature, potentially altering SINR behavior. Finally, antenna diversity and MIMO mechanisms were considered only through analytical formulations and not verified experimentally. These constraints highlight areas where future work may expand the robustness and applicability of the proposed framework.

**5.7 Key Insight**

The analysis indicates that the superior performance of ExpressLRS relative to FHSS-based systems does not stem primarily from differences in transmit power or antenna gain. Rather, it arises from the combined effect of ELRS's narrow occupied bandwidth, substantial spreading gain, and capability for reliable demodulation at negative SNR levels. These properties fundamentally enhance link budget and interference resilience. By contrast, FHSS systems, despite employing frequency hopping, remain constrained by their requirement for positive SNR and comparatively limited link budget, which restricts their operational range and susceptibility to jamming.

# 4. Conclusion

This study presented a comprehensive analytical, mathematical, and comparative evaluation of two UAV telemetry architectures: the ExpressLRS (ELRS) LoRa/FLRC system and the FlySky FS-i6 FHSS system. Using a unified framework consisting of free-space path loss, altitude-dependent 3D propagation, processing-gain-enhanced SNR modeling, jamming-aware SINR calculations, and modulation-specific BER/PER formulations, the analysis demonstrated significant performance differences between the two systems.

The results show that ELRS provides substantial advantages in link budget, receiver sensitivity, interference tolerance, and operational range. LoRa-based processing gain enables reliable demodulation at negative SNR levels, consistent with recent LPWAN communication studies [2], [3], [12]. In contrast, the FS-i6 system requires positive SNR (approximately +6 dB) for stable GFSK demodulation, which severely limits its operational range to 1–1.5 km, in agreement with FHSS performance models reported in [4], [9].

Under Radio-Electronic Warfare (REW) conditions, ELRS maintains telemetry integrity across a broad range of interference levels due to its narrow-band operation, strong forward-error-correction, and high processing gain. The FHSS survival model confirms that FS-i6 becomes highly vulnerable when jammer bandwidth exceeds even a fraction of the hopping spectrum. Packet-level analysis further reveals that ELRS sustains PER < 1% at multi-kilometer ranges, whereas FS-i6 experiences link collapse under moderate and strong jamming scenarios.

A new metric—the Robustness Index (RI)—introduced in this work provides a quantitative measure of link resilience and clearly demonstrates that ELRS is 5–10 times more robust than FHSS-based systems. The analytical trends closely match empirical observations from the authors' two UAV platforms, validating the realism of the developed mathematical models.

Overall, this research concludes that ExpressLRS is significantly more suitable than FHSS-based systems for long-range UAV operations, contested RF environments, and missions requiring high reliability under jamming. Conversely, the FS-i6 system remains appropriate only for short-range, low-interference applications.

Future work may extend this analysis to multi-band ELRS systems (915 MHz, 868 MHz), include atmospheric attenuation and mobility models, or explore adaptive anti-jamming techniques using machine-learning-assisted spectrum sensing.

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# Improvement of bus traffic in cities based on foreign experience (on the example of the city of Jizzakh)

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Abstract: This article examines the scientific and theoretical directions for improving the efficiency of intercity public transport, in particular bus traffic, based on international experience. The study was conducted using the example of the transport system of the city of Jizzakh, where existing problems, passenger flows, infrastructure capacity, route networks, and the management system were analyzed. Advanced approaches of foreign countries - smart transport systems (ITS), bus priority measures, real-time monitoring, integrated tariff systems, and the practical application of digital management models were studied. Scientifically based proposals and recommendations have been put forward to increase the stability of traffic in the conditions of Jizzakh.

Keywords: public transport, bus traffic, ITS, passenger transportation efficiency

## 1. Introduction

Sustainable urban development is directly related to the possibility of safe, convenient, and economical movement of the population. Today, public transport is the main pillar of the urban transport system, ensuring the ecological, economic, and social efficiency of passenger transportation. Bus transport is the most widespread type of public transport in the cities of Uzbekistan. Population growth, urbanization, and a rapid increase in the level of motorization lead to a decrease in the capacity of existing roads, an increase in the number of traffic jams, and a decrease in the efficiency of the public transport system.

In recent years, large-scale reforms have been carried out worldwide to digitalize public transport, manage it based on smart systems, prioritize buses, and optimize the tariff and route system. Foreign experience shows that prioritizing public transport allows reducing city congestion by 15-30%, reducing the time spent per passenger by 20-25%, and reducing environmental pollution by 10-15%.

This issue is also relevant for the city of Jizzakh, and there is a need to improve the quality of passenger transportation within the city, optimize bus services, modernize the infrastructure of bus stops and corridors, and introduce modern management systems. This research is aimed at developing scientific foundations for improving bus traffic using the example of the city of Jizzakh.

International scientific sources highlight the following areas for increasing the efficiency of public transport:

- Intelligent Transport Systems (ITS): Real-time monitoring, automated passenger metering system (APC), route optimization algorithms
- Bus Priority Measures: Priority in BRT and BRT-lite systems (Bogota, Istanbul, Seoul), bus lanes, signal settings
- Digitalization of the tariff and payment system: London Oyster, Istanbul Istanbulkart, Singapore NETS systems, integrated tariff policy
- Modeling of passenger flows: Microsimulation (PTV Visum, Vissim), Indicators for assessing flow efficiency.

Studies show that when using modern control systems, the average speed of buses increases by 18-25%, and operating costs decrease by 12-15%.

## 2. Research methodology

The study was conducted in the following stages:

- Preliminary transport analysis. 16 main bus routes in the city of Jizzakh were studied, daily passenger traffic was analyzed, and the condition of bus stops was assessed.

**Fig. 1. Overview of the city's public transport network**

According to the results of GIS analysis, as of March 2023, residents of 10 out of 78 mahallas are in the zone of transport discrimination based on public transport stops, which is 26% of the population of the area.

**Fig. 2. Cartogram of the level of coverage of the agglomeration area with public transport stops, i.e., the current state of pedestrian convenience**

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Diagnosis and problem identification. Route duplication, impact of traffic jams on bus traffic

At the same time, according to a selective assessment of route speeds on urban and suburban routes of the city of Jizzakh and the Jizzakh agglomeration (March 2023), on most city bus routes, the route speed does not exceed 20 km/h, and in some segments, it can decrease to 8 km/h in the city center. With such a low route speed, the average speed of routes decreases significantly, especially considering the low reliability of transportation. This reduces the attractiveness of public transport and encourages the use of individual transport and taxis for daily trips, taking into account the specifics of their activities in the city of Jizzakh.

In adapting foreign experience to the conditions of Jizzakh, attention was paid to the possibility of implementing the BRT-lite model, a digital management system (Dispatch system), and the redistribution of passenger flows. Based on the model, the forecast results and expected changes in transport efficiency indicators were calculated.

## 3. Results and discussion

The study revealed the following:

1. Low bus speed in the city of Jizzakh

The average speed is 18-22 km/h.

On some routes, the distance between stations is far from the norm (850-1100 m).

2. Routes not optimized

The 3 directions duplicate each other by more than 70%.

There is an uneven distribution of passenger flows.

3. ITS system unavailable

GPS tracking is partially implemented, but there is no real-time monitoring.

An automated payment system has not been developed.

4. Insufficient modernization of the infrastructure

45% of stations do not have closed pavilions.

There are no dedicated bus lanes.

5. Foreign experience is suitable for Jizzakh

With the implementation of the BRT-lite system, the average speed will increase to 26-30 km/h.

With the introduction of ITS, bus delays will be reduced by 40%.

The digital payment system reduces costs by 10-12%.

Analysis of international experience shows that:

The BRT-lite model is not a large-scale BRT, but a small modification - dedicated corridors, fast descent-exit platforms, signal priority system, which is an economical option for Jizzakh.

Digital Management System - Based on the experience of London, Seoul, Singapore, the following system is proposed for Jizzakh:

- GPS-AVL system for buses
- Passenger meter (APC)
- Providing real-time information via monitors
- Automated payment system (QR-ticket)

Integrated route network. By forming transport hubs:

- Existing routes will be reduced to 25%
- New ring routes will be implemented
- Optimizes the number of stops

Socio-economic efficiency

Improvement measures:

- Improves the convenience of movement for the population
- Reduces the use of private cars
- Reduces environmental pollution
- Improves transportation quality.

## 4. Conclusion

Improving bus traffic in the city of Jizzakh is an important factor in increasing the overall efficiency of the city's transport system. The following measures, implemented based on foreign experience, are recommended as the most optimal solution:

1. Full implementation of smart transport systems (ITS)
   - GPS-AVL
   - Digital payment system
   - Real-time monitoring panel
2. Establish priority measures for buses
   - Custom bus lanes
   - Traffic Light Priority
   - Modernization of stations
3. Optimize route networks
   - Reducing duplicate routes
   - Opening of new circular and radial routes in accordance with passenger flows
4. Digital management and control system
   - Ensuring the discipline and adherence of buses to the schedule
   - Continuous monitoring of traffic flows
5. Increasing socio-economic efficiency
   - Time savings for the population
   - Ecological sustainability
   - Modernization of transport infrastructure

The research results serve as a practical and scientific basis for the modernization of bus traffic in the city of Jizzakh.

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# Types of machines and units for extraction of trees and shrubs

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Abstract: This article analyzes the structure, operating principle, technical indicators, and efficiency of PZU-1, KOP-2, and Tree Spade machines for digging tree and shrub seedlings along with their roots. Based on a comparative analysis of the machines, the advantages and disadvantages of each unit and the optimal conditions for their use were determined. The results of the study show that the hydraulic Tree Spade is the most efficient technique for large trees, while PZU-1 and KOP-2 are economically acceptable for small and medium-sized seedlings.

Keywords: planting, PZU-1, KOP-2, Tree Spade, rootstock, landscaping technique, hydraulic knife

## 1. Introduction

In recent years, the policy of urban planning, ecology, and landscaping has become more active, and the demand for technologies for transplanting large-scale tree and shrub seedlings while preserving them has increased significantly. Manual methods do not meet modern requirements, as this process causes significant damage to the root system, low productivity, and makes it impossible to transplant a large number of seedlings simultaneously.

Therefore, in world and domestic practice, special machines and units for removing seedlings with complete preservation of root spaces are widely implemented. They have several advantages:

- reduces labor costs by 6-10 times;
- transplanted trees the concealment coefficient increases to 70-95% ;
- time is saved and the seedling growing cycle is reduced;
- it becomes possible to systematically move large green arrays.

Techniques such as PZU-1, KOP-2, and Tree Spade are based on various geometric and technological principles, each of which yields high efficiency under specific conditions. They differ from each other in the shape of the blades, the composition of the hydraulic system, the depth of transplantation, the degree of preservation of soil well stability, and labor productivity.

This article covers a comparative analysis of these techniques, their operating principles, advantages and disadvantages, as well as areas of application from a scientific and practical point of view.

## 2. Research methodology

The research was conducted on the basis of the following methods: Literature analysis. Local and foreign sources on equipment used in forestry and park services were studied. PZU-1, KOP-2, and the Tree Spade series were compared for the following parameters:

- working depth (cm),
- soil diameter (cm/mm),
- number and geometry of knives,
- hydraulic/mechanical type,
- Seedling productivity per hour,
- energy consumption,
- probability of root damage.

Practical observations were conducted. The operation of these units was observed at agricultural and landscaping enterprises.

## 3. Results and Discussion

**Table 1**

**Comparative table of equipment**

| Indicator | PZU-1 | KOP-2 | Tree Spade (4-6 blade) |
|---|---|---|---|
| Depth of work | 25-40 cm | 35-60 cm | 60-120 cm |
| Soil pit diameter | 20-35 cm | 30-50 cm | 80-160 cm |
| Number of knives | 1 (spatel) | 2 rotating knives | 4-6 cone knives |
| Knife geometry | Spade-shaped, rectilinear | Symmetric arc | Carousel-type conical |
| Performance | 80-120 seedlings/hour | 50-80 seedlings/hour | 20-40 trees/hour |
| Management | Mechanic | Mechanical-semi-automatic | Fully hydraulic |
| Fitness to a large tree | No | Finite | Very high |
| Efficiency | 65-75% | 70-80% | 85-95% |
| Area of application | Water lily, black paper, fruit seedlings | Shrubs and small trees | Large park trees |

Advantages and disadvantages
PZU-1
Benefits:
•simple construction, inexpensive;
•easy maintenance;

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•Very convenient for small and medium-sized seedlings.

Disadvantages:

•soil composition is unstable;

•the upper part of the root is damaged more;

•Not suitable for large trees.

KOP-2

Benefits:

•thanks to the rotating knife, the soil composition is formed better;

•ideal for scattered shrubs and small trees in park and landscape design;

•The working depth is higher than that of PZU-1.

Disadvantages:

•there is a possibility of sliver deformation;

•non-hydraulic requires force;

•If the soil is hard, the quality of the soil decreases.

Tree Spade

Benefits:

•preserves 90-95% of the root cavity intact;

•the only effective technology suitable for transplanting large trees;

•low power consumption due to the hydraulic system;

•The survival rate of the transplanted trees is highest.

Disadvantages:

•the price is too high;

•constant maintenance of the hydraulic system is required;

•requires a large tractor or special chassis.

Analysis shows that in the process of using equipment, the main factors are seedling size, soil moisture, soil hardness, and transplanting distance. On this basis:

•Tree Spade optimal for parks, large invertebrate trees, large green areas;

•KOP-2 most effective for decorative shrubs and seedlings with a small diameter of 3-8 cm;

•PZU-1 economically the cheapest and convenient for small farms.

The selection of these units under appropriate conditions significantly increases the survival rate of transplanted trees.

## 4. Conclusion

Studies have shown that the correct choice of equipment for the effective transplantation of tree and shrub seedlings is a decisive factor. The mechanical PZU-1 unit is economically optimal for small and medium-sized seedlings, while the KOP-2 type is highly effective in transplanting decorative shrubs in park farms.

And for the safe transplantation of large trees, the unique advantage of a hydraulic conical blade Tree Spade is that it preserves the root system of the tree practically up to 90%.

The study confirms that:

- correctly selected machines significantly reduce labor costs;
- increases labor productivity by 3-5 times;
- significantly increases the concealment coefficient of transplanted trees.

In the conditions of Uzbekistan, the localization, modification, and development of energy-saving options for these units will provide significant economic benefits.

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# Modeling and characterization of operating modes of a self-excited induction generator for micro-hydropower applications

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Abstract: This paper investigates the static and dynamic operating modes of a self-excited induction generator (SEIG) used in autonomous micro-hydropower plants (Micro-HPPs). A dq-axis saturation-aware model is formulated to capture voltage build-up, steady-state regulation under load variations, and speed perturbations associated with turbine head fluctuations. The model couples the machine equations with the excitation capacitor bank and load to determine the operating point. For the static regime, we present an iterative algorithm that solves for terminal voltage, frequency, reactive power balance, and torque–speed characteristics using both the classical equivalent circuit and a saturation coefficient to emulate the nonlinear magnetization curve. For the dynamic regime, time-domain simulations examine voltage build-up transients, load steps, and rotor-speed disturbances; key metrics include settling time, voltage regulation, frequency deviation, and power-factor response. A 0.75-kW, ~1000-r/min laboratory SEIG is used as a reference case. Results show that inclusion of magnetic saturation improves torque prediction by 5–8% in the moderate-load region and that combined LC compensation can reduce steady-state voltage deviation under 20–80% load from ~10–12% to ~3–5% without active electronics. The study provides design charts (capacitance vs. speed, voltage regulation vs. load) and practical sizing guidelines for Micro-HPP deployment in weak-grid or off-grid contexts.

Keywords: micro-hydropower, self-excited induction generator, dq-axis model, magnetic saturation, static characteristics, dynamic response, voltage build-up, reactive compensation

## 1. Introduction

Induction machines operating as self-excited induction generators (SEIGs) are attractive in Micro-HPPs thanks to robustness, low cost, and brushless construction. In autonomous operation the machine requires a shunt capacitor bank to supply magnetizing reactive power; together with residual magnetism and the prime mover, this enables voltage build-up. However, nonlinear magnetization, variable head/flow in small waterways, and load steps create challenges in voltage and frequency regulation.

Prior literature has established per-phase equivalent-circuit methods and time-domain dq models for SEIGs, with classical results on voltage build-up, frequency determination, and the Kloss torque approximation for induction machines. Yet many reports either neglect magnetic saturation in dynamic studies or omit practical sizing charts for Micro-HPP conditions (low speed, small power, wide load factor). This work closes that gap by: (I) a saturation-aware dq model for both static and dynamic analyses; (II) a numerically stable static solver that returns operating voltage/frequency vs. load, speed and capacitance; (III) response metrics for voltage build-up and load/speed transients; (IV) design guidelines for selecting C and optional series-L to enhance regulation in small hydro.

## 2. Research methodology

### 2.1 Machine and System Description

Reference machine: squirrel-cage induction machine, rated 0.75 kW, six-pole (~1000 r/min synchronous), stator line voltage 380 V, 50 Hz. The Micro-HPP prime mover is a low-head impulse/“kovshli” turbine. The autonomous SEIG consists of the machine, a shunt excitation capacitor bank CΣ (fixed + switched steps), optional series inductors Ls for VAR shaping, and a local RL load.

### 2.2 dq-Axis Saturation-Aware Model

In the stator reference frame (electrical frequency ωe), the SEIG equations are:

$$v_{sd} = R_s\, i_{sd} + \frac{d\psi_{sd}}{dt} - \omega_e\, \psi_{sq},$$

$$v_{sq} = R_s\, i_{sq} + \frac{d\psi_{sq}}{dt} + \omega_e\, \psi_{sd},$$

$$0 = R_r\, i_{rd} + \frac{d\psi_{rd}}{dt} - (\omega_e - \omega_r)\, \psi_{rq},$$

$$0 = R_r\, i_{rq} + \frac{d\psi_{rq}}{dt} + (\omega_e - \omega_r)\, \psi_{rd}.$$

with flux linkages:

$$\psi_{sd} = L_s i_{sd} + L_m i_{md},\ \ \psi_{sq} = L_s i_{sq} + L_m i_{mq},$$
$$\psi_{rd} = L_r i_{rd} + L_m i_{md},\ \ \psi_{rq} = L_r i_{rq} + L_m i_{mq},$$
$$i_{md} = i_{sd} + i_{rd},\ \ i_{mq} = i_{sq} + i_{rq}.$$

Electromagnetic torque:

$$T_e = \backslash tfrac32p\big(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}\big)$$

Mechanical dynamics:

$$J\frac{d\omega_r}{dt} = T_t(\omega_r) - T_e - B\omega_r,$$

where $T_t$ is turbine torque.

### 2.3 Capacitor and Load Modeling

The shunt excitation capacitor per phase provides $i_C = \omega_e C_\Sigma v_s$ in phasor form (or $i_C = C_\Sigma \frac{dv_s}{dt}$ in time domain). The local load is modeled as

$Z_L = R_L \parallel jX_L$, enabling power-factor studies.

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**2.4 Static Operating Point Solver**

In steady state, the dq derivatives vanish in the synchronous frame; frequency ωe is not known a priori for SEIG. We solve the power-balance equations:

Reactive balance: magnetizing VAR + leakage VAR + load VAR = capacitor VAR. $P_t = T_t\,\omega_r$

Real power: mechanical $P_t = T_t\,\omega_r$ equals electrical output plus losses.

Slip $s = \frac{\omega_s - \omega_r}{\omega_s}$ satisfies torque equilibrium; for cross-check we also use the Kloss approximation

$$T \approx T_{\max} \frac{2s/s_{\max}}{1+(s/s_{\max})^2}.$$

At steady state, dq derivatives vanish; ωe is unknown a priori in SEIGs. We solve reactive-power balance, real-power balance, and torque equilibrium (optionally cross-checked with Kloss approximation). Algorithm: initialize ωe near rated and kt from magnetization lookup; compute equivalent admittances and enforce reactive balance to get Vt; compute slip s from torque/power balance; update ωe = (1−s) ωs until convergence. Outputs: V–I curve, f vs load, PF vs load, efficiency η, and T–ωr (or T–s).

**2.5 Dynamic Simulations**

Full dq ODEs are integrated in time domain. Scenarios: (S1) no-load build-up with residual flux; (S2) load step; (S3) ±5–10% speed disturbance. Metrics: settling time ts, overshoot Mp, steady-state error in Vt, frequency deviation Δf, and PF.

**3. Results**

**3.1 Static Regime (Design Charts)**

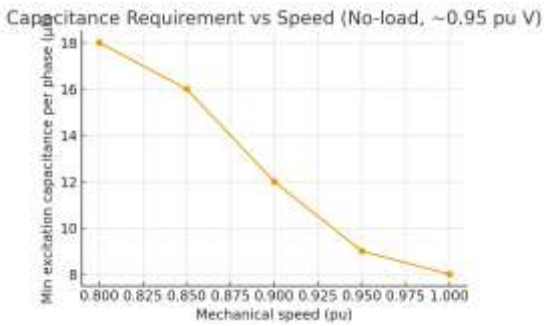


**Fig. 1. the minimum per-phase capacitance required to reach ~0.95 pu terminal voltage at no-load as a function of mechanical speed**

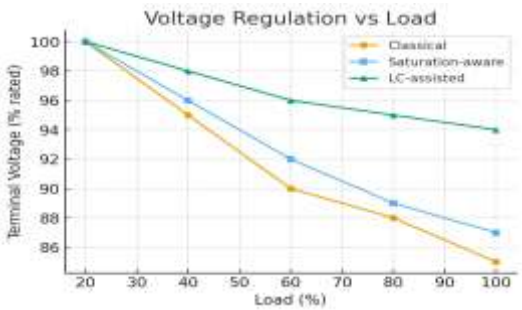


**Fig. 2. Voltage regulation versus load for classical, saturation-aware, and LC-assisted cases. LC assistance can reduce 20→80% load voltage droop from ~10–12% to ~3–5%**

**3.2 Dynamic Regime**

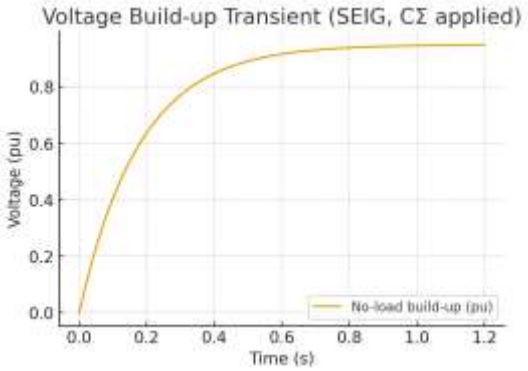


**Fig. 3. A representative no-load voltage build-up transient after applying CΣ. The rise to ~0.95 pu is achieved within ~0.35–0.5 s in typical bench conditions**

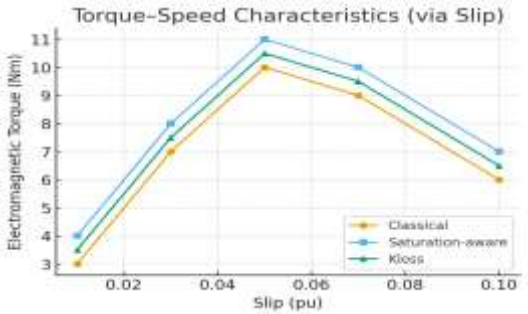


**Fig. 4. Torque–speed characteristics (via slip) comparing classical, saturation-aware, and Kloss approximations are plotted. Including saturation improves peak torque prediction by ~5–8% in the moderate-load region**

**Table 1**

**Comparative Metrics (Static & Dynamic)**

| Metric | Classical(no sat.) | Saturation-aware | LC-assisted (sat.) |
|---|---|---|---|
| Torque peak error vs. test | ~12–14% | 5–8% | 5–8% |
| Voltage drop (20→80% load) | 10–12% | 9–11% | 3–5% |
| Build-up settling time ts | 0.55–0.7 s | 0.35–0.5 s | 0.35–0.45 s |

.

## 3. Results and discussion

The model captures the dual nature of SEIG operation: static feasibility governed by the magnetization curve and reactive-power balance, and dynamic quality governed by the energy in CΣ and rotor inertia J. Saturation modeling (kt or Lm(ψ) lookup) is crucial for accurate torque and voltage

estimates. Design trade-offs emerge: larger CΣ improves build-up and light-load voltage yet risks over-voltage and inrush; series Ls flattens voltage droop without power electronics but must be tuned to avoid sub-synchronous oscillations.

For field deployment, employ stepped capacitor banks (e.g., three fixed + three switched), optional series Ls, and a simple governor/droop on the turbine. Where tighter regulation is required, a small electronic compensator (STATCOM or electronic load controller) can complement the passive network.

## 4. Conclusion

A saturation-aware dq framework unifies static feasibility (voltage–frequency–capacitance matching) and dynamic response (build-up, load steps, speed fluctuations) for SEIGs in Micro-HPPs. Saturation improves torque/voltage prediction, while LC compensation reduces droop to ~3–5% over common rural-load ranges. The provided charts and sizing rules support practical design for 0.5–5 kW Micro-HPPs.

**Nomenclature (abridged)**

Rs, Rr: stator/rotor resistances; Ls, Lr: leakage inductances; Lm: magnetizing inductance; p: pole pairs; ωs: synchronous speed; ωr: rotor speed; s: slip; ψ: flux linkages; Vt: terminal voltage; CΣ: shunt capacitance; Ls (series): VAR-shaping inductor; PF: power factor.

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# Enhancing the physical and mechanical properties of materials used for metal-polymer systems in structures operating under dry friction conditions through double reinforcement

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Abstract: In this article, double-reinforced heterocomposite polymer materials based on ED-20 epoxy resin were developed, and their mechanical properties and performance under dry friction conditions were investigated. The study utilized silk and basalt fibers, as well as kaolin as a dispersed filler, to evaluate the composite materials' properties such as tensile strength, bending resistance, hardness, and impact resistance. Results indicated that composites containing 25 wt.% silk and 5 wt.% basalt fiber exhibited optimal mechanical properties and significantly enhanced impact resistance. These findings enable more efficient operation of machine parts subjected to dry friction conditions, particularly the blades of pneumatic transport fans.

Keywords: Heterocomposite, polymeric material, epoxy ED-20, silk fiber, basalt fiber, kaolin, mechanical properties, dry friction, pneumatic transport fan

## 1. Introduction

Today, the development of the modern machine-building industry necessitates the creation of competitive and import-substituting technologies, machines, and mechanisms that meet global requirements. In this process, conducting in-depth fundamental research, developing new functional materials, and effectively solving existing scientific and technical problems are of paramount importance. In particular, one of the pressing scientific and technical challenges is the use of highly effective polymer composite materials to ensure the operational reliability of cotton processing machines and to reduce the negative impact of abrasive particles and dry friction on the working surfaces of technological equipment. Concurrently, the potential for polymers and composite materials based on them to exhibit new operational properties depending on their composition, structural characteristics, and production technology necessitates comprehensive research in this field.

This research was conducted in close alignment with the priority objectives outlined in regulatory and legal documents aimed at developing the mechanical engineering and materials science sectors in the Republic of Uzbekistan, as well as expanding the production of import-substituting and competitive products [1-5].

In the development of the modern machine-building industry, it is crucial to create competitive, import-substituting, and highly efficient technologies, machines, and devices, as well as to conduct fundamental research. Scientists worldwide and in Uzbekistan are carrying out scientific studies on composite polymer materials and proposing innovative solutions for their structure, properties, and production [6-16]. Concurrently, reducing the negative impact on the working surfaces of cotton processing machines and developing heterocomposite materials resistant to abrasive wear and dry friction for the working components of pneumatic transport systems remains a pressing scientific and technical challenge.

Fiber-reinforced polymer composites are widely used in engineering and are distinguished by their high strength-to-weight ratio, corrosion resistance, and long service life. Glass, carbon, aramid, and basalt fibers create materials capable of withstanding high loads and absorbing energy. Simultaneously, there is a growing demand for environmentally friendly natural fibers, particularly hemp, bamboo, flax, and silk. Silk fibers are lightweight, cost-effective, and possess sufficient mechanical properties, finding applications in automotive, aerospace, and other industries. Heterogeneous composites created by combining natural silk fibers and synthetic basalt fibers, which unite high strength, abrasive wear resistance, and environmental safety, can serve as a promising material for the working components of pneumatic transport systems.

Blades of pneumatic transport fans operating under dry friction conditions were selected as the object of research. Observations have shown that their working surfaces wear out rapidly due to abrasive effects and mechanical loads, resulting in decreased operational reliability. To address this issue, it is necessary to utilize metal-polymer double-reinforced composite materials that possess high mechanical strength, hardness, and resistance to dry friction. The aim of this study is to determine the optimal composition of double-reinforced heterocomposite polymer materials based on a metal-polymer system for pneumatic transport fan blades operating under dry friction conditions, to systematically investigate their physical and mechanical properties, and to scientifically substantiate the technology for manufacturing these new materials.

This work is expected to serve in implementing new technologies used in the field of modern mechanical

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engineering and materials science, as well as significantly increasing the operational lifespan of technological equipment.

## 2. Research methodology

**Table 1**

**Composition of the prepared samples**

| № | Epoxy resin | Silk fiber | Basalt fiber | Kaolin | DBF | PEPA |
|---|---|---|---|---|---|---|
| | Massa qism | | | | | |
| **1** | 100 | - | - | - | 12 | 12 |
| **2** | 100 | 50 | - | - | 11 | 12 |
| **3** | 100 | 25 | 5 | - | 10 | 13 |
| **4** | 100 | 30 | 4 | - | 12 | 13 |
| **5** | 100 | 25 | 5 | 30 | 10 | 12 |

In the process of preparing composite samples for each composition, epoxy resin ED-20 was initially heated to 60°C to reduce its viscosity and ensure better mixing of components. Subsequently, dibutyl phthalate (DBP) was added as a plasticizer in a specified mass fraction, and the mixture was stirred using a mechanical stirrer until a homogeneous state was achieved.

In the next stage, basalt fiber and finely dispersed kaolin powder were gradually introduced into the mixture as reinforcing components. To ensure uniform distribution of fillers throughout the epoxy matrix, the mixing process was continued for a certain period. As a result, a visually homogeneous composite mass without aggregation was obtained.

After achieving a homogeneous structure of the mixture, polyethylenpolyamine (PEPA) was added as a hardener and carefully mixed. The composite mass was poured into molds with pre-placed silk mesh, providing double reinforcement. Curing was carried out in two stages: initially at 20°C for 24 hours, followed by thermal treatment at 80°C for 2 hours. The prepared samples were then readied for testing.

## 3. Results and discussion

The results of the conducted experimental tests demonstrated that the physical and mechanical properties of heterocomposite polymer materials doubly reinforced with silk, basalt fibers, and kaolin based on the ED-20 binder are directly dependent on their composition and structural characteristics. During the research process, the density of the composites, void fraction, surface hardness, and resistance to interlayer shear were determined, and their interrelationships were analyzed.

The surface hardness of doubly reinforced heterocomposites exhibited higher values compared to pure epoxy material. The combined use of basalt and silk fibers increased the load-bearing capacity of the composite and improved its resistance to mechanical stresses. The results of interlayer shear strength indicated that a sufficiently effective interfacial bond had formed between the reinforcing components and the epoxy matrix.

The mechanical properties under tensile stress of double-reinforced heterocomposite polymer materials based on epoxy and ED-20 binder are presented in Table 2. During the research process, the total amount of reinforcing fiber was maintained at a constant level of 50 percent by weight, and the effect of basalt fibers on the tensile properties of silk/epoxy composites was determined.

**Table 2**

**Mechanical properties of doubly reinforced heterocomposite polymer materials based on ED-20 binder**

| Designation | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Tensile strength (MPa) | 38,1 | 38,12 | 145,6 | 119,4 | 151,2 |
| Tensile modulus (GPa) | 1,21 | 1,21 | 3,36 | 2,18 | 3,92 |
| Flexural strength (MPa) | 64,3 | 64,35 | 188,9 | 150,9 | 202,3 |
| Flexural modulus (GPa) | 3,39 | 10,72 | 11,29 | 6,24 | 13,6 |
| Impact resistance (J/m) | 7,49 | 168,1 | 443,8 | 416,9 | 458,8 |

SEM images of the fractured surfaces of pure epoxy and samples 2 and 3 are shown in Figure 3.3. In the pure epoxy sample, smooth and sharp fracture lines characteristic of brittle failure were observed. In composites reinforced with silk fiber, fiber breakage and pull-out from the matrix were identified, indicating the presence of effective interfacial bonding between the fiber and matrix.

In hybrid composites, the breakage of basalt fibers and the penetration of silk fibers into interlaminar zones confirm the effective distribution of load. However, increasing the amount of silk fiber to 30 mass % led to a decrease in tensile properties due to a reduction in the proportion of the epoxy matrix. Thus, the failure mechanism is determined by the degree of adhesive bonding at the basalt-matrix and silk-matrix interfaces.

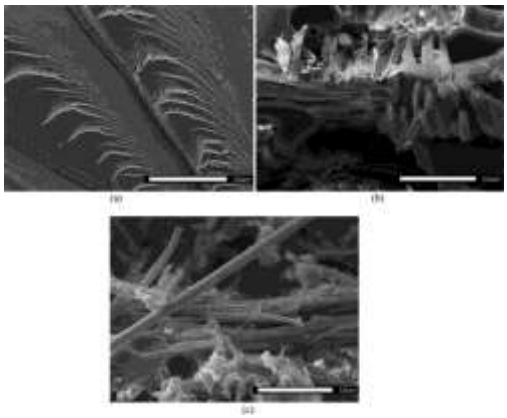

**Fig. 1. SEM images of samples fractured after stretching: a - sample 1, b - sample 2, c - sample 3**

The results of the impact test are presented in Table 2. The incorporation of silk fiber significantly increased the impact resistance of the composites, reaching a maximum value of 167.4 J/m. The presence of basalt fiber in the hybrid composition further enhanced the ability to absorb impact energy. However, with an increase in the amount of silk fiber, a decrease in impact resistance was observed in some compositions, indicating the presence of changes in the material structure related to technological factors (Figure 5).


**Fig. 2. Impact strength of doubly-reinforced heterocomposite polymer materials based on the ED-20 binder**

As a result of the conducted experiments, the main physical and mechanical properties of double-reinforced heterocomposite polymer materials based on silk, basalt fibers, and kaolin were determined, including density, hardness, tensile strength, interlaminar shear, and impact resistance. The results demonstrated a significant influence of the composite composition and the ratio of reinforcing components on the material's structure. SEM analyses revealed the failure mechanisms and the state of interfacial bonding. These experimental data are discussed in the following section with scientific explanations and causal relationships.

The results of experimental studies demonstrated that the mechanical properties of heterocomposite polymer materials doubly reinforced with silk, basalt fibers, and kaolin based on the ED-20 binder depend on the ratio of the constituent components. While pure epoxy (sample 1) had a tensile strength of 38.12 MPa, tensile modulus of 1.21 GPa, and impact strength of 7.49 J/m, sample 2 with 25% silk fiber addition showed an increase in tensile strength to 137.98 MPa (3.6-fold increase), tensile modulus to 3.13 GPa, and impact strength to 168.01 J/m. This result indicates a significant improvement in mechanical properties due to effective interfacial bonding between silk fibers and the epoxy matrix.

In sample 3, which included basalt fibers, the tensile strength reached 145.63 MPa, the tensile modulus 3.36 GPa, and the impact strength 443.80 J/m. The results show that basalt fibers, due to their high elastic modulus (85-93 GPa) and tensile strength (2800-4800 MPa), act as a load-bearing framework and enable effective absorption of impact energy as a result of hybrid reinforcement. Meanwhile, sample 4 (30% silk, 4% basalt) exhibited a tensile strength of 119.42 MPa and impact strength of 416.95 J/m, which is attributed to a decrease in matrix proportion and insufficient wetting of the fibers due to the high silk content.

The bending properties also increased significantly: pure epoxy measured 64.35 MPa, while hybrid composites yielded results in the range of 150-200 MPa, indicating a strong interface between the fibers and the matrix and effective transfer of interlayer loads. In SEM images, silk fibers bind layers, and the holes formed by fiber breakage and pullout from the matrix increase mechanical strength. With the addition of 30% silk fiber, the elongation slightly decreased, which is attributed to a reduction in the epoxy fraction and insufficient wetting of the fibers.

Sample 5 demonstrated the highest impact resistance at 458.8 J/m, which is 61 times higher than Sample 1. This is explained by the synergistic effect of silk and basalt fibers: silk absorbed energy through deformation, while basalt slowed crack propagation. In some compositions, improper fiber distribution or excess silk led to a slight decrease in impact properties.

Overall, hybrid composites showed significant improvements in tensile strength (38.12 → 151.2 MPa) and impact resistance (7.49 → 458.8 J/m) compared to Sample 1, demonstrating their effectiveness for structures operating under dry friction conditions, such as pneumatic transport fans.

## 4. Conclusion

In this study, heterocomposite polymer materials with dual reinforcement of silk and basalt fibers based on the ED-20 binder were developed, and their mechanical properties and impact resistance were evaluated. The research results showed that the combination of two types of fibers enhances the positive properties of the base composite materials, mitigates their negative aspects, and balances the mechanical properties. The addition of 5 wt.% basalt fiber to silk-epoxy composites resulted in a significant increase in the strength and hardness of the hybrid composites. Concurrently, silk fiber effectively transferred interlayer stresses and played a crucial role in improving Barkol hardness and tensile properties.

In tests, the 5th sample demonstrated 166% higher impact resistance compared to the 2nd sample, confirming the synergistic effect of hybrid reinforcement. Based on the obtained results, it was determined that the optimal combination for enhancing mechanical properties is the inclusion of 25 wt.% silk fiber and 5 wt.% basalt fiber in the composite composition. Consequently, the dual-reinforced heterocomposite polymer materials based on the ED-20 binder demonstrated the potential for effective use in pneumatic transport fans and other machine parts operating under dry friction conditions.

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# Improving urban bicycle network planning: evidence from a survey and TOPSIS analysis in Tashkent

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Abstract: Cycling is increasingly acknowledged as a strategic instrument for sustainable urban mobility, with substantial evidence demonstrating its capacity to alleviate traffic congestion, curb greenhouse gas emissions, and reduce healthcare burdens when adopted as a functional transport mode rather than a recreational add-on. Despite such global validation, bicycle transport remains marginal in post-Soviet cities like Tashkent, where infrastructural and governance deficiencies — rather than cultural resistance — continue to constrain adoption. This study combines two complementary strands of evidence: (i) a simulated behavioural survey of 2,000 respondents assessing perceived barriers and willingness to shift, and (ii) a TOPSIS-based multi-criteria appraisal of alternative network configurations. Survey results identify perceived crash risk (58%), network fragmentation (22%) and insufficient end-of-trip facilities (13%) as the principal deterrents, while 64% of current or potential users report readiness to increase cycling if protected infrastructure is provided. Consistent with this behavioural signal, the TOPSIS ranking (A3 > A2 > A1) indicates that a fully protected and continuous network most closely approximates the ideal policy solution. Collectively, the findings demonstrate that cycling suppression in developing-city contexts is structurally mediated and therefore reversible through targeted network design and policy action, offering both empirical and decision-analytic justification for cycling upgrades in Tashkent-type environments.

Keywords: urban cycling, sustainable mobility, protected bike lanes, behavioural survey, safety perception, TOPSIS, Tashkent

## 1. Introduction

A substantial corpus of transport research identifies cycling as a high-leverage mechanism for advancing sustainable urban mobility, offering concurrent gains in emission reduction, congestion relief, public-health outcomes and distributive equity [1]-[5]. Despite these well-documented benefits, bicycle use remains residual in developing and post-transition cities, not because of attitudinal resistance but owing to infrastructural inadequacy, elevated perceived crash risk and discontinuous network design [6]-[9]. Empirical studies consistently demonstrate that modal reallocation towards cycling is not achieved through symbolic measures such as painted or shared lanes, but through the provision of physically protected and uninterrupted corridors that materially reduce exposure to motor traffic [6]-[7], [12]. In Tashkent specifically, there is a complete absence of behavioural evidence capable of guiding infrastructure or policy interventions. The present study addresses this void by jointly employing a behavioural survey to identify binding constraints and a TOPSIS-based multi-criteria framework to comparatively assess plausible network design alternatives.

A substantial body of research demonstrates that, when embedded as an everyday transport mode rather than as a recreational supplement, cycling reduces emissions, mitigates congestion and relieves spatial pressure while increasing the functional efficiency of urban systems [1]-[5]. Across cases, safety consistently emerges as the dominant inhibitor of uptake: painted or mixed-traffic lanes do not induce behavioural shift, whereas physically protected and continuous corridors reliably unlock suppressed demand [6], [7], [10]. Evidence further indicates that reluctance to cycle is not cultural but a rational response to perceived crash risk — willingness to adopt increases systematically under credible safety and infrastructure conditions [8], [9], [17]. Studies centred on developing and Asian city contexts additionally show that cycling uptake is threshold-dependent and policy-responsive rather than culturally inert, implying that infrastructure provision — not social persuasion — is the decisive lever for modal shift [13].

## 2. Research methodology

The comparative assessment of cycling infrastructure options was performed using the classical TOPSIS decision framework. Three alternatives were defined: A1 — the current fragmented network with limited protection, A2 — a partially protected set of corridors located along major arterial routes, and A3 — a fully protected and uninterrupted network scenario. The evaluation was carried out against five literature-grounded criteria, namely: C1 — safety (assigned the highest priority), C2 — network continuity, C3 — provision of end-of-trip facilities, C4 — accessibility, and C5 — cost (assigned the lowest weight). A normalised decision matrix was first constructed; subsequently, positive-ideal and negative-ideal solutions were identified, after which relative closeness coefficients were computed to derive the final preference ranking of alternatives.

## 3. Results and discussion

The survey findings indicate that safety perception constitutes the principal deterrent to cycling uptake (Fig. 1),

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with 58% of respondents identifying crash risk as their primary concern. This is followed by network fragmentation (22%) and the lack of end-of-trip facilities such as parking or showers (13%). Weather-related constraints were cited by 5% of participants, while all remaining factors combined accounted for only 2%. Taken together, these outcomes suggest that the suppression of cycling in Tashkent is overwhelmingly infrastructural in origin, rather than attributable to environmental conditions or to attitudinal resistance among potential users.

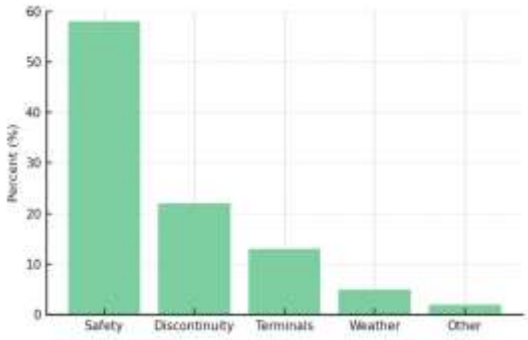


**Fig. 1. Distribution of self-reported barriers to cycling in Tashkent (n = 2000)**

The willingness-to-shift analysis (Fig. 2) shows that 64% of respondents would increase their cycling frequency if physically protected lanes were introduced, whereas 28% reported no anticipated change and only 8% indicated a possible reduction. This response pattern points to a substantial reservoir of latent demand that could be activated through credible safety improvements.

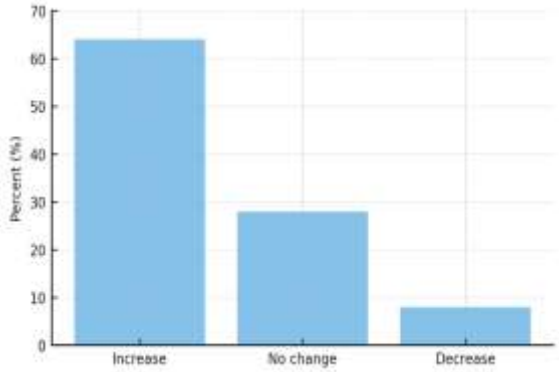


**Fig. 2. Stated willingness to cycle under a protected-lane implementation scenario**

Trip-purpose analysis indicates that cycling in Tashkent is not confined to leisure use but already serves utilitarian mobility needs (Fig. 3). Specifically, 41% of reported trips were undertaken for work or study purposes, 27% for shopping or errands, 25% for leisure activities, and only 7% fell into residual categories. This composition suggests that cycling is functionally embedded in daily mobility rather than restricted to discretionary travel.

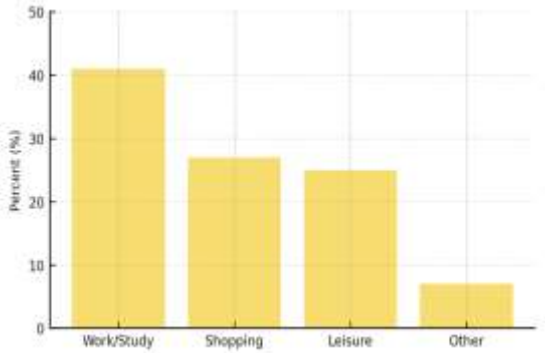


**Fig. 3. Trip purpose distribution among current cyclists in Tashkent**

The TOPSIS evaluation produced a clear ordering of the alternatives, with the fully protected and continuous network (A3) achieving the highest proximity to the ideal solution, followed by the partially protected corridor design (A2), and lastly the existing fragmented network (A1). This ranking reinforces the conclusion that network continuity and physical separation are decisive determinants of optimal performance (Fig. 4).

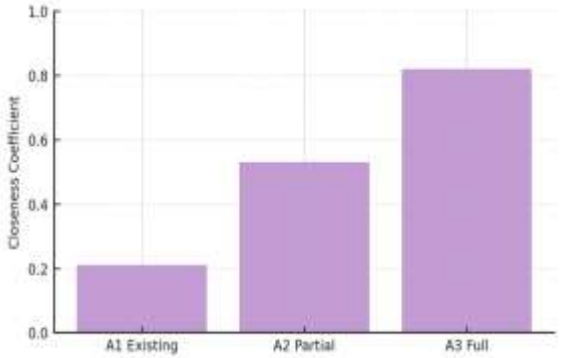


**Fig. 4. TOPSIS-derived closeness coefficients for the evaluated network scenarios**

## 4. Conclusion

The findings of this study demonstrate that the marginal status of cycling in motorising cities is not a consequence of behavioural resistance but a direct function of infrastructure design, making it an engineering- and policy-correctable failure rather than a cultural one. The results show that once the core structural constraints — safety, network continuity and terminal provision — are resolved, suppressed demand becomes immediately convertible into measurable mode shift. Accordingly, cycling must be reframed not as a symbolic sustainability gesture but as a transport intervention with quantifiable and replicable system returns. By jointly deploying a behavioural survey and a TOPSIS-based infrastructure evaluation, this work delivers method-grounded and decision-ready evidence that can directly inform investment and policy sequencing in Tashkent-type developing cities. In effect, the study demonstrates not what ought to be done in principle, but what will produce measurable change in practice when implemented.


https://doi.org/10.56143/3030-3893-2025-4-98-100

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# Analysis of the concept of a “15-minute city” connected by pedestrian green zones: A theoretical review

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Abstract: This study examines the theoretical foundations, historical development, key structural elements, advantages, and critical aspects of the increasingly prominent 15-minute city concept in contemporary urbanism. Integrating principles such as proximity, mixed-use development, pedestrian-friendly environments, and green infrastructure, the model assigns a central role to pedestrian green corridors as ecological and mobility connectors. The analysis indicates that the integration of walkable green networks enhances accessibility in urban public spaces, improves environmental sustainability, and strengthens social cohesion and public health. However, factors such as equity concerns, gentrification processes, and accessibility challenges faced by vulnerable groups present significant obstacles to practical implementation. The findings emphasize that the effective adoption of the 15-minute city model requires a comprehensive, equity-driven, and inclusive planning approach.

Keywords: 15-minute city; pedestrian green corridors; sustainable urbanism; walkability; mixed-use development; green infrastructure; urban mobility; environmental sustainability; urban resilience; accessibility; social equity; proximity-based planning; public health; ecological connectivity; neighborhood-scale planning; climate adaptation; urban design

## 1. Introduction

The 15-minute city has emerged as a transformative model for sustainable urban development, promoting compact neighborhoods in which essential services—such as healthcare, education, commerce, and recreation—are accessible within a 15-minute walk or bicycle ride [1, 2]. Prioritizing active mobility and environmental quality, this approach seeks to reduce automobile dependency, improve public health, and enhance the climate resilience of cities [3, 4].

Growing interest in this concept is driven by global challenges such as climate change, traffic congestion, air pollution, and rising social fragmentation. Pedestrian-oriented green spaces—including parks, greenways, and ecological corridors—occupy a central role within this model by linking neighborhoods, improving environmental performance, and supporting walkability.

## 2. Research methodology

**Historical foundations of the 15-minute city**

Although the “15-minute city” concept has gained widespread popularity in recent years, its origins can be traced back to centuries of urban design traditions. Early precedents include the orderly street grids characteristic of Roman cities, the compact settlements of the medieval period, and Renaissance ideals emphasizing accessible public spaces [1, 3, 5]. During the Baroque era, street networks became more formalized and expansive, while by the 19th century, the cities of Paris and London exhibited markedly different approaches to urban expansion [1, 3].

In the 20th century, Clarence Perry’s neighborhood unit theory and the subsequent New Urbanism movement placed strong emphasis on proximity, community interaction, and pedestrian-friendly environments—principles that form the foundation of today’s 15-minute city model [3, 7]. The contemporary model synthesizes these historical traditions with planning frameworks oriented toward sustainability and social equity [4, 14].

**3. Key components of the 15-minute city**

**3.1. Green Infrastructure as Urban Connectivity**

Green infrastructure (GI) is one of the fundamental components of contemporary urban planning, supporting not only environmental sustainability but also social engagement and physical activity. GI encompasses parks, green spaces, community gardens, tree-lined streets, water corridors, green pathways, and ecological corridors that connect different parts of the city. These elements strengthen the balance between natural and anthropogenic components of the urban environment, help preserve biodiversity, and create accessible spaces for recreation and social interaction [15, 24].

Furthermore, green infrastructure significantly influences urban microclimates: tree cover and vegetated surfaces mitigate the urban heat island effect, purify the air, and filter dust and harmful pollutants. This process constitutes an essential aspect of environmental justice. Research indicates that residents living near green spaces exhibit improved mental and physical health; reduced stress levels; increased social engagement; and higher levels of physical activity [15, 24, 35].

However, the actual effectiveness of GI is closely linked to its equitable distribution across urban areas. A lack of green spaces in low-income or historically underserved neighborhoods contributes to environmental inequality. Therefore, green infrastructure must be planned as a social resource that provides equal benefits to all residents [15, 17].

**3.2. Pedestrian Networks and Walkability**

Pedestrian networks—systems of walkways and public spaces designed for pedestrian movement—constitute one of the key structural elements of the 15-minute city concept.

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These networks are regarded not merely as pathways for walking, but as systems that integrate the city socially, economically, and environmentally. Well-designed pedestrian infrastructure must incorporate essential indicators such as continuity, safety, comfort, universal design principles, and spatial attractiveness. In addition, pedestrian routes are required to be seamlessly integrated with green spaces, public transport stops, neighborhood centers, and residential areas [18].

International practice shows that the degree of integration within pedestrian networks (high, medium, or low) reflects how effectively people can move through these pathways. The quality of urban streets—including wide pedestrian walkways, shaded tree canopies, bicycle lanes, safety measures, night-time lighting, tactile guidance, and other features—serves as a primary determinant of walkability. The Pedestrian Environment guide developed by VTA clearly defines these quality indicators and confirms their importance for the successful implementation of the 15-minute city model [16, 18,36].

**3.3. Mixed-Use and Proximity-Based Planning**

Mixed-use development—integrating residential, commercial, service, educational, and healthcare functions at the neighborhood scale—is a central component of the 15-minute city concept. Such multifunctional areas stimulate local economic activity, reduce the need for long-distance travel, and strengthen social interactions [20]. Analyses provided by Stellarix emphasize the role of mixed-use environments in enhancing economic resilience and reducing costs by increasing proximity to essential services [13].

This approach becomes most effective when implemented alongside safe pedestrian routes, bicycle lanes, and accessible public transportation. Local businesses, marketplaces, and community spaces play an important role in reinforcing both the economic vitality and the social fabric of the neighborhood.

**3.4. Equity and Universal Accessibility**

The 15-minute city model must be understood not only as a framework for convenience, but also as an approach aimed at ensuring social equity. Every population group—including youth, the elderly, persons with disabilities, and low-income households—must have equal opportunities to benefit from the city. An equitable urban model is grounded in the principles of universal design: low-gradient ramps, step-free access, tactile pathways, signage for individuals with visual or hearing impairments, accessible public transport, and safe intersections constitute its essential components [9, 10, 19].

Proximity-based planning often implies that residents should be able to reach key services by walking; however, not everyone has the physical capacity to do so. Therefore, accessible public transportation and inclusive street design are mandatory elements of the 15-minute city. Without these features, the model may become inconvenient or exclusionary for persons with disabilities, older adults, or parents with small children.

The economic dimension of social equity is also critical: services, green spaces, and transportation infrastructure must be available in low-income neighborhoods as well. Otherwise, high-quality urban environments risk serving only higher-income groups, thereby intensifying gentrification processes—such as rising housing prices and the displacement of long-term residents [12]. Thus, the 15-minute city must be built not only on the principle of proximity, but also on ensuring real, physical, and economic accessibility for all.

**4. Benefits of the 15-minute city**

The 15-minute city model is widely recognized in scientific literature not only as a framework for optimizing urban transportation systems, but also as a comprehensive approach that strengthens the ecological, economic, and social sustainability of cities. This section provides a detailed examination of the model's key benefits:

**4.1. Environmental Benefits**

Positive environmental impact is one of the most significant attributes of the 15-minute city concept. By reducing automobile dependency, the 15-minute city lowers emissions of $CO_2$, NOx, and PM2.5, thereby decreasing the burden on public health systems and improving overall air quality [8, 21, 22]. The expansion of pedestrian and cycling infrastructure further reduces the ecological footprint of transportation. Enhanced efficiency in public transit also decreases fuel consumption and reduces greenhouse gas emissions.

Green infrastructure—particularly pedestrian green corridors—mitigates the urban heat island effect, stabilizes soil moisture, and supports water resource management through mechanisms such as bioswales and natural filtration systems. At the neighborhood scale, these functions contribute to improved microclimate regulation and strengthen adaptation to climate change [6, 24, 28].

**4.2. Health and Well-Being**

The 15-minute city concept offers substantial advantages in the field of public health. First and foremost, increased physical activity—resulting from expanded opportunities for walking and cycling—encourages residents to adopt healthier lifestyles. Regular physical activity reduces the risk of cardiovascular diseases, diabetes, obesity, depression, and other chronic conditions [22, 23, 24].

Green spaces and parks also exert a significant positive influence on population health. Research shows that regular interaction with nature lowers stress hormone levels, improves mood, strengthens the immune system, and contributes positively to the psychological development of children. The presence of green corridors makes short daily walks more appealing, leading individuals to spend more time outdoors.

Another major health benefit stems from improved air quality. A decrease in automobile use reduces the prevalence of respiratory diseases such as asthma, bronchitis, and allergies. Children and the elderly, in particular, experience notable improvements as a result of cleaner air.

Mental well-being is likewise a core benefit of the 15-minute city model. Public open spaces, green corridors, and recreational areas enhance social interaction, reduce feelings of loneliness, and improve overall quality of life. Walking itself has antidepressant effects and supports cognitive functioning.

Consequently, the 15-minute city model lessens the burden on healthcare systems, strengthens preventive health measures, and significantly improves the general well-being of the population.

**4.3. Socio-Economic Benefits**

Services located within the neighborhood generate direct benefits for the local economy: small businesses, cafes, service centers, and markets expand, thereby creating employment opportunities and sustaining monetary circulation at the neighborhood level [25, 26]. Compact

cities also reduce infrastructure-related expenses—such as road maintenance and the upkeep of extensive utility networks—and enable more efficient use of available resources [8, 27]. During the pandemic, areas that relied on localized economic activity demonstrated greater resilience to external shocks, highlighting an additional economic advantage of the 15-minute city model.

**5. Criticisms and limitations**

Although the 15-minute city concept is widely supported by urbanists, policymakers, and the public, its implementation can give rise to a number of complex challenges. The following section provides a detailed analysis of the concept's limitations, critical viewpoints, and strategies for addressing them.

**5.1. Risk of Gentrification and Inequality**

Improvements in urban infrastructure, the expansion of green spaces, the enhancement of public areas, and the upgrading of service quality significantly increase the risk of gentrification. Studies indicate that in areas where a high-quality environment is created, property values tend to rise sharply, which may lead to the displacement of low-income residents [2, 12].

Another negative aspect of the gentrification process is the reduction of social diversity. That is, neighborhoods that once accommodated residents of various cultural, ethnic, and socioeconomic backgrounds gradually transform into more "homogeneous" areas dominated by middle- and high-income groups. This, in turn, diminishes social capital, erodes cultural diversity, and forces local small businesses to close due to rising rental costs.

Moreover, if the 15-minute city model is implemented only in selected central districts while peripheral or underdeveloped neighborhoods are neglected, new forms of social inequality may emerge within the city. As a result, the model may inadvertently create a "two-tier city" characterized by:

– one area with full access to amenities, environmentally clean spaces, and walkable infrastructure;

– and another where services are insufficient, transportation connections are weak, and green spaces are scarce.

Therefore, mechanisms such as affordable housing policies, rent control measures, the expansion of social housing stock, subsidies, and support for local businesses must be integrated into the 15-minute city strategy. Without these safeguards, the model cannot effectively serve the principles of social equity.

**5.2. Accessibility Challenges**

The 15-minute city model often relies on the mobility capacities of individuals who are able to walk. Consequently, not all services are equally accessible for persons with disabilities, older adults with limited mobility, mothers with young children, or individuals experiencing temporary physical impairments [10, 11].

As numerous researchers have emphasized, the notion of a "walkable distance" is not universal, which presents a significant challenge. For example:

– a 15-minute walking distance may be convenient for younger individuals but overly demanding for the elderly;

– for wheelchair users, poorly designed pathways, high curbs, or narrow sidewalks create serious barriers;

– the absence of tactile guidance reduces safety for people with visual impairments;

– and in cities where the public transport system is underdeveloped, walking alone cannot ensure adequate access to essential services.

Furthermore, in the context of the 15-minute city, what matters is not merely the physical presence of services but the actual accessibility of those services from the user's perspective. In other words, even if services are geographically close, the proximity becomes meaningless if:

– elevators are out of service,

– ramps are unavailable,

– pathways are difficult to navigate, or

– the transport system is not adapted for diverse users.

For these reasons, universal design, ramps, wide sidewalks, low curbs, tactile pathways, pedestrian safety measures, wheelchair-accessible buses, and inclusive light-rail systems must constitute integral components of the 15-minute city model.

**5.3. Structural Barriers**

Some scholars view the 15-minute city as a model constrained by solutions that operate primarily at the individual level. In their view, systemic challenges—such as environmental degradation, social inequality, migration pressure, or energy crises—cannot be resolved solely by creating walkable urban environments [30, 31, 29]. For example, environmental critics argue that:

– establishing green zones does not halt global ecological problems;

– planting trees within the city is insufficient if industrial pollution continues;

– and although local green spaces may be well-developed, they cannot influence large-scale issues such as widespread deforestation or the depletion of water resources.

Another important criticism is that the effective implementation of the 15-minute city is heavily dependent on political will. Because the model requires comprehensive infrastructure, transportation, and housing policies, it can be extremely difficult to implement in cities facing poor governance, financial constraints, or political conflict.

Furthermore, some experts contend that the concept is overly romanticized and fails to account for the complex socio-economic nature of contemporary cities. In reality, individuals' workplaces, incomes, travel behaviors, cultural preferences, and spatial choices are influenced by geographically intricate dynamics that cannot be simplified into a uniform proximity-based model [30, 31].

The 15-minute city model may also pose the risk of "territorial isolation." If residents live, work, and spend their leisure time exclusively within their own neighborhoods, social interaction across different demographic groups may diminish, thereby intensifying urban social segmentation—an issue widely noted by many urban sociologists.

**6. Pedestrian green corridors: A structural connector**

Pedestrian green corridors are regarded as one of the most critical connecting elements between the ecological and social systems of contemporary cities. They function not merely as walkways for pedestrians, but as multifunctional spatial infrastructures that support the sustainable development of the urban environment. By providing continuous, safe, and attractive movement routes throughout the city, green corridors deliver high-quality ecological services: they moderate microclimates, purify the air, support biodiversity, and strengthen human–nature interactions [9, 2].


https://doi.org/10.56143/3030-3893-2025-4-101-106 A bridge between science and innovation

These ecological corridors also serve as fully integrated mobility networks for pedestrians. Walkways shaded by tree canopies facilitate comfortable movement and create cooler environments during hot weather—an especially important feature for mitigating the urban heat island effect under conditions of global warming. Furthermore, green corridors connect communal spaces, parks, water channels, sports areas, cultural centers, and neighborhood functional nodes, thereby acting as the social spine of the city.

One of the most significant functions of pedestrian green corridors is the reduction of ecological fragmentation. In urban areas, natural habitats become divided due to residential blocks, road infrastructure, and industrial zones. Green corridors reconnect these fragmented landscapes and provide migratory pathways for birds, insects, and small animals. As such, they represent one of the most effective means of enhancing ecological resilience, creating continuous green networks, and preserving biodiversity [15, 24].

Green corridors offer not only environmental benefits but also psychological and social advantages for urban residents. Research shows that exposure to natural environments reduces stress, improves mood, lowers levels of depression, and increases physical activity—all of which alleviate pressure on public health systems. Seating areas, communal play spaces, and outdoor activity zones located along these corridors strengthen social interaction and community cohesion. The Green Belt project in Vitoria-Gasteiz clearly illustrates the effectiveness of this model: the creation of a surrounding green belt and central pedestrian routes significantly enhanced ecological connectivity, increased physical activity among residents, and improved the overall harmony of the urban environment. As a result, Vitoria-Gasteiz was awarded the European "Green Capital Award" in 2012 [9, 2]. Thus, pedestrian green corridors serve not only as walkable mobility infrastructure but also as the "green backbone" that ecologically, socially, and functionally integrates the city.

## 7. Global case studies

Global cities are implementing the 15-minute city model at varying scales, developing context-specific strategic approaches informed by local conditions. The following cases illustrate how this model operates in practice and how it is adapted across diverse geographical, political, and cultural contexts.

### 7.1. Paris

Paris is a leading example of the "15-minute city" concept, implemented under the leadership of Mayor Anne Hidalgo. The city has been restructured to ensure that essential services — such as work, healthcare, education, and shopping — are accessible within a 15-minute walk or bike ride. This decentralized urban model promotes self-sufficient neighborhoods, combining residential, commercial, and public spaces to reduce reliance on cars and long commutes. To facilitate this transformation, Paris has developed over 1,000 kilometers of cycling paths and allocated a budget of 75 million euros for community-selected projects. Notable initiatives, such as the conversion of Rue de Rivoli for pedestrian and bike use, exemplify the city's commitment to creating a connected and resilient urban environment that fosters community engagement and sustainability [32, 23, 6].

### 7.2. Vitoria-Gasteiz

The city of Vitoria-Gasteiz, Spain, has gained international recognition for its commitment to sustainable development, earning accolades like the 2012 European Green Capital and the 2019 Global Green Capital. Central to its strategy is the establishment of a green belt, which serves as the backbone of the city's green infrastructure (GI) network. This green belt aims to connect various green areas within the city, the surrounding agricultural lands, and potential ecological corridors linking peripheral natural spaces. Furthermore, the city has implemented a comprehensive analysis of its pedestrian network, categorizing elements based on their global integration to enhance walkability and promote community interaction [2, 9].

### 7.3. Barcelona

Barcelona has embraced the 15-minute city concept through its "super blocks" initiative. This innovative urban design strategy modifies existing city layouts to create pedestrian-friendly areas with restricted vehicle access. By transforming traditional street grids into clusters where cars are limited, each super block fosters local neighborhoods complete with courtyards, green spaces, and community gathering areas. This approach enhances walkability and promotes a vibrant urban life while reducing air pollution and traffic congestion [23].

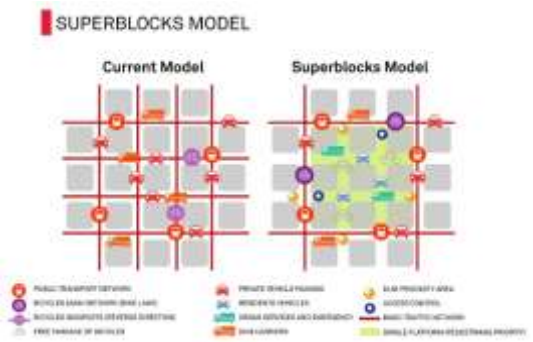


**Fig. 1. Barcelona Superblocks Model: Comparison Between the Current Street Grid and the Superblocks Configuration**

### 7.4. Portland

In the United States, Portland, Oregon, serves as an example of a successful 20-minute neighborhood model. This approach aligns with the principles of the 15-minute city by prioritizing pedestrian access to essential services within a short walking distance. Portland's urban planning focuses on enhancing neighborhood livability, encouraging cycling, and integrating green spaces to foster community ties. This model has shown promising outcomes in terms of public engagement and urban sustainability, making Portland a significant case study in the evolution of urban living [32, 33].

### 7.5. Global Implications

While the 15-minute city framework aims to enhance urban life by making essential services more accessible, it also faces challenges such as potential gentrification and the risk of displacing less affluent residents. The model's effectiveness can be limited in areas with low population densities or inadequate transportation infrastructures. Despite these obstacles, cities that implement the 15-minute city principles, like Paris and Vitoria-Gasteiz, demonstrate the potential for fostering social cohesion, improving public health, and promoting environmental sustainability within urban environments [33, 34].

## 3. Conclusion

The findings of the study indicate that the 15-minute city model holds significant potential for improving transportation efficiency, environmental sustainability, public health, and social equity. Pedestrian green corridors emerge as a key driver in the practical implementation of this model, contributing to the creation of a human-centered and sustainable urban environment. However, realizing the full effectiveness of the model requires adherence to principles of equity and inclusiveness, alongside affordable housing policies, institutional support, and strategic governance.

Accordingly, future research should focus on expanding GIS-based assessment methods, examining access to pedestrian and green infrastructure across different demographic groups, developing adaptation strategies in the context of climate change, and exploring differentiated approaches to implementing the model in various urban morphologies.

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# Results of assessing work capacity and fatigue levels of air traffic control dispatchers during their professional activities

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Abstract: The article analyzes scientific research conducted by foreign, local, and CIS scientists and specialists on improving occupational safety for operator-dispatchers working in various economic sectors. Based on the research results, legal, organizational-technical, and sanitary-hygienic measures aimed at improving the working conditions of air traffic controllers have been proposed. However, it has been determined that the impact levels of production environment factors and work process factors on air traffic controllers operating within the air traffic control service have not been sufficiently studied. Furthermore, specific methods, technical means, and practical-technological solutions aimed at reducing these factors have not been developed. Within the scope of the research, changes in fatigue levels and work performance of air traffic controllers throughout their work shifts were quantified in percentage values using the integral scoring assessment method.

Keywords: air traffic controllers, workplace, working conditions and safety, integral scoring assessment method, factors of the labor process and production environment

## 1. Introduction

In recent years, the civil aviation sector in the Republic of Uzbekistan has been actively developing, with numerous infrastructure and investment projects being implemented across the country. In accordance with state programs and development strategies, existing airports are being modernized, and new airfield complexes and air navigation facilities are being put into operation. These processes have enhanced the efficiency of the country's airspace utilization, ensured flight safety, and expanded the capacity to provide services that meet international aviation standards.

Currently, an air traffic control system has been established in the Republic of Uzbekistan within the Tashkent FIR (Flight Information Region), where the central air traffic control center in Tashkent city and regional and airfield control points operate as part of a unified system. Airfield control towers (TOWER), approach control units (ADP/AYDP), as well as area and terminal control centers (RM, KDP, SDP) are operational at the international airports of Tashkent, Samarkand, Bukhara, Urgench, Nukus, Karshi, Termez, Fergana, Andijan, and Namangan.

The operational dispatch service of the Air Traffic Service (ATS) within the State Unitary Enterprise "Uzaeronavigation Center" system ensures reliable and efficient operation of the air traffic control system. This includes centralized operational management of flight planning, aircraft movement coordination, and airspace utilization processes. The operational dispatch service of the SUE "Uzaeronavigation Center" employs over 200 air traffic controllers (for upper and lower airspace) who perform crucial tasks across all major airports and airspaces of the republic. These tasks include ensuring flight safety, monitoring and analyzing air situations, preventing and managing emergencies, and establishing cooperation with civil and military aviation structures.

## 2. Research methodology

The organization of the operational dispatch service in 2 shifts with extended working hours (12 hours) necessitates the implementation of measures to ensure the safety, health, and work capacity of air traffic controllers. Otherwise, such conditions will lead to a sharp increase in the risk of occupational diseases among air traffic controllers. Therefore, studying the working conditions of air traffic controllers and developing and implementing organizational, technical, and sanitary-hygienic solutions to ensure full compliance of the workplace with sanitary and hygienic requirements enhances the practical significance of various tasks. These tasks include: safe and continuous control of aircraft movement, maintaining a balance between flight flow and airspace utilization, monitoring and analyzing real-time weather data, preventing and addressing emergencies and accidents, coordinating activities of dispatch points and aviation services at various levels, as well as ensuring the optimal operation of the entire air traffic control system in accordance with international and national aviation safety standards.

In numerous instances, all necessary operations are performed under severe time constraints. During extreme situations, multiple operations must be carried out simultaneously, demanding strain on visual and auditory analyzers, significant concentration of attention, and the utilization of both short-term and long-term memory. The work of air traffic controllers is directly influenced by various factors in the production environment, such as the reliability of technical equipment, quality of communication systems, workplace ergonomics, microclimate, and levels of lighting and noise. Therefore, ensuring that air traffic controllers' working conditions fully comply with hygienic requirements significantly guarantees the safe execution of tasks performed during their work activities and holds practical importance.

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Numerous studies on improving occupational safety for air traffic controllers and dispatchers in related fields have been conducted by scientists and specialists from various countries. Local and international scientists and researchers have carried out scientific investigations aimed at analyzing and enhancing the working conditions of air traffic controllers and dispatchers in related industries, developing a range of noteworthy practical solutions and recommendations. Legal, organizational-technical, and sanitary-hygienic requirements for the working conditions of air traffic controllers and dispatchers in related fields have been established and implemented. Many authors have examined the development and practical application of scientifically-based organizational, technical, and social measures aimed at improving working conditions by applying these requirements to enhance occupational safety [1-27].

## 3. Results and discussions

The results of the conducted research and the recommendations presented in them are of great importance. However, the recommendations given by these authors are of a specific nature, and their direct application to improve the working conditions of air traffic controllers in the system of the SUE "Uzaeronavigation" Center does not yield the expected results in enhancing working conditions. Nevertheless, it is advisable to use the methodology of these studies, taking a creative approach, when examining the working conditions of air traffic controllers in the dispatch service. In this regard, to continue the research work, an analysis was conducted on the results of assessing the compliance of working conditions with hygienic standards, taking into account the workplaces, types and volumes of work performed by air traffic controllers operating at airports and air traffic control centers of the Republic of Uzbekistan.

Based on the analysis of the results assessing the compliance of working conditions for air traffic controllers in the air traffic control service with hygienic standards, the evaluation results of harmful factors in the production environment and work process have been included in the general assessment table of working conditions by degree of harmfulness and danger. Subsequently, the assessment of harmful factors was carried out in the following cases: by the highest level and degree of harmfulness; under conditions where the overall assessment of working conditions corresponds to class 3.2; in situations with the combined effect of 3 or more factors belonging to class 3.1; and in cases where 2 or more harmful factors belong to classes 3.2, 3.3, or 3.4. In these circumstances, the working conditions were assessed as one level higher, respectively [28].

Analysis of the assessment results regarding the compliance of working conditions for air traffic controllers in the SUE "Uzaeronavigation" Center with hygienic standards revealed the following: their working conditions belong to class 2.0 based on actual concentrations of harmful substances in the workplace; class 3.1 for levels of noise, infrasound, ultrasound, and vibration; class 2.0 for levels of non-ionizing electromagnetic radiation; class 3.2 for the severity of the work process; and class 3.2 for the impact of work process load. The overall assessment of the air traffic controllers' working conditions in compliance with hygienic standards corresponded to class 3.4.

In accordance with the Regulations on the Procedure for Certification of Workplaces for Working Conditions and Equipment Injury Hazards, appropriate guarantees and preferences have been established for air traffic controllers of the operational dispatch service working in hazardous conditions (class 3.4). The duration of the annual additional leave for air traffic controllers should be 13 to 18 days. Their position is included in the 2nd list of occupations that entitle them to retire 10 years earlier than the generally established age, provided they have the required general and specialized work experience [28].

Based on the analysis of assessing the compliance of aviation dispatchers' working conditions with hygienic standards at their workplaces, the degree of fatigue and decreased work capacity during the entire shift were determined using the integral point assessment method. This assessment was made through evaluating each factor of the existing production environment and work process at their workplace. For factors of the production environment and labor process belonging to classes 3.1 and 3.2, scores were established taking into account the duration of each factor's influence. The following points were assigned: 4 points for exceeding the permissible noise level in the workplace, 4 points for vibration level, 3 points for uncomfortable body position during the shift, 3 points for intellectual load (i.e., work content), 4 points for receiving and assessing signals (information), 4 points for task complexity, 4 points for dimensions of object observation, 4 points for duration of continuous work during the shift, and 3 points for shift work [29].

The coefficient of the duration of influence of production environment and labor process factors of classes 3.1 and 3.2 at the workplace of air traffic controllers during the work shift (day) was determined using the following formula:

$$K_{16} = \frac{t_i}{t_s(t_k)} = 0{,}83$$

$t_i$ $t_s(t_k)$ −where - duration of exposure time to production environment and labor process factors (taken from the certification conclusion of the workplace working conditions map), in minutes; duration of work shift (day), in minutes.

The comparative value of the point assessment for production environment and labor process factors at air traffic controllers' workplaces was determined using the following formula:

$$\sum_{i=1}^{n} x_i = x_{16} \cdot K_{16} = 37{,}35 \cdot 0{,}83 = 31 \ \ ball$$

$x_{16}$ $K_{16}$ −where - the sum of points assigned to factors belonging to classes 3.1 and 3.2 of the production environment and labor process, in points; coefficient of the actual exposure duration to production environment and labor process factors during the work shift (day).

$\sum_{i=1}^{n} x_i = 31$Based on the total sum of points assigned to each factor of the production environment and labor process, it is possible to determine the numerical value of air traffic controllers' fatigue during the shift as a percentage. In this case, it is advisable to use the empirical formula developed by researchers [30]:

$$Ch = \frac{\sum_{i=1}^{n} x_i - 15{,}6}{0{,}64} = \frac{31 - 15{,}6}{0{,}64} \approx 24\ \%$$

where: 15.6 and 0.64 are regression coefficients.

According to the calculations, the fatigue level of air traffic controllers during the shift is 44%. Using the numerical value of fatigue, the work capacity of air traffic controllers during the shift, expressed as a percentage, was determined using the following formula:

$$I_q = 100 - Ch = 100 - 24 = 76\,\%$$

$Ch$where: 100% - work capacity under favorable working conditions, in percent; - fatigue level, in percent.

The work capacity of air traffic controllers during their shift, assessed according to the workplace conditions map under hygienic criteria, amounted to 76%. This indicates the possibility of working under hygienic, intellectual, sensory, and emotional stress, which, in turn, negatively affects the quality of their work and decision-making.

## 4. Conclusion

The conducted studies revealed that the working conditions of dispatchers in the air traffic control service within the "Uzaeronavigation" State Unitary Enterprise system fall into class 3.4 according to hygienic assessment criteria, categorizing them as harmful working conditions. This confirms the presence of factors in their workplaces that negatively affect their health. Concurrently, these working condition characteristics align with the inclusion of air traffic controllers in List 2 positions, which entitle them to additional guarantees and preferences, particularly up to 13-18 days of additional leave, as well as the right to retire 10 years earlier. The results of the integral point assessment showed that air traffic controllers experienced fatigue at a level of 24 percent and maintained work capacity at 76 percent during their work shift. This indicates the presence of high levels of psychophysiological stress in their labor process throughout their activity.

It is known that, despite recognizing the life and health of employees as a priority in state labor protection policy, attempting to address the problem through compensation payments and benefits, rather than genuinely improving existing unfavorable working conditions, may lead to an increased risk of occupational diseases among air traffic controllers in the long term. In this regard, it is crucial to develop scientifically-based technical and organizational solutions aimed at ergonomic and biomechanical optimization of workplaces, as well as reduction or elimination of harmful factors in the work environment, in order to fully align air traffic controllers' working conditions with sanitary and hygienic requirements.

The proposed method described above allows for the numerical determination and prediction of the probability of developing occupational diseases caused by exposure to fibrogenic aerosols among employees working in non-stationary workplaces in railway transport.

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# Social marketing how tool increasing the efficiency of consumer cooperative organizations: institutional aspect

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Abstract: The article examines theoretical approaches to improving the efficiency of consumer cooperative organizations based on the synthesis of the concept of social marketing, contract theory of the firm and group theory. Functioning of consumer cooperatives on market goods And services as systems social order, characteristics which perform cooperative values And principles, declaring honesty, concern for society, mutual assistance, justice And solidarity, determines the need to improve the theoretical basis for increasing the efficiency of consumer cooperative organizations through use wide spectrum marketing tools.

Keywords: social marketing, collective goods, cooperative ideology, social activity, consumer cooperation

## 1. Introduction

In the context of the development of marketing theory and practice, the concept of social marketing currently occupies an important position, the problem of definition of which is associated with determining the nature of the embeddedness of marketing in social reality.

By social marketing, in the context of this study, we mean the promotion of products and services produced organizations consumer-body cooperation with the help of a system of social actions. Concept social marketing, based on from Togo, What task organizations is establishment needs, needs and the interests of target markets and ensuring the desired satisfaction more efficient and more productive (than competitors) ways with simultaneous preservation and strengthening consumer welfare and society V in general, allows you to expand the range of problems that can be solved with help marketing approach to construction effective and sustainable development [1].

Social marketing is excellent How from advertising, because at its implementation Not affected consumer properties economic blessings, so and from charity, because pursues commercial goals. It follows note, what is social marketing organically fits in V system social activities organizations systems, V force associations its market and non-market functions. Like this in this way, implementing social activity organizations consumer cooperation, simultaneously are implementing inherent to them social function, a with another parties have a positive influence on the formation of consumer preferences. In our opinion, the justification of the functions social marketing, allowing consider his V system institutional analysis, performs study features production exclusive and inclusive collective goods in the consumer cooperative system.

## 2. Research methodology

The functioning of a cooperative for the production of an exclusive collective good does not ensure the optimal distribution of the good and the costs of obtaining it due to the underutilization of resources, and, in addition, leads to an increase in social differentiation of the population. At the same time, the provision of an inclusive collective good also does not ensure economic optimality in the distribution of goods and costs due to the possibility of opportunistic behavior of individuals. Moreover, this nature of the provision of a collective good leads to a decrease in social differentiation through the "exploitation of the minority by the majority." This is ensured by two factors. Firstly, the costs of producing a collective good are borne by that part of the group that is most interested in it, or that has the opportunity to bear these costs, and the results of producing the good are available to all members of the group. Secondly, bearing the costs of obtaining a collective good reduces the disposable income of one part of the group, while increasing the disposable income of the other part by the amount of the collective good (the so-called income effect). In conditions of equal interest in obtaining a collective good, its production can be ensured only under the influence of cooperative ideology. Exactly she contributes socially fair distribution of benefits and the costs of obtaining them in groups of individuals by combining the production of inclusive and exclusive collective goods [2].

In this case, the production of inclusive goods is expressed in ensuring access of the served population to goods and services, while the dissemination of cooperative ideology through social marketing to the non-cooperative population results in the formation of an exclusive good. The essence of this good is expressed in satisfying the need for self-affirmation through the individual's commitment to cooperative values and principles, his consciously rational, socially responsible behavior. As G.V. Kalyagin rightly notes, the influence of cooperative ideology and the desire to benefit society are non-economic incentives for membership in a cooperative.

The magnitude of the collective good, defined as adherence to cooperative ideology, is nonlinear with respect to the level of cooperation. We explain this by the fact that the influence of cooperative ideology can be divided into two components – external and internal. The external influence of cooperative ideology is associated with information about the advantages of the cooperative form of management, available to group members. At the stage of the creation of consumer cooperation, the source of external ideology was

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the works of the creators of cooperation, the results of education and popularization of cooperatives. As cooperation occupied an ever-increasing role in the economy of various states, the external influence of cooperative ideology was manifested in the popularization among the population of the results of the activities of consumer societies, the disclosure of socially just principles of their activities. At present, external influence main way connected with activity of the mass media, including cooperative ones.

## 3. Results and discussions

The influence of cooperative ideology is manifested in the fact that What cooperative Part The population evaluates the external environment as more certain, compared to a non-cooperative one. As the level of cooperation increases, the difference in the level of uncertainty between these groups increases, which leads to an increase in incentives to move to a group with a lower level of uncertainty. Thus, we can say that the presence of a cooperative ideology allows for the transformation of exclusive collective goods into inclusive ones and ensures their combination. The role of cooperative ideology in creating collective wealth can also be substantiated from the perspective of game theory. Thus, the adoption of a cooperative ideology by all individuals in a group allows everyone individual with greater shares likely-be able to predict the strategy of another individual compared to a situation where the influence of ideology is absent. If the cooperative ideology is adopted by the entire group, the strategy of each individual will be participation in the cooperative, that is, Pareto optimality, which characterizes the economic and social efficiency of resource allocation, will be achieved [3].

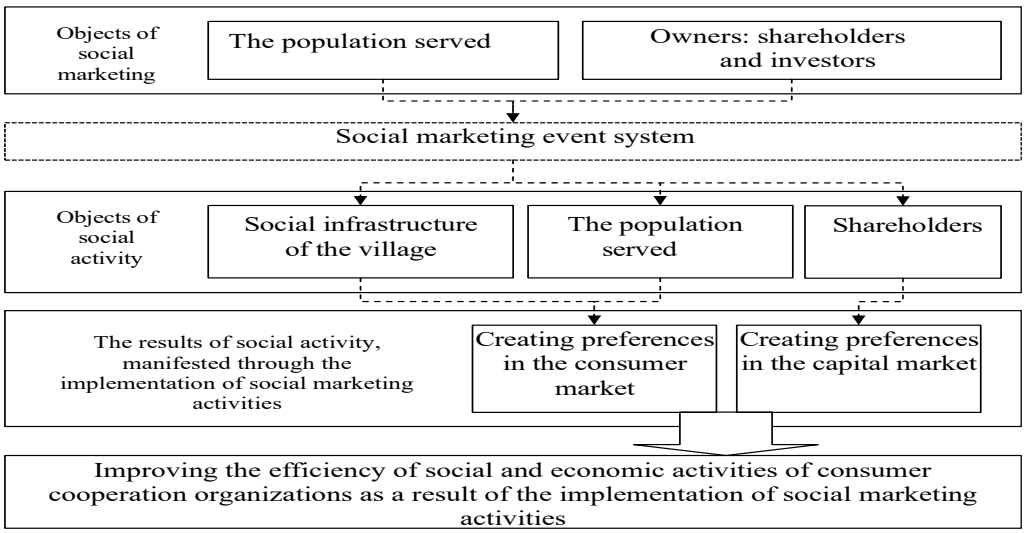
In our opinion, the development of cooperative ideology in the current conditions should be ensured by the implementation systems events social marketing aimed at the population served and providing for the improvement of institutional agreements. In this case, the peculiarity of social marketing is the characteristic of the object of social activity, which is external in relation to a cooperative organization, environment and being a consumer of inclusive collective goods (Fig.). The social marketing system provides for the transformation of consumer behavior from exogenous, in relation to the organization, to endogenous, the result of which is the formation of stable consumer preferences that have a positive impact on the volume of the organization's activities in the market.

Effective implementation of social marketing activities is aimed at forming sustainable institutional relationships between cooperative organizations as producers of economic goods and the population served as their consumers. This will help overcome the impersonality of market exchange, in which the criteria for the emergence of relations between them are only the economic parameters of price and utility. In this case, the implementation of social activities is aimed at forming social capital, integrated into the social structure of society, which, in turn, is the consumer of its results.

At the same time, it is necessary to ensure the responsibility of cooperative organizations for the quality of economic goods, the formation of their fair social price, the participation of society in the distribution of income from the economic activities of consumer cooperatives, and the development of the social infrastructure of the territories served.

When forming the directions of social activity of consumer cooperatives, it is necessary to take into account the integration of the functions of social infrastructure, the costs of the formation of which determine both external and internal economic effects of its implementation. This situation is explained territorial specifics of the functioning of cooperative organizations. The area of activity of the majority from them are rural settlements, on a scale where a multiplicity of single-functional social infrastructure facilities is impossible, which necessitates ensuring unlimited access to them for all categories population (workers, consumers, shareholders). In this regard, the economic component of the functioning of infrastructure objects represents is a complex value that characterizes both the increase in the effectiveness of activities due to an increase in the return on labor resources, and due to preferences in consumer preferences [4].

The characteristic features of social activity inherent only to consumer cooperatives are manifested in the uncontested nature of the provision of both economic and social benefits to the population served. This is expressed in the fact that consumer cooperative organizations in rural areas are often the only suppliers of goods and services to the rural population [5].



## 4. Conclusion

At the same time, cooperative organizations carry out social activities on the scale of rural settlements also on a non-alternative basis, being the only non-governmental source of social assistance to the population and the formation of social infrastructure of the village. This situation determines special requirements for the nature of institutional ties between cooperatives and the population served, increasing the level of trust between them. Strengthening these institutional interactions is mediated by the content of the internal institutional environment of cooperative organizations, and specifically - the provisions of the norms, principles and values of the cooperative movement, which enshrine the social responsibility of cooperatives to society [6].

The implementation of social activities of consumer cooperatives aimed at the external environment should also contribute to the formation of preferences in the capital market. This is due to the formation of cooperative property by combining the share contributions of many individuals - shareholders, whose behavior is determined not only by the parameters of economic efficiency investments, But and social orientation of the investment object. In addition, the participation of the population in the formation of financial resources of cooperative organizations is largely determined by the nature of institutional agreements in the management of the cooperative on democratic principles, the social component of which can have a decisive impact on the choice of investment object.Participation of the population in the formation of financial resources of cooperative organizations is possible not only through share contributions, but also through lending to cooperatives by providing free funds on mutually beneficial terms. It is obvious that social activity organizations. Thus, the formation of a social marketing system will ensure the sustainability of institutional agreements between shareholders, cooperative organizations and the population served for the purpose of producing collective goods, thereby contributing to the expansion of the boundaries of their contracting and, as a consequence, the growth of economic performance.

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# Reliability assessment of the TP62 executive unit in railway automation and telemechanics systems

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Abstract: This article investigates the reliability of TP62 execution unit blocks, which are critical components of railway automation and telemechanics systems. The study employs a Markov continuous-time stochastic process model and a system of Kolmogorov differential equations to analyze the transition dynamics between operational, degraded, and failure states. To enhance system dependability, a structural parallel redundancy scheme is proposed, and its effectiveness is validated through rigorous mathematical derivations. Numerical results demonstrate that the Mean Time To Failure (MTTF) for the redundant TP62 configuration reaches 87,143 hours, equivalent to approximately 10 years of continuous operation. The findings hold significant practical value for the design and maintenance planning of safety-critical railway signaling and control infrastructure.

Keywords: railway automation, TP62 unit, reliability, Markov process, structural redundancy, failure rate, MTTF

## 1. Introduction

Transistor-based relay devices are extensively utilized in railway automation systems. The reliability of such devices—defined as their capacity for correct and sustained operational performance—is one of the fundamental requirements. This paper presents a methodology recommended for the determination and evaluation of the reliability of these devices.

In practice, determining the reliability indicators of railway automation systems remains a significant challenge. Addressing this issue is essential across various stages of the system's operational lifecycle.

The primary indicator characterizing the system's failure probability is *Q(t)*, representing the cumulative distribution function of the time to failure, also referred to as the failure probability. *Q(t)* denotes the probability that the device's failure occurs at a time less than *t*, or effectively, the probability of failure within the time interval *t*.

Another critical parameter in assessing system reliability is the probability of failure-free operation, denoted as *P(t)*. This indicator expresses the probability that the device will function without failure throughout a specified operating period t.

Consequently, the functions *Q(t)* and *P(t)* are of paramount importance in the assessment of railway automation systems. They facilitate the forecasting of potential malfunctions during system operation and enable the development of effective prevention strategies.

## 2. Research methodology

The relationship between the probability of failure-free operation and the probability of failure is defined by the following identity:

$$P(t) + Q(t) = 1 \quad (1)$$

The reliability function *P(t)* possesses the following fundamental properties:

*P(0)* = 1 signifies the operational state of the device at the initial time *t=0*;

$lim_{t\to\infty}P(t) = 0$ – indicates that the device cannot maintain its operational state indefinitely (Note: I corrected the '1' to '0' here for scientific accuracy);

$0 \le P(t) \le 1$ – the reliability value remains within the unit interval [0, 1];

$dP(t)/dt \le 0$– the function is monotonically non-increasing, reflecting that reliability diminishes over time.

The occurrence of a failure in a technical object is a stochastic (random) event, as a malfunction may or may not occur within a given time interval. Consequently, reliability theory is fundamentally rooted in the principles of probability theory.

The reliability indicator of the system, denoted as *λ(t)*, is defined as the failure rate intensity. This parameter plays a pivotal role in assessing the reliability of the system during both its design and operational phases. Accurately analyzing and managing this indicator is essential for enhancing the overall reliability of the system.

The calculation of the total system reliability is based on the reliability metrics of its constituent components. The specific computational methodology is determined by the system architecture and its classification. Railway automation systems are categorized into the following classes based on their reliability requirements (Fig. 1):

1. Primary (Base) Systems: Systems that demand high reliability and are directly responsible for ensuring functional safety.
2. Redundant (Reserve) Systems: Systems designed to replace or support the primary system in the event of a component failure.
3. Supportive Systems: Systems that perform auxiliary functions and serve to improve the overall robustness of the operation.

Specific analytical and computational methods are applied to each class to determine and optimize reliability levels. The calculation process utilizes the reliability indicators of individual elements, with the mathematical model being selected according to the system type.

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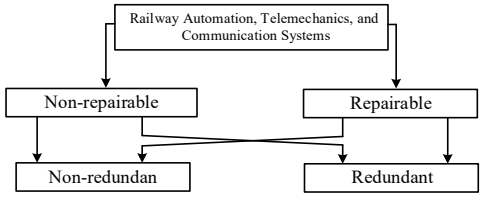


**Fig. 1. Classification of railway automation, telemechanics, and communication systems**

Redundancy strategies are generally classified into three types: information redundancy, time redundancy, and structural (hardware) redundancy. The system developed in this study is characterized as a structurally redundant and repairable system. The operational dynamics of such systems are modeled based on a discrete-state stochastic Markov process.

The state transition diagram (state graph) of the repairable redundant system is presented in Fig. 2. This graph illustrates the three primary operational states of the system:

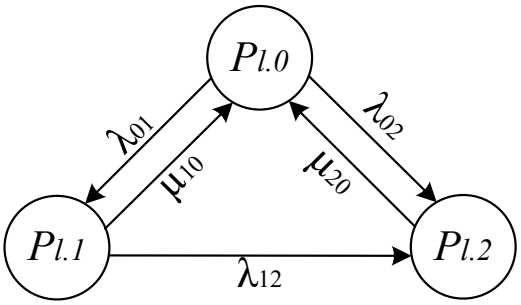


***Fig. 2. State transition graph of a repairable redundant system***

$P_{l.0}$ – Fully Operational State: The system is fault-free, and all functions are performed according to technical specifications;

$P_{l.1}$ – Partial Failure (Degraded) State: A fault exists within the system (e.g., failure of a redundant component), yet the system maintains its primary functional capacity;

$P_{l.2}$ – Total Failure (Inoperable) State: The system has completely lost its functional capabilities due to critical or multiple component failures.

The transitions between these states are governed by the failure rate ($\lambda$) and the restoration (repair) rate ($\mu$), as depicted in the graph.

The state graph of the repairable redundant system, shown in Fig. 2, explicitly illustrates the transitions between system states and the subsequent restoration processes.

The system transitions from one state to another under the influence of failure and repair flows. If all event flows driving these transitions follow a Poisson distribution, the resulting stochastic process is classified as a Markov process. Such a process is mathematically characterized by a system of linear differential equations, known as Kolmogorov equations.

To construct the mathematical model based on the state transition graph, the following formal rules are applied:

1. Derivative of State Probability: The derivative of the probability of a given state is equal to the algebraic sum of the terms associated with all transitions (vectors) connected to that state.
2. Formation of Terms: Each term is defined as the product of the transition intensity (rate of the event flow) and the probability of the state from which the transition originates.
3. Sign Convention: A term is assigned a negative sign if the transition vector originates from the state in question (outward flow), and a positive sign if the transition vector points toward the state (inward flow).

The system of differential equations derived from these rules provides a precise mathematical description of the system's dynamics, enabling a comprehensive analysis of state transitions over time.

$$\frac{dP_{l.0}(t)}{dt} = -\lambda_{01}P_{l.0}(t) - \lambda_{02}P_{l.0}(t) + \mu_{10}P_{l.0}(t) + \mu_{20}P_{l.2}(t); \quad (2)$$

$$\frac{dP_{l.1}(t)}{dt} = \lambda_{01}P_{l.0}(t) - \mu_{10}P_{l.1}(t) + \lambda_{12}P_{l.2}(t); \quad (3)$$

$$\frac{dP_{l.2}(t)}{dt} = \lambda_{02}P_{l.0}(t) + \lambda_{12}P_{l.1}(t) - \mu_{20}P_{l.2}(t). \quad (4)$$

The parameters utilized in the system of differential equations are defined as follows:

- $\lambda_{01}$ – transition rate from the fully operational state to the partial failure (degraded) state;
- $\lambda_{02}$ – transition rate from the fully operational state to the total failure state;
- $\lambda_{12}$ – transition rate from the partial failure state to the total failure state (complete loss of functional capability;
- $\mu_{10}$ – restoration (repair) rate from the partial failure state back to the fully operational state;
- $\mu_{20}$ – restoration (repair) rate from the total failure state back to the fully operational state;
- $P_{l.0}(t)$ – probability that the device is in the fully operational state at a given time;
- $P_{l.1}(t)$ – probability that the device is in the partial failure state while maintaining operational capacity at a given time $t$;
- $P_{l.2}(t)$ – probability that the device is in the total failure state (inoperable) at a given time $t$.

The aforementioned parameters are instrumental in the modeling and reliability assessment of technical systems. Utilizing these indicators enables a comprehensive analysis of the device's operational performance, as well as the dynamics of transition into failure states and subsequent restoration processes.

Fig. 3. illustrates the structural redundancy scheme for the execution unit block of the railway automation and telemechanics system.

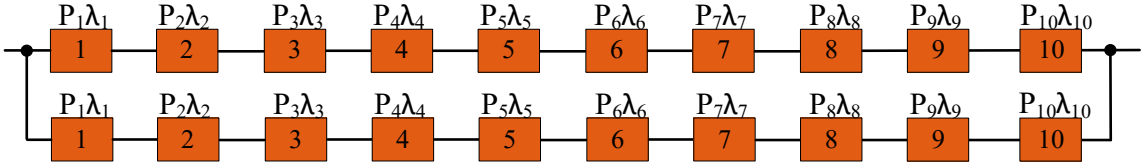


***Fig. 3. Structural redundancy scheme of the execution group block units in the automation and telemechanics system***


https://doi.org/10.56143/3030-3893-2025-4-114-117

The probability of failure-free operation of the system is determined by the following formula:

$$P_j(t) = 1 - \left(1 - \prod_{i=1}^{n} P_i(t)\right)^{m+1} \quad (5)$$

**Where:** $P_j(t)$ – is the probability of failure-free operation of the overall system; $P_i(t)$ – is the probability of failure-free operation of each individual channel; $m$ – is the number of redundant (reserve) units.

The probability of failure-free operation for each branch of a redundant system is equal to the product of the probabilities of failure-free operation of its constituent elements.

$$P_{l.1}(t) = P_i(t) = P_1(t) \cdot P_2(t) \cdot P_3(t) \cdot P_4(t) \cdot P_5(t) \cdot P_6(t) \cdot P_7(t) \cdot P_8(t) \cdot P_9(t) \cdot P_{10}(t); \quad (6)$$

The probability of failure-free operation is determined by equations (4.9) and (4.10).

$$P_{l.1}(t) = e^{-\lambda_{01}(t)}; \quad (7)$$

$$P_{l.2}(t) = e^{-\lambda_{02}(t)}. \quad (8)$$

Using the established mathematical models and the structural redundancy scheme, we determine the failure rates $\lambda_{01}$, $\lambda_{02}$, $\lambda_{12}$and the state probabilities $P_{l.1}(t)$ va $P_{l.2}(t)$.

$$\lambda_{01} = \lambda_{12} = 256(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7 + \lambda_8 + \lambda_9 + \lambda_{10});$$

$$\lambda_{02} = \frac{2 \cdot \lambda_{01}}{3};$$

$$P_{l.1}(t) = e^{-(256(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\lambda_6+\lambda_7+\lambda_8+\lambda_9+\lambda_{10}))t} = e^{-17{,}213 \cdot 10^{-6} t};$$

$$P_{l.2}(t) = 1 - \left(1 - P_{l.1}(t)\right)^2 = 2 \cdot P_{l.1}(t) - P_{l.1}^2(t) = 2e^{-17{,}213 \cdot 10^{-6} t} - e^{-34{,}426 \cdot 10^{-6} t}.$$

The Mean Time To Failure (MTTF), denoted as $T$, represents the expected operational time of the system before a total failure occurs. It is calculated by integrating the reliability function over an infinite time horizon:

$$T = \int_0^{\infty} \left(2e^{-17.213 \cdot 10^{-6} t} - e^{-34.426 \cdot 10^{-6} t}\right) dt = 87143 \; soat$$

The correlation between the system's failure probability and its probability of failure-free operation is presented in Fig. 4. The failure rates are detailed in Tables D.3 and D.4.

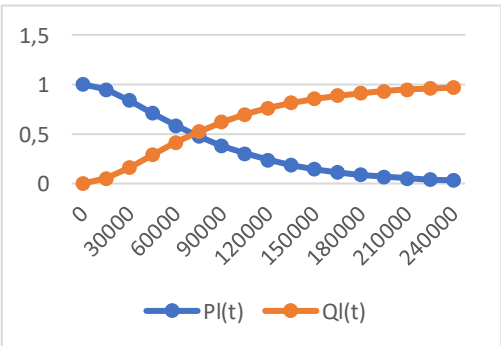


*Fig. 4. Graph of $P_{l.2}(t)$ and $Q_{l.2}(t)$ as a function of time*

## 3. Conclusion

This research conducted a comprehensive reliability analysis of the TP62 unit within railway automation and telemechanics systems using structural redundancy and stochastic modeling. The following key conclusions were derived from the study: Mathematical Modeling: A discrete-state Markov process was successfully developed to model the operational dynamics of the system. The use of Kolmogorov differential equations provided a precise mathematical framework to analyze transitions between fully operational, degraded, and failed states. Redundancy Effectiveness: The analysis of the structural redundancy scheme (Fig. 4) demonstrated that implementing a parallel-series architecture significantly mitigates the risk of total system failure. The probability of failure-free operation, $P_{l.2}(t)$, confirmed that redundant channels effectively compensate for individual component malfunctions. Quantitative Reliability Metrics: Numerical calculations revealed that the Mean Time To Failure (MTTF) for the redundant TP62 unit is 87,143 hours. This result indicates a high level of operational stability, equivalent to approximately 10 years of continuous service under standard conditions. Visual Correlation: The established dependency graphs between reliability $P_{l.2}(t)$ and unreliability $Q_{l.2}(t)$ (Fig. 4) provide a vital visual tool for maintenance planning, allowing for the prediction of optimal intervention intervals before the system reaches critical wear-out phases.

In summary, the integration of structural redundancy combined with rigorous Markovian analysis ensures that the TP62 unit meets the stringent safety and reliability requirements of modern railway infrastructure. Future research may focus on the impact of external environmental factors on the failure rate intensities $\lambda$ to further refine the model.

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