LOGISTICS IN AN ERA OF TECHNOLOGICAL AND GLOBAL CHANGE: INFRASTRUCTURE, MANAGEMENT AND SUSTAINABLE DEVELOPMENT

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Introduction

The beginning of the third decade of the 21st century marks a period of profound transformation in logistics systems worldwide. This transformation is driven by overlapping global megatrends: technological advancement, climate urgency, demographic shifts, geopolitical instability, and the imperative for sustainable development. Logistics—understood not only as the movement of goods, but also as a complex network of data, infrastructure, decision-making and strategic foresight—has evolved into a key component of global resilience and competitiveness.

Amidst this transition, logistics is becoming increasingly digital, autonomous and sustainability-oriented. The deployment of artificial intelligence (AI), Internet of Things (IoT), blockchain, and digital twins is reshaping supply chain visibility, risk management and demand forecasting (NetSuite, 2025; Cleo, 2025). Meanwhile, ecological and social sustainability has emerged as a strategic priority, resulting in ESG-driven transformations in transport infrastructure, energy consumption, reverse logistics and carbon footprint tracking (KPMG, 2025; Wikipedia, 2025). These trends are reinforced by policy shifts such as the European Green Deal and mandatory Scope 3 emission reporting, making logistics a critical area for regulatory compliance and innovation alike.

This monograph presents a multidimensional and evidence-based examination of logistics at the intersection of innovation, globalization, and sustainability. It offers a unique blend of theoretical perspectives, applied research, and regional case studies from Poland, Ukraine, and other European countries, thereby providing both a macroscopic view and local insight.

In Part I, the authors explore cutting-edge innovations in logistics infrastructure and production logistics, including the role of automation, ecological infrastructure, and Industry 4.0 technologies. Particular attention is given to the benefits and limitations of these innovations in various sectors.

Part II turns to logistics management and organizational practices, emphasizing the role of technological foresight, outsourcing, and communicative competence. These chapters underscore the importance of strategic planning, human capital, and decision-making frameworks in a rapidly changing environment.

Part III situates logistics within the broader context of globalization and sustainable development, focusing on maritime transport, ecological road infrastructure, and legal frameworks supporting green transition. The chapters examine how global economic flows and local policies interact to shape the logistics landscape.

Finally, Part IV addresses urban logistics and public transport, investigating passenger mobility, service quality, transport optimization and regulatory standards. These analyses are particularly relevant as cities aim to balance efficiency with inclusivity and environmental impact.

This publication is the result of an international and interdisciplinary collaboration among academics and practitioners representing institutions such as the University of Warmia and Mazury in Olsztyn, the International Academy of Applied Sciences in Łomża, Podillia State University, and Cherkasy State Technological University, among others. The contributing authors combine academic rigor with practical relevance, offering frameworks and insights useful to scholars, logistics managers, infrastructure planners, and policy-makers.

In a time of volatility and complexity, this monograph serves as a timely contribution to the body of knowledge in logistics and supply chain studies. It invites the reader to rethink infrastructure, processes and competencies in a world where innovation is no longer optional—but essential for survival and growth.

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PART I.

INNOVATIONS IN LOGISTICS

Chapter 1.
INNOVATIONS IN LOGISTICS INFRASTRUCTURE

Anna Strychalska-Rudzewicz
Agnieszka Kowalska

1.1. Introduction

Contemporary logistics infrastructure constitutes one of the key pillars of global supply chain operations. Its development is closely intertwined with technological advancement, digitalization, and the concept of sustainable development. Faced with growing market volatility, ecological pressures, and dynamic socio-economic changes, innovation in logistics infrastructure has become an indispensable component of building enterprise competitiveness and transport system resilience (Motowidlak & Tokarski, 2022).

Innovations in logistics encompass technological solutions such as warehouse automation, process robotics, the Internet of Things (IoT), blockchain, and edge computing, as well as organizational, infrastructural, and environmental changes. Their implementation enables not only cost optimization and improved operational efficiency but also the achievement of climate and social goals aligned with the UN Agenda 2030 (Sapiński & Pochopień, 2023; UNEP, 2023). The literature emphasizes that logistics infrastructure is no longer merely a passive component of the transport system, but an active participant in innovation processes, capable of adaptation, data integration, and cross-sectoral collaboration (Nowicka, 2015; Toymentseva et al., 2025). Investments in intelligent intermodal terminals, distribution centers with high operational flexibility, and ecological infrastructure supporting ecosystem services are particularly important.

The aim of this chapter is to identify selected innovative directions for the development of logistics infrastructure, with particular emphasis on their impact on the efficiency, sustainability, and resilience of logistics systems. The discussion takes into account both national and international perspectives, drawing on current scientific research, industry reports, and strategic documents.

1.2. Automation and Robotization of Logistics Facilities

Contemporary logistics is undergoing intensive technological transformations aimed at increasing efficiency, reliability, and operational flexibility. Automation and robotization of logistics facilities are key elements of this transformation, enabling cost reduction, improved service quality, and increased occupational safety (Grabowy & Wielgosz, 2018). One of the most important directions of logistics infrastructure development is the implementation of the following automation solutions:

- highly automated warehouse systems (e.g., AutoStore, AS/RS), which enable dynamic goods handling with minimal human intervention;
- mobile robots (AMRs) and autonomous forklifts, which increase safety and reduce operating costs;
- artificial intelligence and machine learning, which support inventory forecasting and warehouse layout optimization.

Modern warehouses increasingly utilize integrated automated systems that improve the efficiency of storage, picking, and logistics operations management. Among the most important technological solutions are AS/RS (Automated Storage and Retrieval Systems), which enable dynamic warehouse space management and eliminate human error. Pick-by-Light and Pick-by-Voice technologies are increasingly being used in order picking, supporting this process in an ergonomic, fast, and intuitive manner for operators. Warehouse and internal transport management is performed using WMS/MFC systems, which integrate operational data and enable real-time analysis (Grabowy & Wielgosz, 2018).

Faced with growing market demands and the dynamic development of the e-commerce sector, logistics companies are increasingly turning to automated warehouse systems. Technologies such as AutoStore and AS/RS (Automated Storage and Retrieval Systems) enable significant increases in operational efficiency, storage space optimization, and labor cost reductions (Grabowy & Wielgosz, 2018). AS/RS systems are integrated solutions that automate the storage and retrieval of goods. They include stacker cranes, high-bay racking, conveyor systems, and management software. Automated storage and retrieval systems (AS/RS) offer a number of benefits that contribute to increased operational efficiency and warehouse space optimization. Primarily, they enable increased storage density through the efficient use of vertical space, maximizing warehouse capacity without the need for horizontal expansion. By reducing the human factor in storage and retrieval processes, AS/RS systems reduce the risk of operational errors, thereby increasing precision and occupational safety. An additional advantage is the ability to fully integrate with warehouse management systems (WMS) and warehouse control systems (WCS), enabling dynamic inventory management and order picking processes based on real-time data.

AutoStore is an example of an automated robotic cube-based ASRS system, in which autonomous robots navigate a grid placed above cube-shaped containers. This solution is characterized by exceptional space efficiency, as goods are stored in vertically arranged containers, saving warehouse space. The system is also highly scalable and flexible. Its modular design allows for easy expansion without interrupting operations, which is important in the context of dynamically changing operational needs (Logistics Manager, 2024). A key advantage of AutoStore is also the minimization of manual labor, as the robots perform goods-to-person picking, which translates into improved ergonomics and increased employee safety.

The robotization of warehouse processes is one of the key development directions in modern logistics. Faced with growing customer demands, time pressure, and the need to increase operational efficiency, companies are increasingly implementing autonomous technological solutions. Warehouse robots support tasks such as internal transport, order picking, sorting, and palletizing, contributing to cost reduction and improved service quality (Jankowska & Łukasiak, 2017). Modern warehouses increasingly utilize advanced robotic solutions to support key logistics operations. Automated Guided Vehicles (AGVs) play a significant role in intralogistics, operating on designated routes and transporting pallets and containers between warehouse zones. Their use allows for the automation of material flow and reduced operating costs. This technology is complemented by Autonomous Mobile Robots (AMRs), capable of autonomous navigation in a dynamic and changing warehouse environment. Using sensors and SLAM algorithms, they ensure operational flexibility without the need for operator intervention. In the area of order fulfillment, picking and sorting robots are particularly important, supporting the processes of packaging, labeling, and preparing shipments for shipment. Their implementation contributes to increased efficiency, precision, and work ergonomics. Examples of implementations at companies such as Amazon, DHL, and CCC demonstrate that robotization enables the handling of millions of storage units with minimal human intervention (Jankowska & Łukasiak, 2017).

Roboticization of warehouse processes brings a number of tangible benefits that directly impact the operational efficiency of modern logistics centers. One of the main effects of implementing robotic solutions is a significant increase in efficiency and operational throughput, enabling more efficient order fulfillment and faster product turnover. At the same time, the use of robots helps reduce human error, improving the precision of operations, and increases occupational safety by eliminating the most strenuous and risky physical tasks. Furthermore, automation of warehouse processes allows for the optimization of costs related to both employment and infrastructure maintenance, which in the long term helps build a company's competitiveness and resilience to market volatility. At the same time, implementing robots is associated with challenges such as the need for integration with IT systems, staff training, and adapting warehouse space to new technologies (Porębski, 2024).

Robotization also impacts the employment structure in the logistics sector. Although concerns about job losses are widespread, research indicates that robots primarily take over heavy, repetitive, and dangerous tasks, allowing employees to focus on more complex and creative activities (Jankowska & Łukasiak, 2017). This could lead to a transformation in competencies and the creation of new positions related to technology operation and management.

Robotization of warehouse processes brings a number of tangible benefits that directly impact the operational efficiency of modern logistics centers. One of the main effects of implementing robotic solutions is a significant increase in efficiency and operational throughput, enabling more efficient order fulfillment and faster goods turnover. Simultaneously, the use of robots contributes to reducing human error, improving the precision of operations, and increases occupational safety by eliminating the most strenuous and risky physical tasks. Moreover, the automation of warehouse processes allows for the optimization of costs related to both employment and infrastructure maintenance, which in the long run helps build the company's competitiveness and its resilience to market volatility.

Modern warehouse logistics increasingly relies on the use of autonomous mobile robots (AMRs) and automated guided vehicles (AGVs). These technologies form the foundation of modern intralogistics systems, enabling the automation of internal transport, increasing operational efficiency, and improving occupational safety (Surma, 2020). AGVs are vehicles that move along pre-defined routes, most often using magnetic tapes, QR codes, or laser guidance. Their movement is determined by a programmed sequence, which limits flexibility when spatial conditions change (Litwin, 2024). AMRs, on the other hand, utilize advanced sensor and camera systems, as well as SLAM (Simultaneous Localization and Mapping) algorithms, allowing them to navigate autonomously in dynamic warehouse environments without the need for operator intervention (Anuszczyk & Zięba, 2023). Mobile robots such as AMRs (Autonomous Mobile Robots) and AGVs (Automated Guided Vehicles) are playing an increasingly important role in many operational areas of modern logistics. They are particularly useful in internal transport, enabling the automated and safe movement of pallets and components between warehouse and production areas. Their functionality also includes supporting the goods-to-person order picking process, which translates into increased precision and ergonomics. Additionally, these robots are used to operate roller conveyors and loading stations, where they perform tasks related to the movement of load units within integrated material flow systems. A key aspect of their implementation is the ability to integrate with WMS (Warehouse Management System), MES (Manufacturing Execution System), and ERP (Enterprise Resource Planning) systems, enabling automatic task allocation, mission monitoring, and dynamic management of operational resources in real time.

The use of mobile robots in warehouse logistics offers numerous operational benefits, making them a crucial element of an automation strategy. One of the key advantages is the reduction of operating costs, resulting from the reduction of manual labor in transport and picking processes. The introduction of robots also translates into increased occupational safety by eliminating human error and ensuring predictable and repeatable machine movements, potential risks to personnel are reduced. Importantly, AMR and AGV technologies are highly scalable and flexible, allowing them to adapt to changing production and spatial conditions in logistics facilities (Anuszczyk & Zięba, 2023).

However, the implementation process of these solutions also presents significant challenges. Common barriers include high initial costs, including equipment purchase, implementation, system integration, and staff training. Furthermore, the need to adapt IT and physical infrastructure to new technologies can generate organizational disruptions, especially in the initial stages of logistics transformation (Surma, 2020).

AMR and AGV robots are a key element of an automation strategy aligned with Industry 4.0. Their implementation allows for increased efficiency, safety, and reliability of logistics processes. In the long term, these technologies offer a significant return on investment and a competitive advantage in the transport and logistics market.

In an era of rapid e-commerce growth and growing customer expectations for order fulfillment speed, order-picking robots are becoming a key element in warehouse process automation. Their use increases efficiency, reduces errors, and improves work ergonomics in distribution centers (Kowalski & Nowak, 2022).

Picking robots are autonomous units equipped with advanced vision systems, mechanical grippers, and artificial intelligence algorithms, enabling them to precisely identify, locate, and retrieve products from warehouse racks. Depending on the operating model, these devices can operate in various configurations. In a goods-to-person solution, robots deliver containers of goods directly to operator stations, streamlining the picking process and minimizing the need for employee movement. Alternatively, in a person-to-goods model, robots assist employees in locating and retrieving products, combining automation with human interaction. The most advanced configuration is a fully autonomous picking configuration, in which robots complete the picking process completely independently, without human intervention – from product identification to handover for further processing (Dobrzański, 2016).

Picking robots are particularly effective in environments with high product variability and high order volumes, such as e-commerce, FMCG, and pharmaceutical warehouses. Research shows that implementing picking robots can increase operational efficiency by as much as 30–50% compared to traditional manual methods (Jankowska & Łukasiak, 2017). Furthermore, thanks to integration with WMS systems and real-time data analysis, these robots can dynamically adjust picking routes and task priorities.

Despite the numerous benefits of implementing picking robots in warehouse processes, their implementation also presents a number of technical, organizational, and financial challenges. Above all, high investment costs related to both purchasing appropriate equipment and adapting existing logistics infrastructure to new technological solutions must be considered. Simultaneously, integrating robots with existing IT systems, such as WMS or ERP, is essential, requiring standardized interfaces and modified management processes. Proper staff preparation is also crucial, as implementing innovative devices requires specialized training and adapting employee competencies to new operational tasks. Additionally, the specific nature of products may pose a limitation to the use of picking robots: these devices struggle to manipulate objects with unusual shapes, large masses, or those requiring special storage conditions, limiting their application in certain sectors of the logistics industry (Kowalski & Nowak, 2022). Picking robots are a crucial element in the transformation of logistics towards Industry 4.0. Their use allows for increased efficiency, precision, and operational flexibility, which translates into higher-quality customer service and business competitiveness. In the long term, the development of this technology will foster the further automation and digitization of warehouse processes.

The effectiveness of automation in logistics processes remains closely dependent on the level of integration with advanced IT systems, which serve as a central decision-making and coordination module. In particular, artificial intelligence algorithms are used in demand forecasting, enabling the dynamic analysis of historical data and current market trends, which in turn translates into the optimization of transport routes and more efficient resource utilization. Warehouse management systems (WMS) simultaneously coordinate the work of robots, automated equipment, and technical personnel, enabling task synchronization and real-time monitoring of operations. This not only facilitates the smooth flow of materials but also enables rapid response to operational disruptions and fluctuating demand (Dobrzański, 2016).

Modern logistics and warehouse systems operate in an environment of increasing demand volatility, shortening delivery cycles, and pressure to reduce operating costs. In response to these challenges, companies are increasingly implementing artificial intelligence (AI) and machine learning (ML) technologies, which enable dynamic inventory forecasting and warehouse space optimization (Albayrak Ünal et al., 2023; Guzowski et al., 2024). Machine learning algorithms, such as neural networks, regression models, and XGBoost, enable the analysis of historical data, seasonal trends, and external factors such as weather conditions and market events, which translates into precise demand forecasts (Tang et al., 2023). This allows for the automatic determination of replenishment points, reducing the risk of overstocking or shortages, and dynamically adjusting inventory levels to changing market conditions (Nweje & Taiwo, 2025). Implementing AI in inventory forecasting also enables the automation of purchasing processes and efficient production planning, which translates into greater operational flexibility for enterprises.

Machine learning also supports the design and reorganization of warehouse space. Algorithms analyzing data on picking frequency, product location, and material flow enable efficient goods placement, reduced operation time, and increased utilization of vertical and horizontal space. AI systems also support the automatic generation of warehouse layouts based on actual data, allowing for faster implementation of changes to the structure of logistics facilities (Vangari, 2025).

The use of AI in warehouse logistics brings many benefits, including improved forecast accuracy, reduced inventory holding costs, warehouse space optimization, and automated decision-making processes. However, implementing these technologies requires ensuring high-quality input data, integration with existing ERP and WMS systems, and investments in staff training and appropriate IT infrastructure (Lawlor et al., 2024).

In summary, automation and robotization of logistics facilities are an essential element in the development of modern supply chains. Their implementation leads to increased efficiency, reduced operating costs, and improved customer service quality. At the same time, they require investment in technological infrastructure and management skills.

1.3. Sustainable Development and Ecological Infrastructure

Sustainable development, as a concept integrating environmental, social, and economic aspects, is the foundation of contemporary spatial and economic development strategies. Ecological infrastructure, a set of technical and natural solutions supporting the functioning of ecosystems, plays a key role in achieving sustainable development goals, particularly in the context of urbanization, climate change, and the protection of natural resources (Baran, 2010; Tokarski, 2023).

Ecological infrastructure encompasses both natural elements (e.g., forests, wetlands, ecological corridors) and technical solutions based on nature (e.g., green roofs, rain gardens, water retention systems). Its role is to support ecosystem services such as air purification, microclimate regulation, and flood protection (Hawken et al., 2021). Unlike traditional "gray" infrastructure, ecological solutions are multifunctional, adaptive, and less environmentally invasive (UNEP, 2023). Research indicates that ecological infrastructure can contribute to the achievement of up to 79% of the UN Sustainable

Development Goals, and when combined with technical infrastructure, as much as 95% (UNEP, UNOPS & University of Oxford, 2023). For example, urban green corridors support SDG 11 (sustainable cities), SDG 13 (climate action), and SDG 15 (life on land). Investments in ecological infrastructure also contribute to improving the quality of life of residents and increasing the resilience of cities to extreme weather events (Thacker et al., 2019). In Poland, ecological infrastructure is being developed, among other things, in rural areas and cities through the construction of retention systems, the modernization of sewage treatment plants, and the creation of green public spaces (Dolata, 2015; Baran, 2010). At the international level, examples from Tanzania and Belgium demonstrate that investments in coastal ecosystems (e.g., mangroves, coral reefs) can protect infrastructure worth billions of dollars while supporting local communities (UNEP, 2023).

Despite numerous benefits, implementing ecological infrastructure faces financial, institutional, and technological barriers. Integrating cross-sectoral initiatives, developing innovative financing models, and accessing data on the long-term effectiveness of ecological solutions are crucial (Tokarski & Burchard-Dziubińska 2022; UNEP, 2023). It is also necessary to consider the symbolic aspects of infrastructure—such as environmental awareness and organizational culture—which determine the sustainability of implemented solutions (Kośmicki, 2010).

Amide growing pressure to decarbonize the transport sector, intermodal terminals play a key role in integrating various modes of transport—rail, road, and water—enabling more efficient and environmentally friendly cargo movement. Their development is a crucial element of sustainable development strategies, supporting the reduction of greenhouse gas emissions and improving the energy efficiency of logistics systems (Karas, 2024; UNEP, UNOPS & University of Oxford, 2023).

Intermodal transport, implemented using specialized transhipment terminals, is one of the most effective tools for reducing carbon dioxide emissions in the freight transport sector. According to research, its use can reduce CO_2 emissions by up to 60–90% compared to road-only transport. This significant environmental impact stems primarily from the higher energy efficiency of rail and water transport, the potential for electrification of transhipment operations, and the reduction in the number of truck journeys on long routes. Intermodal terminals play a crucial role in this structure, enabling seamless transitions between various modes of transport – rail, road, and water. Their functionality enhances the flexibility and efficiency of supply chains, and high interoperability of transport systems is a prerequisite for the functioning of the single European market (Kornaszewski & Zielaskiewicz, 2018). In the domestic context, it is worth emphasizing the dynamic development of facilities such as the DCT Gdańsk and BCT Gdynia terminals, which have significantly increased domestic transshipment capacity and influenced changes in the direction of cargo flows in international relations.

The operational efficiency of intermodal terminals depends on a number of factors, including the facility's location, the quality of infrastructure, and the degree of integration with the rail and water networks. Terminal design should consider the region's transport accessibility, cargo containerization potential, and the potential for expansion and modernization in response to changing logistics needs (Pyza & Piątek, 2017). Research by Hasani Goodarzi et al. (2025) indicates that optimizing terminal locations can reduce emissions by up to 62%, with only a marginal increase in operating costs.

The construction and development of intermodal terminals constitute a strategic direction in transport policy aimed at reducing CO_2 emissions. Integrating rail, road, and water transport within modern terminals enables not only improved operational efficiency but also the achievement of climate and environmental goals. Supporting investment in terminal infrastructure should be a priority at both the national and European levels. In the context of global efforts to decarbonize the transport sector, intermodal terminals play a key role in integrating various modes of transport – rail, road, and water. Their development enables efficient transshipment of cargo units, shortens transport times, and reduces greenhouse gas emissions, particularly carbon dioxide (CO_2), which is the dominant component of transport emissions (Karas, 2024; Hasani Goodarzi et al., 2025).

Intermodal terminals play a crucial role in increasing the efficiency and flexibility of supply chains, enabling seamless transitions between different modes of transport: rail, road, and water. This type of integration promotes the optimization of logistics processes, reduces costs, and improves the responsiveness of the distribution system to changing market needs. A particularly important functional aspect of terminals is their interoperability, which is a prerequisite for the smooth functioning of the single European market and ensures technical compatibility between diverse transport platforms (Kornaszewski & Zielaskiewicz, 2018). In the domestic context, the dynamic development of intermodal terminals – such as DCT Gdańsk and BCT Gdynia – has significantly increased Poland's transshipment capacity and also influenced the transformation of international cargo flows. However, the efficiency of terminal operations remains strongly dependent on a number of infrastructure and location factors. When designing such logistics facilities, it is important to consider the region's transport accessibility, assess the containerization potential, and the potential for expansion and modernization depending on anticipated changes in operational volume (Pyza & Piątek, 2017). Research by Hasani Goodarzi et al. (2025) indicates that optimizing terminal locations can reduce emissions by up to 62%, with only a marginal increase in operating costs.

1.4. Digitalization and Data Infrastructure

Implementing digital solutions in logistics significantly contributes to increased transparency and integration of operational processes within the supply chain. Key technologies such as the Internet of Things (IoT), blockchain, and cloud and edge computing platforms enable dynamic resource management, infrastructure monitoring, and secure real-time transaction recording.

The Internet of Things (IoT) is one of the most dynamically developing technological concepts, integrating physical objects with digital information space. In the transportation and logistics sector, IoT plays a fundamental role in monitoring the technical parameters of vehicles, road infrastructure, and transport processes. The use of sensors, wireless communication systems, and analytical platforms can improve operational efficiency, safety, and sustainable resource management (Guzowski et al., 2024; Yanginlar, 2024).

A typical IoT system architecture in transportation consists of three functional layers. The sensor layer includes sensors for temperature, humidity, pressure, vibration, GPS positioning, and RFID, which collect data from vehicles and infrastructure (Pamula et al., 2022). The communication layer uses GSM, LTE, Wi-Fi, and 5G technologies to transmit data to servers or the cloud (Salih & Younis, 2021). The application layer is responsible for data analysis, trend visualization, and generating alerts and recommendations for transportation system operators (Szozda, 2017).

IoT enables comprehensive monitoring of transportation parameters, including real-time vehicle location, which supports route planning and fleet management (Salih & Younis, 2021), technical vehicle diagnostics through sensors monitoring engine temperature, oil pressure, fuel consumption, and brake status (Yanginlar, 2024), and monitoring of transportation conditions—

particularly important in the transport of pharmaceuticals and food—through sensors recording humidity, temperature, and shocks (Pamula et al., 2022).

IoT also supports the supervision of the technical condition of transportation infrastructure. Strain gauge and accelerometer sensors are used in bridges and viaducts to detect overloads, vibrations, and micro-damage to the structure (Malucha, 2018). Roads and tracks equipped with sensors embedded in the road surface enable monitoring of temperature, humidity, dynamic load, and deformation (Guzowski et al., 2024). Furthermore, lighting and signaling systems can be remotely controlled and diagnosed thanks to integration with the IoT, increasing their reliability and energy efficiency (Szozda, 2017).

The use of the Internet of Things in monitoring transport and technical infrastructure brings tangible benefits in the form of increased safety, reduced operating costs, and improved quality of logistics services. Integrating data from various sources enables the creation of intelligent traffic management systems, predictive infrastructure maintenance, and dynamic resource planning. With the development of Industry 4.0, IoT is becoming an indispensable component of the digital transformation of the transport, logistics, and logistics sector.

Blockchain, as a decentralized and distributed database, is gaining increasing importance in logistics and supply chain management. Thanks to its properties – immutability, transparency, and tamper-resistance – this technology enables secure recording of transactions and tracking the flow of goods in real time (Rot & Zygała, 2018; Dikariev & Miłosz, 2018). Blockchain is based on a structure of data blocks that are chronologically linked using cryptographic hash functions. Each block contains a set of transactions, a timestamp, and a hash of the previous block, ensuring the integrity and immutability of records (Lawlor et al., 2024). Thanks to its peer-to-peer (P2P) architecture, each network participant has a copy of the ledger, eliminating the need for a central intermediary and increasing the system's resilience to failures and attacks (Rot & Zygała, 2018). Blockchain technology is one of the most innovative solutions for digital data management, offering a decentralized, immutable, and transparent transaction ledger. Its application in logistics and finance enables the secure recording of financial transactions, with each transaction being irreversible and visible to network participants, significantly minimizing the risk of fraud (Międlar, 2019). Additionally, thanks to smart contracts, transaction conditions can be coded and executed automatically upon fulfillment, enabling the automation of business processes

(Yanginlar, 2024). In B2B relationships, blockchain increases transparency by enabling the verification of the source, date, and terms of each transaction within the supply chain (Wodnicka, 2019).

In the context of supply chain management, this technology supports the recording of product origin from producer to consumer, taking into account transport and storage conditions (Guzowski et al., 2024). This is particularly important in industries requiring compliance with stringent quality and sanitary standards, such as the food and pharmaceutical sectors. Furthermore, blockchain enables reduction of operating costs by eliminating intermediaries and automating verification processes (Yanginlar, 2024).

Despite its numerous advantages, implementing blockchain technology presents a number of challenges. Among the most significant are scalability and performance limitations. Traditional blockchain networks are characterized by low transaction throughput, which can limit their use in environments with high data volumes. Another challenge is integration with existing ERP and WMS systems, which requires standardized communication protocols and adapted IT architecture. Regulatory issues and personal data protection are also important, particularly in the context of GDPR regulations and cross-border information transfer (Lawlor et al., 2024). Modern logistics and industrial systems generate vast amounts of operational data, the efficient processing and analysis of which require modern infrastructure solutions. Traditional models of centralized data processing in cloud computing are becoming insufficient in the context of growing demands for responsiveness, security, and real-time data availability. In response to these challenges, hybrid processing models are being developed, combining cloud platforms with edge computing technology, enabling decentralized data management from multiple locations (Angel et al., 2022; Zangana, 2024). Cloud platforms provide scalability, flexibility, and access to computing resources in a service model (e.g., IaaS, PaaS, SaaS), while edge computing enables local data processing near its source – on endpoint devices, network gateways, or microservers (Karami & Karami, 2025).

Decentralized operational data management using edge computing technology and cloud platforms is finding increasing application in logistics, manufacturing, and infrastructure management. In the edge-cloud model, data is processed locally – close to the source – allowing for rapid analysis and response without the need to transmit information to central servers. This approach is used, among other things, in monitoring technical infrastructure, where data from sensors in logistics and industrial facilities is analyzed locally (Guzowski et al., 2024). In fleet and transport management, edge computing enables real-time analysis of GPS data, telemetry, and transport conditions, supporting dynamic route planning and predictive vehicle maintenance (Angel et al., 2022). In the area of production process automation, local analysis of data from machines and SCADA systems allows for early detection of irregularities and optimization of equipment operation (Zangana, 2024). The benefits of using an edge-cloud architecture include, above all, reduced latency – local data processing minimizes the response time of operating systems. Furthermore, security is enhanced because data does not need to be transmitted to external servers, reducing the risk of interception. Cost optimization is also important because lower network and cloud infrastructure load translates into lower operating expenses.

At the same time, implementing decentralized models poses a number of challenges. These include the complexity of managing distributed infrastructure, the need to standardize communication protocols, and integration with existing IT systems and business applications, which requires appropriate orchestration tools and technical competencies (Angel et al., 2022; Zangana, 2024).

Contemporary distribution centers operate in a dynamically changing market environment characterized by seasonal demand, supply uncertainty, and rising customer expectations. In response to these challenges, adaptive distribution centers are being developed, characterized by the ability to flexibly adjust operational functions, such as warehousing, picking, cross-docking, and returns management depending on current market needs (Bukowska-Piestrzyńska et al., 2022). The adaptability of distribution centers lies in their ability to reconfigure logistics processes, spatial structure, and resource allocation in response to demand variability. Modern distribution centers, operating under conditions of high market volatility and seasonal demand, are increasingly implementing adaptive mechanisms that allow for the dynamic adjustment of logistics operations. One of the key solutions in this regard is the modularity of warehouse infrastructure, which enables the reconfiguration of functional zones depending on the current process load and product characteristics, which is particularly important during periods of seasonal increases in order volume (Dyduch et al., 2019). Simultaneously, logistics centers are implementing digital technologies, including the Internet of Things (IoT), warehouse management systems (WMS), and predictive algorithms, supporting dynamic monitoring and optimization of goods flow in real time (Guzowski et al., 2024). Furthermore, the effective operation of adaptive distribution centers requires the use of flexible employment models, allowing for workforce scalability depending on operational intensity, which is particularly useful during peak periods (Nambiar et al., 2020). Seasonal demand, particularly evident in industries such as FMCG, e-commerce, and pharmaceuticals, requires distribution centers to quickly switch operational functions. For example, during the pre-holiday season, centers can function as intensive picking hubs, while during the off-season, they can function as long-term warehousing facilities (Nambiar et al., 2020; Sharma, 2010). Research shows that adaptive distribution centers are being implemented, among others, in the pharmaceutical sector, where adaptation to changing drug storage and distribution conditions is necessary (Bukowska-Piestrzyńska et al., 2022). In urban logistics, micro-distribution centers change their function depending on local demand and infrastructure availability (Budner & Pawlicka, 2020).

The use of adaptive distribution centers brings a number of operational, strategic, and qualitative benefits that increase the efficiency of the entire supply chain. Above all, they contribute to increasing the resilience of logistics systems to disruptions and dynamic market volatility. Thanks to flexible infrastructure configuration and the ability to quickly respond to changes in demand patterns, companies are able to maintain operational continuity even in crisis situations. Furthermore, such centers enable optimization of operating costs through better utilization of resources, both spatial and human, which translates into increased profitability and reduced process inefficiencies. Another significant advantage is improved customer service, achieved by shortening order fulfillment times and increasing product availability during key seasonal moments. However, implementing adaptive solutions is associated with a number of technological, organizational, and investment challenges. This requires integration with complex IT systems such as WMS, ERP, and IoT, which entails data standardization, secure communication, and real-time process synchronization. At the same time, staff training and adapting management structures to models with a high degree of operational variability are essential, which can generate additional costs and organizational resistance during the implementation phase (Ganesan et al., 2020; Zangana, 2024).

1.5. Summary

In the face of growing market, technological, and environmental pressures, logistics infrastructure is undergoing a systematic transformation toward automation, digitalization, and sustainable development. This chapter examines interdisciplinary innovations aimed at increasing operational efficiency, supply chain resilience, and minimizing the environmental impact of logistics operations.

On the one hand, the development of advanced warehouse systems (AS/RS, AutoStore) and the robotization of warehouse operations (AGV, AMR, picking robots) enable process automation, human error reduction, and space optimization. On the other hand, integration with IT systems (WMS, MES, ERP) and the use of tools such as artificial intelligence, the Internet of Things (IoT), and edge computing enable decentralized data management and a predictive approach to infrastructure maintenance.

The concept of sustainable development, implemented through the development of intermodal terminals, ecological infrastructure, intelligent monitoring systems, and adaptive distribution centers, is also a key component of the innovations analyzed. Their implementation allows for the reduction of CO_2 emissions, increased energy efficiency, and better adaptation of logistics processes to changing market conditions. Implementing innovative infrastructure solutions not only increases the competitiveness of companies in the TSL sector but also supports the achievement of global climate goals and the transformation towards Industry 4.0. Thus, logistics infrastructure becomes a platform for the synergy of technology, organization, and environmental values.

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Chapter 2.

NEW TECHNOLOGIES IN PRODUCTION LOGISTICS

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2.1. Production Logistics in the Era of Industry 4.0

Industry 4.0, referred to as the fourth industrial revolution, is a response to the increasing pace of change in the world and the increasing needs of markets and customers. The fourth industrial revolution exemplifies the rational use of IT technologies, combined with the ubiquitous Internet and available devices. The technologies of the digital era are being implemented en masse and form the foundation for automation and digitization of processes. Industry 4.0 is still the dominant model of industrial transformation in most countries, although concepts and discussions are increasingly emerging around Industry 5.0, which focuses on harmonious cooperation between man and technology, personalization and sustainability.

Modern production logistics is a rapidly developing field in which process efficiency is crucial to the competitiveness of companies. In an era of rapid technological development and growing customer expectations, companies cannot rely solely on traditional methods of planning and managing material flow. New technologies are a key tool for streamlining logistics processes of enterprises, revolutionizing the way production is organized and supply chain management. As a result of the digital transformation, production logistics is becoming more and more integrated into the entire business management processes – from forecasting to order fulfillment. Manufacturing logistics today is a network of highly advanced technologies that work together to deliver the highest quality product on time (Nowakowski, 2021). New technologies play a key role in improving efficiency, reducing costs, and increasing the flexibility and reliability of logistics processes. From the point of view of companies, the implementation of new technologies is becoming not only a beneficial solution, but is even necessary to compete successfully in the market. Their implementation makes it possible to automate business processes, streamline and speed up operations, as well as increase the precision and quality of performed activities. Companies that are able to implement innovative technologies gain a huge competitive advantage in the market. At the same time, the introduction of new technologies brings with it certain challenges that must be taken into account in the process of their implementation. Only in this way will it be possible to use them effectively to increase the potential of the enterprise.

The purpose of the chapter is to discuss the importance of the most important technologies applicable in modern production logistics, as well as to show the benefits and limitations of their use in industrial enterprises.

2.2. Overview of new technologies and their application in production logistics

In the era of the great development of digitization and automation, production logistics is becoming an advanced, integrated system in which new technologies play a key role. Companies that can effectively exploit the potential of Industry 4.0 gain not only an operational advantage, but also the ability to respond quickly to changing market conditions. An overview of the most important technologies that find application in modern manufacturing logistics is presented in Figure 1.

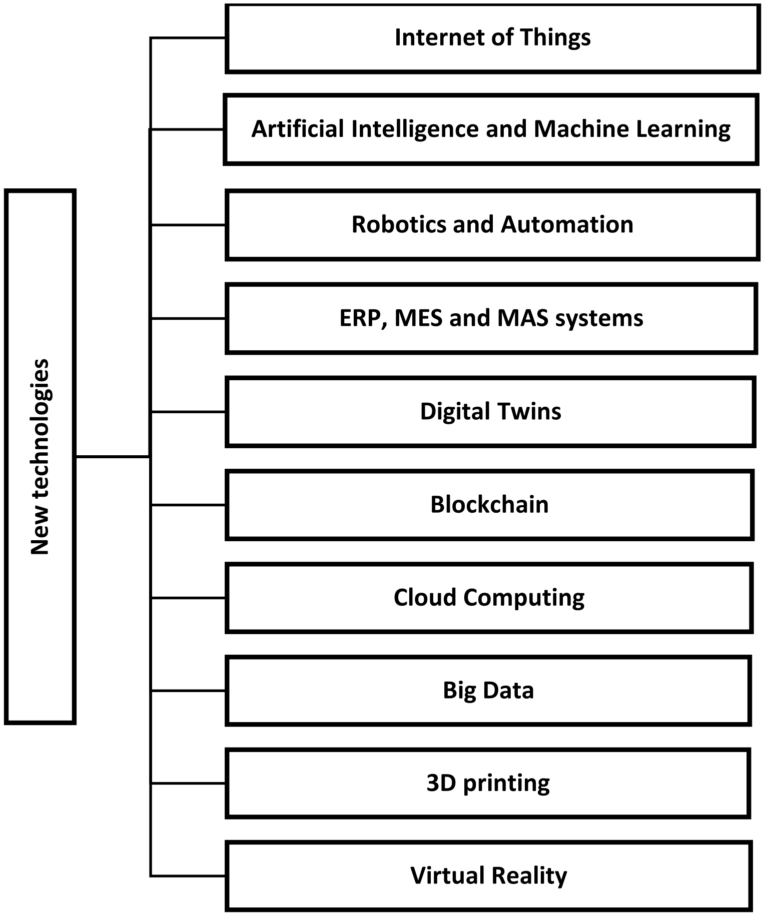

Fig. 1. New technologies in production logistics

Source: own elaboration

(1) Internet of Things (IoT)

The Internet of Things is a concept according to which various devices and objects are equipped with sensors, software and an internet connection, which enables, among other things, communication between each other, collection, processing and exchange of data, as well as automatic action based on analyzed information. In the context of production logistics, the Internet of Things enables full transparency and automation of processes inside a production facility. Thus, by connecting physical objects with digital systems, companies can track material flows, monitor the condition of machinery and control production processes directly from the data. Examples of applications of the Internet of Things in manufacturing logistics include (Bandyopadhyay & Sen, 2018, Wyrwicka & Mrugalska, 2019):

- RFID (Radio-Frequency Identification) sensors and GPS (Global Positioning System) systems integrated into the production system that monitor the position of components in real time,
- AGVs (Automated Guided Vehicles) that use Internet of Things sensors to navigate and coordinate routes between workstations,
- Smart warehouse racks equipped with weight or presence sensors, that report on inventory availability, location and wear and tear.
- Sensors in machinery that collect vibration, temperature and wear data, the analysis of which can detect early signs of failure and prevent process line downtime.

(2) Artificial Intelligence (AI) and Machine Learning

Artificial Intelligence is computer systems and algorithms capable of performing complex tasks that require human intelligence. The object of research in the field of Artificial Intelligence is to determine the rules that govern intelligent human reactions and to transfer them to algorithms and computer programs that can use these rules (Stawiarska, 2016). Artificial Intelligence can be used in many business areas, such as, for example, process automation, data analysis, cost optimization, increasing efficiency, improving product/service quality (Elliott, 2019). From the point of view of manufacturing logistics, Artificial Intelligence is finding more and more applications, optimizing processes, increasing efficiency and reducing costs. As for the scope of application of Artificial Intelligence in manufacturing logistics, it mostly includes (Ding et al., 2020, Zonta et al., 2020):

- demand forecasting – AI analyzes historical data, seasonality, market trends and external factors (e.g., weather, raw material prices) to accurately predict product demand and better plan production,
- inventory management – algorithms optimize inventory levels by identifying order points and minimum stock levels,
- supply chain management – AI integrates data from suppliers, manufacturers and distributors to synchronize activities across the chain,
- quality control – AI-assisted cameras and sensors detect product defects in real time,

- production planning – AI creates dynamic production schedules taking into account resource availability, machine changeover times and order sequence, to avoid downtime and optimize machine utilization.

In turn, the goal of Machine Learning is to create automated systems capable of improving themselves using accumulated experience (i.e., data) and to acquire new knowledge on that basis. Machine Learning is finding increasing application in production logistics, supporting decision-making under conditions of high variability and complexity of processes occurring in enterprises. Self-learning systems make it possible to more accurately forecast demand for raw materials or components taking into account seasonality (resulting in the reduction of excess inventory) (Zhou et al., 2020), they also help dynamically adjust production plans to current conditions (e.g., resource availability, machine breakdowns) (Kumar & Bathia, 2021), as well as support automation and warehouse management, where using historical data it is possible to optimize internal transport routes, the distribution of goods and the allocation of human resources (Ivanov et al., 2019). The application of Machine Learning also contributes to the construction of smart factories, which, operating in the era of Industry 4.0, increase the flexibility and adaptability of the enterprise.

(3) Robotics and Automation

Robotics is the process of designing and using a robot to perform specific tasks. Automation, on the other hand, is the use of mechanized technology to reduce costs, increase the scale of production and speed it up, improve productivity, including the working environment (Duong et al., 2020). Automation can help in many business areas, such as warehouse management, ordering. Through Automation, companies can save time and costs while improving the quality and efficiency of their operations (Schwab, 2016).

Examples of the application of robotics solutions in production logistics are: mobile robots AGV/AMR for internal transport of materials, collaborative robots (so-called cobots) in loading, packing, sorting without the need for human intervention. Unlike traditional transport systems, mobile robots are autonomous, that is, they move directly around the production hall or warehouse based on a map of the environment (often created in real time). They are equipped with sensors and cameras that enable them to avoid obstacles and react dynamically to changes in the environment. They work with

Internet of Things sensors, analyze data and communicate with other machines or systems (they can be connected to digital twins, as well as ERP and MES systems). AGV robots move along predetermined routes through proper navigation (e.g., from a warehouse to a production line along conveyor belts, guides), while AMR robots automatically analyze the environment and avoid obstacles (Kumar et al., 2020, Miś & Kortykowski, 2022).

In terms of Automation, robotic palletizing stations and robotic production lines are an increasingly common solution. Robotized palletizing stations enable greater precision in the creation of palletized load units and relieve workers of heavy and monotonous work (Dobrzanski, 2016). Thanks to their use, the process of packing and palletizing can be supervised by only one worker.

(4) ERP, MES and MAS systems

ERP (Enterprise Resource Planning) systems are integrated software systems, that enable the management of an enterprise's resources in a consistent and transparent manner, for they integrate all of an organization's core functions – from finance and human resources to production and logistics. These systems allow collecting, storing, managing and interpreting data from different areas of the business in real time (Kaczmarek & Wrona, 2018). The key features of ERP systems are data and process integration (which eliminates duplication of information), information flow automation (which increases the efficiency of operations), modularity (which allows the system to be tailored to the specifics of the enterprise), and cloud access (which allows remote work and real-time updates). In the area of production logistics, the ERP system is used in such processes as (Laudon & Laudon, 2021):

- planning of material needs, making it possible to minimize inventory while ensuring production continuity,
- scheduling production, taking into account the availability of raw materials, machinery and employees,
- monitoring the execution of orders in real time, enabling rapid response to disruptions,
- inventory and warehouse management, supporting control of inventory levels and optimizing the distribution of materials in warehouses.

Examples of modern ERP systems and their application in manufacturing logistics are shown in Table 1.

Table 1. Examples of modern ERP systems and their application in manufacturing logistics

ERP systems	Application
SAP S/4HANA	One of the most advanced ERP systems, enabling very fast processing of large data sets and offering advanced analytical tools. It is used in production planning, inventory management, production execution, supply chain management, quality control at various stages of production.
Microsoft Dynamics 365	A system offering modules dedicated to production and logistics, integrated with Office 365 tools, applicable in optimizing processes related to production planning, inventory management, transportation and warehousing.
IFS Applications	A system focused on manufacturing and logistics enterprises, applicable to project, production and service management in a single environment.

Source: adapted from the works *(***Sharma & Gupta, 2021), (Kaczmarek & Wrona,** 2018) and **(Nowicki,** 2019*).*

Modern ERP systems are increasingly being integrated with Internet of Things sensors, Artificial Intelligence, as well as highly advanced information systems, i.e. MES and MAS classes.

Multi-Agent Systems (MAS) are advanced IT solutions that support the management and optimization of manufacturing processes. They consist of autonomous, cooperating software agents that perform specific tasks within a common goal. In the context of production logistics, each agent can represent: a machine, warehouse, operator, production line, order, transport vehicle, procurement department, etc. Agents are capable of making decisions, negotiating and learning from information in the environment. MAS systems find application in production planning and scheduling, warehouse and supply management, optimization of material flows and response to disruptions (e.g., order changes, breakdowns) (Leitão, et al., 2016). Such technologies are a key component of smart factories. where we are dealing with high complexity and the need for precise coordination of production processes. MAS and ERP systems perform complementary functions. Agent-based systems can support ERP through dynamic production scheduling, optimization of routes and material flows, local autonomy of decisions (e.g. autonomous response to disruptions) (Giret, et al., 2015).

MES (Manufacturing Execution Systems), on the other hand, is responsible for production management at the operational level enabling ongoing monitoring and control of production processes, collection of shop floor data, quality control, production resource management and reporting of results. Integration of MES with ERP enables, among other things: the transfer of production orders from ERP to MES, ongoing production reporting to ERP, better planning based on actual data, reduced response time to production disruption, as well as quality improvement and cost reduction (Liu et al., 2018, Monostori et al., 2016).

ERP, MES and MAS systems are not in competition with each other, but complement each other. Implementing these systems in an integrated structure allows companies to more fully control production and make better use of data in the enterprise.

(5) Digital Twins

Digital Twins are one of the breakthroughs in the digital age. This is because they make it possible to create virtual models of physical objects that are continuously updated with real-world data. This makes it possible to simulate, analyze and optimize production logistics without interfering with the real process. In manufacturing logistics, Digital Twins are realistically used in optimizing internal transportation, managing warehouse and shop floor layout, simulating emergency scenarios, and integrated collaboration with production and procurement (Liu et al., 2020). Their implementation consequently leads to reduced operation time, reduced errors, better planning and forecasting, greater resilience to disruptions in the logistics process.

(6) Blockchain

Blockchain is an emerging technology that allows secure storage of data and transactions without the need for intermediaries. Blockchain is otherwise known as a distributed data registry, which stores information in the form of blocks cryptographically linked into an immutable chain. Every participant in the network has access to the same version of the data, which eliminates the need to trust about one central entity and significantly reduces the risk of information manipulation. In the context of manufacturing logistics, Blockchain acts as a secure platform for sharing data between manufacturers, suppliers, logistics operators and customers. With Blockchain technology, companies can save time and costs associated with intermediaries, while improving the security and transparency of their operations. Blockchain is used in supply chain management (transport tracking, quality control, delivery confirmation), returns logistics (efficient determination of the source of a defective product and automation of the claims process), sustainability (documenting the ecological origin of raw materials, controlling the carbon footprint), among others. Blockchain therefore brings a new quality to manufacturing logistics in terms of security, transparency and process automation(Nartey et al., 2019). When combined with other Industry 4.0 technologies, it can significantly improve efficiency and trust in complex global supply chains.

(7) Cloud Computing

Cloud Computing is a system for storing data on multiple servers, most often managed by a hosting company, ensuring both data availability and security. Cloud technologies form a service-oriented architecture (PaaS), software as a service (SaaS) and information as a service (IaaS) (Wodnicka, 2019).

In manufacturing logistics, the cloud enables the integration of data and systems (e.g., ERP and MES), streamlines the flow of information, and enables real-time access to up-to-date data. This is crucial in manufacturing environments based on rapid response and precise planning. Cloud technologies can also play a key role in sustainable manufacturing through process linking, automation, increased resilience and significant waste reduction, reuse and recovery (Wodnicka, 2019). Using Cloud Computing allows companies to reduce energy consumption, while at the same time speeding up the execution of certain logistics operations through access to information.

(8) Big Data

Big Data, as a collection of diverse data of huge volume, is an important part of collecting and selecting specific values. They represent a huge potential to exploit and improve efficiency. Their processing makes it possible to optimize all processes in the various phases of the supply chain (Jagtap et al., 2021). In addition, the data are generated systematically, multiple times a day, and are thus constantly updated. Databases and analysis of the information collected increase the reliability of process planning and scheduling, thanks to knowledge of demand and also the availability of resources in real time (Sun et al., 2022). The breadth of data also facilitates forecasting, inventory and transportation management but can also be helpful in developing innovative solutions. In terms of resource depletion, information is extremely valuable for optimal management and reducing waste. Big Data analytics provides the opportunity to realize flexible production, with resource efficiency but also reduction of waste (Kręt, 2020). Innovative technologies therefore facilitate the optimization of production processes, signal the emergence of critical points, and facilitate the identification of inefficient processes.

(9) 3D Printing

3D Printing is a technology that creates physical objects based on a digital design by applying successive layers of material – such as plastic, metal or resin. Unlike cavity technologies (such as milling or turning), 3D Printing is an additive method, which means less material consumption and the ability to create complex geometries. The application of 3D Printing in manufacturing logistics most often includes: on-demand production of spare parts, creation of fixtures, covers, as well as assembly jigs and other elements supporting the production line, creation of prototypes of products and their components, which reduces the time of introducing new products into production, and customization of products without modifying the entire production line (Wojciechowska 2020, Kotlinski 2019, Blazejewski 2022).

3D Printing in manufacturing logistics is one of the most important tools for modern industrial transformation. Although it will not replace all traditional manufacturing methods, its role as a complement and support for logistics and production processes is constantly growing. In the face of the need to reduce lead times, reduce costs and increase flexibility – this technology will certainly gain in importance in the future in supply chain management and production organization.

(10) Virtual Reality

Virtual Reality is a technology that allows the user to interact with a computer-generated environment in a manner similar to the real one. Thus, it allows the creation of virtual environments that can be used to train employees, design products and conduct business simulations (Biocca et al., 2019).

In manufacturing logistics, Virtual Reality is used to design production facilities in a virtual environment, making it possible to: test production line layouts and machine layout, virtually analyze material flow, and optimize warehouse space and internal transportation. In addition, VR provides opportunities for realistic training in a safe environment (e.g., learning how to operate machinery and equipment without the risk of accidents), picking and assembly support (interactive instructions), and virtual inspections and audits (remotely conducting production reviews, audits and engineering meetings without the need for physical presence) (Pamula, 2020, Kowalski, 2019).

Virtual Reality is becoming an increasingly important tool in manufacturing logistics, as it allows to improve the efficiency, safety and quality of processes. Despite the existing technical and organizational barriers (high initial cost, lack of standardization of solutions, competence barriers, problems with simulation accuracy), the potential of Virtual Reality in industry is enormous. Its importance will grow with the further development of Industry 4.0, while in the perspective – Industry 5.0, it can play a key role in building a more human industry of the future, harmonizing the work of man and technology.

2.3. Benefits and limitations of implementing new technologies

New technologies are currently the basis for maintaining a strong position on the market by the company, because the numerous benefits of using these technologies enable the development of a strong competitive position of the company. The benefits resulting from the implementation of technologies in production logistics described in subchapter 1.2 are highlighted below.

The most important benefits of implementing the Internet of Things in production logistics include (Mourtzis et al., 2016, De Vass et al., 2022):

- real-time monitoring of the flow of materials and products,
- predictive maintenance (less downtime),
- faster detection of disruptions in the production process,
- more precise planning of production and internal logistics.

Considering Artificial Intelligence, the main benefits of its application include (De Vass et. al., 2022):

- more precise forecasting of demand and material requirements,
- automatic production scheduling (more flexible and optimized),
- improvement of the information flow process,
- the ability to set task priorities,
- avoiding empty runs in internal transport processes,
- optimization of the way goods are distributed in warehouses.

The significant advantages of using Automation and Robotics in the area of production logistics include (Trzop, 2020):

- increased operational efficiency (automatic warehouse systems and mobile robots can work without interruptions, faster detection of repetitive tasks),
- savings resulting from the optimization of production processes,
- increased product quality,
- reduced level of errors and risks,
- improved work safety,
- reduced problems related to staff shortages,
- better planning of production and internal logistics thanks to,
- reduced waste of raw materials and materials.

Key capabilities resulting from the use of ERP and MES include (Rokicki & Ziółkowska, 2020, MDPI, 2023):

- full integration of production and logistics systems,
- faster response to deviations and better production planning,
- reduced storage costs and reduced production downtime,
- improved delivery timeliness and production flexibility,
- data-driven management and fast decision-making.

The most important benefits provided by Digital Twins include (Li et al., 2024):

- optimization and improved visibility of the supply chain, identification of bottlenecks, estimation of safety stocks and resource availability,
- increased efficiency of production scheduling,
- predictive maintenance and extension of machine life,
- optimization of energy and resource consumption and support for sustainable development.

When it comes to the capabilities of MAS agent systems, they include:
- quick response to changes in the environment, e.g. delivery delays, machine failures,
- decentralized decision-making and reduced load on other systems,
- optimization of resources that are constantly monitored by system agents,
- reduction of operating costs.

The main benefits of Blockchain technology include (Francisco et al., 2018):
- the ability to monitor the origin of raw materials, materials and finished products in real time,
- improved product safety,
- increased process efficiency and the ability to quickly verify information,
- better risk management,
- replacing traditional auditors and electronic data exchange systems,
- reduced operating costs.

The use of Cloud Computing in logistics processes brings many benefits – both operational and strategic. The key ones include (Nowicka, 2018, Yao, 2024):
- access to real-time data,
- increasing the efficiency of logistics processes,
- shortening the information flow path by integrating production and logistics systems,
- the possibility of avoiding the need to allocate funds for building and developing your own IT infrastructure,
- scalability and flexibility of resources (the possibility of increasing data space during periods of increased production).

3D Printing technology provides the following benefits (Błażejewski, 2022, Wojciechowska 2020):
- reduction of warehouse stocks thanks to "on-demand" production,
- reduction of logistics costs, especially in the case of small-scale production,
- shortening of order fulfillment times,
- greater flexibility in managing production changes,

- sustainable development thanks to lower consumption of raw materials and energy.

In turn, Virtual Reality creates the following possibilities (Kowalski 2019, Bartosik, 2020, Pamuła 2020, Saniuk, 2021):

- faster and safe employee onboarding,
- shortening the time of process implementation,
- avoiding design errors,
- flow optimization,
- technical support,
- improving the quality of decisions thanks to better visualization and analysis of processes.

Although solutions from the field of Industry 4.0 and new digital technologies bring many benefits, there are also significant limitations in their implementation from the point of view of modern enterprises.

Firstly, the implementation of new technologies in most cases involves large financial outlays, which not every company can afford. This applies especially to small and medium-sized enterprises, for which the implementation of advanced technologies is often a significant obstacle due to high investment costs. In addition, many companies implement technologies in stages, without a long-term digital transformation strategy, which translates into low investment efficiency.

Secondly, the use of new technological solutions is often associated with the need to entrust valuable information resources of the enterprise to an external entity. Industry 4.0 generates huge amounts of data, and therefore the key challenges in this matter are primarily: data quality, protection of availability and resistance to cyberattacks.

Moreover, the implementation of such advanced technologies involves significant changes in the organization of processes, requiring appropriate change and risk management skills from the management staff. There is also no doubt that the problems in this regard are compounded by the lack of qualified staff, especially IT specialists, data engineers and digital system operators.

In summary, in the era of Industry 4.0, production logistics is undergoing a dynamic digital transformation aimed at increasing the operational efficiency, flexibility and resilience of manufacturing systems. New technologies are the foundation of modern industry and completely revolutionize the way logistics processes are planned, monitored and implemented in the production environment. Digital era technologies support companies in achieving better material traceability, shortening order fulfillment times, reducing storage and transportation costs, and improving communication between systems and departments. It is also worth noting that individual technologies often complement each other, which increases the benefits obtained. At the same time, the implementation of advanced technologies is associated with significant challenges, such as: high initial costs, difficulties in integrating new technologies with existing infrastructure, threats from data security, or a lack of digital competences of employees. Therefore, the implementation of innovative solutions requires not only technological investments, but also a change in organizational culture and a systemic approach to managing the digital era. Nevertheless, new technologies are the foundation of modern industry and a promising perspective for Industry 5.0. The appropriate way of their implementation allows enterprises not only to increase their competitiveness, but also to better meet the requirements of the modern market.

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PART II.

STRATEGIC LOGISTICS MANAGEMENT

Chapter 3.
TECHNOLOGICAL FORESIGHT IN LOGISTICS PROCESS MANAGEMENT

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Andrzej Borusiewicz

3.1. Introduction

The contemporary business landscape is characterized by accelerating change, heightened uncertainty, and increasing complexity, demanding that organizations look beyond immediate operational concerns towards anticipating future possibilities (Rohrbeck et al., 2015). In this dynamic environment, traditional planning methods based solely on historical data often fall short. This necessitates the adoption of strategic tools capable of navigating ambiguity and proactively shaping the future. One such critical capability is technological foresight.

Technological foresight can be defined as a systematic process involving gathering and processing information about potential long-term technological developments, trends, discontinuities, and their potential impacts, with the aim of informing strategic decision-making, guiding innovation efforts, and building future preparedness (Popper, 2008; Martin, 1995; Havas et al., 2010). It is distinct from forecasting, which typically extrapolates past trends, by incorporating qualitative insights, exploring multiple plausible futures (scenarios), identifying weak signals of change, and considering disruptive innovations (Slaughter, 1997; Coates et al., 2001). It involves not just predicting *what* might happen but understanding *why* and *how* technological shifts could reshape industries, markets, and operational paradigms.

Five important aspects of the definition of foresight should be pointed out (www 1):

- Attempts to look into the future must be systematic in order to be called 'foresight'. This is what distinguishes foresight from the endogenous scenario building that we all do in everyday life.
- Foresight must refer to a longer period, which is usually perceived as longer than the normal planning horizon. Foresight time horizons therefore range from 5 to 30 years.
- The progress of science/technology should be balanced with market demand. Although this is a rather strict way of thinking about the innovation process, the fact is that technology foresight should not be dominated exclusively by science and technology (S&T). Consideration should also be given to socio-economic factors, which are also known to shape innovation.
- Foresight focuses on emerging generic technologies where there is a legal basis for government support. This is because companies are often reluctant to fund strategic research that supports emerging generic technologies.
- Attention should be paid to social impact, not just wealth creation. This leads to the adoption of some recent foresight tasks, more problem-oriented perspectives from the outset, for example, focusing on issues such as crime prevention, education and skills, ageing societies, etc.

Foresight acts as a crucial input for robust strategic management, enabling organizations to identify emerging opportunities, anticipate competitive threats, allocate resources effectively towards future growth areas, and build resilience against potential disruptions (Vecchiato & Roveda, 2010; Bootz, 2010). By scanning the technological horizon, companies can make informed choices about R&D investments, strategic partnerships, and capability development needed to maintain or gain competitive advantage (Day & Schoemaker, 2005; Rohrbeck & Gemünden, 2011). Furthermore, foresight is inextricably linked to innovation management; it fuels the innovation pipeline by identifying unmet needs, revealing potential applications for nascent technologies, and guiding the development of novel products, services, and business models (Salerno et al., 2015; Andersen & Andersen, 2014). Without foresight, strategic and innovation efforts risk being reactive, incremental, or misaligned with long-term market and technological trajectories.

The logistics sector, serving as the circulatory system of the global economy, faces a unique confluence of pressures – intense cost competition, demand for speed and reliability, increasing customer expectations for visibility and customization, sustainability mandates, and vulnerability to geopolitical events, infrastructure limitations, and natural disasters (Christopher, 2016; Sheffi & Rice, 2005; Ivanov et al., 2019). These factors make logistics particularly susceptible to disruption and necessitate a proactive approach. Technological foresight in logistics specifically focuses on anticipating how emerging technologies (e.g., automation, AI, IoT, blockchain, alternative fuels) will reshape logistics processes, infrastructure, business models, and workforce requirements (Hofmann & Rüsch, 2017; Barreto et al., 2017; Preindl et al., 2020). It involves assessing the maturity, scalability, cost-effectiveness, and potential impact of these technologies on core functions like transportation, warehousing, inventory management, and last-mile delivery, enabling logistics providers and shippers to make strategic investments and operational adjustments ahead of the curve (Waller & Fawcett, 2013a; Kayikci, 2018). This chapter explores the multifaceted role and application of technological foresight in navigating the complexities and shaping the future of logistics management.

3.2. The Role of Technological Foresight in Logistics

Technological foresight is transitioning from a peripheral activity to a core strategic enabler within modern logistics and supply chain management (SCM). Its role extends beyond simple trend awareness to fundamentally influencing operational planning, strategic decision-making, and the very architecture of logistics systems.

The integration of foresight transforms logistics planning from a predominantly deterministic exercise based on past performance to a probabilistic and adaptive process focused on future readiness (Melnyk et al., 2014; Gölzer & Fritzsche, 2017). Instead of relying solely on historical demand patterns, foresight-informed planning incorporates predictions about technology adoption rates (e.g., autonomous vehicle penetration), potential regulatory changes (e.g., emissions standards), infrastructure developments (e.g., new port capacities), and potential disruptions identified through scenario analysis (Tukamuhabwa et al., 2015; Da Costa et al., 2008). This allows for:

- Proactive Resource Allocation: Directing investments towards technologies identified as strategically important (e.g., warehouse automation, predictive analytics platforms) rather than purely reacting to competitor moves (Porter & Heppelmann, 2014).

- Risk-Informed Planning: Developing contingency plans and building resilience based on anticipated technological risks (e.g., cybersecurity threats to IoT networks) or technology-driven disruptions (e.g., impact of drone delivery on existing networks) (Ivanov, 2020; Blackhurst et al., 2011).
- Strategic Network Design: Making long-term decisions about facility location, transportation modes, and network structure based on foresight regarding future trade patterns, infrastructure availability, and the capabilities of emerging logistics technologies (Meixell & Gargeya, 2005; Lim et al., 2018).
- Capability Development: Identifying future skill requirements driven by new technologies (e.g., data scientists, robotics technicians) and proactively initiating training or recruitment programs (Knol et al., 2018; Frank et al., 2019).

Integration of Foresight into Supply Chain Management (SCM) Systems: For foresight to be operationally effective, its insights must be integrated into the core SCM systems that manage daily logistics execution. This involves moving beyond standalone foresight reports towards embedding predictive and prescriptive capabilities within platforms like Enterprise Resource Planning (ERP), Transportation Management Systems (TMS), Warehouse Management Systems (WMS), and Supply Chain Control Towers (Fosso Wamba et al., 2017; Barratt & Oke, 2007). Integration enables:

- Real-time Data Feeds: Foresight models are continuously updated with real-time operational data (from IoT, TMS, WMS) combined with external data streams, allowing for dynamic adjustments to predictions and plans (Hofmann & Rüsch, 2017; Kache & Seuring, 2017).
- Embedded Analytics: Predictive algorithms (e.g., for ETA calculation, demand sensing, predictive maintenance) become standard features within operational systems, providing decision support directly to planners and managers (Waller & Fawcett, 2013b; Queiroz et al., 2020).
- Automated Responses: Increasingly, foresight insights trigger automated responses within SCM systems, such as automatically adjusting inventory parameters based on predicted demand shifts or rerouting vehicles based on anticipated congestion (Wang et al., 2016; Baryannis et al., 2019).
- Enhanced Visibility and Control Towers: Foresight capabilities are central to advanced supply chain control towers, providing not just

visibility into the current state but also predictive alerts about potential issues and simulating the impact of proposed interventions (Trzuskawska-Grzesińska, 2017; Fawcett et al., 2011).

Examples of Application:

- Transport: Foresight informs strategic decisions on fleet composition (e.g., investment in electric or autonomous trucks), predicts fuel price fluctuations, anticipates infrastructure bottlenecks (port congestion, road closures), optimizes long-term network design, and enables highly accurate, real-time ETA predictions by integrating diverse data sources (weather, traffic, driver behavior) through ML models (Van Hinsbergen et al., 2011; Cacchiani et al., 2014; Psaraftis, 2019).
- Warehousing: Foresight guides decisions on automation investments (AGVs, robotic picking systems), predicts optimal warehouse layouts based on future order profiles, forecasts labour needs, anticipates equipment failures through predictive maintenance (using IoT sensor data), and informs strategies for managing returns logistics based on predicted return rates (Azadeh et al., 2019; Li et al., 2017; Boysen et al., 2019).
- Demand Planning: Technological foresight enhances demand forecasting accuracy by incorporating insights about technology adoption curves (e.g., predicting demand shifts driven by new product introductions enabled by tech), competitor technological moves, and the impact of external technological factors (e.g., 5G rollout enabling new services). AI/ML models analyze vast datasets to identify complex demand drivers beyond simple historical extrapolation (Carbonneau et al., 2008; Nikolopoulos et al., 2021; Choi et al., 2018).

In summary, technological foresight is becoming an indispensable element of modern logistics, fundamentally reshaping planning and decision-making processes and requiring deep integration with operational SCM systems to unlock its full potential across all logistics functions.

3.3. Technological Foresight Methods and Tools

Conducting effective technological foresight requires a structured approach utilizing a diverse toolkit of qualitative and quantitative methods. No single method is sufficient; often, a combination is employed to capture different facets of technological change and its potential impacts (Popper, 2008; Becker, 2003).

- Trend and Scenario Analysis:
  - *Trend Analysis/Extrapolation:* Involves identifying existing technological trends (e.g., miniaturization, increasing processing power, adoption rates of specific technologies) and extrapolating their future trajectory, often using quantitative modeling (e.g., S-curves, diffusion models) (Martino, 2003; Dosi, 1982). While useful, it is less effective at identifying discontinuities or novel developments.
  - *Scenario Planning:* A cornerstone of foresight, scenario planning develops multiple plausible, internally consistent narratives about how the future might unfold based on key uncertainties and driving forces (technological, economic, social, political) (Schoemaker, 1995; Schwartz, 1991; Ringland, 2010). In logistics, scenarios might explore futures dominated by hyper-automation, extreme localization, or stringent sustainability regulations, allowing companies to test the robustness of their strategies and identify necessary adaptations for each potential future (Von der Gracht & Darkow, 2010; Fink & Schlake, 2000).
- Expert-Based Methods:
  - *Delphi Method:* A structured communication technique relying on iterative rounds of questionnaires sent to a panel of experts, aiming to reach a consensus or identify divergent views on future technological developments, adoption timelines, and impacts (Linstone & Turoff, 1975; Gordon & Pease, 2006; Skulmoski et al., 2007). Widely used to assess the potential of emerging logistics technologies.
  - Expert Panels/Workshops: Bringing together diverse experts (technologists, industry practitioners, academics, policymakers) for structured discussions, brainstorming, and qualitative assessments of future trends and their implications (Keenan & Popper, 2008).
- Roadmapping and Mapping Techniques:
  - *Technology Roadmapping:* A visual method used to align technological developments with business objectives and market needs over time. It maps anticipated technological milestones, required resources, product/service evolution, and market drivers, providing

a strategic plan for technology development and implementation (Phaal et al., 2004; Kostoff & Schaller, 2001; Garcia & Bray, 1997). Essential for planning long-term logistics technology investments.
- Technology Mapping/Scanning: Systematically identifying and categorizing existing and emerging technologies relevant to the logistics sector, often assessing their maturity level (e.g., using Technology Readiness Levels – TRLs) and potential impact (Gerdsri et al., 2009; Daim et al., 2006).

– Environmental Scanning and Analysis Frameworks:
  - *STEEP/PESTEL Analysis:* Frameworks used to systematically scan the broader external environment across Social, Technological, Economic, Environmental, Political, and Legal dimensions to identify key driving forces and trends that could influence technological development and adoption in logistics (Aguilar, 1967; Yüksel, 2012).
  - *Weak Signal Analysis:* Actively searching for early, often ambiguous indicators of potential future changes or disruptions that are not yet widely recognized trends (Ansoff, 1975; Hiltunen, 2008). Requires monitoring fringe sources, patent filings, startup activities, etc.

– Visualization and Monitoring Tools:
  - *Technology Radar:* A visual tool used to map and monitor relevant technologies based on their maturity/readiness and potential strategic importance to the organization, helping prioritize monitoring and investment efforts (Rohrbeck, 2010; Eidhoff et al., 2016).

– Use of AI and Big Data in Trend Prediction: Modern foresight increasingly leverages computational power:
  - *Data Mining and Text Mining:* AI algorithms analyze massive datasets (scientific publications, patents, news articles, social media, market reports) to automatically identify emerging technological concepts, track sentiment, map innovation networks, and detect nascent trends much faster and more comprehensively than manual methods (Daim et al., 2006; Yoon, 2012; Thorleuchter et al., 2012).
  - Predictive Modeling: ML models can be trained on historical data of technology adoption, funding patterns, and performance metrics to predict future diffusion rates or identify technologies likely to achieve breakthroughs (Gao et al., 2014; Kaplan & Vakili, 2015).

The choice and combination of methods depend on the specific foresight objective, timescale, available resources, and the nature of the technologies being assessed (Cuhls, 2003; Glenn & Gordon, 2009).

3.4. Key Technology Trends in Logistics

Technological foresight activities consistently highlight several key trends poised to fundamentally reshape logistics operations in the coming years. Understanding these trends is essential for effective planning.

- Automation and Robotisation of Warehouse Processes: Driven by labour shortages, rising wages, and the need for speed and accuracy, automation is rapidly advancing beyond traditional conveyor systems. Key technologies include Autonomous Mobile Robots (AMRs) for goods-to-person picking, robotic arms for sorting and palletizing, automated storage and retrieval systems (AS/RS) for dense storage, and autonomous forklifts (Boysen et al., 2019; Lambán et al., 2020; Van Geest et al., 2021). Foresight focuses on predicting adoption rates, integration challenges, impact on labour, and the emergence of next-generation robotics (e.g., collaborative robots).
- Internet of Things (IoT) and Logistics 4.0: The proliferation of sensors on assets, infrastructure, and products creates unprecedented real-time visibility and data streams (Hofmann & Rüsch, 2017; Ben-Daya et al., 2019). This enables hyper-accurate tracking, condition monitoring (temperature, humidity, shock), predictive maintenance, and optimized asset utilization. Logistics 4.0 represents the broader integration of IoT, cyber-physical systems, Big Data, and AI to create intelligent, interconnected, and autonomous logistics systems (Barreto et al., 2017; Winkelhaus & Grosse, 2020). Foresight assesses cybersecurity risks, data interoperability standards, and the value derived from integrating diverse IoT data.
- Artificial Intelligence in Route Prediction and Optimisation: AI/ML algorithms are revolutionizing transportation planning. They provide highly accurate ETA predictions, enable dynamic real-time route optimization considering numerous variables, optimize fleet deployment, predict traffic congestion patterns, and can potentially automate dispatching decisions (Choi et al., 2018; Wang et al., 2016; Ticha et al., 2019; Baryannis et al., 2019). Foresight tracks algorithmic

advancements, data requirements, and the potential for fully autonomous transport planning.
- Blockchain in Supply Chain Management: Blockchain offers a decentralized, immutable ledger technology with potential applications in enhancing supply chain transparency, traceability, security, and trust among partners (Kshetri, 2018; Saberi et al., 2019; Ølnes et al., 2017). Potential use cases include tracking high-value goods, verifying product provenance (e.g., for fair trade or organic goods), streamlining customs processes, and facilitating secure financial settlements (e.g., via smart contracts) (Babich & Hilary, 2020; Cole et al., 2019). Foresight evaluates scalability limitations, interoperability challenges, regulatory acceptance, and the most viable applications beyond initial hype.
- Green Technologies and Sustainable Logistics: Driven by regulations, corporate social responsibility (CSR), and customer demand, sustainability is a major force. Key technological trends include the electrification of delivery fleets, development of alternative fuels (hydrogen, biofuels) for heavy transport, optimization algorithms minimizing fuel consumption and emissions, adoption of circular economy principles (reverse logistics), and technologies for measuring and reporting environmental impact (Psaraftis, 2019; Shaw et al., 2012; Centobelli et al., 2020; Dekker et al., 2012). Foresight assesses the pace of adoption, infrastructure requirements (e.g., charging networks), cost parity with traditional technologies, and evolving regulatory landscapes.

Monitoring these and other emerging trends (e.g., 3D printing impacting distributed manufacturing, augmented reality in warehousing) through systematic foresight is crucial for logistics organizations to remain competitive and relevant.

3.5. The Future of Logistics and Technological Foresight

Looking towards the medium to long term (2030-2050), technological foresight suggests several potential trajectories and disruptions for the logistics sector, demanding strategic preparedness.

Scenario planning helps envision distinct future possibilities:
- *Scenario 1: Hyper-Automated & Efficient:* Dominated by widespread adoption of AI, autonomous vehicles (trucks, drones, ships), and robotic warehousing, leading to highly efficient, low-labour, potentially

24/7 operations, but requiring massive capital investment and facing cybersecurity risks (Fagnant & Kockelman, 2015; Feng et al., 2021).

– *Scenario 2: Sustainable & Circular:* Driven by stringent environmental regulations and consumer pressure, logistics focuses on electrification, alternative fuels, optimized routing for minimal emissions, extensive reverse logistics networks, and circular economy models. Technology enables precise environmental impact tracking (Dekker et al., 2012; Ellen MacArthur Foundation, 2013).
– *Scenario 3: Localized & On-Demand:* Enabled by advanced manufacturing (e.g., widespread 3D printing) and e-commerce platforms, supply chains become more localized, with emphasis on rapid, flexible, on-demand last-mile delivery using drones, autonomous pods, and micro-fulfillment centers (Weller et al., 2015; Hopkins, 2021).
– *Scenario 4: Resilient & Fragmented:* Geopolitical instability, climate disruptions, and protectionist policies lead to more fragmented, regionalized supply chains focused on resilience and redundancy. Foresight tools are crucial for navigating constant disruptions and managing complex risk landscapes (Sheffi & Rice, 2005; Ivanov, 2020).

These scenarios are not mutually exclusive; the future will likely blend elements of each. Foresight helps organizations prepare for the strategic implications of these different potential futures.

Certain "wild card" technologies could radically alter logistics:

– *Hyperloop:* High-speed transportation systems using pods in low-pressure tubes could revolutionize long-haul freight transport for high-value or time-sensitive goods, though significant infrastructure and cost hurdles remain (Van Goeverden et al., 2018; Janic, 2018).
– *Advanced Drone Delivery:* Beyond small packages, larger cargo drones or autonomous vertical take-off and landing (VTOL) aircraft could enable rapid point-to-point delivery, bypassing ground congestion, especially in urban or remote areas (Thiels et al., 2015; Aurambout et al., 2019).
– *Fully Autonomous Vehicles (Level 5):* Widespread deployment of fully autonomous trucks and delivery vehicles without human oversight would dramatically impact labour costs, operational efficiency (potentially 24/7 operation), and safety, but faces immense technical, regulatory, and societal acceptance challenges (Bagloee et al., 2016; Milakis et al., 2017).

– *Advanced AI and Quantum Computing:* Future AI could enable truly self-optimizing, adaptive supply chain networks. Quantum computing could potentially solve highly complex optimization problems currently intractable for classical computers (Preskill, 2018; Bova et al., 2021).

The implementation of these advanced technologies raises significant concerns:

– *Job Displacement:* Automation and autonomy threaten widespread displacement of logistics workers (drivers, warehouse staff, planners), requiring strategies for workforce transition and reskilling (Acemoglu & Restrepo, 2019; Frey & Osborne, 2017).
– *Data Privacy and Security:* Extensive use of IoT and tracking technologies raises concerns about surveillance and data privacy for workers and customers. Cybersecurity of interconnected logistics systems is paramount (Martin, 2019; Roman et al., 2011).
– *Algorithmic Bias:* AI algorithms used for routing, hiring, or risk assessment could perpetuate or even amplify existing biases if not carefully designed and audited (Buolamwini & Gebru, 2018; Mittelstadt et al., 2016).
– *Safety and Liability:* Ensuring the safety of autonomous systems (vehicles, drones) and establishing clear liability frameworks in case of accidents are major regulatory hurdles (Goodall, 2014; Bonnefon et al., 2016).
– *Regulation Lag:* Technology often outpaces regulation, creating uncertainty for investment and deployment, particularly for autonomous systems and drone operations (Marchant & Lindor, 2012).

Navigating these ethical and regulatory landscapes will be as critical as mastering the technology itself for the future of logistics. Foresight must incorporate these dimensions alongside purely technical considerations.

3.6. Case Study: Logistics Innovator Alpha's Foresight Journey

Context: Logistics Innovator Alpha (LIA), a hypothetical global third-party logistics (3PL) provider, faced increasing pressure from e-commerce clients demanding faster, cheaper, and more transparent deliveries, coupled with rising labour costs and capacity constraints in key markets. Recognizing the limitations of their reactive planning, LIA initiated a strategic technological foresight program in the mid-2010s.

Foresight Process Implemented:

1. *Environmental Scanning & Trend Identification:* LIA established a dedicated foresight team tasked with continuous environmental scanning using PESTEL analysis, monitoring technology news, academic research, patent filings, and startup activities relevant to logistics. They identified key trends like warehouse automation, AI-driven optimization, IoT visibility, and increasing sustainability pressures.
2. *Expert Workshops & Delphi Study:* They conducted internal workshops with operational managers and external expert panels (including technologists and academics). A Delphi study was used to assess the likely adoption timelines and impact levels of identified technologies (e.g., AMRs, predictive ETAs, blockchain).
3. *Scenario Planning:* Four distinct 10-year scenarios for the logistics landscape were developed, focusing on uncertainties around automation adoption speed and the stringency of environmental regulations.
4. *Technology Roadmapping:* Based on the trend analysis and scenarios, LIA developed technology roadmaps for key service areas (warehousing, transportation), outlining prioritized investments in automation (AMRs in specific fulfillment centers), IoT tracking devices, and a new AI-powered TMS module for predictive ETAs and dynamic routing.
5. *Pilot Projects & Technology Radar:* Promising technologies identified (e.g., specific AMR vendors, AI ETA providers) were subjected to pilot projects. A technology radar was implemented to continuously track the maturity and relevance of emerging tech.

Effects and Outcomes:

- *Strategic Investments:* The foresight process directly informed LIA's capital expenditure, leading to early, targeted investments in warehouse automation (AMRs) in high-volume e-commerce facilities and the development/procurement of an AI-enhanced TMS.
- *Improved Operational Efficiency:* Pilot projects and subsequent rollouts demonstrated significant improvements: reduced picking times and labour costs in automated warehouses, improved fuel efficiency and on-time performance through dynamic routing, and enhanced customer satisfaction due to more accurate ETAs.

– *Enhanced Resilience:* Scenario planning prompted LIA to diversify its carrier base and explore alternative fuel options sooner than initially planned, improving resilience during subsequent fuel price spikes and capacity shortages.
– *Competitive Differentiation:* LIA leveraged its early adoption of predictive ETAs and enhanced visibility as a key differentiator in securing new e-commerce contracts.
– *Challenges Encountered:* Initial challenges included securing buy-in from skeptical operational managers, integrating new technologies with legacy IT systems, recruiting data science talent, and managing the change process for warehouse staff adapting to automation. Data quality from some carriers initially limited ETA prediction accuracy.

LIA's experience demonstrates how a systematic foresight process, combining diverse methods and integrated with strategic planning, can enable a logistics company to proactively navigate technological change, improve performance, and build competitive advantage.

3.7. Recommendations for Logistics Managers

To effectively leverage technological foresight and adapt to the rapidly evolving logistics landscape, managers should consider the following recommendations:

– Build Organisational Capacity for Foresight:
  • *Establish a Dedicated Function (or Role):* Depending on size, create a dedicated foresight team or assign clear responsibility to individuals/groups for scanning the horizon, analyzing trends, and facilitating foresight processes (Rohrbeck & Kum, 2018).
  • Foster a Foresight Culture: Encourage curiosity, openness to new ideas, long-term thinking, and constructive challenging of assumptions across the organization. Leadership commitment is crucial (Vecchiato, 2012).
  • Integrate Foresight into Strategy: Ensure foresight insights are systematically fed into the strategic planning, budgeting, R&D, and innovation management processes, not treated as isolated reports (Bootz, 2010; Day & Schoemaker, 2005).

- Develop Necessary Competencies and Tools:
  - *Invest in Talent:* Cultivate or recruit personnel with skills in data analytics, AI/ML, technology assessment, scenario planning, and strategic thinking. Upskilling existing logistics professionals is vital (Gölzer & Fritzsche, 2017; Knol et al., 2018).
  - Utilize Foresight Methods: Train staff in core foresight methodologies (scenario planning, roadmapping, Delphi, environmental scanning) suitable for the organization's context (Popper, 2008).
  - Leverage Technology: Adopt appropriate tools for data gathering (scanning software, databases), analysis (analytics platforms), and visualization (roadmapping software, radar tools) (Højland & Rohrbeck, 2018).
- Foster External Cooperation:
  - *Engage with Research Centres & Universities:* Collaborate on research projects, access cutting-edge knowledge, participate in foresight studies, and recruit talent (Perkmann et al., 2013; Schartinger et al., 2002).
  - Monitor and Partner with Start-ups: Keep abreast of innovations emerging from the start-up ecosystem; consider pilot projects, investments, or partnerships to access novel technologies (Blank & Dorf, 2012; Weiblen & Chesbrough, 2015).
  - Collaborate with Technology Partners: Work closely with software vendors, automation providers, and other technology partners to understand their roadmaps and co-develop solutions aligned with future needs (Hughes & Perrons, 2011).
  - Participate in Industry Consortia: Engage in industry associations and foresight consortia to share insights, benchmark practices, and collaborate on pre-competitive challenges (Gray et al., 2000).

By proactively building internal capabilities, developing talent, utilizing appropriate tools, and fostering external collaboration, logistics managers can embed foresight effectively, enabling their organizations to anticipate change and thrive in the future.

3.8. Summary

This chapter has explored the critical role of technological foresight in navigating the complexities and uncertainties of modern logistics process management. We defined technological foresight as a systematic approach to anticipating long-term technological developments and their impacts, highlighting its crucial role in informing strategic and innovation management, particularly within the dynamic logistics sector. The integration of foresight transforms logistics planning from reactive to proactive, requiring deep integration with operational SCM systems for maximum effect across transport, warehousing, and demand planning. A diverse toolkit of methods, including trend analysis, scenario planning, Delphi, roadmapping, and increasingly AI/Big Data analytics, underpins effective foresight practice. Key technology trends driven by foresight – automation, IoT/Logistics 4.0, AI optimization, blockchain, and sustainable technologies – are fundamentally reshaping the industry. Looking ahead, scenarios envision futures shaped by hyper-automation, sustainability, localization, or fragmentation, while potential breakthroughs like hyperloop and full autonomy loom, accompanied by significant ethical and regulatory challenges.

The Role of Foresight as a Competitive Advantage Tool: The analysis underscores that technological foresight is no longer optional but a fundamental requirement for competitive advantage in the future of logistics. Organizations that systematically anticipate technological shifts, understand their implications, and proactively adapt their strategies, operations, and capabilities will be better positioned to:

- Optimize efficiency and reduce costs through early adoption of impactful technologies.
- Build resilience against disruptions by anticipating risks and developing mitigation strategies.
- Enhance customer value through improved speed, reliability, visibility, and innovative service offerings.
- Attract and retain talent by aligning workforce development with future skill needs.
- Make more robust long-term investment decisions regarding infrastructure and technology.

In conclusion, embedding technological foresight into the organizational DNA is essential for logistics companies aiming not just to survive but to thrive and lead in an era of unprecedented technological change and market volatility. It is a key enabler for building agile, resilient, efficient, and future-ready logistics operations.

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Chapter 4.
OUTSOURCING IN LOGISTICS MANAGEMENT

Jarosław Klimaszewski

4.1. Introduction

Contemporary business management is based on change, which is treated partly as an opportunity and a threat. This state of affairs contributes to organizations' need to review how they organise and manage their businesses. In striving for business efficiency, companies must be able to develop and assimilate new ideas and create new value continuously.

The modern economy is characterised by extreme volatility and high competitiveness. This forces companies to be constantly evolving, innovative, and highly customer-oriented. Companies are looking for new management applications to increase their organization's competitiveness and create the conditions for greater, faster growth using popular management concepts.

Outsourcing is not new to management science. Various authors have repeatedly pointed out the benefits and costs of such solutions. Indeed, the dilemmas of whether to internalise, whether together or separately, whether to concentrate, and whether to diversify or accumulate are dilemmas that management practitioners and theoreticians face sooner or later. These dilemmas are not identical to the concept of outsourcing, but in each of these pairs of activities at least in each of these pairs of activities, at least to a limited extent, this problem occurs and should be analysed.

Analysing the effectiveness of outsourcing is simultaneously an analysis of the problem of internalisation, or the profitability of keeping certain functions internal. Just as many examples of decisions evidence the fact that this is the case in practice

In the current market conditions, logistical processes, including material, product, and information flow within and between enterprises, significantly impact meeting customers' wishes and expectations. Logistics determines the creation and maintenance of the competitive advantage of modern enterprises. Logistical processes are realised within a logistical system constructed differently in each economic entity. In order to meet the growing and changing wishes and expectations of customers, modern enterprises create very complex logistics systems based on the cooperation of many companies from different countries. Logistics processes are increasingly complex, costly, and uncertain. Companies should strive not only to provide exemplary customer service at the lowest possible costs but also to reduce the impact of logistics process disruptions (A. König, S. Spinler, 2016).

A company's logistics system should be tailored to the internal and external conditions of the specific company and ensure the efficient and effective realisation of its goals. An inappropriate configuration of logistics processes leads to an increase in the costs of logistics activities and a reduction in the level of customer service, which translates into a weakened competitive position of the enterprise (M. Brzezinski, 2015).

An efficient and effective flow of materials and information can create unique customer value, translating into a competitive advantage. Logistics processes are market-related, and their optimisation requires the cooperation of all organisations that are suppliers and customers to each other. Today, companies strive to create and deliver the most excellent value for the customer, which translates into increased sales, market share, and profitability. Using resources from multiple sources, domestic and foreign, is one way to create a competitive advantage. Outsourcing is a method that allows companies to source external resources. This article aims to analyse logistics outsourcing and assess its impact on the performance of modern companies based on selected Polish manufacturing and trading companies (Schwarc, 2014; Rinsler, 2010).

4.2. Essence of outsourcing

In order to ensure the development and improve the efficiency of the organisation, modern companies are faced with necessary changes. Above all, we are talking about changes in the sphere of management, which allow them to react quickly and adapt their and adaptation of organisation's capabilities to the challenges posed by the situation in the environment (Mikolajczyk, 2002). Economic organisations do not have a one hundred percent capacity to tie up all resources in every area of their functioning due to increasing market pressure and competitiveness. Therefore, the question of whether to perform all functions in-house or to concentrate on what the company can do best and use the services of specialised companies needs to be considered.

The essence of outsourcing was brought out by Henry Ford when he uttered the words that became the motto of outsourcing in 1923: "If there is something we can't do more efficiently, cheaper, and better than our competitors, there is no point in us doing it, and we should hire someone to do it better than us" (Grudzewski, Hejduk, 2004).

According to Lankford and Parsa, it is the transfer of tasks that can be dispensed with or done more cheaply and often better outside the company. They explain the separation from the parent company's structure and transfer them to external businesses (Lankford, Parsa, 1999).

M. F. Greaver II defines outsourcing as the transfer of internal areas of an organisation's activities and decision-making rights to external entities on a contractual basis. Outsourcing is not contracting out services commonly used by many organisations, but establishing long-term and permanent partnerships between organisations (Greaver II, 1998).

Outsourcing is the permanent transfer of an activity that has hitherto been carried out within a company to an external, independent company. Essential for outsourcing is the permanent or long-term transfer of an activity to a legally independent entity with which a legal agreement is made on a specific form of cooperation, including conditions and guarantees for the performance of the transferred activities. The cooperating unit is an independent entity and generally also has other partners as recipients of the results of its activities (Carter, Vlcek, 2003). In outsourcing, the results obtained so far internally are transferred to other independent enterprises, which consequently take over the responsibility for obtaining them in the future.

Logistics is becoming an increasingly important field these days. More and more people are working in logistics departments or companies providing logistics services. We are more inclined to use courier services instead of the post or online shopping instead of traditional shopping. We are also seeing more people studying logistics or becoming logistics technicians. This is how we notice that logistics surrounds us from all sides.

One of the management concepts in Polish companies is logistics outsourcing. What is it? The term comes from English: "outsourcing" is an abbreviation created by combining two English words: outside, external, from outside, and resource – resources, means, possibilities. The word "outsourcing" is an abbreviation that comes from the combination of two English words: outside – external, "from outside," and "resource," meaning external resources or capabilities. It means using external sources (Greaver II) or, according to other authors, using external resources (Trotsky, 2001). The term outsourcing was first used in the 1980s by General Motors, which used this name to describe a system of external sourcing of parts (Trotsky).

Figure 1 shows the evolution of the approach to separating functions from the company over the years, which distinguishes four ways outsourcing is perceived by outsourcing companies.

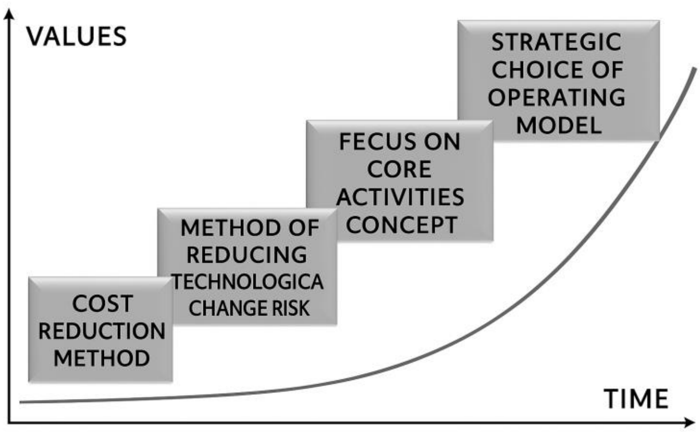

Figure 1. The evolution of outsourcing – perceptions

Source: (Kalinowska, 2010, p. 255).

At its inception, outsourcing services were considered an excellent method of reducing a company's costs. Subsequently, its impact on reducing business risk was also discovered. It was also recognised that outsourcing effectively protected an organisation from adverse economic changes and applied them to leading meaningful activities. When outsourcing became a permanent part of the economic landscape and widely used by organisations, it became a strategic choice for the company to conduct business (Kalinowska, 2010).

Originally, outsourcing was understood as a sourcing strategy manufacturing companies (especially automotive companies) used. It consisted of abandoning the manufacture of all prefabricated components needed for production in favour of sourcing them from other manufacturers. It only covered activities that were ancillary to the company. In later years, outsourcing became commonly used to describe the strategy of delegating support operations of a company's core business to external entities specialised in managing them.

The specificity of logistics outsourcing lies in the outsourcing of logistics-related functions. This is how logistics outsourcing should be defined in a broad sense. In a narrower sense, it will be understood as cooperation, the subject of a contract involving a company's outsourcing of logistics functions. Outsourcing can greatly vary and include only the transport organisation or the entire supply chain management. In turn, supply chain management encompasses the organisation of transport and in-house logistics, including planning material flow systems in production, the supply of raw materials, warehousing, information flow management, and control of these processes. Currently, outsourcing is a modern management strategy that consists of taking certain activities not directly related to the core business of an organisation to an outside company, and outsourcing them to another company so that the company can focus its resources on those areas that constitute the basis of those activities where it achieves a competitive advantage. Outsourcing is identified with activities such as:

- obtaining external generating forces,
- the transfer of part of a given company's activities outside its organisational framework,
- a multi-annual contract between the customer and the supplier of goods and services,
- strategic action is an attempt to find the right company size to adapt to the new environment (Kopczynski, 2010).

In doing so, a clear distinction must be made between outsourcing and subcontracting. We speak of subcontracting when we outsource an activity when we do not have the production capacity to do it ourselves. It is simply the purchase of specific custom-made products, including indications, quantities, and technical details. Outsourcing, however, means letting another entity obtain and take over the results as agreed in the contract. Outsourcing leads to changes in organisational structures and should be seen as a form of company restructuring. In contrast, subcontracting does not involve structural changes to the company (Krawczyk, 2011).

4.3. Types and objectives of outsourcing

Outsourcing is presented in many varieties and divided based on different types and criteria. The basic and, at the same time, most important types of outsourcing are those based on the criterion of the form of subordination: contractual and capital-based. These are very important for the nature, procedures, and functioning of outsourcing.

Contractual outsourcing occurs when we give up carrying out a selected function in the organisation and hand it over to an independent economic entity based on a contract, i.e., an agreement or contract (Kalinowska). Here, a change from organisational subordination and influence to contractual subordination, e.g., dismissal of employees and sale of assets.

In equity outsourcing, a capital-linked daughter company separates functions from the company (Kopczyński). Thanks to this form, elements related to the realisation of functions within the organisation are not liquidated. However, they are transferred to the newly established economic entity, i.e., the parent company, e.g., avoiding redundancies, keeping assets organized, wider control possibilities, and greater price formation freedom.

M. J. Power proposed another division of outsourcing, K. C. Desouza and C. Bonifazi (Power, Desouza, Bonifazi, 2008):

1. Location of outsourcing – inside and outside the organisation.
2. Depth of outsourcing – individual, functional, competence.
3. Type of work – process, project.

A distinction is made between two forms of outsourcing: external (ring-fencing) and internal (unbundling). In ring-fencing, an economically and legally independent external service provider contractually takes over part of the functions from its principal. With this solution, the outsourcing company has little influence over the service. The outsourced function is transferred to a legally independent but capital-linked service provider in a carve-out. This solution transfers the outsourced function to a subsidiary, a directly affiliated company, or a company with a shareholding (Siepermann, 2002). Figure 2 shows the forms of outsourcing in a company.

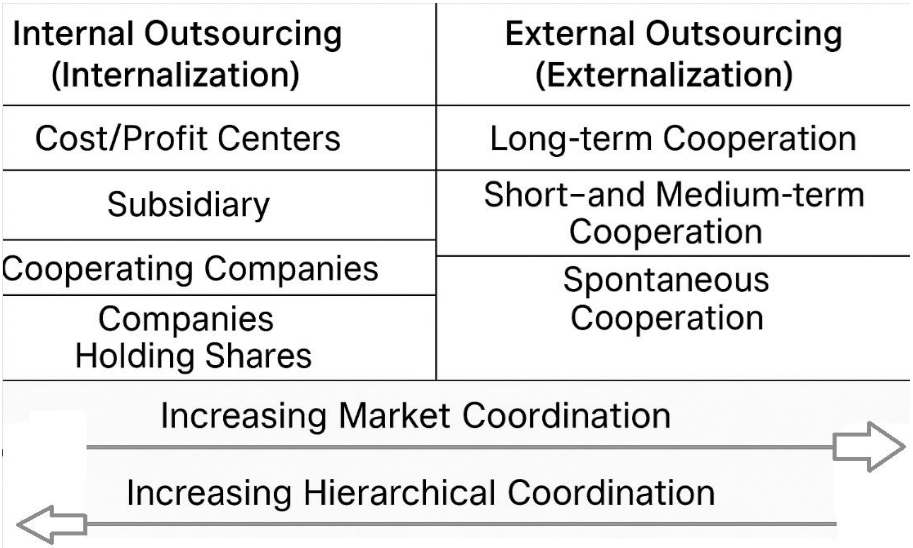

Figure 2. Forms of outsourcing

Source: (Siepermann, 2002, p. 1049)

The primary strategic objective of outsourcing is for the parent organisation to focus on key activities that determine its development. Once a company has achieved its strategic objectives, it can achieve its market objectives more fully, e.g., improving its competitive position, which is expected to lead to better achievement of economic objectives (Lendzion, Srankiewicz-Mróz, 2005). The most frequently distinguished categories of outsourcing objectives are presented in Table 1.

Table 1. Outsourcing objectives

Goal Group	Parent Company Goals
STRATEGIC	• Concentration on strategic issues • Increase in strategic operational freedom • Improvement in effectiveness and efficiency of operations • Increase in operational flexibility • Access to external know-how • Expansion of the scope of strategic influence
MARKET	• Improvement of competitive position in the area of continued operations • Increase in scale of operations by leveraging potential • Focused activities
ECONOMIC	• Cost reduction and improvement of cost structure • Improvement of financial results • Reduction of economic risk
ORGANIZATIONAL	• Reduction of organizational structure • Simplification of structures and procedures
OPERATIONAL	• Reduction of operational issues • Improvement in the quality of operational process execution
MOTIVATIONAL	• Comparison of internal results with those of external entities • Objectification of financial outcomes • Application of economic thinking and action

Source: (Lendzion, Srankiewicz-Mróz, 2005, p. 19).

4.4. Areas of application of outsourcing

Analysing the areas of a company's business (tasks, functions, processes) that can be separated and outsourced is one of the main issues in identifying outsourcing.

Two basic areas of outsourcing application are identified in the literature. "The theorists of the subject emphasise that outsourcing most often concerns either the area of procurement (which is related to the production of goods or the process of providing services) or the area of services performed in a functional arrangement by the departments of a company" (Matejun, 2007).

Outsourcing focuses on the key areas of an organisation's operations, meaning extensive production is abandoned in favour of the most important parts (Zimniewicz, 2003). The second area of outsourcing application usually includes various services, which are carried out in a functional arrangement by the organization's departments.

Developments in the market accurately indicate that, despite the not always top performance of outsourcing, it is still a thriving management concept covering various business areas.

Figure 2 shows the popular areas of outsourcing use in business practice by function, among which information systems and technology, logistics, production, and human resource management are critical.

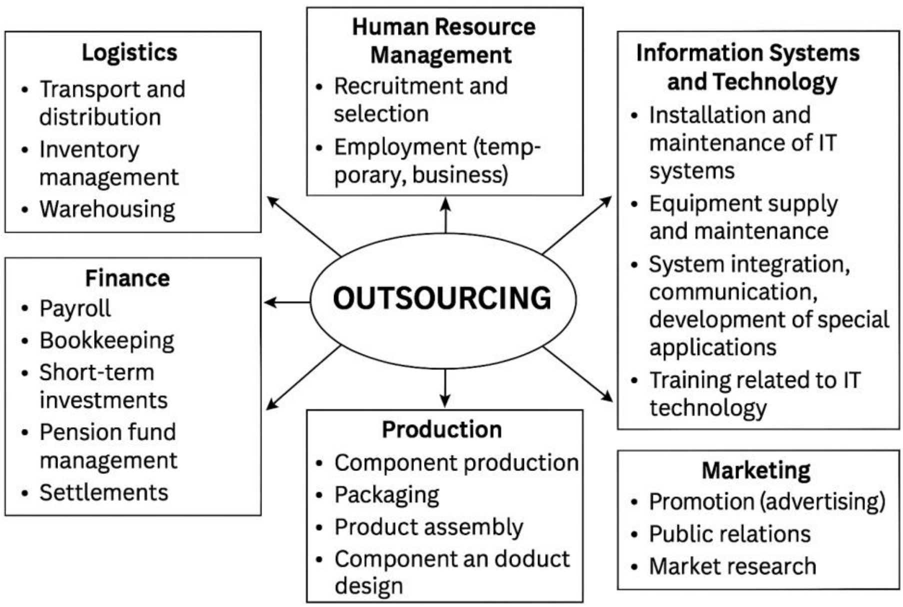

Figure 3. Areas of outsourcing in companies

Source: (Kopczynski, 2010, p. 80).

The figure above shows only some outsourcing solutions in a functional arrangement. The choice of areas to be outsourced and the identification of functions depend on the specifics of the individual company (Ratinski, 2002).

Organisational process outsourcing (BPO – Business Process Outsourcing) is a development of the classic outsourcing concept. It refers to diverse processes unrelated to a company's core business, which are needed for its functioning but do not create a sizeable competitive advantage (Matejun, 2007).

Organisational process outsourcing is seen when a company hands over the management and execution of various business areas to an external partner. Under BPO, the outsourcer assumes responsibility for the implementation of the process. Also, it undertakes a commitment to systematically optimise the process, including implementing new technologies or improving those used to ensure the most beneficial improvements in operations (Kopczynski). The BPO concept is fundamental in IT, accounting and finance, and human resources management.

Logistics tasks, which include supporting processes, are particularly susceptible to being delegated to others, according to the first of the abovementioned premises. Their performance is delegated to service providers and becomes precisely an outsourcing decision in the case of system services.

4.5. Outsourcing management process

In today's economic reality, outsourcing is perceived as a method of organisation and management that boils down to reducing the scope of tasks performed directly by an enterprise and delegating their execution to an external entity. Carrying out outsourcing in an organisation is a complex process; its success depends on various economic, social, and organisational factors. It is essential to determine the effectiveness and efficiency of outsourcing.

When discussing the concept of efficiency in business management, reference should be made to organisational theory, where efficiency is defined as effectiveness, productivity, profitability, effectiveness, efficiency, or rationality (Weinert, 2014). Moreover, it is precisely to ensure improved efficiency and increased effectiveness that outsourcing is implemented in the company. The efficiency and effectiveness of outsourcing as a way of developing an organisation depends on the areas and functions of the company that are spun off, which are of greater or lesser strategic importance.

The general outsourcing process is characterised by the separation of functions and is carried out in organisations in three phases (stages). This division is intended to exclude, relatively quickly, initiatives and spin-off projects that do not offer the possibility of success in the future (Heywood, 2001).

1) **Stage I** – Analysis and assessment of the situation.
   In the "preliminary analysis and evaluation" phase, the applicability of the outsourcing and determine the components (products, services, business areas, processes) that can be outsourced to an external

company (Kopczyński). The most important thing is for the company to determine the goals for which it decides to outsource (e.g., reducing costs and improving the quality of products or services). An analysis prior to outsourcing is carried out by almost 90% of companies.

After this stage, a preliminary decision is made about separation: if a function turns out not to be amenable to separation, it is abandoned, and if there are no objections to the possibility of separating a function, it is moved to the next stage (Piper, 2003).

2) **Stage II** – Identification of needs and selection of suppliers.
This is the research phase. When selecting the most favorable option for the organisation, it is important to consider the conditions that must be fulfilled to cooperate with an external company. The company understands its needs and decides which potential suppliers will best fulfil them. Sound identification of bidders is essential, as outsourcing creates a situation in which the contractor becomes part of the outsourcing company (has an influence on the final form of the products and services).and services) (Patterson, Haas, 1999).

3) **Stage III** – Implementation and management of the outsourcing process.
The final phase is the implementation phase, which involves many changes concerning the organization's structure, the employees, and the communication within the company. During this phase, it is necessary to decide on the form in which the relationship with the business partner is to be maintained, how it is to be managed, and to set up a system that allows to analyse tasks quickly and honestly to help the company's employees adapt to the new performance of their duties, and to monitor and evaluate business performance (Piper).

The logistics service provider is actively involved in creating value for the customer. The logistics services sector is changing and developing per the changing market conditions. The decision on the extent of logistics outsourcing is largely determined by the price level of logistics services, which determines the logistics costs of the enterprise and the prices of manufactured and/or sold products. The result of a company's cooperation with a logistics operator can be the realisation of objectives such as improved quality of customer service, shorter order cycles, improved quality and reliability of delivery, more efficient flow and transparency of information, and better utilisation of assets. Logistics process outsourcing is also linked to areas of the company's strategic logistics activities. Companies entrust logistics operators with creating the logistics system, modelling logistics processes, and creating and implementing the logistics strategy. Treating a logistics service provider as a strategic partner can be important in achieving and maintaining a competitive advantage (Jeszka, 2013).

4.6. Advantages and disadvantages of outsourcing

Outsourcing can increase the company's flexibility and give access to the latest products and processes. The risk of technology obsolescence falls on the shoulders of the outsourcing company. The capital required to produce a product or deliver a service is significantly reduced. It allows the use of expertise without incurring additional costs (Bengtsson, Berggren, 2008). Companies, through outsourcing, can shape a competitive market advantage by using external specialised resources and capabilities (Matejun, 2009). Reducing operating costs improves profitability, which directly affects competitiveness. Using an outsourcing strategy can influence greater price flexibility of supply, and there is the possibility of finding cheaper sources of financing for operations and making new investments that will increase the company's competitiveness (Orlinski, 2013). With this strategy, companies can access specialised knowledge that is unavailable on the market or would have to be paid at a high cost. This is particularly important for high-tech companies, IT, biotechnology, etc.

Research by the Economist Intelligence Unit, conducted in 47 countries around the world, indicates that managers most often cite the benefits of outsourcing (Perechuda, 2000):

1. Lower costs for contracted work.
2. Improving company performance.
3. Clearer specialisation of the company.
4. Access to external skills.
5. Improved quality and efficiency of contracted work.
6. Greater competitiveness.
7. New revenue streams.

It is worth adding to this set of advantages. Outsourcing allows greater control of revenues and costs, better order availability and execution, guarantees greater availability and continuity of order provision, and, as O. E. Williamson has already emphasised, outsourcing allows the "export" of risk and uncertainty. The work "Radical changes in the company," emphasises another significant advantage – the possibility of better allocation of physical, financial, and human resources saved due to outsourcing activities (Kupczyk, 1990).

Outsourcing also has opposing sides. Cost reduction is a benefit of outsourcing, but too much emphasis on cost reduction may put the contractor on the edge of profitability, affecting the service quality. There is a risk of poor selection of an outsourcing company that does not have the right expertise, qualified staff, or practical experience in the projects it offers (Bengtsson, Berggren). There is a risk that companies choosing to outsource may lose important skills and technologies that are part of their core competencies. Therefore, companies exercise control over key project work and operations and try to analyse customer expectations in terms of meeting needs on an ongoing basis, thus counter such risks (Bozarth, Handfield, 2021).

Among the most recent concepts of virtual organisations, one can also find one that defines it as an organisation that has outsourced all its processes and accounts for them using the language of a contract. It seems that such a company can theoretically function, but practically, it thus risks losing its identity and threatening its physical existence. Such dangers are pointed out by J. Pfeffer (Pfeffer, 1998).

The use of logistics outsourcing carries both benefits and risks. The implementation of outsourced logistics services is a complex process in which priority is given to guaranteeing their quality, reducing operating costs (H. Rosic, G. Bauer G., Jammernegg W.(2009)) and allowing the company to be more concerned with the development of its core business (M. Kasperek, J. Szołtysek, 2008). As identified by the American Outsourcing Institute Membership, the top 10 reasons why companies use outsourcing include opportunities (Gay, 2002):

1. Reduce and control operating costs.
2. Increasing the company's focus on its core business.
3. Gain access to the best quality production capacity.
4. Release of own resources for other purposes.
5. Obtaining resources that the company does not have.
6. Accelerate the emergence of the benefits of restructuring.
7. Dealing with a function that is difficult to perform or impossible to control.
8. Capital raising.

9. Risk sharing.
10. Cash inflow.

4.7. Summary

Intense competition is forcing companies to streamline their operations and, at the same time, reduce costs. The answer to market needs is outsourcing, which aims to outsource the execution of complementary functions so that the organisation can focus on its core tasks.

Outsourcing is an important phenomenon that occurs in the management of economic enterprises, aiming to improve the efficiency of an organisation's operations and ensure growth and market success.

The term 'outsourcing' is relatively new, but its services are gaining popularity among Polish entrepreneurs, resulting in the economic development of many business entities. For many years, outsourcing has evolved from a cost-reduction tool to a strategy that influences the strategic management of an organisation (Kopczyński).

Outsourcing can be applied to many different types of relationships between buyers and suppliers, but it is simply one way of carrying out tasks in the final analysis. Outsourcing is a close partnership where mutual trust plays a huge role in corporate secrecy, and the partners establish a special business bond.

Outsourcing is a method that helps organisations achieve first-class efficiencies, increase their chances of outdistancing their competitors, and provide opportunities for productivity gains. “But like the engine in a car, outsourcing puts things into motion, but what matters is who is behind the wheel, where it is going, and why it is going in that direction." The scale of this phenomenon varies, with virtually all large companies and quite a few smaller ones deciding to hand over to external contractors operations that were performed in-house until a few years ago (Nogalski, 2010).

In recent years, companies worldwide have increasingly outsourced various processes to increase their operations' efficiency (R. Gonzalez, J. L. Gasco, J. Llopis, (2015). Efficient and effective logistics processes shape the efficiency of a company. Efficient processes allow the achievement of a predefined objective. Efficient logistics processes result from rational action, enabling the best possible relationship between the effects of the action and the associated resource consumption (T. Engler, (2012).

Logistics outsourcing can be used as a tool to improve the efficiency of a company. Cooperation with a logistics service provider contributes to cost reduction, improved liquidity, increased return on sales, return on assets, and equity, improved turnover ratios, lowered break-even points, and increased enterprise efficiency. In creating the desired efficiency of logistics outsourcing, adaptability is important, as it enables the enterprise to achieve synergies resulting from the cooperation of the enterprise with the logistics service provider and reduces the impact of logistics process disruptions. The close cooperation of enterprises in the supply chain provides the opportunity to increase the efficiency of both the individual enterprises in the chain and the supply chain as a whole.

Outsourcing reduces costs by relinquishing departments not part of a company's core business (e.g., providing certain services or products, accounting activities, waste management, industrial security, etc.) and outsourcing them. This simplifies organisational structures and reduces costs related to wages, infrastructure, depreciation, rent, etc. while incurring acquisition costs for products or services. The profitability of the acquisition costs must be lower than the reduced in-house costs. Usually, the quality of companies specialising in production requiring a high level of competence is better than companies that perform products or services sporadically, treating them as a side business.

More and more organisations operate as virtual organisations, and all their activities (procurement, production, sales, transport, accounting) are outsourced. Virtual organisations only brand and coordinate the work of the network (outsourced workers). However, regardless of the benefits of outsourcing, some departments of the company may be of strategic importance to the company, and these must remain under the organization's control.

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Chapter 5.

THE ROLE OF COMMUNICATIVE COMPETENCE IN THE PROCESS OF MAKING ADMINISTRATIVE DECISIONS IN THE FIELD OF LOGISTICS MANAGEMENT

Nataliia Moshenets

5.1. Introduction

Modern logistics companies are rapidly developing, adapting to the conditions of a globalized market, innovative digital transformation, the development of economic interaction and external challenges in their implementation, including new approaches to the active large-scale implementation of the concept of "Logistics 4.0".

This concept fills the logistics industry with a new meaning, approaches, goals, tasks, technologies, which, among other things, requires an emphasis on “increasing flexibility and cooperation in supply chains” (Camila Patricia Malagon-Suarez, Javier Arturo Orjuela-Castro, 2023) to “reduce response time”, which can be ensured through professional communication, clear interaction in the process of making administrative decisions.

Competition in the logistics services market and the demand for their high level of quality creates the need for continuous improvement of processes, implementation of changes, organization of a clear management approach. Logistics management always requires coordinated, balanced, accurate and fast decision-making, which is impossible without effective communication between manufacturers, suppliers, providers and consumers of logistics services. That is why communicative competence is an important component in the field of logistics management as a chain of close interaction between all participants in the field of logistics management.

For the development of personality, professional skills in the conditions of rapid scientific and technological progress and intensive globalized changes in society, communication skills are a necessary component of career success. It is this approach that will ensure the personal and professional realization of an individual in any field of knowledge, production or service sector (G. S. Degtiareva, L. A. Rudenko, 2010).

Communicative competence is an important component of professional competence, which forms the basis of the activities of service specialists in the logistics industry.

An important aspect in the organization of logistics enterprises is the organization of their activities, management at each stage of production processes, where they are connected by professional communication, building both internal and external communication.

Communication with all employees within the team provides management and organization at each of the processes, communication between them, ensures coordinated activities aimed at fulfilling the assigned functions, tasks, responsibilities by each employee, departments, divisions and the enterprise as a whole. During communication, employees acquire professional knowledge, skills, methods of professional and social activity and experience, which is an important factor in the development of the individual and a specialist. Professional communication, which is based on the formation of communicative competence in young specialists in the logistics service sector, accelerates their professional adaptation in the workplace. The exchange of professional information, advice, and experience from experienced employees helps to avoid mistakes, to perform the functions and responsibilities assigned to them qualitatively, using the acquired general and special professional competencies.

Successful decision-making in logistics and their effective implementation often depends not only on the purely analytical and narrowly professional skills of the manager, but also on the ability to communicate effectively. The communicative competence of the manager directly affects the trust and quality of internal interaction in the team, the level of results of management decisions, the minimization of errors in logistics processes, flexibility and adaptability in crisis, conflict or force-major situations. The use of communicative competence allows at each level of interaction to ensure an understanding of the goal, purpose and method of achieving them in a specific decision, to unite performers around a systemic process and to interact harmoniously in order to achieve the desired result.

The section analyzes the role of communicative competence in the process of making administrative decisions in the field of logistics management. The content, meaning and use of communicative competence skills in the professional activities of a manager are determined; the main approaches that influence managerial decision-making in the logistics industry and the role of communication in this process are characterized; ways of forming communicative competence in managers in the logistics industry are considered.

The first section examines the history and evolution of the concept of "communicative competence"; the structure and components of communicative competence and its role in the context of management; the importance of communicative competence in the logistics environment as a management tool.

The next section reveals the decision-making process in logistics management: tasks, features, levels (operational, tactical, strategic); the stages of information exchange (collection, analysis, decision-making, implementation, evaluation) are analyzed; the role of communications is determined (in eliminating "bottlenecks"; in rapid response to changing situations; in inter-departmental interaction; communicative competence is considered as a prerequisite for effective management decisions in a complex logistics environment.

Furthermore, the market requirements for communicative training of logisticians are analyzed (according to modern standards, competency profiles); the methods of formation are disclosed in detail: in the vocational education system (examples from curricula); in the workplace (trainings, role-playing games, communication simulations); examples of the use of not only digital, technical, but also communicative tools are given: ERP systems, CRM, MS Teams, corporate messengers; the need for systematic and continuous development of communicative competence, the prospects for integrating soft skills into advanced training of logistics managers are substantiated. The section ends with general conclusions and a list of sources used.

5.2. Communicative competence of a manager: content, meaning and use in professional activities

Human life is impossible without society. Communication is one of the most important needs of a human being. The social environment contributes to the exchange, accumulation and transmission of information, knowledge, and experience, which contributes to the development of the individual. The concept of "communication" consists in intensive interaction between people based on the exchange of various types of information. Communication is a fundamental feature of human culture (Psychological Dictionary, 1982).

Communication skills begin to form in the family, as well as in educational institutions at all levels, in the process of performing official duties at the workplace. At each of these stages of communication, corresponding interaction plays an important role, especially when it comes to management activities. It is important for managers of different levels not only to be able to convey information, but also to have oratory skills. Possession of above-mentioned skells, as well as the ability to speak in public, the ability to persuade, to speak, to lead a discussion will make it possible to ensure interaction with subordinates and colleagues. These rhetorical abilities in combination with communication skills will contribute to the effective operation of the organization, the implementation of all production processes both in individual structural units and the enterprise as a whole.

Theoretical and methodological foundations of communication, communicative competence, intercultural communication are widely represented in the works of domestic and foreign scientists (Pometun O., 2004). For example, the foundations of communication theory are laid in the works of foreign scientists G. Armstrong, D. Heims, F. Kotler, D. Amuntz, N. Chomsky, S. Cutlip, T. Harris. The founders and scientists who developed the theories of intercultural communication are K. Berger, F. Brass, W. Wundt, E. Hirsch, G. Hofstede, W. von Humboldt, S. Dahl, W. Leibniz, E. Hall and others.

The concept of "communicative competence" is multidimensional and has an interdisciplinary nature, the development and research of which was carried out on the basis of linguistics, psychology, pedagogy and management sciences. At the beginning of its transformation, this concept was considered as a simple transfer of information, from the point of view of the linguistic aspect and was focused on the knowledge of grammatical structures. The term "communicative competence" was first proposed by the American linguist Dell Hymes in 1966 as an alternative to the concept of "linguistic competence" introduced by Noam Chomsky (Noam Chomsky, 1966). The basics of communication, political and public communication were studied in detail by Bogusława Dobek-Ostrowska (1998) and substantiated modern communication systems.

Investigating communicative competence, Theresa Lillis (2006) described in detail the results of the scientific achievements of these researchers in her work. The concept of communicative competence refers to the ability of an individual to communicate successfully from the point of view of both effectiveness in the context of achieving the goal and expediency in terms of acceptability in relation to the context (Constanze Vorwerg, 2015).

Later, the concept of communicative competence finds its development in pedagogy, where it is considered as an integral part of professional development and professional training of a future specialist in any field. The scientific and theoretical aspects of professional competence are substantiated and generalized using the example of the Ukrainian scientific school (Terlytska A., 2018). From the point of view of training specialists at the higher school level, in order to build interaction between all participants in the educational process, it is proven that communicative competence is an important tool and lever (Iryna Androschuk, 2022), which contributes to a clear productive organization of work and achieving the implementation of curricula, educational programs, and the formation of general and special competencies.

When using interdisciplinary integration, where interactive technologies are used to combine educational components of general professional and special disciplines in the process of training students of higher education institutions, communicative competence will be more effectively formed as a component of professional training of future specialists in the higher education system (Liubov Gavryliak, 2019), including the organization of the educational process in distance learning conditions (Polishchuk, A. V., Duganets, V. I., & Duganets, V. I., 2023).

A number of scientists have focused their attention on the issues of forming communicative competence in their research. In particular, in the formation of communicative competence in the process of continuous professional education of customs service specialists (Pavlenko O., 2005); the role of continuous professional education in the formation of knowledge, skills, and abilities of managers of financial sector companies (Nataliia Moshenets, 2024); the formation of communicative competence in the process of professional training of future translators (Pidruchna Z., 2009); management of internal communications in a commercial enterprise (Anna Rogala, 2011); the role of communications management and employee engagement in stimulating the growth of the organization (Nataliia Moshenets; Anna Strychalska-Rudzewicz, 2024). An important study is the understanding of the organization of the educational process with the features of the formation of communicative competence in applicants with special educational needs during the study of a foreign language for a professional purpose (Zoia Sharlovych, Viktor Fedorchuk, Maryna Voloshchuk, 2024).

The professional and communicative competence of specialists in the tourism sector was described by Pisarevskyi I. M. (2017), and the formation of communicative competence in the process of training future engineers using educational programs in psychological and pedagogical disciplines was analyzed in detail by Tetiana Butenko (2011). She structured, substantiated and proved the cognitive, communicative-activity and evaluative components of communicative competence, and developed her own pedagogical technology and experimentally proved the effectiveness of pedagogical conditions for the formation of communicative competence.

For the formation of communicative competence in students, it is worth noting that the result largely depends on the structure and stages of formation and the level of formation of the communicative competence of the teacher, their professional training, as a component of effective practical pedagogical activity (Nadiia Ashytok, 2015).

From the point of view of psychology, communicative competence is considered through the prism of such components as empathy, emotional intelligence, associated with social adaptation, the ability to resolve conflicts and build partnership relationships. Nyzovets O. (2011), studying the communicative competence of future psychologists, considered their professional and communicative development through personal determinants.

Of interest is the study of the formation of communicative competence of future practical psychologists in view of the current circumstances and the need to transition to a distance learning form (Antonina Navrotskaia, 2024). From the point of view of practical psychology, Zabrotskyi M.M. (2009) investigated the communicative competence of a teacher through the ecopsychological dimension. Shevchuk, V., Teslenko, M., & Klevaka, L. (2024) investigated the formation of communicative competence of future psychologists, relying on the analysis and assessment of their psychological characteristics considering value orientations.

In the field of management, communicative competence is considered one of the main skills of a modern leader. One of the determining factors of management is an effective communication system, which directly depends on the communicative competence of a formal or informal leader (Frolenko, 2023).

Communicative skills play an important role in management activities. A manager must possess communicative tools and successfully use them to establish interaction with subordinates and colleagues, motivate them to fulfill the tasks set, plans of the enterprise, institution, organization. The effectiveness of the organization's activities directly depends on the understanding, awareness and implementation of the management decisions made, and the implementation of the mission, in accordance with the strategy, is possible if communication processes are clearly established. (T. M. Burmaka, K. O. Velikikh, 2019).

Let us describe only some of the key components of communicative competence that we find in the research of various scientists:

- speech – “the ability to apply knowledge of the language in practice, to use language units” (Dictionary-reference book on Ukrainian linguodidactics, 2003); the ability to speak and the ability to build communicative interaction are different concepts, and therefore the highest level of speech communication is formed communicative abilities and skills (Oksana Grydzhuk, 2016);
- strategic – the use of means (strategies) with the help of which the set goals can be achieved in the process of communication, for example, verbal, non-verbal (M. Canale, M. Swain, 1980), according to Ukrainian scientists, strategic competence is a component of foreign language communicative competence (Nataliya Mukan, Tetyana Horokhivska, Oleksandr Ievlev, Nataliya Chubinska, Vasyl Kobryn, 2023);
- social – a person's ability to be a full-fledged part of society, to build relationships with other people, satisfying their own needs and goals in accordance with expectations, but within the framework of socially acceptable behavior. (Marina Doktorovych, 2009; Oksana Kovaleva, 2014);
- emotional – manifested through emotional “sensitivity and ability to understand the emotional state of another person” in the process of communication (Vira Averchenko, 2025);
- intercultural, which indicates “the ability to communicate effectively in different cultural contexts, which has numerous components, including motivation, knowledge of oneself and others, tolerance of the unknown, etc.” (Svitlana Kostyuk, 2020; Vasylenko O., 2022);
- digital communicative competence involves "a combination of acquired digital skills and knowledge, communicative ways of thinking, and other necessary personal qualities that will help not only to finally socialize, but also to carry out one's educational or professional activities using digital technologies" (Olga Luchaninova, Lyudmila Nikolenko (2023).

Assessing the intensive development of scientific and technological progress, the introduction of information and communication technologies, which are constantly being improved, back in the 20th century, scientists and philosophers Daniel Bell, Marshall McLuhan, Alvin Toffler put forward hypotheses and forecasts for updates, innovative changes that will also affect the sphere of communication. That is, the theory of the information society fully confirms the futurological approach to communication, and new technologies, as we see, are already actively influencing changes in the behavior and communication of people, communication ties in society, science, education, the sphere of production and provision of services, which positively affects the economic and social development of countries in the world space.

Each scientist, researcher, has his own vision of the concept of competence, communicative competence, professional communicative competence. Thus, that competence is based on three key components: cognitive, which encompasses knowledge about the essence and structure of communication; emotional, which includes the ability to empathize and adequately respond emotionally; and behavioral, which is implemented through verbal and non-verbal skills of effective interaction, was highlighted in her dissertation research by Olena Nyzovets-Kropta (2011).

Communicative competence is a set of knowledge, skills and abilities that ensure effective communication in various social contexts. It includes the ability to perceive, analyze, adequately interpret and respond to verbal and non-verbal messages (Fedorenko Yu, 2022).

Communicative competence encompasses not only the ability to verbal interaction, but also the ability to listen, analyze the context and adapt one's behavior to the situation. It allows not only to better understand the interlocutor, but also to avoid misunderstandings, resolve conflict situations and find common grounds for compromise. The need to develop and implement training programs aimed at developing communicative competence is extremely relevant (Ihor Kusiak, 2024).

An important issue is the construction of communication ties, because "communication is the basis of the functioning of any institution and permeates all human resource management systems." The authors analyzed communication management technologies used by state authorities in public administration and substantiated the theoretical principles of communicative ties that are built and established in the process of public administration in the interaction of authorities, civil society and other participants in the management process, and also developed recommendations that will contribute to the improvement of communication mechanisms (Gromova O.V., Shevchuk R.I., 2019).

Communicative competence should be considered as an integrative structure that links all these components together into a complex complementary system (Borys Nykytiuk, 2024) and encompasses various elements and components (motivational, cognitive, operational-technological, personal-behavioral), skills and abilities, and reflection.

Thus, generalizing various theories of communication, we come to the conclusion about the multifaceted approaches to understanding the concept of communicative competence, depending on the angle from which we consider this scientific problem. The ways of exploiting communication in everyday life, family, work, and social environment depend on many factors, including the level of development of communicative skills; motivation; knowledge; ability to manage emotions and experiences; strong-willed qualities; level of upbringing and tolerance; ability to own communication tools, etc.

The evolution of the concept of communicative competence demonstrates relevance and interest from various sciences and forms a multifaceted vision from grammatical accuracy, speech competence, socialization, intercultural communication, strategic and professional excellence. The intensification of all spheres of human life expands the influence and emphasizes the importance of possessing communicative competence.

5.3. Features of managerial decision-making in logistics and the role of communication in this process

In the modern world, logistics management is an important component of the functioning of business structures and enterprises. The success of logistics systems largely depends on the effective management of all components of logistics processes, among which one of the key factors is high-quality communication. It is the communicative competence of a manager in the field of logistics that acts as the resource that determines the effectiveness of both internal and external interaction.

Communicative competence is considered an integral characteristic of a person, which includes knowledge, skills, abilities, as well as attitudes that ensure effective interaction in a professional environment. It involves mastering verbal and non-verbal means, knowledge of the norms and rules of business communication, the ability to listen, persuade, and argue one's position, considering the peculiarities of the communicative situation (V. Bezruk, 2019, 2021).

In the field of logistics, communication is the basis of many processes: supply chain management, route optimization, interaction with partners, solving delivery or inventory accounting problems. Therefore, a manager with a high level of communicative competence has a competitive advantage, as they can coordinate the actions of various participants in the logistics process quickly, accurately and without conflict.

Research by A. Polishchuk (2022) indicates that modern management approaches in logistics require specialists not only professional competence, but also communicative maturity, that is, the ability to constructively resolve conflicts, negotiate, persuade, and receive feedback. This is of particular importance in the conditions of multifunctional logistics teams, where the decision-making process is collegial and responsibility is distributed.

Managers with a high level of communicative competence demonstrate better results in organizing logistics processes, especially in conditions of stress, resource shortages, or changes in the external environment. They can create a trusting atmosphere in the team, to communicate management decisions in a timely manner, considering the psychological state of the staff.

On the other hand, Y. Yasenchuk and L. Bondarchuk (2024) emphasize the importance of developing soft skills during the professional training of future logistics managers. They consider communicative competence to be one of the main elements of these skills, which should be formed based on reflection, interactive interaction and adaptation to the conditions of a changing environment in the process of training specialists who will be competitive in the labor market and will build a successful career with well-developed communication skills.

Communicative competence as a management resource covers three key areas: strategic interaction with partners and suppliers, internal team communication and representation of the company's interests before external structures. All these areas require different communication styles, appropriate formal and informal communication formats, as well as the ability to transform information according to the needs of the audience.

Table 1. Types of administrative communication in logistics systems

Type of communication	Scope of application	Example of a situation
Verbal (oral speech)	Daily verbal communication in the team, personnel management, interaction of departments, interaction with customers.	Conducting briefing for employees before starting work; communication during the performance of production tasks.
Nonverbal (wordless, behavioral, gesture-based, etc.)	Introducing yourself and others through behavioral signals in the team using posture, behavior, facial expressions, gestures, looks, tactile, etc.).	Body language during a meeting or conversation; reaction to verbal communication.
Written (exchange of letters, written messages, etc.)	Preparation of documentation (accounting, business trips, invoices, shipping documents, etc.).	Communication with customers, logistics officers, dispatchers, warehouse employees.
Electronic (information exchange by email; via applications (Google meet, MS Teams, Zoom, etc.)	Remote coordination, organization of conferences, meetings, negotiations.	Messages in the CRM system (internal database, software for creating an information environment).

Source: created by the author based on processed scientific and literary sources

Considerable attention in modern research is paid to intercultural communication competence. In a globalized logistics environment, managers are faced with the need to cooperate with foreign suppliers, customs services, and logistics operators who represent different cultural contexts. False and/or unproductive communication caused by ignoring corresponding norms and cultural context can lead to delays, misunderstanding, and even loss of partnership.

Therefore, an important component of communicative competence is cultural sensitivity – the ability to adapt one's communication style to the norms and expectations of representatives of other countries. This requires knowledge of national features of negotiations, decision-making, organization of working hours, as well as social codes of body language.

Effective interpersonal communication contributes to the creation of long-term and reliable relationships in logistics chains. According to A. Polishchuk (2022), it is the establishment of trusting relationships through high-quality communication that reduces transaction costs, increases the stability of cooperation, and allows for a faster response to changes in demand or disruptions in the logistics cycle.

Communicative competence is also the basis for leadership in logistics teams. Managers who have the skills of active listening, empathy, the ability to formulate goals and feedback create a favorable environment for the productive work of staff. This approach corresponds to the concept of service leadership, where the manager acts not as a controller, but as a facilitator of the process (Y. Yasenchuk & L. Bondarchuk, 2024).

Interactive methods of training future logistics managers, in particular role-playing games, case methods, debates, communication training, contribute to the development of relevant competencies. As indicated in the study by Y. Yasenchuk and L. Bondarchuk (2024), such approaches allow not only to master communication techniques, but also to learn to adapt to new conditions, quickly respond to situations, while maintaining efficiency.

In a practical context, this means that a future logistics specialist must be prepared for daily interaction with numerous participants in the process – suppliers, customers, drivers, inspectors, security services, warehouse personnel. His effectiveness depends not only on the ability to organize a route or document, but also on the ability to convince, agree, explain, correct, and analyze.

Thus, communicative competence as a management resource is a strategic element of logistics management. It ensures systematicity, predictability and adaptability of interaction, which in a dynamic market is the key to the competitiveness of the enterprise.

Example of an administrative management situation. The manager of a logistics company coordinates the delivery of medical equipment between Warsaw and Kyiv. During the delivery process, the driver reports a change in customs requirements at the Ukrainian border. The manager promptly contacts the Ukrainian customs broker, reformats the accompanying documents and contacts the customer to update the delivery date. All communication is conducted in a three-way format – by email, phone and messengers. Thanks to clear and professional communication, delays can be avoided, and customer loyalty can be maintained. This example illustrates the importance of prompt, accurate and multi-channel communication in logistics processes.

The scientific substantiation of the role of communicative competence as a management resource is also confirmed by the results of research conducted by domestic and foreign scientists. Thus, V. Bezruk (2019, 2021) indicates that it is important for a manager not only to possess basic communicative skills, but also to demonstrate a high level of emotional intelligence, which enhances the effectiveness of team interaction. In Polish sources (np. Tomasz. Rojek, 2020), special attention is paid to the development of internal communication in logistics structures, in particular in the aspect of knowledge management, organizational culture and digitalization of communication channels. It is indicated that modern logistics requires a transition from a linear hierarchical model to a flexible network interaction, while special attention is paid to the importance of internal communication, as it significantly affects the resolution of operational processes and increases the efficiency of their implementation in the activities of logistics firms, organizations and enterprises.

The formation of communicative competence should be integrated into the vocational training programs of each country with a view to the requirements of the internal education system. However, it is important not only the internal integration of the competency-based component of specialist training, but also its compliance with international programs in accordance with international programs. The educational standards of the European Union expand the possibility of interpersonal and intercultural communication, the formation of soft skills competence includes communicative, which will expand the opportunities of graduates in the international labor market (Strategies of intercultural communication in language education of modern universities, 2017). Employees, including the logistics service sector, must possess communication tools for the active use of simulations, team tasks, facilitation practices and negotiation.

The logistics sector is developing intensively and dynamically, so it is necessary to focus attention not only on the transfer of information, but also on feedback. This improves interaction within the company, strengthens ties between customers, intermediaries and performers, forms the ability of employees to analyze production tasks, make independent decisions, promotes high-quality communication, emphasizes the role of communicative management.

It is worth mentioning separately the problem of information overload. In logistics, a large amount of data can become a barrier to understanding if communication is not structured and purposeful. It is communicative competence that allows logistics managers to identify key messages and convey them clearly to different levels of employees.

In addition, in the context of crisis situations, such as disruptions in logistics chains during the COVID-19 pandemic or the war in Ukraine, the role of anti-crisis communication is growing. Managers must have not only technical knowledge, but also the ability to convey confidence, understanding and a plan of action in difficult conditions (Y. Yasenchuk & L. Bondarchuk, 2024).

Management decisions in the field of logistics are complex actions aimed at optimizing the flows of materials, information and finances in conditions of high dynamics of the external environment. Decision-making in logistics management involves considering many variables: geographical coverage of supplies, availability of transport infrastructure, changes in demand, risks associated with suppliers, as well as internal operational processes of the enterprise. In this context, communication is not only an auxiliary tool, but a key factor in achieving the efficiency and adaptability of the logistics system.

The decision-making process consists of several key stages: problem identification, information collection and analysis, development of alternatives, selection of the optimal option, implementation of the solution and evaluation of its effectiveness. Effective communication is important at each of these stages. It is divided into vertical, which occurs between management levels and affects the effectiveness of management processes, and horizontal, which is built between functional units. However, when there are "information gaps between departments", problem situations may arise that will potentially lead to logistical errors in companies (Danuta Zwolińska 2024). Hence the conclusion that managers of all levels are required to have knowledge, the ability to organize production processes, communicate, motivate, plan, analyze and evaluate the quality of joint production activities.

Strategic decisions in logistics include long-term route planning, selection of warehouses and partners, inventory policy. These decisions are often made at the senior management level and require not only analytical information, but also a deep understanding of the state of internal and external communications. Logistics managers must have interpersonal communication skills and be able to coordinate cross-functional teams in conditions of uncertainty. However, middle managers must be able to convey strategic plans and objectives to employees, justifying the need for their implementation.

At the tactical level, we are talking about operational planning of supplies, warehousing, and shipment schedules. Here, communication is especially important when resolving conflict situations, for example, due to delivery delays or order changes. The presence of clearly established information exchange channels allows you to quickly respond to changing conditions and avoid chain delays in the logistics chain. A significant lever in the formation of communicative interaction in logistics companies is the introduction of innovative (T. Kolodizeva, G. Rudenko, 2013), information and communication technologies (Nataliia Moshenets, 2024). All these processes depend on the modernization of the organizational mechanisms of the structure of logistics enterprises. Competitiveness in the logistics services market requires the development of the organization, including the activities of forwarders, the organization of cargo transportation, and compliance with requirements for the storage of cargo in warehouses to satisfy the logistics services market. The most important thing is to ensure timely deliveries of goods to customers. And it is on this path that logistics companies should adopt innovative approaches in internal and external communications, in building transparent relationships with employees and customers, in compliance with collegial culture, moral principles and ethical norms, rules of conduct for openness in the team, preservation of values and strategy of the logistics company (Volodymyr Polyniak, 2024). It is such approaches that will ensure the successful functioning of logistics companies and the image and prestige of the logistics company in the modern market.

Operational decisions relate to the direct coordination of processes in real time: dispatching, route changes, cargo queue management. Here, the speed, accuracy and clarity of the transmitted information are critically important, as well as communication skills, the presence of communication competence.

Another important aspect is the role of communication in building team decisions. Logistics almost always involves the participation of several departments and external partners. In such conditions, not just the transfer of information is needed, but rather coordinated communication that contributes to the development of a common vision. Investigating the problem of statistical assessment of the national logistics services market, Grinchak N. established that “innovative transformation of logistics forms, opening fundamentally new communication channels and communication systems" contributes to positive changes in the organization of economic activity in the process of providing quality logistics services (Nataliya Grinchak, 2021). That is, the level of communication, communicative competence of logistics industry employees, as one of the components of the process, has a positive effect on effective management decision-making. A significant part of the problems in decision-making in logistics is the lack of efficiency of interdepartmental communication and information barriers in multi-level management processes.

Digital transformation of logistics processes requires clear communication management between departments (Zhuravel V., Muradyan L., 2024). Moreover, overcoming any communication barriers within a logistics enterprise will contribute to the formation of the marketing communications process (Tovkanets G. V., 2006), which will ensure effective interaction between manufacturers, suppliers, intermediaries, consumers, employees of a logistics company, and effective marketing communication will create "an atmosphere of emotional mutual understanding, goodwill and trust between the manufacturer and consumers, society" (Inna Korol, 2018). Marketing communication policy requires the use of communication tools for enterprise management and the use of productive communication channels, which, in turn, will contribute to its integration into the overall management system (L. Shulga, I. Tereshchenko, T. Borovyk, O. Chukhlib, 2021).

In addition, it is important to consider the cultural and organizational characteristics of the communication process. In large logistics structures, employees with different experiences, thinking styles, even from different countries, often work. This requires the use of adaptive communication styles, the development of intercultural competence, as well as the creation of a corporate culture of openness to feedback. The publication Poliszczuk (2022) emphasizes that a modern logistics manager must not only coordinate transport and warehouse operations but also be able to build trust and coordinated communication in the team, build relationship tactics on the principles of collegiality, communicative culture, tolerance, ethics, and mutual understanding.

Digital tools are increasingly used in logistics to support the decision-making process. This includes not only ERP systems, but also integrated collaboration platforms (Microsoft Teams, Slack, Asana), CRM systems, and analytical dashboards. According to the results of the study by Adamczak M., Kolinski A., Trojanowska J., & Husár J. (2023), the trend of digitalization significantly optimizes the operational processes of manufacturing companies, which is also relevant for logistics. Their proper use significantly increases the level of transparency of decisions, reduces response time and allows for a personalized approach to customers, suppliers and partners. Of course, all these processes can be successfully implemented if digitization is used in the training of human resources in the higher education system (Sharlovych Z., Vilchynska L., Danyliuk S., Huba B., Zadilska H., 2023).

Communication in logistics is also a risk management tool. Distributed information about market changes, delays, changes in customs regulations, etc., if transmitted in a timely manner, allows you to adjust actions promptly. Without a clearly structured notification system, even the best strategic plans may not be implemented. Effective interaction largely depends on configured communication channels, clear exchange of operational information and transparency in notifications.

Another aspect that needs to be highlighted is the role of informal communication in the decision-making process. In logistics structures, where daily interactions between employees of different departments are of great importance, it is informal communication that can play an important role in identifying problems, initiating changes or making operational decisions.

It is also worth paying attention to the problem of information overload. In the conditions of digitalization of logistics processes, employees have access to a large amount of information from various sources, including internal reports, CRM data, documents in ERP systems, e-mails and instant messengers. If the information is unstructured or comes without filtering, it makes it difficult to make informed management decisions.

It is worth highlighting the specifics of communication during the implementation of innovations in logistics companies. The introduction of new technologies, changes in processes or strategic priorities require not only technical training of personnel, but also clear communication of goals, expectations and benefits. If employees do not understand the meaning and necessity of changes, the likelihood of their resistance increases significantly. According to the results of the study by Natesan Andiyappillai, Dr.T. Prakash (2019), the implementation of the WMS system (software) significantly increases the efficiency of warehouse operations: inventory control is improved, order fulfillment time is reduced, and errors are mostly avoided. The authors emphasize that the success of the project largely depends on the configured communication between IT departments, management and warehouse personnel.

Concluding the consideration of this subsection, it is worth noting the following: in the complex, dynamic environment of logistics management, communication acts not as an additional tool, but as a critically important factor that ensures the integrity, adaptability and effectiveness of management decisions. The level of communicative competence of participants in the logistics process directly affects the quality of implemented strategies, the effectiveness of cooperation between departments and the company's ability to flexibly respond to market challenges.

In general, effective communication in the field of logistics management is not just about passing orders or responding to problems. It is a constant two-way process of building a common information field, developing trust between employees and partners, and forming a culture of interaction. Without this, even the most modern logistics models remain ineffective. Thus, the communicative competence of a logistics manager becomes not only an operational necessity, but also a component of the company's strategic advantage.

5.4. Formation and development of communicative competence of logistics managers

In the previous section, it was substantiated that the communicative competence of a manager in logistics is a strategic resource that directly affects the effectiveness of management decisions. However, even a high level of basic knowledge and skills in the field of communications does not guarantee success if these skills are not supported by systematic development and adaptation to modern challenges. The dynamic environment of logistics processes, the growth of information volumes, the digitalization of activities and the multiculturalism of teams require the manager to constantly improve his communicative competence. In this context, it is relevant to identify and implement effective tools and methods for developing communicative competence that will ensure the manager's ability to make timely and high-quality decisions.

Communication competence development tools can be divided into three main groups: educational, corporate and digital. Each of these groups has its own characteristics, advantages and areas of application in the process of making managerial decisions in logistics.

Educational tools include advanced training programs, thematic training in business communication, international certification courses (for example, FIATA, CILT), as well as modular programs for managers. They are aimed at forming a comprehensive set of knowledge and skills that can be adapted to the specifics of logistics processes. Systematic completion of such programs has a positive effect on the quality of interaction in the team and helps to increase the efficiency of decision-making due to better coordination of information flows.

Corporate tools include mentoring, coaching, internal seminars and platforms for exchanging experiences between employees. Mentoring ensures the transfer of practical experience from more experienced colleagues to new managers, while coaching focuses on the individual development of leadership and communication skills. The implementation of corporate programs for the development of communication skills reduces the level of conflict in the team and increases staff involvement.

Digital tools involve the use of modern technological platforms, such as CRM, ERP and project management systems, which integrate communication functions. They allow for the rapid transfer of information, coordination of team actions and transparency of all stages of logistical operations. As noted by the European Commission (2022), the implementation of digital solutions in training and work processes reduces the adaptation time of new employees and increases the efficiency of internal communications.

Table 2. Comparison of tools for developing communication competence of managers in logistics

Tool group	Advantages	Possible limitations	Scope of application
Educational	Form systemic knowledge and skills	Requires time and resources	Training and advanced training
Corporate	Promote internal exchange of experience	May depend on the mentor's personal qualities	Internal staff development
Digital	Rapid transfer of information and process control	Requires technical training	Operational management and coordination

Source: compiled by the author based on data synthesis (V. Bezruk, 2019, 2021; A. Polishchuk, 2022; V. Lukanov et al., 2023; European Commission, 2022).

Effective development of communicative competence requires the use of methods that combine theoretical training, practical skills development and feedback in the process of continuous professional development of managers in logistics systems. In logistics management, these methods should consider the dynamism of the operating environment, the multifunctionality of teams and the need to quickly respond to changes.

1. **Case method.** The case method involves the analysis of specific situations from the practice of logistics companies that require management decisions. Participants consider the problem, analyze the circumstances, propose solutions, and justify their choice. This method contributes to the development of critical thinking, argumentation skills, and the ability to adapt communication strategies to different audiences. As noted by Vyacheslav Bezruk (2019, 2021), the use of cases in the training of managers allows for the formation of a systemic vision of processes and the consideration of the interests of all stakeholders.
2. **Role-playing and negotiation simulation.** Role-playing allows you to recreate situations of interaction between managers, customers, suppliers and other parties to the logistics process. They help train the skills of active listening, persuasion and improvisation. Y. Yasenchuk and L. Bondarchuk (2024) note that role-playing significantly increases the participants' confidence in negotiations and contributes to the development of emotional intelligence.
3. **Facilitation method.** Facilitation is a method of organizing group work, when the facilitator helps to achieve agreement between the discussion participants. In logistics, facilitation is effective during strategic sessions on optimizing supply chains or discussing anti-crisis measures. V. Lukanov et al. (2023) emphasize that facilitation ensures the involvement of all participants in the decision-making process and reduces the time for finding consensus.
4. **The 360-degree method.** The 360-degree method involves an assessment of a manager's communication skills by colleagues, subordinates, management, and self-assessment. This allows for a comprehensive understanding of the manager's strengths and weaknesses and the development of an individual development plan. The European Commission (2022) notes that the use of this method in international companies improves internal communication and reduces the number of conflicts.
5. **Trainings.** Communicative competence includes not only the ability to verbally interact, but also the ability to listen, analyze the context and

adapt one's behavior to the situation. It allows not only to better understand the interlocutor, but also to avoid misunderstandings, resolve conflict situations and find common grounds for compromise. The need to develop and implement training programs aimed at developing communicative competence is extremely urgent (Ihor Kusyak, 2024). Trainings are aimed at practical development of practical skills and bringing their level of formation to automatism; the presence of communication helps to transfer the trainer and participants to a specific situation of applying skills, helps to adapt situational tasks in production situations; during the development of skills, there is an impact on the development of critical thinking, the ability of participants to work in a team.

6. **Seminars.** Participation in seminars contributes to the combination of theoretical aspects, their transfer to the practical plane by analyzing situations and discussing them, as well as updating knowledge, their integration into production conditions; exchange of experience. For example, Volodymyr Dzega (2022), in the process of researching the scientific problem of developing organizational competence of local government officials, a seminar "Communication and Motivation of Employees" was developed, the purpose of which was to teach participants to master various communicative technologies: conducting a discussion, organizing and conducting debates, organizing and conducting group and individual discourse, which will ensure the integrity of the interaction of the lecturer, listeners, interpersonal interaction with an understanding of the essence, content and intentions of professional communication.

Table 3. Comparison of methods for developing communicative competence

Method	Advantages	Limitations	Scope of application
Case Method	Development of analytical thinking, argumentation	Requires preparation of materials	Educational and corporate programs
Role Playing	Increased confidence, emotional intelligence	May seem artificial to participants	Training, education
Facilitating	Rapid achievement of agreement	Requires an experienced facilitator	Strategic sessions, planning

360° Method	Comprehensive assessment, objective feedback	Requires certain degree of openness from participants	Personnel assessment, HR-related processes
Trainings	Focused on practical work, communication, development of critical thinking, ability to work in a team	Requires presence and active participation, as well as an experienced trainer.	In the workplace and/or professional education centers
Seminars	Participation in a mixed format, aimed at theoretical assimilation of material and exchange of experience.	Requires an experienced lecturer	In the workplace and/or professional education centers online and offline

Source: formed by the author based on data synthesis (V. Bezruk, 2021; Yu. Yasenchuk & L. Bondarchuk, 2024; V. Lukanov et al., 2023; European Commission, 2022 Ihor Kusyak, 2024, Volodymyr Dzega, 2022).

How does the development of communicative competence affect management decisions? The development of communicative competence is directly related to improving the quality of management decisions in the field of logistics. Effective communication provides a clear understanding of tasks, timely feedback and coordination of actions between all participants in logistics processes. This is especially important in conditions of high dynamics and the need to quickly respond to external and internal challenges.

Situation where a logistics company is faced with a sudden closure of a transport route serves as an example. Thus, a manager with a high level of communicative competence can quickly convey information to drivers, dispatchers and customers, agree on alternative routes and ensure minimal delays in delivery. Professional communication helps maintain the trust of partners.

Otherwise, when excess warehouse stocks are identified, the manager holds a series of short meetings with the purchasing and sales departments, which allows you to quickly agree on a plan to reduce purchases and increase sales. Y. Yasenchuk and L. Bondarchuk (2024) emphasize that timely information and clear formulation of tasks contribute to reducing operating costs.

Clear communication as a tool helps a company retain markets and increase customer loyalty, including the means of modern technologies and digital communications (Materynska O.A., 2024). During crisis situations, such as the COVID-19 pandemic, regular internal briefings and transparent communication with customers helped reduce the level of uncertainty and maintain stability of work and shape the company's image.

To some extent, the success of the activity depends on leadership and communication in the organization, the presence of formed competencies, "related to effective teamwork and communications, mastering the basics of effective leadership, conflict resolution, persuasion and negotiation" (N. Ya. Mykhalytska, M. R. Yatsyk, 2024).

The development of communicative competence is one of the key factors in increasing the effectiveness of management decisions in the field of logistics. The tools and methods described in this section demonstrate high efficiency if they are systematically implemented and adapted to the specific conditions of the company. The combination of educational, corporate and digital tools with the case method, role-playing games, facilitation and 360° assessment create a comprehensive approach that allows managers to develop the ability to make decisions quickly and reasonably, reduce the number of errors and increase the level of satisfaction of customers and partners.

5.5. Conclusions and prospects for further research

The logistics management system is aimed at finding ways to optimize the industry, preserve human resources, reduce costs, decrease information processing time and strengthen supply chains.

There is a growing need for highly qualified personnel who have knowledge and industry standards; technical skills; understand the holistic structure, tasks and strategy of a logistics enterprise; quickly adapt to changes in the competitive conditions of the logistics services market; have soft skills and professional and communicative competencies.

At the same time, employees in the logistics industry are required to have digital skills, because digitalization is firmly embedded in production logistics processes, including autonomous system programs, the use of artificial intelligence programs, the introduction of robotization and the use of robotics in warehouses and other innovative tools. The introduction of modern forms, methods and tools in logistics improves the organization and activities of logistics company teams but requires continuous development of human resources.

Communicative management is a relevant and important component of the organization of enterprise activities in the modern environment for interaction between people in society in production, industry and inter-industry space. The issue of the role of communicative competence in the process of making managerial decisions in the field of logistics management is given attention to by scientists and specialists in the logistics industry. To overcome barriers and improve the interaction of participants in the logistics process, the priority task is the formation of communicative competence of employees in the logistics industry. Each employee must understand the importance of the ability to listen and hear; understand how to convey information in all possible ways; create an atmosphere of trust and mutual understanding; prevent conflicts and resolve complex communication situations; understand the meaning of intrapersonal, interpersonal, collective, inter-collective, industry and inter-industry communication and their impact on the results of joint activities.

That is why the formation of communicative competence should become an educational need for everyone to feel confident in communication, understand the interlocutor, correctly build a professional dialogue, understand communicative logistics situations of the moment, the ability to react to them and correctly and professionally resolve them. Only in an environment of mutual understanding and understanding of the significance of one's role in the logistics industry at one's workplace, awareness of one's own responsibility for the results of joint activities, the ability to build relationships with colleagues, suppliers and customers can one achieve one's own success and create an atmosphere of trust and image of the company.

The material presented in the section does not exhaust the entire issue, but requires analysis and further scientific exploration, accumulation of information, conducting experimental research and processing of materials to present sound proposals. Considering the results of further research will allow logistics companies to provide competitive advantages, flexibly and promptly respond to fluctuations in market demand in logistics, which will increase the efficiency and effectiveness of supply chains and contribute to the achievement of better results for logistics companies in the logistics services market.

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PART III.

LOGISTICS IN THE CONTEXT OF GLOBALISATION AND SUSTAINABLE DEVELOPMENT

Chapter 6.

THE IMPACT OF GLOBALIZATION ON THE DEVELOPMENT OF MARITIME LOGISTICS

Waldemar Kozłowski

6.1. Globalization in logistics processes

Globalization in economic terms can currently be characterized as a dynamic process of economic changes in the world, manifested through: the development of foreign trade, the mobility of capital and investments, the development of international corporations, the development of digital technologies, as well as the creation of global logistics corridors (Sudarshan, 2025). Globalization describes the process in which national and regional economies, societies and cultures have been integrated through a global network of trade, communication, immigration and transport (Ceniga and Sukalova, 2015). According to D. Held and A. McGrew, economic globalization is the process of internationalization of markets, in which the mutual dependence of states, enterprises and consumers on a global scale is growing, leading to the integration of economies and economic flows (Held, McGrew 2003).

The increase in the competitiveness of capital has forced enterprises to reorganize their business processes with particular emphasis on logistics processes in cooperation with external partners (logistics companies). The reorganization of logistics results from changes in economic structures, which in turn influences the formation of global supply chains. Logistics plays a key role in international supply chains today, which, due to the increase in the volume of goods and raw materials in international trade, face challenges related to the permeability and cost-intensity of global logistics channels. World trade driven by the globalization process has significantly increased the demand for transport services. It is estimated that the growth of world GDP has generated a 2-3 times greater increase in the volume of transported containers (Burnewicz, 1998). The interdependence between GDP and maritime transport results largely from the fact that a product manufactured in one country requires not only the delivery of raw materials to that location, but also semi-finished products and parts often manufactured in other countries located on different continents, which may also require the delivery of parts from still other parts of the world, etc. Globalization has enabled the emergence of global supply chains, which require the coordination of TSL services. Referring to global logistics processes, we can distinguish a number of "global" forces that affect their efficiency and effectiveness (Fig. 1).

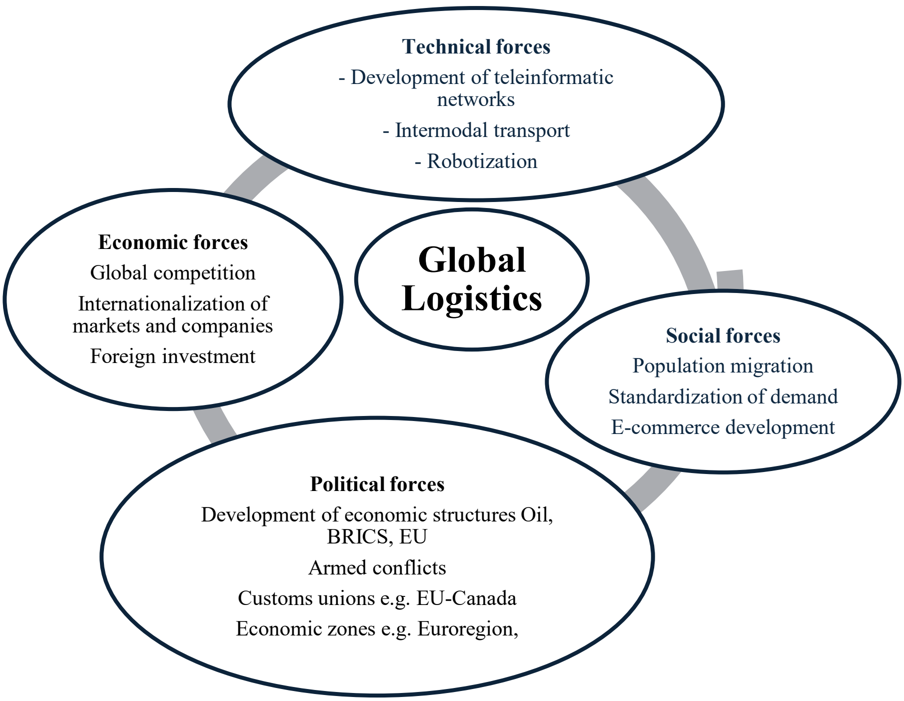

Fig.1. Forces influencing global logistics

Source: own study based on Haggard, 1995, Gołębiewska 2009.

The current global political situation is very dynamic and tense, which is largely due to the current armed conflicts and changes in the trade policy of the world's strongest economy, the USA. The most dangerous from the point of view of future trade relations and thus the development of global logistics are currently the wars between Israel and Iran in the Middle East and

Ukraine and Russia in Europe. The US decisions to raise tariffs on products from most countries around the world have led to the need to modify production strategies and thus supply chains. Political dynamics are high and it is difficult to predict when and how the current conflicts will end, and thus what economic structures will emerge after the dust of war has settled. The main economic forces influencing global logistics include the increase in the competitiveness of individual world economies and thus the transfer of production plants to their territory. A typical example of this is currently South America, which is currently enjoying great interest from manufacturers and service providers. The main premises guiding investors are the availability of cheap labor, pro-investment policies, simple regulations and low costs of obtaining raw materials.

Technological forces are mainly related to the development of artificial intelligence, teleinformatics systems, robotization in production and logistics. The compatibility of teleinformatics systems in the economies of individual countries of the world is largely due to the merger of enterprises into international network organizations that exchange technological and technical innovations. Similar mechanisms apply to TSL logistics companies, where we can observe the consolidation process. The globalization of markets has contributed to the increased interest in partnership as a way to achieve the strategic goals of the company [Witkowski, 2000].

The expansion of the areas of operation of organizations and their presence on global markets implies changes among logistics operators who want to fully meet the needs of customers. Another block of forces influencing global logistics are changes in consumer behavior in terms of expectations regarding both the product and the conditions of its delivery. This is particularly noticeable in the area of e-commerce, where the number of people buying via the Internet is constantly growing. This in turn forces the development of global logistics due to the location of manufacturers and traders. According to data from the Statista Report, global e-commerce turnover in 2021 amounted to $5.2 trillion. Statista predicts that the global e-commerce market will be worth $25.93 trillion in 2023, and by 2030 it will reach $83.26 trillion, which means an average annual growth of 18.9% in the years 2024-2030[1]. There are over 150,000 companies on the Polish market offering access to goods and services through online stores and sales platforms.

[1] Raport Statista https://www.statista.com/statistics/379046/worldwide-retail-e-commerce-sales.

According to estimates, the value of e-commerce in Poland is currently PLN 92 billion and is one of the fastest growing e-commerce markets in Europe. Forecasts show that by 2026 the value of Polish e-commerce will reach PLN 162 billion. The basis of globalization is trade between countries often from different continents. Currently, the main production center is China, which sells its products to different continents. Globalization can be characterized as a direct process, as evidenced by the existence of global international organizations, e.g. the UN, WTO, G7, as well as indirectly through regionalization, e.g. the EU, NAFTA, BRICS. The effects of globalization are, however, different for small and medium-sized enterprises and different for large transnational corporations (Staszczak, 2008).

The process of globalization brings many negative effects, including impoverishment of economically weak countries, may destabilize national economies, migration to developing countries, supports large corporations (Grzybowska, 2013).

6.2. Maritime logistics

Maritime logistics is often understood as a process of planning, organizing, controlling and coordinating the movement of cargo and the flow of information related to ocean transport. In particular, maritime logistics emphasizes the significant role of maritime transport in global logistics and the supply chain and its strategic role within the existing logistics integration system (Notteboom, 2002).

A more general approach to the definition of maritime logistics is presented by J. Kubicki, as the management of the flow of goods together with accompanying information and related services within the land-sea supply chain, with the application of ideas, concepts, methods and tools of logistics to the specialized conditions of this chain (Kubicki, 2006). Maritime logistics is interested in individual functions related to maritime transport as well as efficient logistics flow, as a systematic unit of logistics system integration. The land-sea supply chain creates specific conditions that are crucial for shaping the efficiency and effectiveness of the entire chain.

Maritime logistics consists of various branches of applied logistics, which are linked to operational areas, taking into account the spatial structures of operations, which create specific segments of the land-sea supply chain. The following segments can be distinguished in the operational structure of the land-sea supply chain (Luks, Szwankowski 2001):

- loading port logistics, related to the management of logistics services provided at the loading port,
- maritime transport logistics, related to the management of logistics services provided on a sea vessel and maritime transport,
- discharge port logistics, related to the management of logistics services provided at the discharge port.

The general idea of maritime logistics focuses on all the above-mentioned segments of the maritime supply chain and on the creation of a specific system oriented to the maritime nature of the supply chain (Grzelakowski, Matczak, 2012). The management of the entire land-sea logistics supply chain is concentrated in one institutional solution, which is the logistics operator (Pluciński, 2013).

6.3. Maritime transport

Transport in maritime logistics plays an extremely important role in the global economy, enabling the transport of goods over long distances and connecting markets around the world (Liberadzki, 1998). Thanks to its ability to transport huge amounts of cargo at a relatively low cost, maritime transport has become the foundation of international trade. Every day, thousands of ships cross the oceans, delivering goods to ports on all continents, which affects the lives of billions of people. One of the main advantages of maritime transport is its ability to transport bulk cargo. Bulk ships (bulk carriers), container ships and tankers can transport huge amounts of goods in a single voyage, which significantly reduces the transport costs per unit of cargo. In comparison, air cargo transport is much more expensive and more limited in terms of the amount of goods transported. Sea transport is also more environmentally friendly per ton of cargo transported, making it the preferred option in terms of sustainability. Table 1 shows the tonnage transported globally by sea.

Table 1. World sea freight by main cargo types

WORLD SEABORNE TRADE BY TYPE OF CARGO				
TYPE OF CARGO	2020	2021	2022	2023
TRANSPORT IN MILLION TONES				
TOTAL	**12407**	**11998**	**12388**	**12584**
Liquid bulk	**4285**	**4007**	**4083**	**4254**
of which:				
crude oil and oil products	3457	3204	3264	3376
liquified natural gas	484	490	516	542
Dry bulk	**5368**	**5279**	**5442**	**5546**
of which:				
ore	1455	1505	1525	1475
coal	1300	1181	1226	1229
Grain	481	524	530	516
Containers	1827	1809	1923	1850
General cargo	927	903	940	935

Source: Shipping Statistics Yearbook 2024, Institute of Shipping Economics and Logistics, Brema.

The largest tonnage transported by sea in 2023 is crude oil 3376 million tons, the second largest in terms of goods transported are containers 1827 million tons. Growing dynamics can also be seen in general cargo transport, which is mainly related to the development of e-commerce.

6.4. Seaports

Modern large seaports are spatially extensive, complex in their entity-production, organizational-technical and functional structure economic organisms (Kuźma, 2004). On their territory, various economic activities are usually carried out, including industrial and commercial, which are derived from transport activities, as the basic form of realization of production performed on the territory of these technical transport infrastructure facilities. Ports are integral elements of the transport and logistics system of each coastal country. They play an important role in its economy, actively influencing not only the efficiency and effectiveness of the TSL sector, but also the processes of economic growth and development. However, this impact varies and depends on the size of the port, its nature as a production center and the scale of the activities carried out there. The largest container port in the world in terms of cargo tonnage has been Shanghai for several years, with over 49.1 million TEU handled in 2023. This means an increase of 3.9% compared to the previous year. Also on the podium were Singapore, which handled 39 million TEU (an increase of 4.6%), and Ningbo–Zhoushan, where 35.3 million TEU were handled[2]. Places 4 to 6 are also occupied by Chinese ports, which only swap the order. Last year, Qingdao came in 4th with 30 million TEU and an increase of 16.9%, ahead of Shenzhen, where 29.9 million TEU were transhipped (a decrease of 0.5%), and Guangzhou with a turnover of 25 million TEU and an increase of 1.8% (Table 2).

Table 2. The world's largest ports by TEU cargo volume

No.	Port	Country	Number of TEU 2019	Number of TEU 2022	Number of TEU 2022	Dynamics 2023/2019
1	Shanghai	China	43 303 000	47 303 000	49 158 000	13,5 %
2	Singapore	Singapore	37 195 636	37 289 500	39 012 954	4,9 %
3	Ningbo-Zhoushan	China	27 535 000	33 360 000	35 300 000	28,2 %
4	Qingdao	China	21 010 000	25 660 000	30 000 000	42,8 %
5	Shenzhen	China	25 771 700	30 040 000	29 900 000	16 %
6	Guangzhou	China	23 236 200	24 600 000	25 040 000	7,8 %
7	Busan South	South Korea	21 992 000	22 078 196	23 151 328	5,3 %
8	Tjanjin	China	17 300 700	21 030 000	22 160 000	28,1 %
9	Los Angeles,	USA:	16 969 666	19 044 816	16 648 349	- 1,9 %
10	Dubai	United Arab Emirates	14 111 000	13 971 000	14 473 000	2,6 %
..13.	Rotterdam	Netherlands	14 810 000	14 456 000	13 446 709	- 9,2 %

Source: Based on Actia Forum 2024 data from ports.

[2] UNCTAD, https://hbs.unctad.org/merchant-fleet/ (accessed: 01.06.2025).

The top seaports in the world have remained unchanged for a dozen or so years, apart from minor changes in the ranking. Chinese ports dominate, which results from China's dominant role as a producer. The leader among world ports is Shanghai with constant growth. The biggest jump was recorded by Dubai/Jebel Ali, which entered the TOP10 from 12th place. In 2023, over 14.4 million TEU were transhipped in these ports, which is 3.6% more than a year earlier. The TOP10 also included: Busan (23.1 million TEU, an increase of 4.9%), Tianjin (22.1 million TEU, an increase of 5.4%) and Los Angeles (16.6 million TEU, a decrease of 1.9%) compared to 2022. The highest ranked European port is traditionally Rotterdam, which currently ranks 13th in cargo transhipment. In 2023, 13.4 million TEU were transhipped there, which is 9.2% less than in 2019.

In 2024, Baltic seaports recorded an increase in container transhipment by over 8%, reaching a total of 10.75 million TEU. This means an increase of over 800 thousand TEU compared to the previous year. Despite this, this result remains lower than in the years before the pandemic and the conflict in Ukraine. Polish ports also recorded significant increases.

Table 3. The largest Polish ports in terms of the amount of TEU cargo.

Lp.	Port	Number of TEU 2020	Number of TEU 2019/2024	Dynamics 2023/2019
1	Gdańsk	1 923 785	2 248 723	16,9 %
2	Gdynia	905 121	946 769	4,6 %
3	Szczecin/Świnoujście	86 816	75 292	-13,3 %

Source: Based on Actia Forum 2024 – data from ports.

The leader among Polish ports is the Gdańsk Baltic Hub terminal, which handled 2,248,723 TEU in 2024, which proves its growing importance in the region. The increase in transshipment in the Baltic Sea indicates economic recovery in the region and adaptation to new trade routes, especially in the context of geopolitical changes. However, global challenges, such as port congestion and armed conflicts, affect the dynamics of maritime transport. For example, the attacks of the Houthi rebels in the Red Sea region in 2024 resulted in an increase in freight rates and the need to change shipping routes, which affected global supply chains. The situation is similar with the conflict between Israel and Iran, which threatens the sea route through the Strait of Hormuz, through which 20% of the world's total demand for crude oil flows.

6.5. Importance of Maritime Logistics in the Global Economy

Maritime logistics play a major role in the functioning of the global economy, enabling the transport of large volumes of goods over long distances at a relatively low cost. Today, around 90% of global trade is carried by sea, which shows how important ships and ports are to international trade. Maritime transport can transport a wide range of goods, from raw materials such as oil, coal and metal ores, to finished industrial products and consumer goods.

One of the main advantages of maritime transport is its ability to transport bulk cargo. Bulk carriers, container ships and tankers can transport large volumes of goods in a single voyage, significantly reducing the cost of transport per unit of cargo. In comparison, air cargo transport is much more expensive and more limited in terms of the amount of goods transported. Maritime transport is also more environmentally friendly per tonne of cargo transported, making it the preferred option in terms of sustainability.

The global maritime logistics market is witnessing several key trends and challenges, including:

- Decreased demand for transport and port services in Europe – European imports of mainly finished products are at a relatively low level, mainly due to high production costs (energy, green deal, political uncertainty).
- Increased occupancy of ports in Asia, mainly in China, resulting in longer waiting times for clearance in ports and affecting the overall fluidity of global supply chains.
- Congestion on the main maritime corridors, i.e. the Suez Canal and the Panama Canal, resulting mainly from the increase in the number of ships passing through these canals, and the turmoil related to the armed conflicts of neighboring countries around these isthmuses, e.g. Houthi rebel attacks in the Red Sea.
- Growing geopolitical tensions related to armed conflicts in Eastern Europe, in the South China Sea region and in the Middle East, which affect the instability of global trade routes.

– Search for new alternative sea routes, e.g. the northern route through the Arctic Sea.

The constantly growing increase in the value of cargo transported by sea forces shipowners to change their strategies, including new alliances and the development of a low-emission fleet, rerouting routes due to threats and infrastructure problems. Further development of global maritime logistics will depend on adaptation to new challenges and effective implementation of technologies that reduce emissions and increase operational efficiency. The increase in the amount of transported raw materials and finished goods carries with it increased threats to ports, including in terms of transshipment capacity, terrorist attacks or cyber hackers, which poses a serious challenge to port security. Forecasts for the next years 2025-2030 predict continued growth in international trade, especially in the Asia-Pacific region. Apart from China and South Korea, the countries recording an increase in exports include Japan, Singapore, Vietnam, Bangladesh, the Philippines, and Thailand. The US customs policy will be of great importance for maritime logistics, which may affect the formation of new global supply chains and port operations. In the face of these challenges, carriers will have to flexibly adapt to changing market conditions in order to maintain profitability in the coming years. The implementation of logistics solutions in maritime logistics is subject to constant improvement, which is related to the dynamically developing economic structure of the world.

Currently, we are dealing with a high dynamics of economic changes in the world, through: the development of digital technologies, customer orientation of enterprises, internationalization of trade, automation of production, reduction of production costs, etc. Along with the business challenges of enterprises, especially in the area of customer service and satisfaction, logistics, which is currently global in nature, is also taking on a new dimension. Logistics today plays a key role in international supply chains, which, due to the increase in the volume of goods and raw materials in international trade, face challenges related to the permeability and cost-intensity of global logistics channels.

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Chapter 7.

ROLE OF ECOLOGICAL OPTIMIZATION OF INFRASTRUCTURE OBJECTS OF THE ROAD NETWORK IN LOGISTICS UNDER THE CONDITIONS OF SUSTAINABLE DEVELOPMENT

Lesia Sheludchenko
Yuriy Firman

7.1. Introduction

Ukraine's integration into the global economic system creates opportunities for the development of logistics services between Ukraine and various European countries, where the transport system plays a crucial role. Accordingly, Ukraine's transport links must meet international standards, with a primary focus on ensuring a high level of transport infrastructure safety and overall sustainability (Wornalkiewicz, 2021). To achieve this, it is essential to clearly identify potential hazardous situations, analyze their causes, assess possible consequences, and develop effective strategies to support the stable development of the transport system in the context of sustainable development. Thus, the key directions for ensuring transport safety in logistics within the framework of sustainable societal development include:

- creating safe conditions for logistics services;
- maintaining the reliable functioning of road infrastructure and traffic flows;
- ensuring economic and environmental safety.

It is important to note that the transportation system is a complex structure composed of numerous interconnected elements. As a result, achieving a state of “absolute safety” is relative, as it is nearly impossible to eliminate all potential risks. Therefore, a combination of managerial and engineering measures is essential to mitigate negative consequences. This includes the development and implementation of organizational, engineering, and technical solutions, such as the environmental optimization of infrastructure of the road network. Enhancing the transport model will not only improve the efficiency of logistics services but also ensure environmental safety, which is a crucial component of Ukraine's national safety.

6.2. Analysis of the normative-legal basis in forming an eco-friendly transport system.

Formation of an eco-friendly transport system in Ukraine is regulated by a number of laws, subordinate acts and international agreements that set environmental requirements for transport, infrastructure and transportation. In particular, the main legislative acts of Ukraine include:

- Law of Ukraine "Upon transport" (1995, No. 232/94-VR)[1] that defines general principles of functioning of the transport system, and in particular the legal, economic, organizational and social principles of the transport industry, including environmental safety requirements;
- Law of Ukraine "Upon automobile transport" (2001, No. 2344-III)[2], regulating road transport, contains provisions on environmental requirements for vehicles;
- Law of Ukraine "Upon environmental protection"[3] (1991, No. 1264-XII) that establishes legal principles of environmental regulation in the field of transport, including control over harmful emissions and noise levels;
- Law of Ukraine "Upon alternative fuels" (2000, No. 1391-XIV)[4] that contributes to the development of eco-friendly modes of transport;

Besides, among normative legal acts, the following should be worth noting:

- The National Transport Strategy of Ukraine for the period up to 2030[5] contains measures for development of environmentally safe transport, modernization of infrastructure, and introduction of "green" technologies;

[1] https://www.pz.gov.ua/nhtml/transport.pdf
[2] https://zakon.rada.gov.ua/laws/show/2344-14#Text
[3] https://zakon.rada.gov.ua/laws/show/1264-12#Text
[4] https://zakon.rada.gov.ua/laws/show/1391-14#Text
[5] https://zakon.rada.gov.ua/laws/show/430-2018-%D1%80#Text

- State Construction Standards (DBN V.2.3-4: 2015) "Roads"[6] regulate the requirements for road design with regard to environmental standards and minimization of negative impact of transport upon the environment;
- Resolution of the Cabinet of Ministers of Ukraine "Upon approval of the plan for reduction of atmospheric air pollution" provides for transition to environmentally friendly transport, introduction of electric vehicles and decrease in the use of diesel fuel.

It is worth noting that the legal framework of Ukraine is being gradually adapted to the European environmental standards, and being constantly improved.

Attention should be also paid to the Directive 2008/96/EC[7] of the European Parliament and Council "Upon road infrastructure safety management". The main focus of this Directive is aimed at road safety issues, not at environmental protection. Therefore, there are no provisions that regulate environmental issues in this Directive, but the organization of safe and effective road infrastructure will also have a positive environmental effect.

Regulation of environmental issues is reflected in other EU directives, and in particular in the 2011/92/EU Directive "Upon environmental impact assessment" (EIA Directive). Table 1 shows the basic terms and their interpretations, as they emphasize the importance of a comprehensive approach to the management of road infrastructure safety, which is offered by the Directive.

Table 1. Terms and definitions of the 2008/96/EU Directive

Term	Definition
Assessment of impact on road safety	A strategic comparative analysis of the impact of a new road or a substantial modification of the available transport network on safe operation of the entire road system;
Road safety audit	Independent, systematic and technical testing of safety of the project design characteristics, at all stages from planning to the beginning of operation;
Safety rating	Classification of sections of the existing road network by categories, depending on their objectively defined structural safety;

[6] https://e-construction.gov.ua/laws_detail/3074920736381470676?doc_type=2
[7] https://zakon.rada.gov.ua/laws/show/984_030-08#Text

Targeted inspection of road safety	Purposeful studies of roads to identify hazardous areas that may increase the number of road accidents and potential injuries;
Periodic inspection of road safety	Periodic check of characteristics of those roads that require ongoing repair for safety purposes;
Infrastructure project	The project of constructing a new road infrastructure or significantly modifying an existing transport network, which affects transport flows.

7.3. Functional features of a traffic flow

Technical characteristics of the motor roads of Ukraine is determined in accordance with the State Construction Standards of Ukraine (DBN V.2.3-4-2000) and includes different categories of roads which differ in intensity of movement, calculated speed, number of lanes, width of lanes and other parameters.

Classification of roads by categories from I-a to V takes into account their traffic capacity and design features.

Basic technical parameters of motor roads in accordance with the State Construction Standards of Ukraine (DBN V.2.3-4-2000):

1) Road categories:
   - Categories I-a and I-b: Roads with high traffic intensity (over 7000 cars per day), with the speed of up to 150 km/h, with 4-8 traffic lanes and the width of the lanes being 3.75 m. Such roads have dividing strips 5-6 m wide.
   - Category II: Traffic intensity: 3000-7000 vehicles/day, estimated speed: 120 km/h, with 2 traffic lanes.
   - Category III: Traffic intensity: 1000-3000 vehicles/day, estimated speed: 100 km/h, with 2 traffic lanes.
   - Category IV: Traffic intensity: 200-1000 vehicles/day, estimated speed: 80 km/h, with 2 traffic lanes.
   - Category V: Traffic intensity: less than 200 vehicles/day, estimated speed: 60 km/h, with 1 traffic lane.
2) The width of the roadbed varies from 28.5 m (for roads of Category I – a) to 6 m (for roads of Category V). The turning radius of turns and permissible longitudinal slope also vary depending on the category, affecting the traffic safety.

The distribution of roads by categories is as follows in Ukraine:

- Roads of Categories I-a and I-b make up only 1% of the total traffic network.
- Roads of Category II make up 8%, Category III – 18%, Category IV – 65%, and Category V – 8%.

However, despite the compliance of technical solutions, the public roads do not fully provide safe and comfortable traffic conditions for road users, which is a big problem in Ukraine (Колодяжний, 2023).

This indicator plays an important role in logistics and affects the speed, safety and cost of transportation. Development of high-quality road infrastructure allows you to optimize logistics chains, reduce transportation costs and improve environmental indicators, which is important for the sustainable development of the Ukrainian economy (Безуглий, 2017). Therefore, an important step is to study the formation of transport flows that serve as the basis for logistics processes. Technical characteristics of roads determine the traffic density, capacity, speed of transportation and overall efficiency of the transport network (Кононов, 2021).

The traffic flow is a set of vehicles participating in joint movement along a certain section of a motor road and is characterized by such physical features as: clearance, dynamic clearance, traffic interval, oppositely directed subsets of vehicles, etc. The movement of a vehicle as part of vehicles will be significantly different from a single vehicle, which causes a change in load-speed modes of operation of engines, and therefore, in indicators of fuel consumption and emissions of harmful substances. The main factors causing the impact of motor vehicles on the environment are as follows: types and structures of motor vehicles in the flow, speed, loading regime, intensity and density of traffic, technical condition and operational properties of individual physical units of the flow, and chemical composition of fuel.

In addition to the technical factors of the traffic flow, a determining factor of migration processes of pollutants within the natural-technogenic geo-ecosystem is the characteristics of the motor transport network. These should include the following: indicator of the motor transport capacity of the territory of the natural-technogenic geo-ecosystem, landscape features of the layout and structural parameters of the motor road, technical condition and operational indicators, compliance with the level of intensity of traffic flow. Besides, variability of the established functional condition of the traffic flow is also observed in the sections of a motor road with special traffic conditions.

These include crossroads and junctions of the transport system, descents and rises, serpentine roads, tunnels, bridge crossings, wildlife crossings (Шелудченко, 2018) etc.

Let's consider a fragment of a traffic flow as a directed set of vehicles on a road (along the axis *x-x*), subsets (C_1 and C_2) that move in opposite directions (Fig. 1). At the same time, we believe that the contribution of subsets C_1 and C_2 is equal to the number of them in length, which fall on the area of A_x-B_x of the road. Let's denote this number through R (t, x_{A-B}).

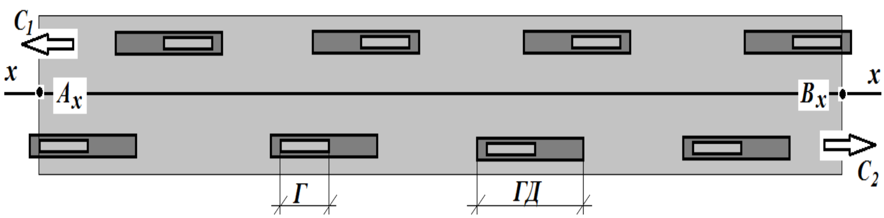


Fig. 1. Fragment of a traffic flow, the subsets (C_1 i C_2) of which move along x-x

Since each vehicle from $R(t, x_{A-B})$ is defined by a set of real numbers on a given interval, then the function $R(t, x_{A-B})$ is continuous by *t*, is smooth, and therefore has piecewise-continuous derivatives of the first and second orders. Thus, $R(t, x_{A-B})$ is a piecewise-linear by *t* (subject to a steady speed of the traffic flow). In this case:

– Traffic flow intensity:

$$\frac{\partial R}{\partial t} = q(t, x) \tag{1}$$

– Traffic flow density:

$$\frac{\partial R}{\partial x} = \rho(t, x) \tag{2}$$

In this case, the speed of the traffic flow is the following function:

$$V(t,x) = \frac{q(t,x)}{\rho(t,x)} \tag{3}$$

If the speed V of the traffic flow is a known function of its density ρ, then we get:

$$V = f(\rho) \tag{4}$$

We will consider the expression (4) to be a function of the condition of the traffic flow. That is why:

$$q(t,x) = \rho(t,x) \cdot f[\rho(t,x)] \tag{5}$$

and also:

$$\frac{\partial R}{\partial t}(t,x) = \frac{\partial R}{\partial x}(t,x) \cdot f[\rho(t,x)] \tag{6}$$

According to (6), we distinguish the following traffic modes:

- free traffic is characterized by the low intensity of vehicles, the absence of mutual obstacles between them and the appropriate speed V_c. The slight density of motor vehicles causes nondense correlation between V_c and ρ;
- collective traffic is determined by the increase in density ρ of the traffic flow, and the collective speed $V_к$ of motor vehicles is determined by the design capacity of the road. The correlation relationship between V_c and ρ is dense enough;
- saturated (synchronized) traffic flow is characterized by a significant interaction of individual vehicles, and the speed of the traffic flow $V_н$ is closely correlated with the intensity q and density ρ.

A characteristic feature of the synchronized traffic flow is a significant variation in the average flow rate. The technical and operational conditions of the motor road become decisive.

For the purpose of further analysis of the collective flow modes we coordinate correspondence of the estimated intensity q of the flow with the technical classification of roads as per DBN V.2.3-4: 2007.

By representing the value of density, intensity and speed of the entire totality of vehicles in the fragment A_x–B_x of the road (Fig. 1) in the basic units of *SI* (meter, second), the function of the traffic flow condition (4) can be represented in the form of matrix. The results are given in Table 2.

If we determine the road category by some point index *K*, which acquires the values of $K = 1a;\ 1б;\ 2;\ 3;\ 4;\ 5$ and considering the piecewise-linear nature of the functions (3) and (4) by the numerical values of the matrix, which are given in Table 2, the response surface can be constructed in the *K*~*ρ*~*q* coordinates (Fig. 2).

Table 2. Functional signs of the condition of traffic flows

Road category	Traffic flow speed, m/s	Flow intensity 1/s	Flow density, 1/m
1-a	41	> 0,17	> 0,005
1-б	38	> 0,17	> 0,004
2	33	0,17	0,005
3	27	0,07	0,003
4	25	0,03	0,001
5	25	0,003	0,0001

The graphic analysis of the rising left-sided trend of the *q* and *ρ* values (Fig. 2) in the direction opposite to the growth of the coordinate *K* clearly determines the coordinates of the characteristic plane *Φ*, which separates the free traffic mode from the collective and synchronized flows. By values *q* and *ρ*, the coordinates of this plane are:

$$\begin{cases} q = 0{,}035\ [{}^{1}/_{\text{с}}] \\ \rho = 0{,}0021\ [{}^{1}/_{\text{м}}] \end{cases} \qquad (7)$$

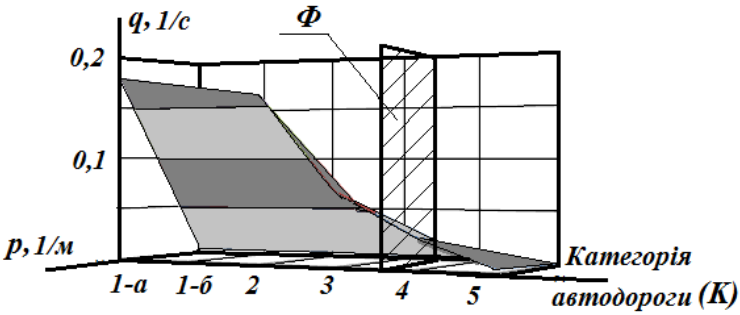


Fig. 2. The response surface of the functional signs of the condition of traffic flows in coordinates: road category (К) ~ traffic flow density (ρ) ~ traffic flow intensity (q)

The values of the intensity q and density ρ of the traffic flow showed in (7) determine the minimum speed V of motor vehicles, at which there occurs shifting from free traffic to collective and synchronized flows, which will be according to (3) as follows:

$$V = \frac{q}{\rho} = \frac{0{,}035}{0{,}002} = 17{,}5\ [{}^{\text{м}}/_{\text{с}}] \qquad (8)$$

The minimum values of V, q and ρ, at which the nature of the movement of vehicles acquires signs of the collective traffic flow with the subsequent synchronization of the traffic flow, are given in Table 3.

Table 3. Minimum values of density ρ, intensity q and speed V, at which the traffic flow acquires characteristic features

Traffic flow intensity, vehicles/24 hours	Traffic flow density, vehicles/km	Traffic flow speed, km/h
3024	2,1	63,0

The analysis of data, by the parameters of intensity q, density ρ and speed V of the traffic flows, as given in Table 3, indicates that only roads of Categories of 1-A, 1-B, 2 and 3 can be classified as the roads with the collective synchronized traffic flow in accordance with DBN V.2.3-4:2007 C.188 “Transport facilities. Motor roads”.

7.4. Ecological and technological optimization of the support frame of the road system

One of the methods of analysis of territorial structures (including communication structures) is the analysis of the support frame. From the point of view of systematic analysis of the territorial communication structure, one of the defining features of this structure is the road network, as a component of transport and communication transit "corridors" of energy and substance exchange within the system, which determine some natural-technogenic geo-ecosystem as a single geodynamic whole. In general, "transport functions" in the natural-technogenic geo-ecosystems are performed both by natural objects: river valleys, watersheds, other elements of landscape, and by artificial structures: road and railway routes of communication, power lines, gas and oil pipelines, other transport mains that form a demographic and economic frame.

The functioning of the demographic and economic frame inevitably leads to a negative transformation of the functioning of the natural frame, which, as a result, disrupts the ecological balance of the entire natural-territorial complex. Therefore, the main task of ecological and technological optimization of the support frame of the road network is to ensure ecological equilibrium (ecological safety) of the territory (**Шелудченко, 2021**).

The structure of the support frame of the transport and communication traffic network of the territory of Ukraine is shown in Fig. 3. In this case, the support frame is a hypergraph $G \coloneqq (V, E)$, for which the conditions are as follows: V is a set of vertices or nodes, E is a set of ribs. The geometric implementation of such a graph is a flat figure consisting of a nonempty finite set V of points (vertices) and a finite set E of un-oriented (oriented) segments of lines (ribs) that connect some pairs of vertices V.

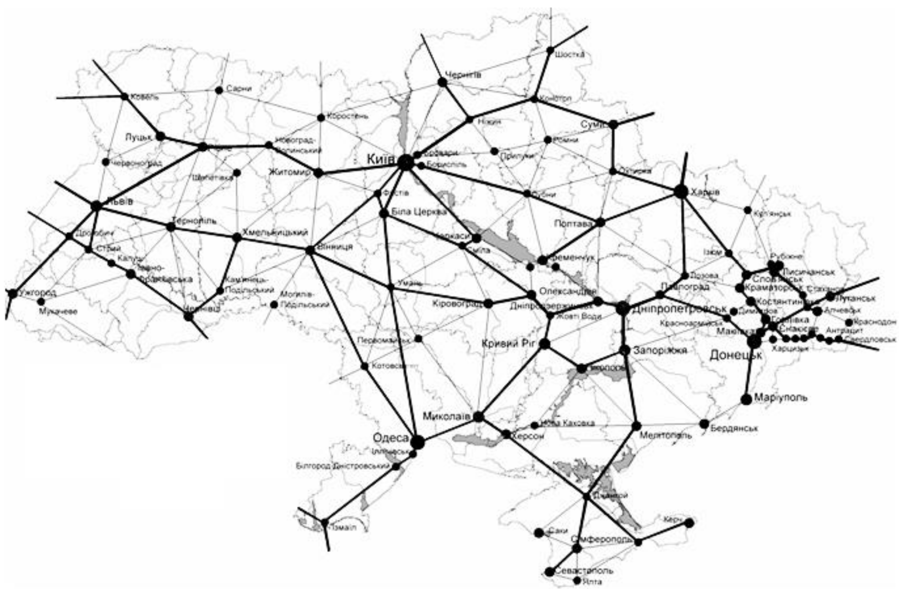


Fig. 3. Graph of the transport and communication support frame of the natural-territorial complex of the territory of Ukraine

Ecological and technological optimization of the support frame of the road network is carried out for the Podilskyi area of Khmelnytskyi region, as for one of the most typical regions of Ukraine in the length of roads.

The main subgraph of the road network of Khmelnytskyi region of the initial graph, as shown in Fig. 3, is a partial graph which contains a certain set of vertices and all the ribs are incident with the set of the initial graph. The distinguished subgraph (the partial graph hereinafter referred to as the graph) of the Khmelnytskyi region road network with the ribs that take into account the motor roads of categories 2 and 3, is shown in Fig. 4 and can be defined as:

$$\begin{cases} V \ni \{A, B, C, D, E, F, G, K, R\} \\ E \ni \{AB, AF, AG, AD, AC, BE, CR, CK, CF, BF, BG\} \end{cases} \quad (9)$$

Within the graph, the functioning of the natural-technogenic geo-eco-system at issue is not clearly distinguished, the regular graph with the *CD* and *DG* cycle that can be generally described as (Fig. 5):

$$\begin{cases} V \ni \{A, B, C, D, F, G\} \\ E \ni \{AB, AF, AC, AD, AG, CF, BF, BG\} \end{cases} \quad (10)$$

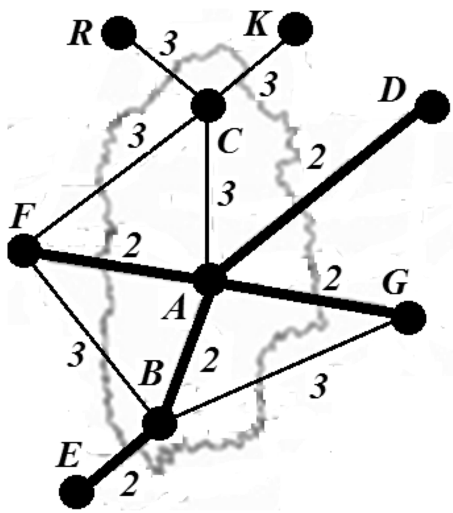


Fig. 4. Graph of the Khmelnytskyi region road network with the ribs indicating categories of motor roads

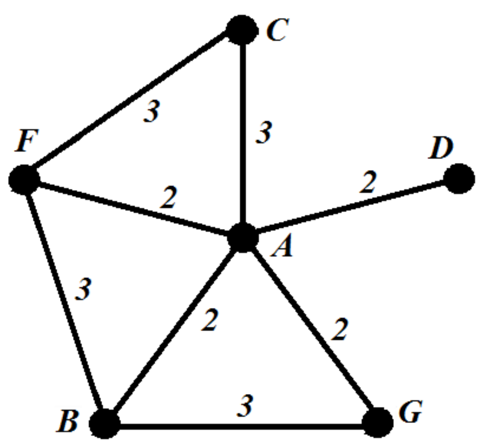


Fig. 5. Partial graph of the Khmelnytskyi region road network

Based on the rule of supplementing graphs, which is that the supplement is implemented above the same set of vertices as in the initial graph, and the vertices are connected with a rib when there is no rib in the initial graph, the initial partial graph (Fig. 5) is supplemented with the rib of the adjacent graph (Fig. 6).

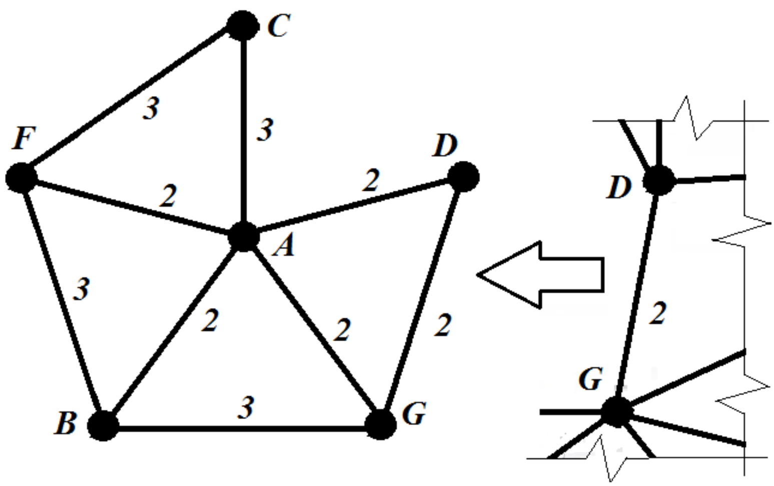


Fig. 6. Supplemented partial graph of the Khmelnytskyi region road network

Partial graph, shown in Gig. 6, is described as:

$$\begin{cases} V \ni \{A, B, C, D, F, G\} \\ E \ni \{AB, AF, AC, AD, AG, CF, BF, BG, DG\} \end{cases} \quad (11)$$

In order to obtain a complete regular partial graph of the road network of the Podilskyi area of Khmelnytsky region, it is necessary to supplement the graph, given in Fig. 6, with the rib *CD*, which in this case should connect vertices *D* (Zhytomyr) and *C* (Shepetivka) in accordance with Fig. 3. For the purpose of implementation of this option, transport and technological rationalization of the Zhytomyr-Denyshi-Dubrivka-Shepetivka route can be suggested.

At the same time, the sections of the specified route Zhytomyr-Denyshi with a length of 21 km are part of the category 2 road H03, and the Dubrivka-Shepetivka road, with a length of 38 km, part of category 3 road P49, and the Denyshi-Dubrivka section, with a length of 77 km, is the district road TO612, TO618 of category 4.

Subject to transport and technological optimization of the Denyshi-Dubrivka route, which will provide for reconstruction of the road TO612, TO618 into category 3, the length of the designed rib (Fig. 6) will be 136 km, which is 41% less than the current route Zhytomyr-Berdychiv-Hrytsiv-Shepetivka with a length of 229 km.

Thus, the ecological and transport rationalization of the motor transport network of the Podilskyi area of Khmelnytskyi region, which provides for the organization of a road network in accordance with the 5-regular partial graph (Fig. 7):

$$\begin{cases} V \ni \{A, B, C, D, F, G\} \\ E \ni \{AB, AF, AC, AD, AG, CF, BF, BG, DG, CD\} \end{cases} \quad (12)$$

allows to increase the overall level of motor transport capacity of the region by 15.2 % (Table 4.3).

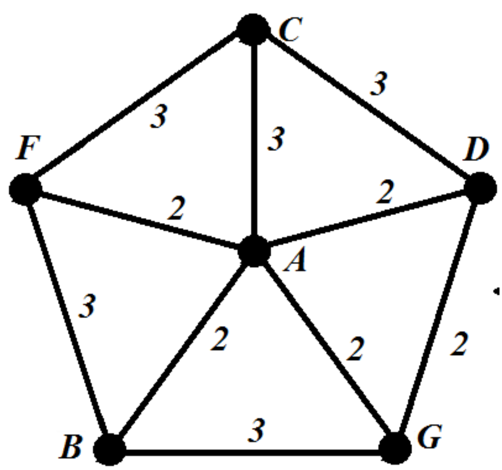


Fig. 7. Regular partial graph of the Khmelnytskyi region road network

The partial graph of the road network of the Podilskyi area of Khmelnytskyi region, shown in Fig. 7, is part of the hypergraph of the transport support frame of the territory of Ukraine.

It can be defined as a cubic graph of minimum weight by the sum of weighted values of the ribs. Therefore, the organization of the motor transport network on the principle of the shown partial graph (Fig. 7) provides a reduction in energy expenditure of traffic flows that move between the set of vertices *V* along the set of ribs *E*. This helps to achieve reduction of total fuel consumption by the motor transport complex and, as a consequence, impact on the environment.

Table 4. Indicators of motor transport capacity of the Podilskyi area of Khmelnytskyi region

Designation of the partial graph ribs	Rib length, km		Generalized intensity of motor transport flows $\times 10^{-6}$	
	Control option	Proposed option	Control option	Proposed option
AB	97	97	1,4	1,4
AF	112	112	1,6	1,6
AC	101	101	0,7	0,7
AD	184	184	2,7	2,7
AG	120	120	1,8	1,8
BF	148	148	0,9	0,9
FC	170	170	1,2	1,2
CD	229	136	3,5	0,9
DG	128	128	1,8	1,8
GB	180	180	1,2	1,2
Σ	1469	1376	16,8	14,2
Increase of the overall level of the motor transport capacity of the natural-technogenic geo-ecosystem, %				15,2

Other variants of organization of the transport and communication frame of the motor transport networks within a certain natural-technogenic geo-ecosystem on the principle of partial graphs in the form of a complete regular planar *n*- lattice, are shown in Fig. 8.

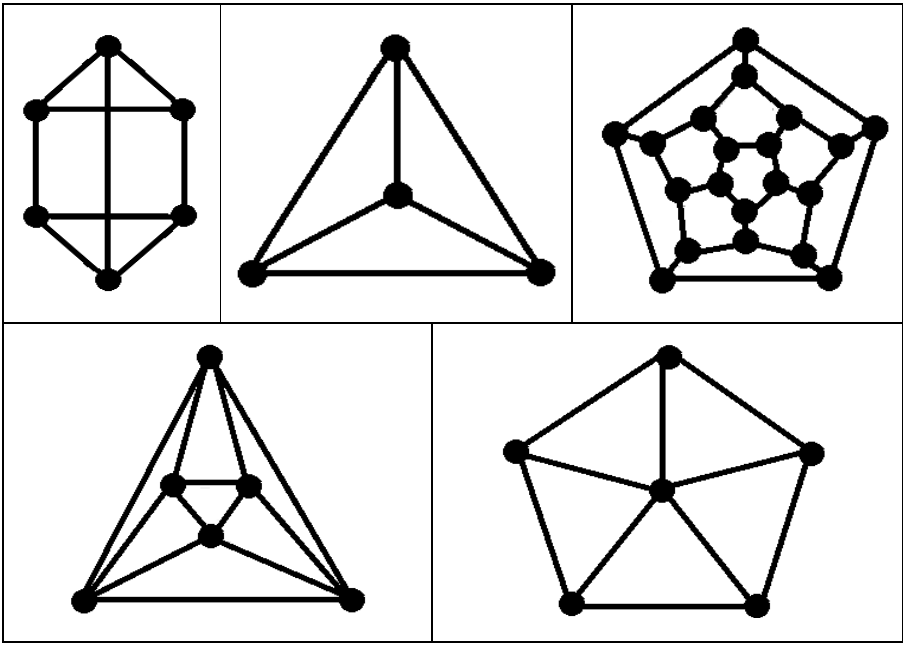


Fig. 8. Variants of organization of the transport and communication frame of the motor transport networks in the form of a complete regular planar n-lattice

The next stage of the ecological and technological optimization of the road network support frame is the rationalization of the “traffic capacity” of the ribs of the graph, that should provide for the synchronization of the collective traffic (Cl. 4.1) as part of motor vehicle flows by an average speed index. For this purpose, let's display the graph shown in Fig. 4 and Fig. 5 in the form of a physically implemented model of the graph, which is a horizontal flat rod-like frame with a hinged connection of the ribs at the nodes of the graph (Fig. 9).

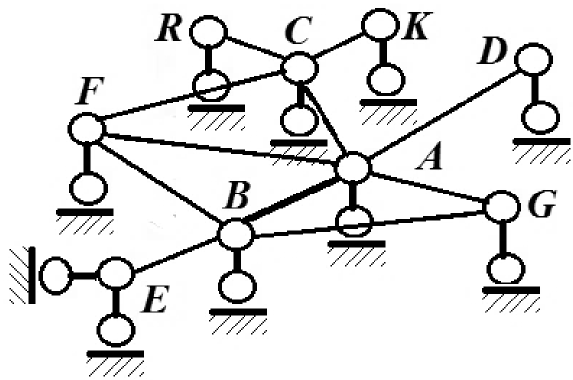


Fig. 9. Model of physical implementation of the motor transport network partial graph

Let's consider the *AB* rib of the graph, which is shown in Fig. 9, as a separate beam that puts pressure on a solid elastic base, the reaction of which at each point of the base may be chosen, with some approximation, as proportional to the elastic deflection of the beam. At that, the external distributed load on the specified beam is imitated by the value of the specific intensity q of the motor transport flow moving along the individual sections of the road that is modeled by the *AB* rib of the partial graph at issue (Fig. 10-a).

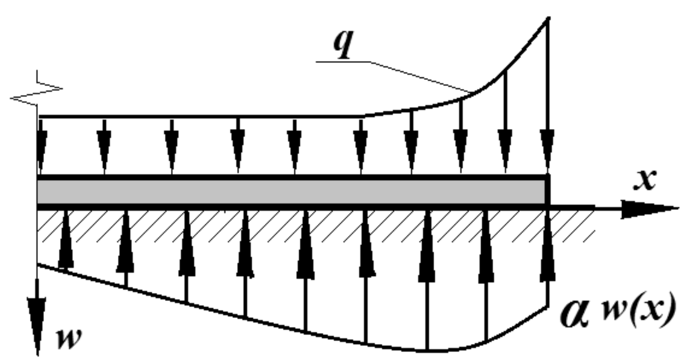


Fig. 10-a. Scheme of the rib fragment of the road network graph with the intensity q of the motor transport flow

The specified statement corresponds to a physical model in which the elastic base can be modeled to consist of an endless amount of unrelated springs and characterized by absolute elasticity (Fig. 10-b).

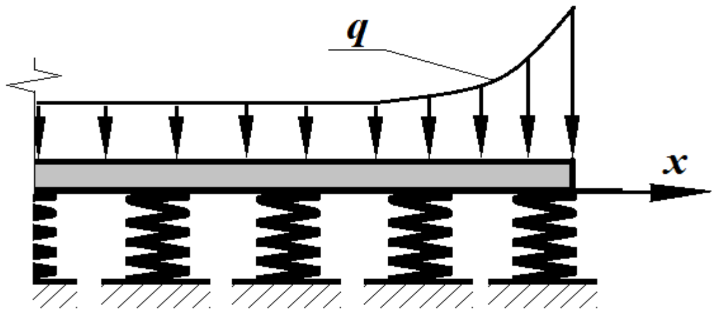


Fig. 10-b. Its corresponding physical model

Let's consider some segment of the graph rub, which is adjacent to its top (Fig. 11). In the general case, the universal equations obtained by the initial parameters for the beam fragment resting on the elastic base, will be as follows:

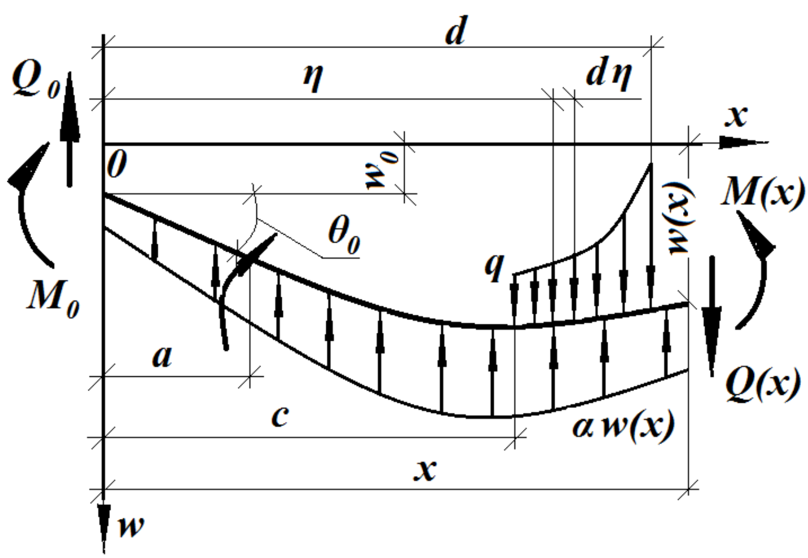


Fig. 11. Design scheme of the graph rib of the motor road network

$$\Theta(x) = \Theta_0 Y_1\left(\frac{x}{L}\right) + \frac{1}{EJ}\Big\{M_0 L Y_2\left(\frac{x}{L}\right) + Q_0 L^2 Y_3\left(\frac{x}{L}\right) +$$

$$+\alpha L^3 w_0 Y_4\left(\frac{x}{L}\right) + L\sum M_i Y_2\left(\frac{x-a_i}{L}\right) - L^2\sum P_i Y_3\left(\frac{x-b_i}{L}\right) - \tag{13}$$

$$-L^3\sum q_i\left[Y_4\left(\frac{x-c_i}{L}\right) - Y_4\left(\frac{x-d_i}{L}\right)\right]\Big\}$$

$$M(x) = M_0 Y_1\left(\frac{x}{L}\right) + Q_0 L Y_2\left(\frac{x}{L}\right) + \alpha L^2 w_0 Y_3\left(\frac{x}{L}\right) +$$

$$+\alpha L^3 \Theta_0 Y_4\left(\frac{x}{L}\right) + \sum M_i Y_1 - L\sum P_i Y_2\left(\frac{x-b_i}{L}\right) + \tag{14}$$

$$L^2\sum q_i\left[Y_3\left(\frac{x-c_i}{L}\right) - Y_3\left(\frac{x-d_i}{L}\right)\right]$$

$$Q(x) = Q_0 Y_1\left(\frac{x}{L}\right) + \alpha L w_0 Y_2\left(\frac{x}{L}\right) + \alpha L^2 \Theta_0 Y_3\left(\frac{x}{L}\right) -$$

$$-\frac{4M_0}{L} Y_4\left(\frac{x}{L}\right) - \frac{4}{L}\sum M_i Y_4\left(\frac{x-a_i}{L}\right) - \sum P_i Y_1\left(\frac{x-b_i}{L}\right) + \tag{15}$$

$$+L\sum q_i\left[Y_2\left(\frac{x-c_i}{L}\right) - Y_2\left(\frac{x-d_i}{L}\right)\right]$$

where,

q – external distributed (dispersed) load that mimics (simulates) the intensity of the motor transport flow;

P – external focused load that is $P = 0$ (Fig. 9) in this case;

$Q(x)$, $M(x)$ – a system reaction to external loads q in the form of internal forces and moments;

Y_1, Y_2, Y_3, Y_4 – Krylov's functions which, in this case, characterize the deformation properties of the system to the external load q in the dimensionless geometric units of the length of the considered section of the graph rib, as x/L;

Θ – a deformation criterion in the form of the turn angle of the virtual elastic line of the graph rib.

From the point of view of further analysis of the "deformation" response of the road section to the external influence in the form of a traffic flow with the intensity q, the most informative is equation (13) which determines the "deformation" measure Θ depending on q.

We determine that in the extreme left crosscut of the graph rib, according to the scheme of the road network fragment which is shown in Fig. 10, the intensity $q = Q$ of the traffic flow is a specified established value and we accordingly consider that the left butt end of the design scheme (Fig. 11) is made in the form of an absolute rigid draft.

In this case, in equation (13) $\Theta_0 = 0$; $M_0 L Y_2\left(\frac{x}{L}\right) = m$; $Q_0 L^2 Y_3\left(\frac{x}{L}\right) = n$; $w_0 = 0$ and in the absence of focused P_i and M_i ($P_i = 0$; $M_i = 0$), in consideratio of the before-mentioned, we obtain:

$$\Theta(x) = \frac{1}{EJ}\left\{am + bn - L^3 \sum q_i \left[Y_4\left(\frac{x - c_i}{L}\right) - Y_4\left(\frac{x - d_i}{L}\right)\right]\right\} \tag{16}$$

If for the analyzed AB rib of the graph (Fig.4.10) the characteristic of the road traffic capacity (road category) is a constant magnitude, i.e. $^1/_{EJ} = const = Z$, then we have:

$$\Theta(x) = Z\left\{K - L^3 q_i \frac{\partial x}{L} Y_4\right\} = Q - q_i L^2 \partial x Y_4 \tag{17}$$

where,

Q – the intensity of the motor transport flow is correspondent to the road category along the rib AB.

According to A.M. Krylov, the function Y_4 is defined as:

$$Y_4(\zeta) = \frac{1}{4}(ch\zeta \cdot sin\zeta - ch\zeta \cdot sin\zeta) = \\ = \frac{1}{8}\left[\left(e^{\zeta} + e^{-\zeta}\right)sin\zeta - \left(e^{\zeta} + e^{-\zeta}\right)cos\zeta\right] \tag{18}$$

where, by definition, ζ:

$$\zeta = \frac{x}{L} = 1 \tag{19}$$

According to the tables, for $\zeta = 1$ $Y_4 = 0{,}1659$ and according to (17) we have:

$$\Theta(x) = Q - 0{,}17 \cdot q_i L^2 \partial x \tag{20}$$

Therefore, maintaining transport and technological equilibrium through synchronizing the collective traffic flows, given that their intensity Δq increases at the approach to the graph nodes (Fig. 9), provides for the condition as follows:

$$\Delta Q = 0{,}17 \cdot \Delta q \cdot L^2 \tag{21}$$

Let's determine the value of the "traffic capacity" of the *AB* rib of the graph (Fig. 4) of the Category 2 road H03 in the segment that borders on the node A (Khmelnytskyi), the model of physical implementation of which is shown in Fig. 9.

The H03 motor road is characterized on the whole by the traffic flow intensity $q \leq 0{,}17 \left[\frac{1}{c}\right]$ and its density $\rho \leq 0{,}005 \left[\frac{1}{м}\right]$.

When approaching the node *A* of the graph (Fig. 12), then from a distance of ~ 35 km (Yarmolyntsi) the intensity of the traffic flow linearly increases up to $q = 0{,}5 \left[\frac{1}{c}\right]$, and its density up to $\rho = 0{,}02 \left[\frac{1}{м}\right]$.

Synchronization of collective movement of motor vehicles in this case can only be ensured through building additional traffic lanes (increase in "traffic capacity" of the *AB* rib of the graph at the approach to the node *A*) (Шелудченко, 2018).

According to (21), landscape-geometric parameters of development (increase in traffic lanes) of the Khmelnytskyi-Kamianets-Podilskyi section of the Category 2 road H03, which is adjacent to Khmelnytskyi, can be set up.

The proposed method of analytical optimization of the intensity of traffic flows, by means of physical simulation of the transport and technological process, allows to optimize the "traffic capacity" of a specific section of a road, to ensure the synchronization of speed of the collective flow within the range of $V = 30\text{-}35$ m/s and the density index of the flow, that moves in one lane, which does not exceed $\rho = 0{,}0025\text{-}0{,}003$ 1/м (Fig. 12).

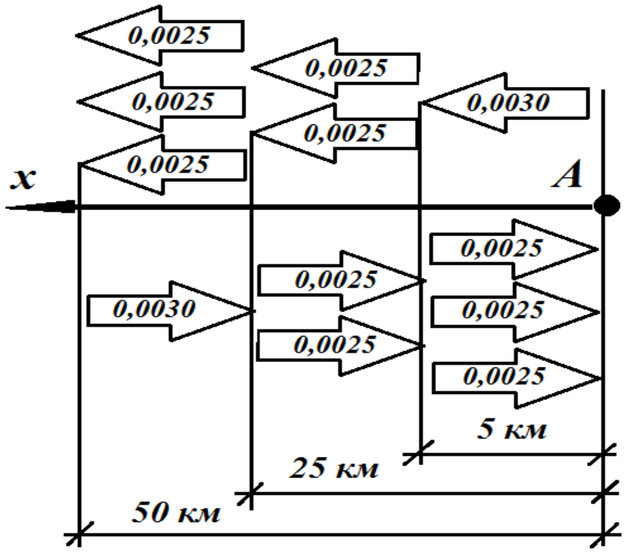


Fig. 12. Synchronization of traffic flows by the flow density in each lane of the road

Synchronization of the collective traffic flows allows to stabilize the modes of operation of engines, which causes a decrease in the volume of gas-dust emissions produced by vehicles.

7.5. Ecological optimization of the dynamics of traffic flows in the sections of motor roads with special traffic movement conditions

All road segments where there occurs scattering of the collective traffic within the traffic flow, should be qualified as specific sections of motor roads with special traffic conditions. In particular, these are primarily the nodes of a motor transport network, where several traffic flows intersect.

The nature of the collective traffic is generally determined by its (the flow) speed $V(t,x)$, which is accordingly a function of the intensity $q(t,x)$ and density $\rho(t,x)$ of the traffic flow. In the case of approaching the road network node, the likelihood of maneuvers by individual vehicles increases, which should be regarded as random events. Correspondingly, there occurs scattering of the collective flow, and thus, the dispersion index σ_V^2 of the flow speed $V(t,x)$ goes up.

The most noticeable is the scattering of the collective traffic at intersections of two (or more) motor transport flows that are commensurate by their intensity $q(t,x)$ and density $\rho(t,x)$.

In this case, it is necessary to distinguish as follows:

– $V(t,x)$ – Synchronized spatial flow velocity, that is, the average speed of vehicles that are on a given section of the road at a certain point in time *t*;

– V_D – Average instant velocity of a motor vehicle, that is, the average speed n of motor vehicles that move through a certain cross-section of the road (in this case through the intersection point) in a specified amount of time *t*.

At that:

$$V(t,x) = V_D\left[1 + \left(\frac{\sigma_D^2}{V_D}\right)\right] \tag{22}$$

It comes out of (22) that in order to ensure the synchronization of the collective traffic as part of intersecting flows, the following condition should be ensured:

$$V(t,x) = V_D \tag{23}$$

which can be obtained at the observance of:

$$\lim_{V_D \to V(t,x)} \sigma^2 = 0 \tag{24}$$

Thus, the synchronization of the collective traffic at the road network nodes is ensured through observing synchronized spatial velocity of each of the flows that have to move independently one from another with a consecutive tangent change of motion paths. Let's consider the intersection of the *mm'* and *nn'* motion paths at an arbitrary angle *α* in some rectangular coordinate system *xOy* (Fig.13).

If we determine that the direct lines *mm'* and *nn'* of the motion paths of motor vehicles are asymptotes of the second-order curves on the coordinate plane *xOy*, then we get the family of conjugated hyperbolas (Fig.14) that are generally described by the equation as follows:

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1 \tag{25}$$

where *a* and *b* are the real and imaginary semi-axis of the hyperbola (Fig. 15).

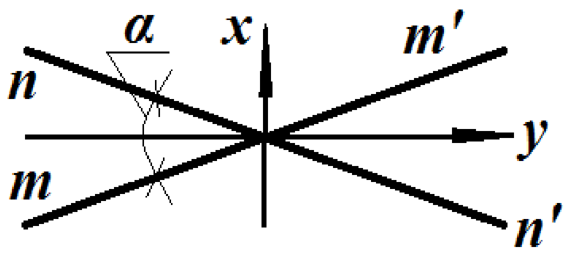


Fig. 13. Motion paths mm' and nn' of the crossed traffic flows on the coordinate plane xOy

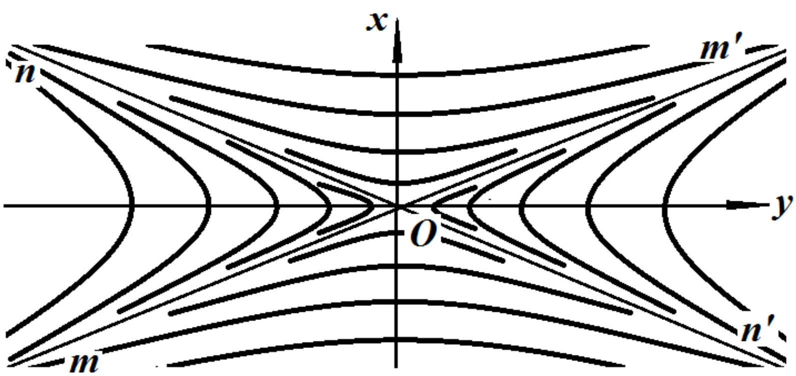


Fig. 14. Family of conjugated hyperbolas with the asymptotes mm' and nn'

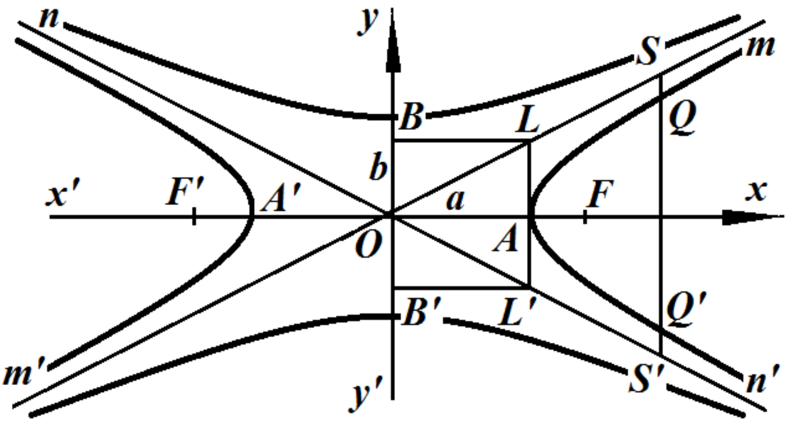


Fig. 15. Geometric signs of conjugated hyperbolas

The main characteristics of the hyperbola are the segment of *FF'* which determines its focal distance *c* (points *F* and *F'* – parabola focuses), namely *FF'=2c*; the real axis of hyperbola *2a*, which is determined by the points *A* and *A'* that are the vertices of the both branches of the hyperbola, i.e. *AA'=2a*; the imaginary axis of the hyperbola *BB'=2b*, which are related according to (25) by the equation as follows:

$$b^2 = c^2 - a^2 \qquad (26)$$

At that, *c>a* is always executed, and the hyperbola branches are symmetrical relative to the point *O* which determines the center of the hyperbola. The trajectories of the motion paths of the traffic flows *mm'* and *nn'* are asymptotes of the hyperbola, pass through the center *O* of the hyperbola, are described by the equation *y=k·x*, whereby $|k| \geq {}^{b}/_{a}$, and therefore the equations of the hyperbola asymptotes are $y = \frac{b}{a}x$ and $y = -\frac{b}{a}x$.

So, if some straight line *SS'*, which is parallel to the *yy'*, coordinate axis, will be indefinitely moved away from the center *O* of the hyperbola (to the right or to the left), then the segments *QS* and *Q'S'* between the hyperbola branches and the trajectories *mm'* and *nn'* of the traffic motion paths will be indefinitely reduced (points *Q* and *Q'* belong to the straight line *SS'*).

On the basis of the above signs of the hyperbola, proposed is the variant (Fig. 16) of synchronization of collective traffic at the node of intersection of traffic flows (roads of Category 2) equivalent in intensity *q*.

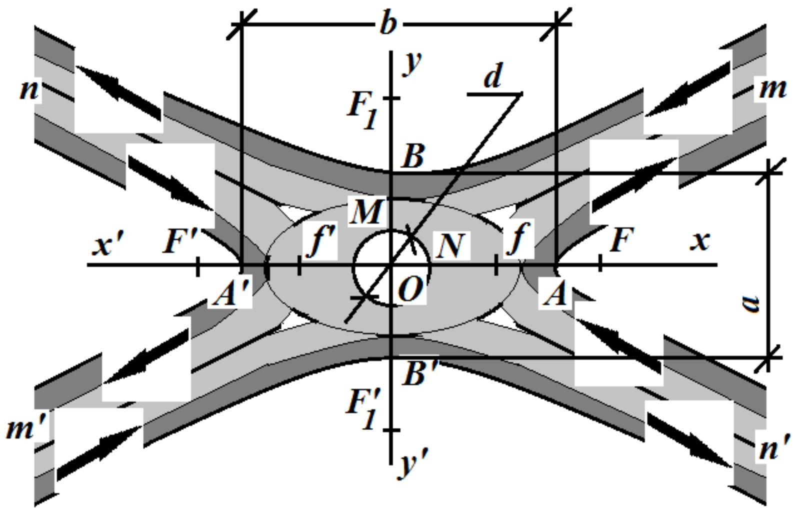


Fig. 16. Intersection of traffic flows at the nodes of the motor road network

The shape of the inner zone of the traffic flow intersection node is determined by an ellipse with focuses located at points *f* and *f'*. The contour (completeness) of the ellipse depends on the angle α, and in the case of $\alpha = \frac{\pi}{2}$, is converted to a circle. To ensure the maximum possible synchronization of the motor transport collective traffic with intensity *q* at the node of the road network, decisive are the dimensions of the real *2a* and the imaginary *2b* axes of the conjugated hyperbolas, i.e. the size of the segments *NA* and *MB*. The *NA* and *MB* sizes for the roads of Categories 1-a, 1-b, 2 and 3 are defined as:

$$NA(MB) = k \cdot s \quad (27)$$

where *k* is the number of traffic lines;

s is the width of a traffic lane, in meters.

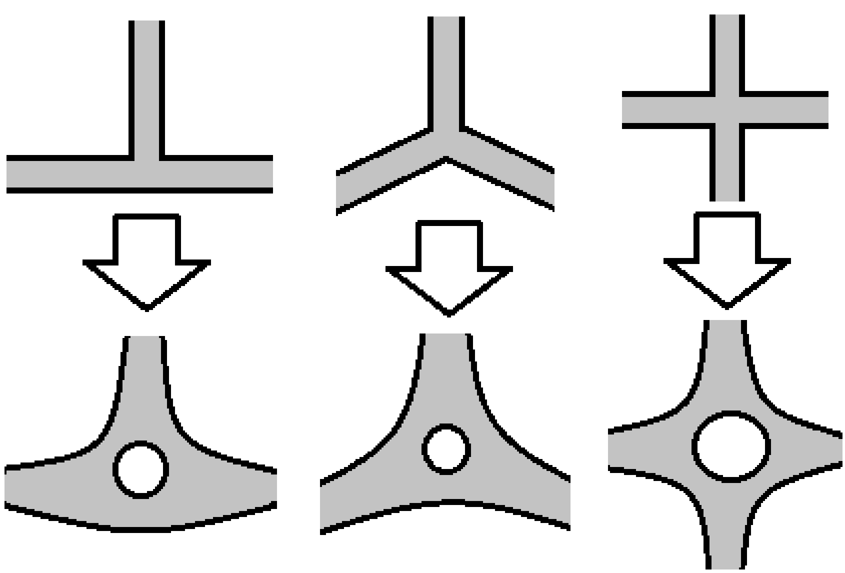
Dimensions of the carriageway (*NA* and *MB*) for the roads of the respective categories are indicated in Table 5.

Table 5 Minimum permissible width of the carriageway at the motor transport network nodes for motor transport flows of a certain intensity *q*, in meters

Road category (DBN V.2.3-4:2007)	1a, 1b	2	3
Minimum permissible width of the carriageway at the intersection of the traffic flows, m	11,3 (7,5)	11,3 (7,5)	10,5 (7,0)
Within the brackets, specified is the value of the width of the carriageway in the direction that is oriented along the smaller one of the axes of the conjugated hyperbolas			

On the basis of the above studies, we propose the principle schemes of motor transport flows in the nodes of the road transport network with options for organizing the directions of movement of vehicles (Fig. 17).

The proposed optimization of the structural parameters of the road network at the nodes of intersection of motor transport flows provides for the possibility of synchronization of collective traffic as part of motor transport flows, which ensures stabilization of operation modes of the motor transport engines and, therefore, reduces the impact on the environment.



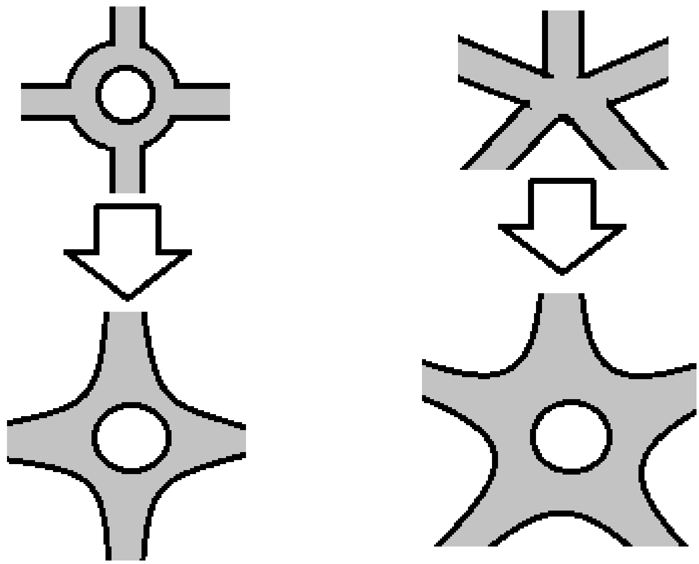


Fig. 17. Options for organizing traffic flow directions

7.6. Conclusions

Logistics is concerned with planning, managing and optimizing the processes of movement of goods, services, information and resources from the point of origin to the final consumer. It covers a wide range of activities aimed at ensuring the efficient functioning of supply chains. In particular, transport logistics plays an important role, focusing on the selection of the optimal mode of transport, planning transportation routes, organizing international transportation, and introducing innovations. All of its activities are focused on developing an effective strategy to ensure the stable development of the transport system in the context of sustainable development of society. Thus, important attention should be focused on creating safe conditions for logistics services, maintaining reliable functioning of road infrastructure and traffic flows, and ensuring sustainable economic and environmental safety.

Thus, ecological and technological optimization of the support frame of the road network of the natural-technogenic geo-ecosystem was carried out. It ensures ecological balance (ecological security) of the natural-territorial complex. As an example of this optimization of the support frame of the road network, the paper presents graph-analytical optimization of the motor transport infrastructure of the Podolsk region within the Khmelnytsky district.

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PART IV.

URBAN LOGISTICS AND PUBLIC TRANSPORT

Chapter 8.

METHODS FOR ASSESSING THE QUALITY OF PASSENGER SERVICE ON URBAN TRANSPORT

Liudmyla Tarandushka
Ihor Shlonchak
Yan Tarandushka

8.1. Normative and methodological prerequisites for improving the standardization of urban passenger transport parameters

8 .1.1. Relevance of the research

The problem of passenger quality transportation by road was studied and was specifically reflected in the works of many scientists. As a result, the basics of integrated quality management of services and the quality system of transport organizations, mechanisms and processes of quality managing passenger transportation have been developed. In general, general methodological approaches to managing the passenger quality transport services have been formed. However, at present there are no clear and unambiguous recommendations for establishing the nomenclature and normative values of indicators that determine the quality of transport services for the population by urban passenger transport. A common feature of the works reflecting the standardization of urban passenger transport (UPT) quality is that the list of quality indicators presented in them and the determination of its normative values are formed only taking into account the "opinions of specialists", based on previous experience, and there is no reference to actual quality indicators.

Therefore, the standardization of quality indicators and functioning of urban passenger transport requires improvement.

7.1.2. Analysis of the regulatory framework in the field of public urban passenger transport parameters standardization

In Ukraine, in accordance with the Resolution of the Ukraine Cabinet Ministers "On approval of the Rules for the provision of passenger road transport services" dated 18.02.1997 No. 176. Parameters of passenger transportation quality can be divided into the following elements:

1) economy;
2) information service;
3) comfort;
4) speed;
5) availability and timeliness;
6) safety.

Economy. This element can be determined by the level of passenger fares and the level of transfers (the percentage of passengers making trips with transfers), that is the level of development of the route network. Passenger fares are currently regulated by the state.

It should be noted that there is a minimum level of tariffs, which determines the possibility of safe operation transport system. On the other hand, the regulated level of passenger fares limits other parameters of the transport services quality, for example, comfort (to achieve the cost price set by the limited tariff, the level of utilization of rolling stock capacity increases).

To ensure the efficiency of transport services, it is necessary to ensure that the level of transport system service meets the needs of the population, that is, to ensure the transportation of existing passenger flows.

Information service is evaluated:

- the availability of a bus schedule or interval for routes with heavy traffic;
- access to information about the current state of traffic (information boards at bus stations, availability of information on the Internet, etc.);
- appropriate registration of rolling stock (the presence of a traffic pattern in the vehicle, announcement of bus stations, and so on);
- the ability to obtain additional information in the vehicle (location of the object, route, and so on).

Comfort. The comfort of the trip is determined by the passenger compartment occupancy and the technical characteristics of the bus, which ensure normal travel conditions (entrance-exit, aisle width, availability of orders, etc.).

Currently, the maximum level of filling the vehicle interior is determined at 8 passengers per 1 m^2 of free cabin space. (Industry standard ISTU 60.2-00017584-011-2001 “Road vehicles. Technical requirements for the safety general purpose buses design in service”.)

According to this regulatory document, vehicles are subdivided into:

- Class I vehicles, the design of which provides for standing passengers zones, providing the possibility of passenger circulation;
- Class II vehicles designed to carry mainly seated passengers and to carry standing passengers in aisles or areas not exceeding the area required to accommodate two double seats;
- Class III vehicles designed exclusively for the carriage of seated passengers.

Class I buses should be used to service city routes, since during these transportations the possibility of passenger circulation is a prerequisite. Otherwise, conditions for safe boarding and disembarkation of passengers are not provided. In addition, in the absence of the passenger turnover possibility, the quality of transport services decreases, and the transport fatigue of passengers increases. A class I vehicle has other specific parameters (different from class II and III buses) established based on the conditions of transportation on urban routes.

This is, firstly, the number of service doors (in class I buses, the number of service doors should be higher due to the specifics of urban passenger transportation). Secondly, the service doors of a class I vehicle are larger in size compared to class II and III buses. Thirdly, the Class I vehicle has wider aisles, which, in combination with the specific layout of the cabin, provide the possibility of passenger circulation. Fourthly, class I buses have a lower height of the first step of the service door (compared to class II and III buses) to ensure safe boarding and disembarkation of passengers in urban transportation conditions.

Other requirements for rolling stock are also defined: safety and quality of passenger transport services in accordance with specific conditions in different types of transportation (for example, the size of passenger seats, the availability of seats for the disabled, the availability of emergency vehicle doors inside and outside, and so on).

In accordance with the above, it should be concluded that only class I rolling stock should be used on urban routes.

Speed. The time spent on moving from places of residence to places of work, depending on the population of the city, is determined in Building codes and regulations 2.07.01-89 Urban Planning. Planning and development of urban and rural settlements. The travel time includes the approach to the stop, the duration of the bus wait, the travel time and the transfer time in the absence of direct communication.

Currently, about 30% of passengers in Cherkasy spend more than 30 minutes on a trip with a standard of 10 – 20%, that is, the public passenger transport system does not provide the required speed of delivery. One way to reduce travel time is to increase the speed of communication (which is defined as the ratio of the length of the route to the travel time from the starting to the end points).

Due to this, you can reduce the duration of the trip. Within reasonable limits, it is possible to reduce the duration of the trip by introducing speed modes.

The availability of services is determined by the rational planning of the route network, which should provide the permissible time of the pedestrian approach to the public transport stop.

The density of the network of ground public passenger transport lines in the built-up areas of the city should be within 1.9...2.5 km/km^2. The recommended distance of pedestrian approaches to the nearest bus stop should be, depending on the climatic area, within 300...500 m. in industrial and communal storage zones – no more than 400 m from checkpoints; in areas of mass recreation and sports – no more than 800 m from the main entrance. (Building codes and regulations 2.01.01-82 "Building Climatology and Geophysics").

Standards of intervals of movement and saturation of routes with buses for different passenger flows are established in accordance with the order of the Ministry of Transport of Ukraine dated 21.01.98 "Procedure and conditions for organizing the transportation of passengers and luggage by road". The timeliness of the provision of services is ensured by extending the working time of buses and adherence to the timetable through the use of modern information systems.

In foreign practice, the quality of transport services is usually assessed by the level of service (Level of Service – LOS). The LOS indicators were extended to the assessment of the quality of transportation by fixed-route passenger transport and included in the TCQSM manual ("The Transit Capacity and Quality of Service Manual, First Edition"; «Transit Capacity and Quality of Service Manual. Transit Cooperative Research Program Web Document

No. 6. TRB, National Research Council, Washington, D.C., 1999»). In addition, a number of studies on this problem have been carried out in Florida (FDOT Quality/Level of Service Handbook). When developing the methodology for assessing the level of passenger service according to TCQSM, the principle of “assessment from the user's perspective” was followed. In accordance with this, criteria were selected that characterize all components of a trip using passenger route transport (Vovk &Vovk, 2021).

Table 1.1 Levels of passenger service by road according to TCQSM

Service level	Cabin area per passenger, m^2	Number of passengers per seat	Note
A	More than 1,2	Not more than 0,5	Large selection of seating, passengers may not sit next to each other
B	0,8… 1,19	0,51-0,75	Choice of seating
C	0,6… 0,79	0,76-1	All passengers can sit
D	0,5… 0,59	1,1-1,25	Nominal Bus Load Level
E	0,4… 0,49	1,26-1,5	Maximum bus load level
F	Less than 0,4	More than 1,5	Bus overflow

Source: adapted from the works (Vovk & Vovk, 2021) and (Tarandushka et al., 2021).

The complexity of this task did not allow reducing the assessment to any one indicator. The factors influencing the subjective assessment of users include:

- pedestrian accessibility of bus stops;
- the quality of the pedestrian environment (the convenience of pedestrian communications and the features of their design);
- route schedule;
- improvement of stops;
- time spent on the trip;
- the cost of the trip;
- travel safety (personal safety);

- fullness of rolling stock;
- design of rolling stock;
- reliability (evaluated by the ability to maintain specified route intervals).

The rolling stock occupancy rate was chosen as the main criterion for assessing the level of service (tab. 1.1). Accounting for other factors listed above is carried out by correction factors. The example of the development of service level indicators for passenger route transport once again proves the great potential of this approach to the assessment of transport systems as a whole. A natural consequence of the current system of indicators should have been the idea of moving from the assessment of individual types of traffic (transport, pedestrians, fixed-route passenger transport, and so on) to their joint assessment, consideration of their interaction and mutual influence.

In this regard, methods for assessing the joint movement of different road users have been developed – a comprehensive assessment of the level of service (Multimodal LOS).

Since different types of users interact in the space of a city street, it is important to establish how a change in the level of service of one type user affects the level of service of others. In this regard, methods for assessing the joint movement of different road users have been developed – a comprehensive assessment of the level of service (Multimodal LOS). The most important Multimodal LOS application for bus transportation is to identify road sections where public transport should have priority over other road users.

Assessment methods in this case, as a rule, are based on a comparative assessment of the total time loss of public transport passengers and users of individual transport. There are a number of prerequisites for the development of this direction, the main of which are: – the Transportation Equity Act for the 21st Century (TEA – 21) (Tarandushka et al., 2021) and the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). – "Manual on Carrying Capacity and Assessment of the Quality of Service by Passenger Route Transport" (TCQSM) The main aspect of the development of the service level indicator at the moment is the integration of this criterion with methods for assessing traffic safety.

8.1.3. Analysis of existing research on the assessment of indicators of the functioning of urban passenger transport

The system of established standards presented above is the basis for measuring the quality of transport services. The main indicator of quality is the quality coefficient K_q, which is defined as the ratio of the amount of time spent on a trip under given theoretically absolutely comfortable conditions of the trip t_t^c, to the actual time spent on the trip in real conditions t_t^a

$$K_q = \frac{t_t^c}{t_t^a}. \tag{1.1}$$

The standards for spending time per passenger on trips by city bus (for a city with a population of 250-500 thousand people are 28, 35 and 43 minutes for exemplary, good and satisfactory levels of service quality) do not take into account the planning of cities (Panchenko et al., 2021).

The time spent on the trip includes the approaches to the stopping point and destination; travel in transport; transfer to another route; waiting for transport due to denials of boarding due to overloading of the vehicle. The disadvantage is that the peculiarities of urban planning and infrastructure are not taken into account.

Vakulenko K. E. (Vakulenko, Dolya, 2015) recommends determining the indicator of the quality I_q of transport services in cities according to the formula:

$$I_q = \frac{t_s}{t_a} \cdot \frac{y_s}{y_a} \cdot R \tag{1.2}$$

where is

t_s − the standard of time spent by the passenger on the trip, min. (40 minutes for cities with a population of more than 1 million, 35 minutes − from 500 thousand to 1 million, 30 minutes − from 250 to 500 thousand, 25 minutes − less than 250 thousand);

t_a − the time actually spent by the passenger on the trip, min.;

y_s − the standard filling factor of vehicles for urban transportation is on average not more than 0,3 and during peak hours – 0,8;

y_a − the actual value of bus filling factor;

R − indicator of regularity buses movement.

The author proposes a differential assessment of quality in the form of the ratio of the standard level indicator to the actual one.

In order to conduct a comparative assessment of the quality of transportation, a four-level system of assessments is established: exemplary, good, satisfactory and unsatisfactory quality levels.

The most important element of service quality assessment is the integrated value of the quality coefficient, which includes assessments based on the following indicators:

- filling the bus;
- time spent on the trip;
- regularity of rolling stock movement;
- safety of passenger traffic during transportation.

The disadvantage is the difficult process of determining the standard level of the travel time indicator for different cities.

Bosnyak M.G. (Bosnyak, 2009) offers the following quality indicators:

- duration of movement;
- comfort;
- the cost of moving.

Disadvantage: the waiting time of the vehicle is not taken into account; The work of passenger enterprises in observing the specified interval of bus movement on the line is not assessed.

In the work (Shlyonchak, Luk'yanchenko, Tarandushka, 2022), the quality of service for passengers of UPT is determined by many indicators:

- Availability;
- ride comfort;
- minimum time spent on moving around the city;
- high reliability of rolling stock;
- regularity of connections with full safety of transportation.

Ignatenko O.S., Marunych V.S. (Ignatenko, Marunych, 2017) provide the following system of indicators for assessing the quality of passenger transportation (fig. 1.1).

The Integrated Passenger Transportation Quality Management System provides for the introduction of a system of indicators for assessing the activities of the production, technical and operational services of the enterprise, a number of structural units. Indicators of service quality for bus passengers are:

- the number of passengers per 1 m^2 of free floor area;
- bus capacity utilization factor;
- regularity;
- safety of rolling stock.

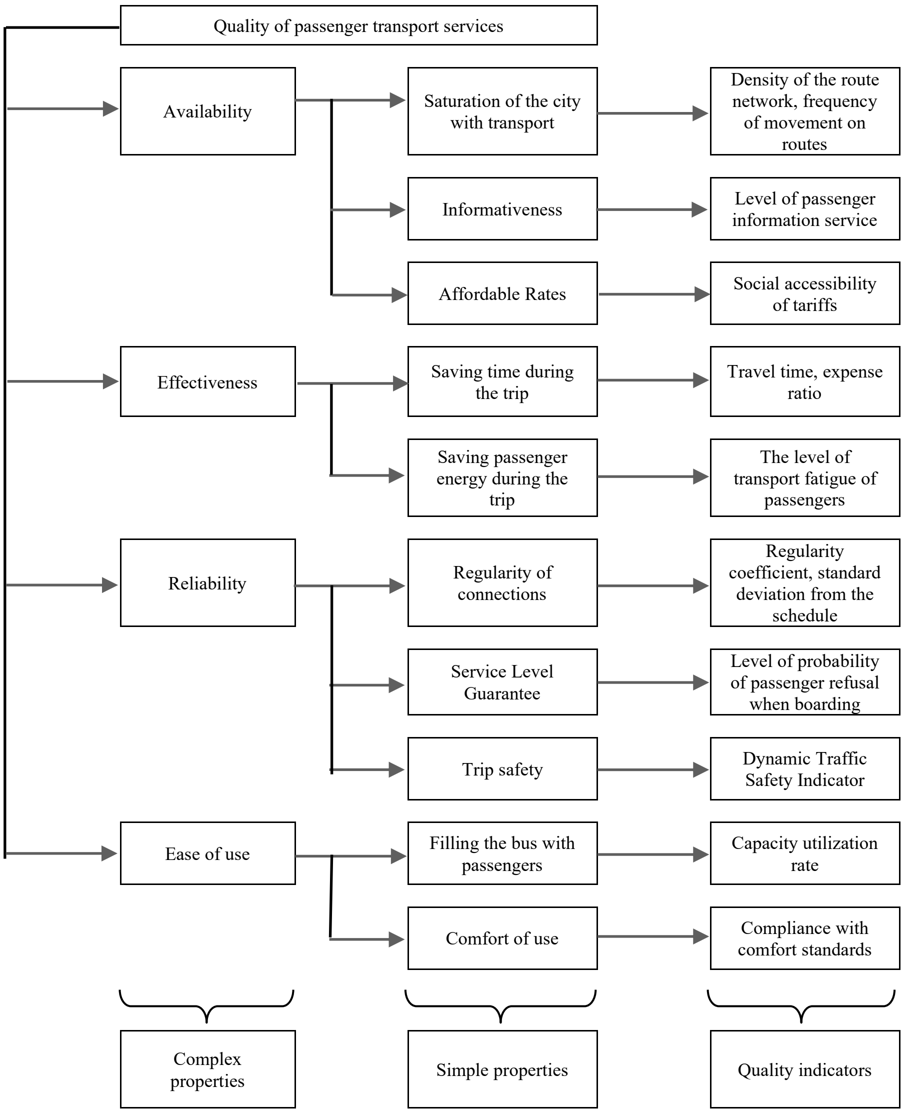

Fig. 1.1. Structure of passenger service quality indicators (on the example of bus transportation)

Source: adapted from the work (Ignatenko, Marunych, 2017)

These indicators, characterizing the efficiency of the functioning of passenger enterprises, do not fully reflect the degree of satisfaction of passenger needs during transportation. The main definitions and formulations relating to the quality of transport services are set out in ISO 9000:2000.

Basic requirements for the services of transport enterprises:

– safety of passenger transportation services;
– reliability of transport services;
– timeliness of passenger transportation;
– timeliness of delivery of goods (baggage);
– preservation of cargo (baggage) transportation;
– comfort of passenger transportation;
– compliance with the standard terms of cargo delivery.

It was proposed to evaluate the quality of passenger service on each route by time of day and day of the week, an indicator of the regularity of vehicle movement, since violation of the schedule leads to overcrowding of vehicles, an increase in the cost of waiting time, boarding, and a decrease in the speed of communication. It is calculated as the ratio of the number of scheduled bus trips to the number of actually performed bus trips and multiplied by the coefficient of scheduled bus trips (Gómez-Lobo, 2011).

The concept of a comprehensive, integrated quality indicator that takes into account various factors of passenger service is also used. The complex indicator of the level of passenger service S is determined by the dependence:

$$S = S_1^{K_1} \cdot S_2^{K_2} \cdot S_3^{K_3} \cdot S_4^{K_4} \cdot S_5^{K_5} \cdot S_6^{K_6} \qquad (1.3)$$

S_1 – reliability of movement according to the schedule (travel time);

S_2 – accessibility (frequency of public transport);

S_3 – safety (probability of trouble-free operation of public transport);

S_4 – comfort (ride quality);

S_5 – cost indicator – the value of the transport tariff;

S_6 – indicator of information service (level of information support);

$K_1 \dots K_6$ – measure indicators that characterize the weight of these corresponding indicator of service level.

Two integral characteristics are widely used to determine the integral assessment of quality. The first of them K_i represents the geometric values of quality indicators and is used for the integral characteristic of the generalized quality level:

$$K_i = \sqrt{\prod_{i=1}^{i=max}(D_i)}. \tag{1.4}$$

The second characteristic ΔK serves to assess the degree of disagreement of vectors reflecting the actual and normative quality:

$$\Delta K = \sqrt{\sum_{i=1}^{i=max} D_i^2}. \tag{1.4}$$

The issues of improving the level of customer service in market conditions are closely related to the problem of the services quality.

Consumers of urban passenger transport services are evaluated:

- minimum delivery time;
- maximum safety;
- reliability of transportation;
- regularity of bus movement;
- guaranteed operating time of buses on the route;
- availability of additional services;
- the presence of different levels of transport services;
- adaptability to customer requirements (flexibility of service);
- convenience, comfort;
- debugged information system;
- acceptability of the cost of transportation.

The above review shows that there are many scientific works aimed at improving certain indicators of the quality of transport services for the population. Measures reflecting modern trends in the development of urban public transport, aimed at improving the quality of transport services for the population, can be classified as follows:

1. Improvement of traffic organization:
   - restriction of private and official transport movement on the busiest sections of the street and road network (ensuring the unimpeded passage of public transport);

- restriction of vehicles parking on the roadway of the busiest sections of the city (increasing the capacity of roads, reducing the attractiveness of individual transport);
- organization of dedicated lanes for urban route transport;
- installation of priority signs, taking into account the provision of preferential travel for public transport;
- improvement of traffic light regulation organization in order to ensure the priority of urban public transport (installation of additional sections; equipping traffic light objects with sensors that register the approach of public transport);
- construction of multi-level transport interchanges and underground (aboveground) pedestrian crossings;
- arrangement of bus stations in accordance with the requirements of the current regulatory documentation.

2. Improvement of the route transport network:
   - reducing duplication of urban public transport traffic patterns;
   - organization of public transport traffic schemes, taking into account the detour of busy sections and sections with difficult passage;
   - justification and implementation of a sufficient density of the route network, taking into account the permissible walking accessibility of bus stations;
   - formation of reasonable length urban routes, ensuring the optimal correspondence of vehicles number to the size of passenger flows;
   - optimization of bus stations location.

3. Improvement of rolling stock structure:
   - the predominant use of large capacity city buses with a low floor, adapted for the transportation of people with limited mobility;
   - the use of rolling stock that meets the requirements of higher environmental classes;
   - the use of rolling stock running on environmentally friendly fuels;
   - increasing the share of public electric transport;
   - the use of rolling stock with hybrid drive schemes.

4. Improvement of urban passenger transport organizational structure. The organizational structure of urban passenger transport assumes a certain interconnected functioning of three structural subdivisions: the

administration (passenger transport department), the central dispatch service and carriers.

5. Application of modern information technologies. The analysis of the methods developed by the authors showed that there is a common nomenclature of quality indicators, which can be divided as follows: availability, reliability, regularity, economy, safety. These indicators and methods of their assessment were identified by the authors based on the analysis of previous experience and are the result of the analysis of theoretical data that are not tied to the features of the actual current state of the transportation process and taking into account the opinion of passengers.

In this regard, when assessing the quality of the real transportation process, in some cases there is an inadequate assessment of the transport services level for passengers of general use UPT.

So, as a result of the analysis, it was determined:

1) The problem of standardization general use UPT quality exists and is determined by the fact that the known methods of quality assessment contain a list of quality indicators formed on the basis of theoretical experience. The method of determining the values of all the presented indicators is quite complex in application and in some cases not objective.
2) The significance of a separate quality indicator evaluated by a specialist does not take into account the opinion of the end user of the service – the passenger.
3) There is no connection between the normative values of quality parameters and the actual values inherent in the transport service system of public transport services specific route network, in this regard, there is an inadequate assessment of the quality transport services level.

In this regard, it is proposed to develop a methodology for standardizing the quality of public UPT. This methodology should consist of the following steps:

- To develop a list of quality indicators, taking into account the existing methods, approaches and indicators identified by passengers as the most significant for them.
- To assess the impact of a separate indicator on the quality transport services level, taking into account their significance for passengers. Assign weight to each indicator.

- To determine the actual values of the selected indicators of service quality to the population of Cherkasy by the UPT of general use.
- To combine the indicators into an integral system for assessing the quality of transport services of general use.

8.2. Formation of passenger transportation quality indicators nomenclature

8.2.1. Formation of indicators list for assessing the quality of transport services of urban passenger transport on the basis of expert opinions

Due to the fact that the standards of quality indicators do not meet modern requirements and regional features of the transport services market, there is a need for theoretical substantiation of quality indicators standards of road transport. The use of scientifically based standards will provide an opportunity to increase the level of quality of transport services to the really necessary.

To solve the task, it is necessary to justify:

- list of indicators for assessing the quality of transport services of urban passenger transport;
- standard values of each established quality indicators.

In this case, it is necessary to link the actual level of indicators to the scale of quality assessments. The standards should generalize the existing experience as much as possible and differentiate in accordance with the operating conditions of road transport.

When solving the problem of improving the standardization of quality indicators, it is necessary to take into account the experience and results of previously performed research. The data form restrictions on the normative values of quality indicators. On the other hand, it is necessary to conduct a statistical study that allows you to find out the requirements of passengers to the indicators of transport services quality. Standardization of the quality of transport services – determination of critical and most effective values of indicators. All measures are aimed at improving the quality of passenger transportation. As the quality of passenger service grows to a certain reasonable level, the total revenues of the carrier increase.

However, then the quality becomes very expensive for passengers and they choose alternative ways of transportation. Therefore, it is necessary to determine this level of quality, rationally. Based on this, the standard values of quality indicators are established. The main goal is the common interests of passengers and carriers.

The structure of passenger service quality indicators can be considered as a basis for the formation of quality indicators of passenger service in urban transport. There are four main (complex) properties in the structure:

- accessibility, which characterizes the possibility and ease of travel by passengers;
- effectiveness, reflecting the effect received by passengers from the use of transport services;
- reliability, which shows the probability of completing the trip in compliance with the established service requirements;
- convenience, which characterizes the conditions in which the trip is carried out.

In order to determine the degree of manifestation of requirements essence, which is reflected in the indicators, a standard is established – the reference value of the indicator value.

Formation of quality indicators. Let us consider the formation of quality indicators list on the part of experts and on the part of consumers of transport services – passengers.

Passenger transportation quality indicators:

- accessibility;
- timeliness;
- comfort;
- economy;
- information service;
- safety.

Transport accessibility is one of the most important criteria necessary to assess the quality of transport services in the city. In foreign practice, the term Transportation Accessibility has two meanings:

- accessibility – the total expenditure of time on movement carried out for some purpose (movement to the place of work, movement for cultural and domestic purposes, and so on);
- accessibility – the possibility of receiving transport services for people with disabilities (disabled, elderly). In addition, in the USA and Canada, the term Transport Affordability is used (Tarandushka,

Shlyonchak, Tarandushka, 2022), which denotes an economic assessment of the availability of transport (or the availability of transport services), which is carried out in the form of monitoring of socio-economic data characterizing the ratio "cost of transport services – profits".

In urban planning practice, only some indicators of accessibility are normalized:

- availability of transportation to places of work – the cost of one-way transportation to the place of work;
- accessibility of public transport stops.

Based on the above, availability is evaluated by the following criteria:

- network density;
- transfer coefficient;
- the range of approach to bus stations;
- distance between bus stations;
- time spent on movement.

The density of the transport network δ is determined by the ratio of streets total length and roads along which the routes of public ground urban passenger transport pass (L), to the built-up area of the city (F):

$$\delta = \frac{L}{F} \tag{2.1}$$

where L – the total length of streets and roads along which the routes of ground urban passenger transport of public use pass, km; F – city square, km^2.

For the city of Cherkasy

$$\delta = \frac{L_1 + L_2}{F} = \frac{286{,}6+345{,}6}{78} = 8{,}1\,\frac{km}{\text{km2}}$$

L_1 – length of streets and roads along which trolleybus routes pass, km.

L_2 – the length of streets and roads along which bus routes pass, km.

Exceeding the standard density of the route network leads to an increase in the number of route crossings, as a result of which the speeds of buses are reduced, and their productive capacity decreases. With a decrease in density, the approach time to the stop increases.

Transplantability coefficient. The route network should provide the lowest interchange connections, the main transport microdistricts should have direct communication with the city center, objects of the external transport hub and, if possible, with each other.

In cities with a significant number of transport microdistricts, it is almost impossible to organize direct communication, since the number of possible routes is growing sharply. A more compact development of the urban area contributes to a decrease in the transfer rate. The coefficient of transplantability K_t is determined by the ratio of the total number of trips made by the population per year Z to the total number of trips made during the same period N:

$$K_t = \frac{Z}{N} \tag{2.2}$$

Z − the total number of trips made by the population per year.

N − the total number of movements carried out per year.

The transfer rate shows the average number of landings per trip. Transfer capacity decreases with the optimization of the route system, the rational arrangement of main streets, the introduction of high-speed and express types of connections. This makes it possible to reduce the travel time of passengers from the point of departure to the point of destination. The approach distance to the bus stations and the distance between the bus stations depend on the density of the network, the average length of the race, climatic conditions, the number of buildings storeys and are regulated by the standard rules of transport services for the population in urban and suburban traffic.

Average length of the run L_a (distance between bus stations) on the route, km:

– for linear routes:

$$L_a = \frac{2L_r}{N_s^{-2}} \tag{2.3}$$

where L_r – the length of the route, km;

N_s – the number of stops on the route.

– for linear routes (one direction):

$$L_a = \frac{L_r}{N_s^{-1}} \tag{2.4}$$

– for circular routes:

$$L_a = \frac{L_r}{N_s} \tag{2.5}$$

The passenger's time spent on movement t_m consists of the time:

– approach to the bus stop t_{ap};
– waiting for transport t_w;
– for a trip t_{trip};
– for a transfer t_{tr}.

$$t_m = t_{ap} + (t_w + t_{trip} + t_{tr}) \cdot K_t \tag{2.6}$$

Time spent on approach to the bus stop: t_{ap}

$$t_{ap} = \frac{60}{V_{ap}} \cdot \left(\frac{1}{3\delta} + \frac{L_a}{4}\right) \approx 15 \cdot \left(\frac{1}{3\delta} + \frac{L_a}{4}\right) \tag{2.7}$$

where is V_{ap} – the speed of approach to the bus stop, km/h.

The average speed of walking for cities V_{ap} is 4 km/h.

The time spent waiting for landing t_w in general is determined by three factors:

– the interval of movement on the route;
– accuracy of compliance with the timetable by drivers;
– passenger capacity of the vehicles used.

$$t_w = \frac{I}{2} + \frac{\sigma_1^2}{2I} + P_{b.d.} \cdot I_{ef} \tag{2.8}$$

where I − planned (calculated) interval of movement on the route, min.;

σ_1^2 − standard deviation from the planned interval of movement (characterizes irregularity of movement), min.;

$P_{b.d.}$ − the probability of boarding denial to a passenger due to limited passenger capacity;

I_{ef} − effective interval of movement on the route, min.

The duration of the passenger's stay on the trip t_{trip} contributes to the properties of transportation, which include the following indicators:

- average distance of the trip;
- average speed of passenger's movement.

The time spent on a trip in rolling stock is determined by the formula:

$$t_{trip} = \frac{l_{av}}{V_{av}} \tag{2.9}$$

where l_{av} – the average distance of the trip, km.

V_{av} − average speed of passenger's movement.

The speed of communication is the average speed of passenger delivery. It is determined by the ratio of the length of the route L_r to the time of the route

$$V_{av} = \frac{L_r}{t_t + t_{i.s.}} \tag{2.10}$$

where t_t – the travel time and $t_{i.s.}$ – an intermediate stop time in the total delivery time, hours.

Timeliness indicators characterize the properties of passenger transportation that facilitate the movement of vehicles in accordance with the announced schedule or other regulatory requirements. Indicators of timeliness include:

- a fraction of vehicles departing on schedule;
- the share of vehicles arriving on schedule;
- average interval of movement;
- maximum interval of movement.

The regularity of movement is estimated by the regularity coefficient K_{reg} is the ratio of the number of trips N_{trips} provided for by the timetable for a certain period of time to the number of actually performed routs according to the schedule N_{act}.

$$K_{reg} = \frac{N_{trips}}{N_{act}} \tag{2.11}$$

A regular trip is the trip with an allowable deviation from the schedule ±2-5 minutes.

Interval of movement.

$$\mathrm{I} = \frac{T_{r.t.}}{\mathrm{A}} \tag{2.12}$$

where $T_{r.t.}$ − hour of the round trip; A − the number of rolling stock units on the route.

With a decrease in the interval of movement, the waiting time for transport is reduced, but the filling of the bus is also reduced. Effective bus traffic interval:

$$I_{ef} = \mathrm{I} + \frac{\sigma_1^2}{\mathrm{I}} \tag{2.13}$$

where σ_1^2 is the standard deviation from the planned interval of movement, characterizes the irregularity of movement.

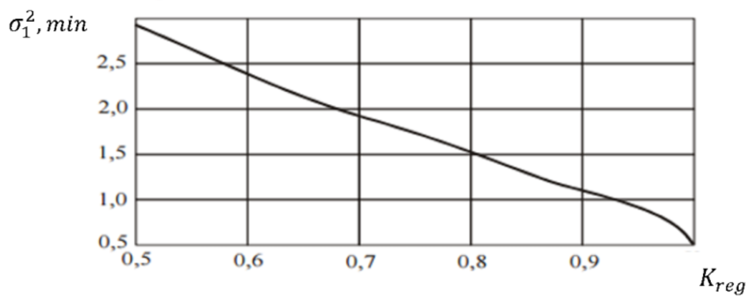

Fig. 2.1. Graph for determining the standard deviation of the movement interval by the coefficient of regularity of bus movement

Source: results of my own scientific research.

Indicators of trip comfort include:

- the area (volume) per passenger;
- frequency of cleaning vehicles;
- air temperature in the passenger compartment;
- illumination in the vehicle and at stops;
- permissible values of noise, vibration and humidity;
- average (permissible) filling of the transport interior.

Comfort for passengers during the trip is primarily determined by the degree of occupancy of the passenger compartment of the rolling stock. The physical and mental fatigue of passengers depends on it, which affects not only their performance, but also their health. The filling of buses with passengers in intracity traffic is characterized by a coefficient γ_s.

$$\gamma_s = \frac{Q_a}{q} \quad (2.14)$$

where γ_c – factor of statistical filling;

Q_a, – the actual passenger capacity of the bus;

q – the nominal passenger capacity of the bus.

For a more complete characterization of the comfort of the passengers' trip, it is necessary to know the value of the capacity utilization factor not only the average daily, but also necessarily during peak hours on the busiest route direction. When characterizing the capacity of buses, taking into account the distance of trips, a dynamic capacity utilization factor γ_d is used.

$$\gamma_d = \frac{l_a \cdot Q_ф}{q \cdot L} = \frac{W_a}{W_p} \quad (2.15)$$

where l_a – the average distance of the passengers' trip, km;

L – the total mileage of the rolling stock, km;

W_a – actually performed transport work, pass./km;

W_p – possible transport work, pass./km.

For high-quality operation of the bus on the route, it is necessary to minimize the probability of boarding denial to a passenger due to the limited capacity of the vehicle.

$P_{b.d.}$ – the probability of boarding denial to a passenger due to limited passenger capacity.

The probability of denial of boarding to a passenger is understood as the share of passengers who could not use the transport service on time and the share of passengers who were transported in unacceptable conditions.

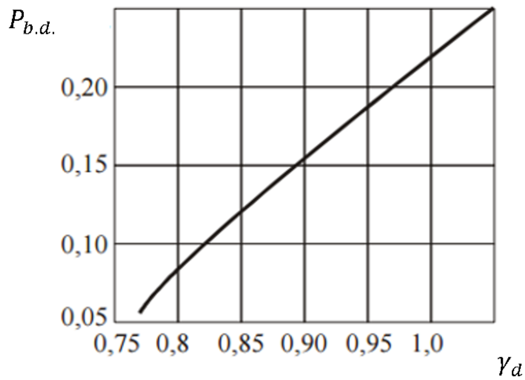

Fig. 2.2. Graph for determining $P_{b.d.}$ on dynamic capacity utilization factor γ_d during peak hours

Source: results of my own scientific research.

The economic availability of passenger transport services for the population is determined by the ratio of the average estimated normal costs of one resident for receiving the service, which correspond to the actual costs determined by the current tariffs of municipal and intermunicipal transportation by public road transport. The average estimated standard costs of one inhabitant for public road transport services $C_{p.t.}$ are calculated according to the formula:

$$C_{p.t.} = Inc_{av} \cdot R_{a.sh.} \tag{2.16}$$

where Inc_{av} – the value of the average annual income of a resident of a city or town, uah.;
$R_{a.sh.}$ – the average share of a resident's expenses for passenger transport services in the total amount of his income (in %).

The average estimated actual costs of one resident for public road transport services C_{act} are determined:

$$C_{act} = T_{a.an.} \cdot B \cdot l_{av} \tag{2.17}$$

where $T_{a.an.}$ – the average annual tariff of transportation by public road transport (uah/km);
B – average annual transport mobility of the population in a given city or town (number of trips);
l_{av} – average travel distance of a passenger in this locality (km).

Average estimated actual costs of one inhabitant for public road transport services. should not exceed the average estimated normative.

$$C_{act} \leq C_{p.t.} \tag{2.18}$$

8.2.2. Formation of the quality transport services indicators based on the results of the questionnaire

The proposed methodology for quality standardization, in addition to the analysis of regulatory documentation and scientific papers, is based on the development of questionnaires for consumers of public urban passenger transport services.

There are many research methods that can be used to identify consumer satisfaction with the quality of services. The problem of determining satisfaction with the quality of transport services is especially difficult due to the fact that it must cover a significant number of passengers. Therefore, in this case, the survey method is adopted.

A survey is a systematic collection of information through a questionnaire. To obtain the most accurate results, it is necessary to use only carefully formulated questions. In addition, the error is minimized by compiling a sufficiently large sample of respondents, which would representative the composition of the population. The survey consists of collecting primary information by asking questions regarding the advantages and disadvantages related to a specific service. There are quite a few ways to conduct surveys. Preference, as a rule, is given to a survey by the method of a personal interview with a respondent or a telephone survey, which allows you to obtain reliable information about the state of the object of study.

With regular data collection in the warm season, it is better to use personal interviews, for example, at bus stops, and in cold weather – by phone. This is one of the most efficient and inexpensive experimental methods.

When compiling questionnaires, it is proposed to group questions related to the assessment of the level of quality of transport infrastructure services into several blocks. At the same time, when developing questionnaires, it is planned to use differentiated methods depending on the type of questions:

– open questions ("Please explain what high-quality service for public transport passengers means to you personally?") allow you to get different answer options that help to consider the problem from different angles;
– questions to which the respondent can only answer "yes or no" are easy to answer, simple to analyze the facts;
– questions that involve a choice of several options ("What types of public transport do you use most often"?) are convenient if there are alternatives.

In addition, to receive proposals for improving the operation of public transport, the questionnaire uses the method of open questions. The questionnaire is presented in Appendix A.

A scale for determining the importance of the proposed indicator was also used, which is presented in fig. 2.3.

0	1	2	3	4	5	6	7	8	9	10

It doesn't matter at all Very important

Fig. 2.3. Ten-point scale to determine the importance of indicator

Source: results of my own scientific research.

The algorithm for assessing the quality of transport services based on the results of a passenger survey is presented in fig. 2.4.

Determination of the sample size of the statistical population in order to obtain reliable data:

$$n = \frac{\sigma^2 \cdot t^2}{e^2} \tag{2.19}$$

where n – the sample size;

σ^2 – standard deviation;

t – level of trust;

e – desired accuracy (error).

The population of the city of Cherkasy was 274108 people (Tarandushka, Kostyan, Tarandushka, 2021). Characteristics of the sample population: the volume of the sample population of the objects of study is 400 respondents. The sample type is probabilistic. Taking into account the confidence probability (no more than 95% in this case), a change in indicators by more than 5% up or down can be considered reliable or statistically significant. According to the calculation table of V.I. Paniotto, for the volume of the general population 100000, the sufficient sample volume is 398, for the volume of the general population 10000, the sufficient sample volume is 385 to provide an error of 5%. That is, a sample unit provides almost 7000 of the general population. In our case, with a population of 274108 people, where almost half of the residents use their own vehicle, a sample of 400 people will be enough.

A regular increase in the sample is expensive, and therefore it does not make sense to increase it in order to gain one percent in the value of the confidence interval.

After determining the required sample size, studies are carried out, according to the results of which the results are evaluated.

400 passengers using public bus transport were interviewed One average passenger has the following number of trips per week: for work − 7.9; for training − 4.8; cultural and domestic − 5.7. On average, there are 18.5 trips per passenger per week, that is, 2.6 trips per day (fig. 2.5).

Stage 1
Research of the main transport services market subjects of public transport services

Consumer research with segment groups

Passengers

Demographic segmentation
- gender
- age

Segmentation by behavior
- Purpose of the trip
- Frequency of trips
- Favorites

Stage 2
Development of the necessary primary documentation

Development of questionnaires
- Block 1: Transport Availability and Accessibility
- Block 2: Performance
- Block 3: Reliability
- Block 4: Comfort and convenience

Stage 3
Determination of the sample size

Stage 4
Conducting research – passenger questionnaires

Stage 5
Evaluation of research results

Stage 6
Transfer of the obtained data to the integrated quality assessment system

Stage 7
Development of recommendations

Fig. 2.4. Procedure for assessing the quality of public transport services

Source: results of my own scientific research.

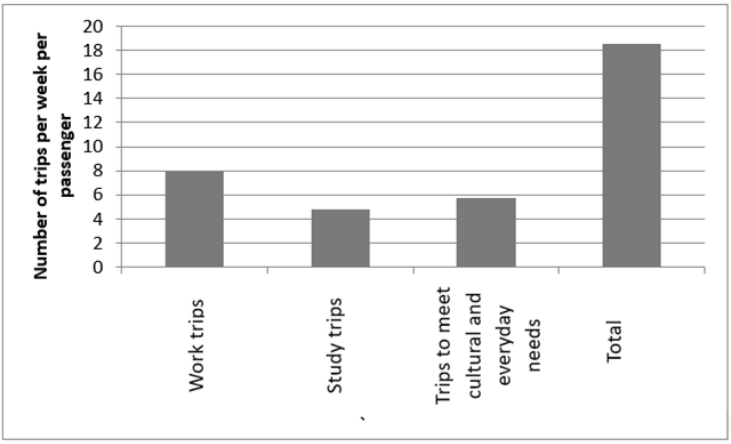

Fig. 2.5. Distribution of trips per week per passenger

Source: results of my own scientific research.

8.2.3. Analysis of significant parameters affecting the quality of public transportation

The structure of travel time of passengers is shown in the table. 2.1. The table shows that the approach time to the stop for most passengers is less than 10 minutes. (i.e. less than 650 m). It should be noted that about 39% of passengers wait for transport for more than 10 minutes. It can be assumed that the main reason for this problem is the low speed of communication of rolling stock during peak periods of transportation due to heavy traffic. From this we can conclude that the task of increasing the speed of communication and the regularity of passenger transport is urgent. This is also evidenced by the large share of passenger proposals to increase the number of the rolling stock on the routes.

Now there is a large share of passengers (25%), whose travel time is more than 40 minutes. About 30% of passengers spend 30 to 40 minutes on one trip. Thus, about 55% of passengers spend more than 30 minutes in a vehicle per trip. This also confirms the conclusion that it is expedient to increase the speed of communication of rolling stock on routes in order to improve the quality of transport services by reducing travel time.

Table 2.1 Structure of passenger travel time

Stop approach		Waiting for transport		Trip	
Time, min.	Parameter's Weight, %	Time, min.	Parameter's Weight, %	Time, min.	Parameter's Weight, %
0-5	44,6	0-5	15,4	0-10	1,8
5-10	41,4	5-10	46,1	10-20	13,7
>10	14,0	10-15	31,7	20-30	29,3
		15-20	4,8	30-40	29,9
		>20	2,0	>40	25,4
Total	100,0	Total	100,0	Total	100,0

Source: results of my own scientific research.

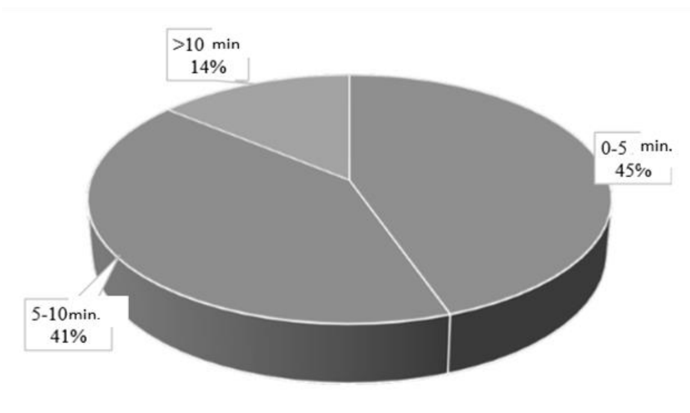

Fig. 2.6. Time of approach to the stop

Source: results of my own scientific research.

As can be seen from fig. 2.6 The approach time to the stop of 14% of passengers is more than 10 minutes.

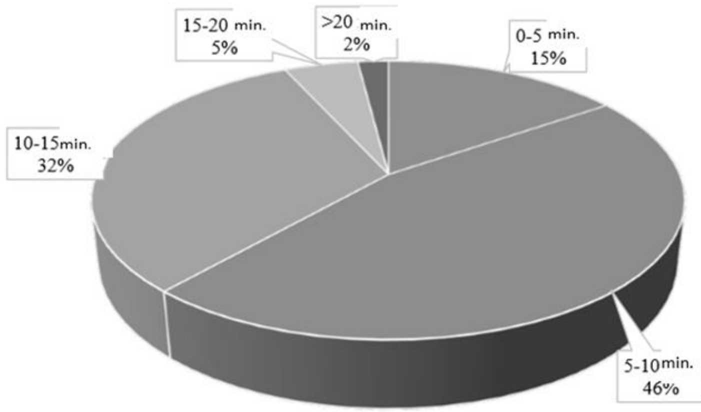

Fig. 2.7. Waiting for transport

Source: results of my own scientific research.

As can be seen from fig. 2.7 the waiting time of 39% of passengers is more than 10 minutes.

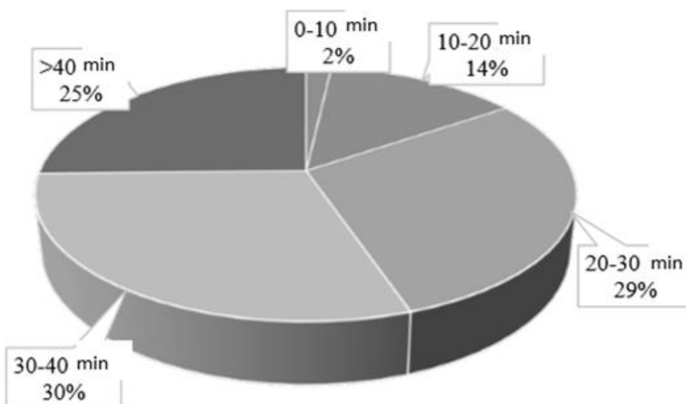

Fig. 2.8. Travel time

Source: results of my own scientific research.

As can be seen from Fig. 2.8 55% of passengers spend more than 30 minutes in a vehicle. The tab. 2.2 presents an analysis of the results of a passenger survey on the state of public transport stops. The table shows that about a third (30.5%) of passengers note unsatisfactory information about the movement of public transport at bus stations. 26.4% of passengers note the unsatisfactory sanitary condition of the bus stations. Passengers recognize the equipment of most intermediate bus stations as satisfactory, but about 19% of passengers consider this problem important, the task of reconstruction of some bus stations should be recognized as relevant.

Table 2.2 Condition of public transport stops

Parameter name	Well	Satisfactorily	Unsatisfactorily
Information about traffic (availability, clarity, correspondence to reality)	20,9	48,6	30,5
Sanitary condition of bus stops	17,7	55,9	26,4
Equipment of bus stops (canopies, boarding platforms, garbage bins, etc.)	30,5	50,9	18,6
Work of transport in the evening	14,8	52,0	33,1

Source: results of my own scientific research.

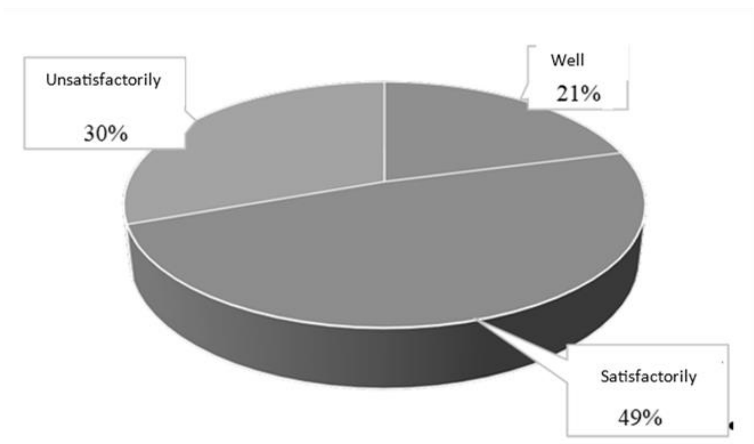

Fig. 2.9. Evaluation of traffic information

Source: results of my own scientific research.

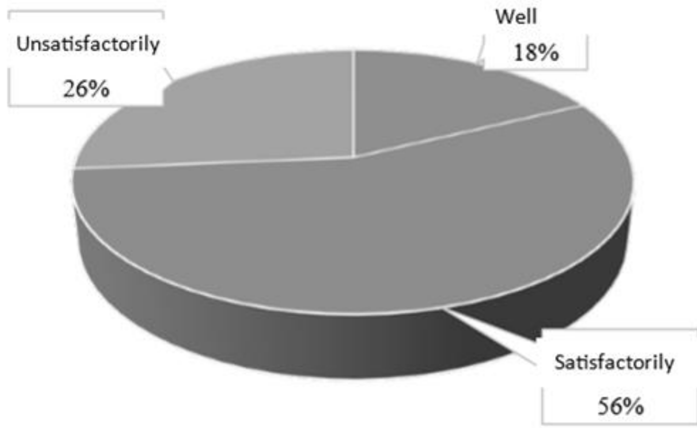

Fig. 2.10. Assessment of the sanitary condition of stops

Source: results of my own scientific research.

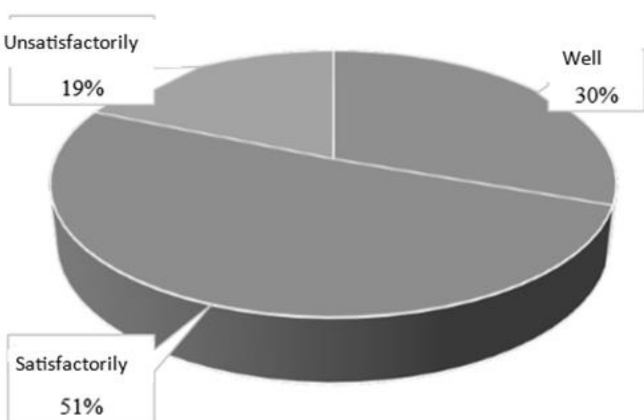

Fig. 2.11. Evaluation of stop equipment

Source: results of my own scientific research.

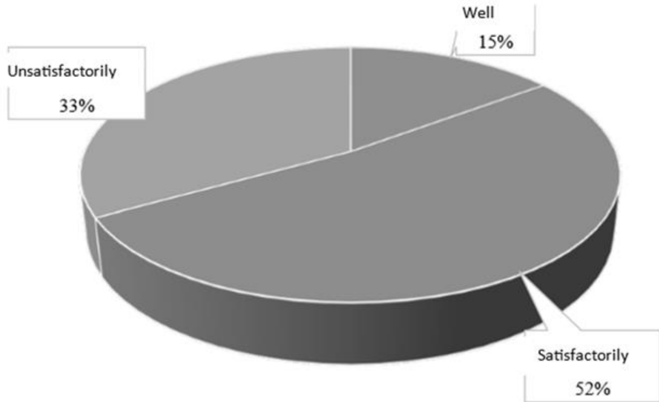

Fig. 2.12. Evaluation of the work of transport in the evening

Source: results of my own scientific research.

A particular problem is the work of transport in the evening. 33% of passengers gave a negative assessment of this indicator of the functioning of the city's transport system in the questionnaire. The table 2.3 gives an assessment of the comfort of public transport. The table shows that only such a parameter as the convenience of the vehicle scored the least number of negative ratings (14.6%). Passengers pay special attention to unsatisfactory ventilation of cabins: 36.7% of negative ratings. Perhaps this result is related to the examination period (the end of the summer period), when this problem seems especially relevant for passengers. Thus, it should be recognized as an urgent task when updating the rolling stock fleet to pay special attention to the efficiency of ventilation and heating of the cabin (perhaps consider the mandatory use of air conditioners).

One of the directions for increasing the comfort of public transport is to provide information in the rolling stock and the correct attitude of the crew.

Table 2.3 Assessment of the comfort of public transport

Parameter name	Well	Satisfactorily	Unsatisfactorily
Convenience of the vehicle (wide aisles, large storage areas, comfortable seats, etc.)	29,2	56,2	14,6
Sanitary condition of transport	23,2	56,6	20,2
Thermal regime in the cabin	24,5	50,9	24,6
Cabin ventilation, no exhaust odor	18,6	44,7	36,7
Information in transport (announcement of stops, availability and clarity of the route scheme information about the owner of the vehicle)	29,9	40,9	29,2
Appearance of the crew and level of service (polite correct attitude)	17,0	58,0	25,0

Source: results of my own scientific research.

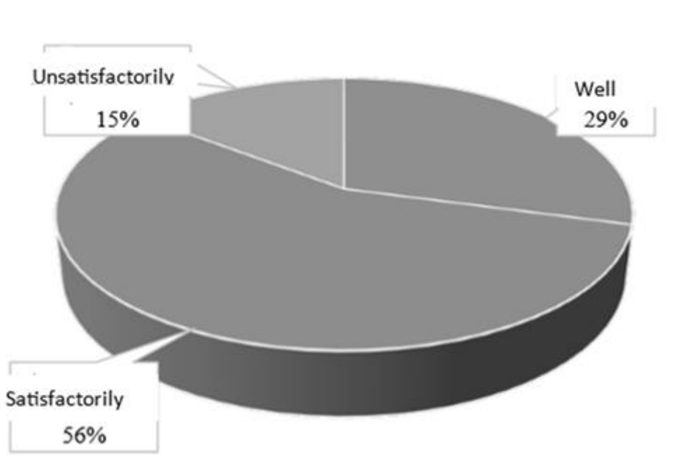

Fig. 2.13. Vehicle convenience

Source: results of my own scientific research.

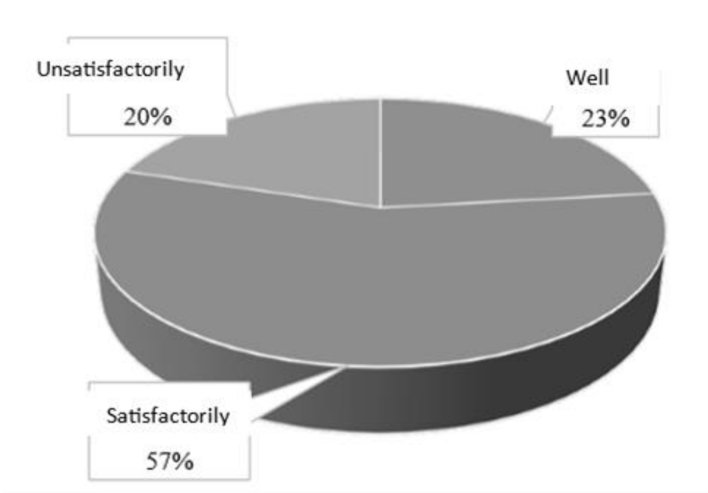

Fig. 2.14. Sanitary condition of transport

Source: results of my own scientific research.

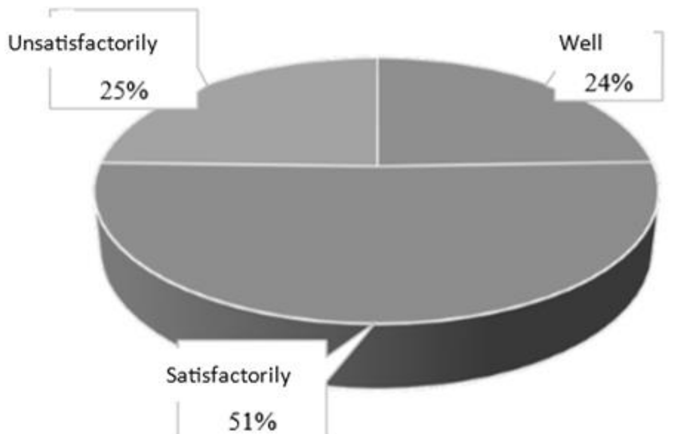

Fig. 2.15. Thermal regime in the cabin

Source: results of my own scientific research.

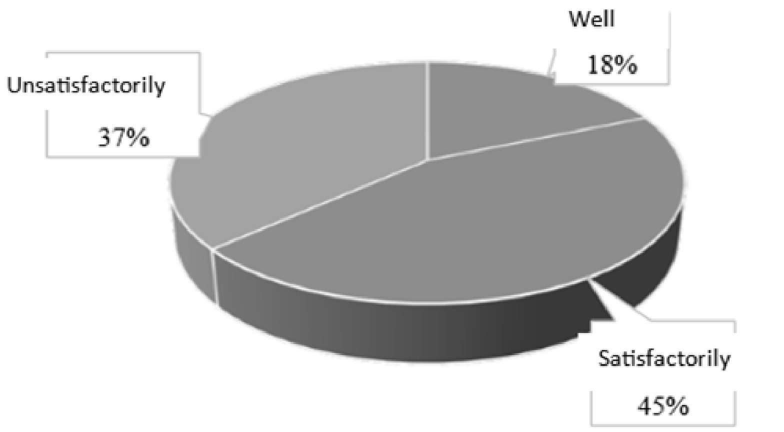

Fig. 2.16. Ventilation in the cabin

Source: results of my own scientific research.

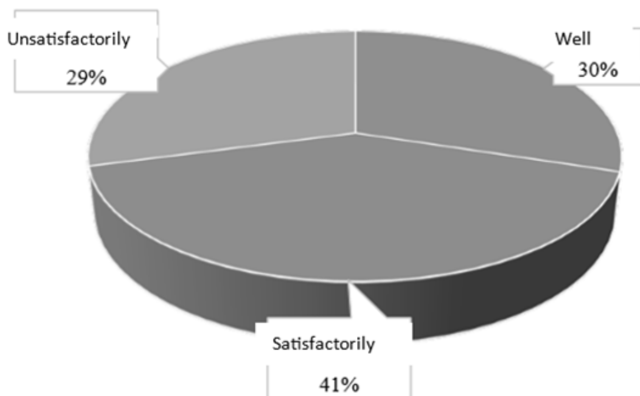

Fig. 2.17. Information in transport

Source: results of my own scientific research.

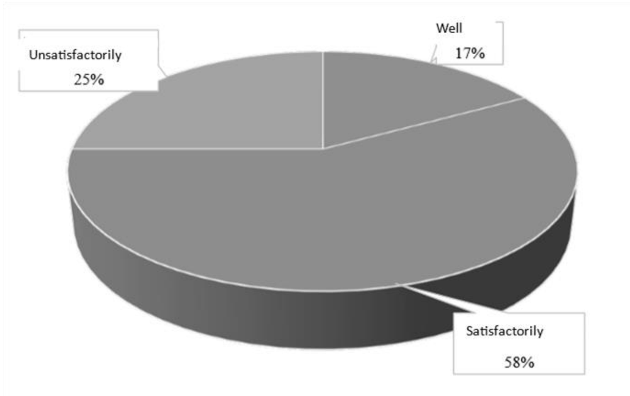

Fig. 2.18. Crew appearance

Source: results of my own scientific research.

Table 2.4 Passengers' proposals for improving the work of transport

Suggestion	Parameter's Weight, %
Renewal of the rolling stock fleet	26,5
Improve the quality of service	22,9
Qualifications, appearance and work of the crew	12,0
Increase the number of the rolling stock on the line	9,6
Increase the level of transportation safety	8,4
Increase the level of transportation comfort	4,8
Improvement of the route network	8,4
Improvement of bus stations	3,6
Lower passenger fare	3,6

Source: results of my own scientific research.

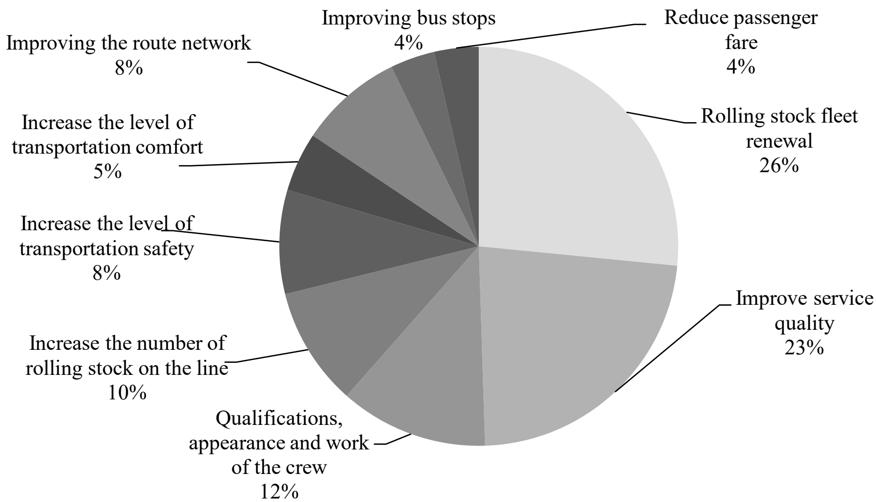

Fig. 2.19. Passengers' proposals for improving transport services

Source: results of my own scientific research.

Table 2.5 The importance of quality indicators for passengers

Indicator	Importance
Minimum waiting time for transport at the bus stop	13,7
Regularity	10,1
Environmental safety	1,8
Frequency of movement	5,7
Stop equipment	4,0
Minimum travel time	20,3
Seat softness	0,9
Illumination in the cabin	1,8
Direct trip	6,2
Announcing the names of stops	5,3
The proximity of the house to the stop	9,3
Fares	3,5
External attractiveness of transport	1,3

Timetable information	2,2
Availability of route maps in the cabin	0,9
Filling the bus cabin	9,3
Driver's skill	3,1
The width of the doors is clear	0,9

Source: results of my own scientific research.

As can be seen from the table, the main significant indicators for passengers are:

- minimum waiting time for transport at the bus stop;
- regularity;
- minimum travel time;
- direct trip;
- the proximity of the house to the stop;
- filling the bus cabin.

8.3. METHODOLOGY FOR ASSESSING THE QUALITY OF TRANSPORT SERVICE AND DEVELOPING WAYS TO IMPROVE IT

8.3.1. Methodology for assessing the quality of transport services

The indicators used to determine the quality of transport services are calculated for the reporting period. All indicators are traditionally divided into the corresponding components.

Accessibility of transport services is assessed using indicators:

- coefficient of territorial accessibility of stopping points;
- coefficient of accessibility of stopping points, bus terminals and bus stations for low-mobility population groups;
- coefficient of accessibility of vehicles for low-mobility population groups;
- coefficient of affordability of trips on regular transportation routes;
- coefficient of equipment of stopping points, bus terminals and bus stations with means of visual information for passengers;

– share of stopping points serviced with the minimum standard frequency (Tarandushka, Shlyonchak, Tarandushka, 2022).

1) Coefficient of territorial accessibility of stopping points, $k_{ac.st.}$:

$$k_{ac.st.} = \frac{Q_{\text{st.norm}}}{Q_{\text{st.p.}}} \tag{3.1}$$

where $Q_{\text{st. norm}}$ – the number of stopping points found within the normative values of the smallest distances of pedestrian paths to the stopping point;

$Q_{\text{st. p.}}$ – the number of stopping points.

2) The coefficient of accessibility of stop points, bus stations and bus stations for low-mobility population groups $k_{st.\ p.\ pg}$:

$$k_{st.p.pg} = \frac{Q_{st.DBN}}{Q_{st}} \tag{3.2}$$

where $Q_{\text{st. DBN}}$ – the number of stopping points that comply with DBN V.2.2-17:2006.

3) Coefficient of accessibility of vehicles for low-mobility population groups $k_{acc.p.g.}$:

$$k_{acc.p.g.} = \frac{Q_{v.lmg}}{Q_{tv}} \tag{3.3}$$

where $Q_{v.lmg}$ – the number of vehicles equipped with devices for transporting people with low-mobility and meeting the requirements established in DBN V.2.2-17:2006. Accessibility of buildings and structures for people with low-mobility; Q_{tv} – the total number of vehicles.

4) Affordability coefficient of trips on regular transportation routes k_{aff}:

$$k_{aff} = \frac{\text{B}}{\text{AIpers}} \tag{3.4}$$

where B – average monthly passenger expenses for trips by urban passenger transport, UAH;

AI_{pers} – average income per person in a region, UAH.

5) The reliability of transport service is assessed using the coefficient of adherence to the schedule of regular transport routes. The coefficient of adherence to the schedule of regular transport routes $k_{sch.\ r}$:

$$k_{sch.r} = \frac{Q_{\text{p}.tr.}}{Q_{\text{p}}} \tag{3.5}$$

where $Q_{p.tr.}$ – the number of trip when carrying out passenger transportation by urban passenger transport according to the schedule, or within the limits of permissible deviations from the schedule.

Q_p – the total number of trips when carrying out passenger transportation by urban passenger transport.

6) The comfort of transport service is assessed using indicators:

- the coefficient of equipping vehicles with passenger information means, k_{eq}:

$$k_{eq} = \frac{Q_{mv}}{Q_{tv}} \tag{3.6}$$

where $Q_{m.v.}$ – the number of vehicles equipped with passenger information devices.

- the share of vehicles with a standard noise level in the cabin, D_v:

$$D_v = \frac{Q_{\ v.norm}}{Q_{tv}} \tag{3.7}$$

where $Q_{\ v.norm}$ – the number of vehicles with a noise level in the cabin that meets the requirements established by Article 22 of the Law of Ukraine "Road Transport".

- the share of trips with a standard temperature in the vehicle cabin, $\text{D}_{\text{norm temp}}$:

$$D_{norm\ temp} = \frac{Qnorm\ trip}{Q_t} \cdot 100 \tag{3.8}$$

where $Q_{norm\ trip}$ – number of trips performed with the standard temperature in the cabin (Tarandushka, Kostyan, Tarandushka, 2021);

Q_t – the total number of MPT trips on regular transportation routes.

- the coefficient of compliance with capacity standards, k_{compl}:

$$k_{compl} = \frac{Q_{rout\ norm}}{Q_{\text{p}}} \tag{3.9}$$

where $Q_{rout\ norm}$ – is the number of trips complying with capacity standards (Oklander, 2021).

– the transfer coefficient k_{trans}:

$$k_{trans} = \frac{N_{n\,norm}}{N_n} \tag{3.10}$$

where $N_{n\,norm}$ − the number of passengers who make the standard number of transfers when moving to any point of the settlement (Fornalchyk et al., 2018).

N_n − the total number of passengers who make transfers when moving to any point of the settlement.

The share of vehicles of high environmental classes D_{eco}:

$$D_{eco} = \frac{Q_{v\,eco}}{Q_v} \tag{3.11}$$

where $Q_{v\,eco}$ – the number of vehicles of environmental classes EURO-4 and higher, intended for the transportation of passengers and luggage by road along regular transportation routes.

Depending on the interval of values calculated by formulas (3.1-3.11), the coefficient is assigned a score in accordance with tab. 3.1-3.5.

Table 3.1 Evaluation of quality coefficient values

Value range	Score for $k_{ac.\,st}$ $k_{st.\,p.\,pg}$ $k_{acc.p.g,}$ $k_{aff,}$ $k_{sch.\,r}$
less 0,11	1
from 0,1 to 0,2	2
from 0,2 to 0,3	3
from 0,3 to 0,4	4
from 0,4 to 0,5	5
from 0,5 to 0,6	6
from 0,6 to 0,7	7
from 0,7 to 0,8	8
from 0,8 to to 0,9	9
more 0,9	10

Source: adapted from work (Smirnov, Kosareva, 2021)

Table 3.2 Evaluation of quality coefficient values

Value range	Score for k_{aff}
less 0,02 and over 0,071	1
from 0,02 to 0,03 and from 0,06 to 0,07	4
from 0,03 to 0,04 and from0,05 to 0,067	7
from 0,04 to 0,05	10

Source: adapted from work (Smirnov, Kosareva, 2021)

Table 3.3 Evaluation of quality coefficient values

Value range	Score for $k_{sch.\ r}$
less 0,65	1
from 0,65 to 0,70	2
from 0,70 to 0,75	3
from 0,75 to 0,80	4
from 0,80 to 0,85	5
from 0,85 to 0,88	6
from 0,88 to 0,90	7
from 0,90 to to 0,93	8
from 0,93 to 0,95	9
More 0,95	10

Source: adapted from work (Smirnov, Kosareva, 2021)

Table 3.4 Evaluation of quality coefficient values

Value range	Score for k_{eq}
less 0,1	1
from 0,1 до 0,3	2
from 0,3 до 0,4	4
from 0,4 до 0,5	6
from 0,5 до 0,7	8
from 0,7 до 0,9	9
more 0,9	10

Source: adapted from work (Smirnov, Kosareva, 2021)

Table 3.5 Estimated values of the share of vehicles with regulatory noise levels in the cabin

Value range %	*Score for* D_v, $D_{norm\ temp}$, D_{eco}
less 10	1
from 10 to 20	2
from 20 to 30	3
from 30 to 40	4
from 40 to 50	5
from 50 to 60	6
from 60 to 70	7
from 70 to 80	8
from 80 to 90	9
more 90	10

Source: adapted from work (Smirnov, Kosareva, 2021)

The quality of transport services for the population during regular passenger transportation is determined by summing up the points assigned to the indicators given in the tables. Based on the results of the calculations, a conclusion is formed on the quality of transport services for the population along regular transportation routes in accordance with the values in tab. 3.6.

Table 3.6 Assessment of the quality of transport services for the population

The sum of the points assigned to the indicators	Quality of transport services to the population
less 39	unsatisfactory
39 – 65	minimum
65 – 104	average
more 104	high

Source: adapted from work (Smirnov, Kosareva, 2021)

The paper proposes a comprehensive assessment of the quality of transport services, based on the assessment of quality indicators with a detailed consideration of the most significant for passengers, namely: regularity coefficient; vehicle waiting time, travel time and transfer coefficient.

8.3.2. Analysis of the main quality indicators of the route network of the city of Cherkasy, the most significant for passengers

The assessment of the quality of passenger transportation is carried out using the quality indicators most significant for passengers. According to the results of the questionnaire, it was found that the main technical characteristics include parameters that determine the convenience of using the network and the level of transport service for the city's population:

- pedestrian accessibility of stops, population of the pedestrian accessibility zone;
- transport accessibility of the main transport centers of the city, the proportion of population movements with time costs that do not exceed the norms of the State Transport Code.

1) Pedestrian accessibility. Pedestrian accessibility of stops is defined as the distance of approach or time spent on movement to them. In accordance with the recommendations (Oliskevich, 2017), the maximum radius of pedestrian accessibility of stops (taking into account the non-linearity of the approach) is 400 m for areas with multi-storey buildings and 560 m in areas with low-rise (manor) buildings. Taking into account the non-linearity of the approach, the maximum permissible distance of pedestrian access to stops is 500 m for areas with multi-storey buildings and 700 m in areas with low-rise buildings. The average distance between passenger transport stops in Cherkasy is 0,6 km, the shortest distance is 0,2 km, the longest is 1,2 km. The average distance between stops in the central part of the city is 500 m. When analyzing pedestrian accessibility, we consider the city of Cherkasy without adjacent settlements. The results of the analysis of pedestrian accessibility of stopping points are given in Table 3.7.

Table 3.7 Number of residents living at different walking distances

Pedestrian accessibility radius, м	Specific gravity, %
0-100	29,9
100-200	31,7
200-300	18,8
300-400	5,3
400-500	4,0
500-600	10,0
600-700	0,3
Total	100,0

Source: adapted from work (Smirnov, Kosareva, 2021)

The table shows data on the number of residents living at different distances of the walking radius. From these data it can be seen that about 30% of the population lives within a walking distance of up to 100 m. About 86% of the population lives within a walking radius of up to 400 m. Within the maximum walking radius of 640 m, 100% of the population of Cherkasy lives.

The average interval of bus traffic on the route network is 2,5 minutes. Moreover, during off-peak periods, the interval practically does not change, that is, during periods of decreasing passenger flow intensity, the intensity of vehicle traffic does not decrease. There are 3 buses per 1 km of the public passenger transport network.

Within the regulated walking radius of public transport stops of 640 m, 100% of the population of Cherkasy lives. The average walking distance is about 87 m. Thus, we can conclude that the existing route network of the city of Cherkasy fully complies with the regulated parameters of pedestrian accessibility of stopping points.

Transport accessibility of the main transport centers of the city. The State Standard of the Russian Federation establishes the following norms for travel time (difficulty of connection) in work trips: the maximum time spent on a one-way trip for 80-90% of residents should not exceed 40 min. in large cities and 30 min. in other settlements. Travel time consists of the following costs:

- walking to the stop;
- waiting for transport at the stop;
- moving in a vehicle to the destination stop;
- walking to the destination (Smirnov, Kosareva, 2021).

If we roughly assume the average approach time to the stop is 2,5 minutes (average distance 200 m), the waiting time for the vehicle is about 1,5 minutes, then the travel time in a vehicle should not exceed 26 minutes. At an average connection speed of 20 km/h. the distance of the passenger's trip should not exceed 10 km.

To determine transport accessibility, we will consider the distribution of transportation by trip length. From fig. 1.1 it is clear that in Cherkasy about 30% of passengers spend more than 40 minutes on a trip with a standard of 10-20%, i.e. the route network of Cherkasy does not fully meet the requirement of transport accessibility. To meet this standard, it is necessary to increase the speed of communication on public passenger transport routes, i.e. to ensure priority movement of public rolling stock on the street and road network.

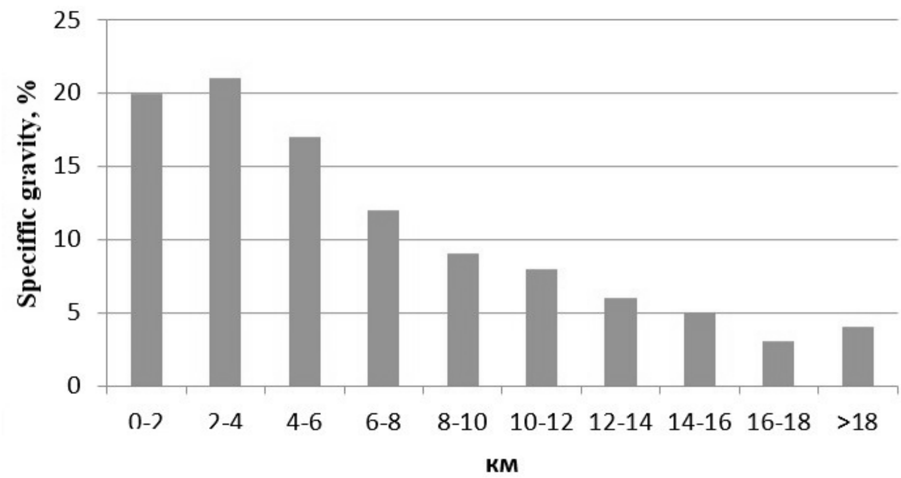

Fig. 3.1. Distribution of transportation by trip length

Source: results of own research.

Today, the route network of Cherkasy does not meet the requirement of transport accessibility: 25% of passengers spend more than 40 minutes on a trip (with a norm of 10-20%).

Let's consider the indicator "speed of connection", which affects the reduction of travel time, that is, the ratio of the length of the trip to the time of travel from the initial to the final point, taking into account the time spent on boarding and disembarking passengers at intermediate stops. The productivity of rolling stock, and therefore the cost of transport service, directly depends on the speed of connection. The average speed of bus connections is 21,5 km/h.

Routes are served with a higher speed of connection (up to 33 km/h), a significant part of which passes outside the densely populated part of Cherkasy.

Reliability and regularity of traffic is determined by the probability of completing the trip and the probability of disruptions in the traffic schedule (Will, 2018). Increasing the regularity of traffic is ensured by centralization and automation of traffic dispatching management, creation of a rolling stock reserve, transfer of drivers to a brigade form of labor organization, rational stimulation of drivers and dispatchers, increasing the reliability of rolling stock in operation, compliance of the route's carrying capacity with the needs for passenger transportation. Regularity of traffic is estimated by the regularity coefficient, K_{reg} – the ratio of the number of trips provided for by the traffic schedule N_{tr} for a certain period of time to the number of actually performed trips according to the schedule N_f.

$$K_{reg} = \frac{N_{tr}}{N_f} \tag{3.12}$$

Regular trip is a trip with an acceptable deviation from the schedule of ±2-5 minutes. Quality indicator K_{reg} – from 0.83 to 1 presents a summary of the release and trips of transport on routes. The number of vehicles assigned to the route and the value of the regularity coefficient are graphically depicted in fig. 3.2, 3.3.

Table 3.8 Summary of production and trips of transport on routes of Cherkasy from 01.01.2018 to 31.12.2018

Route number	Bus production			Trips		
	planned	actual	%	planned	actual	%
2	2920	2892	99,0411	11680	10480	89,72603
3	2555	2521	98,66928	10220	9175	89,77495
4	4380	4302	98,21918	26280	24993	95,10274
5	3285	3150	95,89041	13140	12042	91,64384
6	1825	1753	96,05479	7300	6344	86,90411
7	2920	2872	98,35616	14600	13632	93,36986
8	2920	2854	97,73973	11680	10813	92,57705
9	2555	2511	98,27789	10220	9185	89,8728
10	2920	2852	97,67123	11680	10926	93,54452
11	3285	3147	95,79909	13140	12264	93,33333
12	3650	3615	99,0411	10950	9796	89,46119
13	3285	3240	98,63014	13140	12184	92,72451
14	4380	4288	97,89954	17520	16486	94,09817
15	4015	3982	99,17808	16060	15167	94,4396
18	2555	2460	96,2818	10220	9108	89,11937
20	5475	5421	99,0137	27375	24530	89,60731
21	2920	2892	99,0411	11680	10635	91,05308
22	3650	3575	97,94521	14600	12725	87,15753
24	3285	3242	98,69102	13140	12075	91,89498
24	4380	4338	99,0411	17520	16155	92,2089
26	2555	2529	98,98239	10220	9575	93,68885
27	4015	3902	97,18555	20075	18788	93,58904
28	2555	2528	98,94325	10220	9222	90,23483
29	3650	3615	99,0411	10950	10077	92,0274
30	3285	3127	95,19026	13140	11601	88,28767
31	4380	4338	99,0411	17520	16353	93,33904
33	4015	3970	98,8792	12045	10713	88,94147
36	2920	2892	99,0411	11680	10480	89,72603

Source: results of own research.

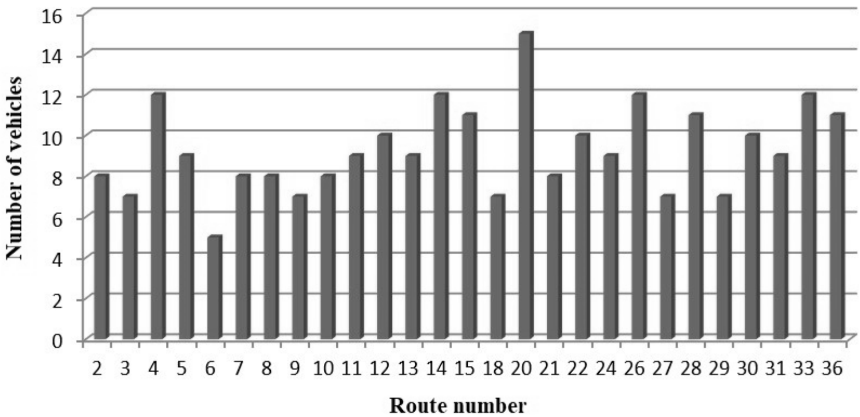

Fig. 3.2. Number of vehicles assigned to a route

Source: results of own research.

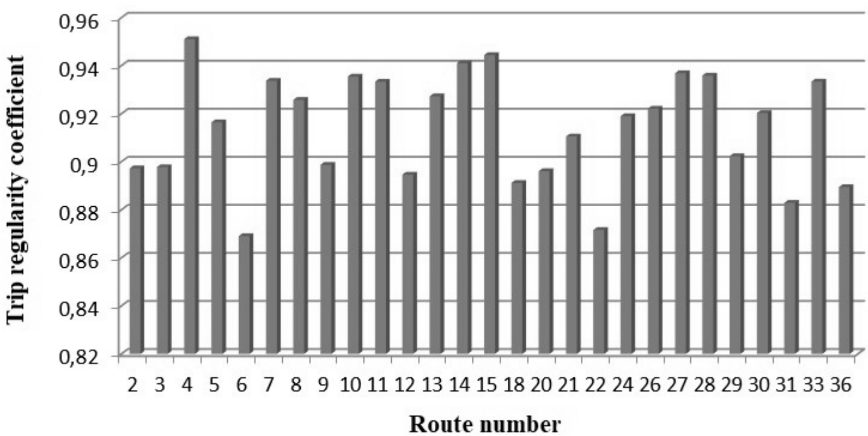

Fig. 3.3. Regularity coefficient of trips by route

Source: results of own research.

The average value of the regularity coefficient is 0,91, which indicates a high quality of transport service in terms of regularity of traffic. These indicators indicate a high quality of transportation.

Table 3.9 Results of the assessment of the quality of urban passenger transport services in the city of Cherkasy

Quality factors	Value	Score
$k_{ac.\ st}$	0,86	8
$k_{st.\ p.\ pg}$	0,17	2
$k_{acc.p.g}$	0,04	1
k_{aff}	0,5	5
$k_{sch.\ r}$	0,65	7
k_{eq};	0,025	4
k_{compl}	0,91	8
k_{trans}	0,9	9
D_v	35	4
$D_{norm\ temp}$	62	7
D_{eco}	70	8
Total		63 – minimum level

Source: results of own research.

8.3.3. Measures to improve the quality of transport services

The most important problem in the transport service of passengers in Cherkasy is the unsuitability of stopping points and vehicles for low-mobility population groups. Therefore, it is necessary to increase the number of vehicles equipped with devices for transporting low-mobility population groups. It is also necessary to equip stopping points for the convenience of use by these population groups.

The next problem of transport service in Cherkasy is the quality of service. The low quality of service is primarily due to:

- the use of rolling stock with inappropriate technical characteristics (the resource of use of vehicles has long been exhausted);
- the inadequate condition of the vehicle interior (sanitary condition, the presence of foreign objects in the interior, faulty passenger seats, etc.);
- the insufficiently polite attitude of the crew, the lack of additional information services, the provision of which is practiced in public transport of developed countries;

- unacceptable in some cases the interval of movement of vehicles along the route (the waiting time for the bus in some cases significantly exceeds the schedule due to traffic jams on the street and road network);
- poor technical and sanitary condition of stopping points (final and intermediate), lack of information about the movement of rolling stock (Kravchenko, 2008).

According to the results of the passenger survey, the following most urgent tasks for improving transport services for the population were identified: increasing the regularity of traffic on routes (today about 39% of passengers wait for transport for more than 10 minutes);

- increasing the speed of rolling stock connections on routes (the travel time of 30% of passengers exceeds 40 minutes, 20% of passengers spend more than 30 minutes in a vehicle per trip);
- improving information support for passengers;
- equipment of final and intermediate stopping points.

In Cherkasy, about 100 stopping points do not meet the requirements of the standard:

- at 45 stopping points there are no (or improperly equipped) landing areas;
- 55 stopping points are not equipped with pavilions (canopies) and the stopping areas are in unsatisfactory condition (uneven road, potholes).

According to approximate calculations, measures to equip and reconstruct intermediate stopping points in Cherkasy, taking into account the design estimate and installation work, are estimated at UAH 5.061 million.

When developing measures to technically equip final stopping points, they are divided into two categories: final points and final stations. Final stations must have appropriate infrastructure for the storage of rolling stock, household services for crew members. Final points are equipped mainly with turning areas (without storage facilities). Final points (with minimal technical equipment) are allowed in cases where: up to three routes are connected to them; each route must have at least one final station.

Table 3.10 Presents calculations of the cost of equipment of stopping points

Event name	Quantity	Price thousand UAH	Total, thousand UAH.	Design estimate and installation work (15%), thousand UAH.	Total, thousand UAH.
Landing pad equipment, м^2	675	1	675	101,25	776,25
Equipment for stopping areas, м^2	825	1,4	1155	173,25	1328,25
Additional equipment					
Pavilion, unit.	55	32,2	1771	265,65	2036,65
Stop signs, trash cans, etc., units.	100	0,8	800	120	920
Total					5061,15

Source: results of own research.

So, the measures that need to be taken to improve the quality of transport services in the Cherkasy MPT:

– introduction of vehicles for transporting low-mobility groups of the population;
– equipment of stopping points for convenient use by low-mobility groups of the population;
– increasing the level of comfort of vehicles;
– ensuring the safety of rolling stock movement and boarding and disembarking of passengers.

The mechanism of influence of quality of transport services on results of activity of motor transport enterprises is rather complex, and its action has the significant stochastic component which is explained by situational character. In general case, cause-effect and logical connections look as follows:

– improvement of quality of transport service at regional level leads to increase of satisfied solvent demand for transportation and excess of part of latent demand over satisfied demand for transportation;
– improvement of quality of transport service leads to redistribution of demand.

Persons who make short distance travel, begin to give preference to trips in buses instead of walking (it is economically most profitable), persons who previously used other types of transport, are attracted to these transportations;

- attraction of additional number of passengers provides increase of incomes. At the same time cost of transportation of passengers is reduced, since in proportion to growth of volume of transportations only variable expenses of the carrier increase;
- fixed costs (about 38% of all costs) remain practically at the initial level, since the growth in transportation volume usually does not exceed 10-15%. Thus, improving the quality of transport services improves the final economic indicators of the carrier.

8.4. ASSESSMENT OF PASSENGER FLOWS IN URBAN PUBLIC TRANSPORT

8.4.1. Frequency of population movements

The main concept of the theory of passenger transport, which characterizes the transport needs of the population, is correspondence. Correspondences are the movements of people associated with labor activity, social, cultural and household purposes.

Correspondences that are implemented using individual transport or public transport are called transport.

The set of passenger correspondences that are implemented is called passenger flows. Passenger flows have spatial and quantitative characteristics. The spatial characteristics of passenger flows are determined by observing the correspondence in the process of implementation.

The process of implementing correspondence consists of certain operations: movement to a public transport stop, waiting for transport, trip, transfer, trip after transfer, movement to the destination.

The main quantitative characteristics of passenger flows include:

- volume of transportation,
- transport work,
- intensity of transportation,
- average distance of the trip.

Volume of transportation Q – the number of passengers (correspondences) transported in a certain time.

The volume of transportation is determined in terms of the corresponding transport subsystem:

- route,
- network sections,
- stops,
- networks of a certain type of transport, and so on.

The number of passengers transported during a certain observation period T is equal to the number of route trips performed during this time, therefore:

$$Q = \sum ij \frac{Q_{ij}}{T} \tag{4.1}$$

where i is the index of the departure point;
j is the index of the arrival point.

Transport work (passenger turnover) P can be defined as the sum of the distances of correspondence sales for a certain time. Transport work is grouped according to the same principles as volume.

If l_{ij} is the distance of passenger correspondence Q_{ij}, then:

$$P = \sum ij \frac{Q_{ij} l_{ij}}{T} \tag{4.2}$$

One of the important characteristics is the trip distance L_{cp}, which can be defined as the average length of all passenger correspondences on a given route or across the network as a whole:

$$L_{\text{cp}} = \sum ij \frac{l_{ij}}{n} \tag{4.3}$$

where n is the total number of trips.

The main factors determining the average trip length are the territorial size of the city, the routing of the transport network, the route system and the planning structure of cities. This means that the mutual location of residential areas, industrial areas and recreation areas plays a major role. Most often, the demand for passenger transport services is presented in the form of a matrix of passenger correspondences. Correspondence matrices can be formed according to various criteria: by the purposes of transport correspondences, by types of transport, and so on.

Population mobility is the intensity of population movements, quantitatively expressed by an indicator called population mobility. Population mobility reflects the needs for movement and consists of the following parameters:

- time,
- point of departure and destination,

type of movement.

In general, mobility is understood as a set of correspondences that are brought to one person from a certain group of people for a particular calculated period of time (usually a year, day or hour of peak load of the transport network).

The study of the patterns of population mobility is a key issue for solving a wide range of transport and urban planning tasks. The main urban planning tasks are:

- development of the street and road network,
- development and optimization of passenger transport routes.

The relevance of this problem is now acutely felt in large cities, in which the transport system in many respects does not provide satisfaction of the needs of the population at the proper level.

8.4.2. Methods for assessing population mobility

Recent studies show that the transport mobility of the population is influenced by many factors, the study of which requires a systematic approach. Preliminary forecasting of the redistribution of transport flows by modes of transport and routes can significantly contribute to the development and use of more adequate transport technologies.

There are concepts of potential, realized, absolute, general, pedestrian and transport mobility.

Potential mobility is called mobility that meets the population's demand for movement, which is determined by its production needs, biological and social needs, the development of information and communication technologies, lifestyle, and cultural needs. Since potential mobility is influenced by a large number of factors that have a complex relationship with each other, it is impossible to determine potential mobility.

Actual mobility is called realized mobility, which is realized in given conditions of place and time. It depends on the limitations of the daily budget, self-organization, and time. It can be determined by surveys. The mobility of the urban population, which is realized, depends on the planning features of cities, their size, the location of centers of gravity in them, the development of transport systems serving them. All these factors determine the accessibility of mass-visited objects, which is estimated by the time spent on movement.

Absolute mobility is the number of movements that occur per unit of time (year, day) by one person belonging to a certain population group and participating in movements. Absolute mobility of the city's own population (p_{nm}), participating in movements, the population of the suburbs, arriving depending on labor and cultural and household needs (p_{np}) and the population arriving from other cities (p_{nim}) (Kashkanov & Kashkanov, Varchuk, 2017):

$$p_{nm} = \frac{P_m}{N_m} \tag{4.4}$$

$$p_{np} = \frac{P_{pm}}{N_{pm}} \tag{4.5}$$

$$p_{nim} = \frac{P_{nim}}{N_{nim}} \tag{4.6}$$

where P_m, P_{pm} and P_{nim} are the number of trips in the estimated time period made in the city, respectively, by the city's own population N_m, the population of the suburbs participating in trips on the urban transport network N_{pm} and the population from other cities N_{nim}.

Absolute mobility is the actual mobility that can be determined by field surveys of road traffic within the city, within the district, within the city zones (for the central, middle and peripheral zones of the city).

Total mobility is the number of trips on the urban transport network per unit of time (year, day, hour) by all population groups participating in the trips, relative to the number of population N_m registered within the administrative boundaries of the city (Kashkanov & Kashkanov, Varchuk, 2017):

$$p_t = \frac{P_m + P_{pm} + P_{nim}}{N_m} = \frac{P_0}{N_m} \tag{4.7}$$

where $P_0 = P_m + P_{pm} + P_{nim}$ – the total number of trips on the urban transport network for the estimated time period.

Total mobility is a calculated characteristic that does not determine the actual movements of city residents. It is used only for calculations of urban transport routes.

Movement on urban transport networks is carried out partly on foot on footpaths, on urban passenger transport (UPT) and individual passenger transport (IPT). Therefore, total mobility p_t is divided into pedestrian and transport, and transport – into UPT mobility and IPT mobility (Kashkanov & Kashkanov, Varchuk, 2017):

$$p_{\mathrm{t}} = \frac{\mathrm{P_0}}{\mathrm{N_m}} = \frac{\mathrm{P_{ped}} + \mathrm{P_{tr}}}{\mathrm{N_m}} = p_{\mathrm{ped}} + p_{\mathrm{TP}} \tag{4.8}$$

$$p_{\mathrm{tr}} = \frac{\mathrm{P_{tr}}}{\mathrm{N_m}} = \frac{\mathrm{P_{UPT}} + \mathrm{P_{IPT}}}{\mathrm{N_m}} = p_{\mathrm{UPT}} + p_{\mathrm{IPT}} \tag{4.9}$$

where P_{ped}, P_{tr} – the number of pedestrian and transport movements per city resident per year;

P_{UPT}, P_{IPT} – the number of transport movements carried out using UPT and IPT (per inhabitant per year);

P_{ped}, P_{tr}, P_{UPT}+P_{IPT} – mobility, respectively, pedestrian, general transport, mobility of urban passenger transport and mobility of individual passenger transport.

Transport mobility, which includes only full trips, that is, from the place of boarding to the required end point of the trip, is called network transport mobility. Such mobility does not take into account transfers within one mode of transport or from one mode of transport to another. If trips are taken into account only within one route and each trip with one transfer is considered two, and with two – three, then such mobility is called route.

Usually, route trips are indicated in reporting and statistical data, therefore, the transport mobility calculated on them will be route. It should be noted that the transport mobility p_t and p_{mp} in (4.8) and (4.9) are defined as the number of trips per year per inhabitant, carried out using vehicles. It is numerically equal to the number of network trips of the population in the city for a given period. During surveys and according to reporting data, the volume of trips in route trips is determined. Mobility in route trips can much exceed the calculated one in network (Kashkanov & Kashkanov, Varchuk, 2017):

$$p_{\text{UPT(m)}} = p_{\text{tr}} \cdot k_{\text{per}} \tag{4.10}$$

where k_{per} is the average transfer coefficient in network trips.

Trips of a particular passenger are of a completely specific nature. However, transport movements (as a manifestation of mass behaviour of a large number of passengers) can be considered a statistical phenomenon, that is, they can be described only with a certain probability. Therefore, the characteristics of the need for movement are random variables. In the absence of specific data, aggregated standards are used.

Transport mobility has large limits of fluctuation. It varies depending on the size of the city, its planning, the city's provision with vehicles and other factors. Usually, the population of the city is taken as a generalized indicator when analyzing transport mobility, and the influence of other factors is taken into account by the permissible limits of fluctuation of this indicator.

Transport movements are studied in terms of types of transport, purposes and time of travel. Depending on the purposes, trips are considered:

- labor − to work and from work, these trips are the most stable and in cities make up 50 – 60% of trips on UPT routes;
- educational − trips of students to educational institutions and back, which are also of a sustainable nature with breaks during vacations;
- cultural and everyday trips − trips for various personal and everyday needs of citizens, such as those that are episodic and significantly dependent on income, social status, occupation and age of passengers;
- business trips, carried out during the passenger's working hours in connection with production needs.

Work and educational trips make up up to 3/4 of the total number of trips. The share of trips for various purposes varies depending on the development and composition of the urban-forming base, the proximity of its objects to the places of residence of the population. The need for trips naturally varies by period of the day, reaching a maximum during peak hours.

Peak hours are called periods of time during which the carrying capacity of the transport system is used to the maximum extent. During peak hours, mainly work and educational trips are carried out. The following characteristic periods are distinguished by the intensity of demand for transport services:

- initial (from the start of traffic to 7 a.m.);
- morning peak (7...9 a.m.);
- interpeak period (9...17 hours);
- evening peak (17...20 hours);
- final (from 20 hours to the end of the movement) (Shlyonchak, Lukyanchenko, Kharenko, 2022).

It is incorrect to assume the same norm of population mobility for different cities in different topographical, climatic and especially socio-economic conditions. The most influential factors on population mobility are the number of the population, the territory of the city, as well as a number of factors (Zaporozhets, Boychenko, Matveeva, 2017):

- age composition of the population;
- social composition of the population;
- cultural level of the population;
- housing security of the population;
- material well-being of the population;
- the presence of a large number of transit persons;
- the shape, size and nature of the city's planning;
- the quality of the vehicles.

The dependence of the population's mobility on its total number is explained by three factors (Zaporozhets, Boychenko, Matveeva, 2017).

The absolute number of trips among residents of a large city is greater than among residents of a small city. Residents of small cities stay at home more, since such cities have fewer cultural recreation facilities, entertainment, etc. The attraction to large cities is explained precisely by the fact that they have the best theatres, cinemas, libraries, stadiums and other cultural benefits, which are inaccessible to a small city in such a volume and with such a high degree of perfection.

Distances of trips. Since the distances of trips in a small city are shorter, most of the trips in it are made on foot. The share of trips by mechanical transport, even with its best development, in the total number of trips is less than in a large city. The quality of the operation of means of transport, which in a small city usually receive less development.

The factors listed above for the growth of population mobility are valid for small and medium-sized cities, and for large cities play a smaller role. The main factors influencing the increase in the mobility of large cities are as follows:

- increase in the material well-being of the population;
- increase in cultural needs;
- improvement in the quantity and quality of means of transport, introduction of new types of transport, increase in speed of movement, development of the street and road network, etc.

It should be noted that the development of large cities also creates such factors that cause a decrease in mobility. First of all, this direction is influenced by the growing housing construction, the ability to change apartments, settle near the place of work. The construction of shopping centers, cinemas, stadiums in district centers, etc. also plays a large role.

For large cities, it is also necessary to take into account the large percentage of commuters. Every large city, in its growth and the growth of its industry, attracts suburban settlements into its orbit. Suburban passengers put an additional burden on urban transport. It is likely that with the growth of housing construction, the number of suburban residents arriving in the city daily will decrease slightly, but the number of summer cottage and excursion trips will increase.

8.4.3. Methods for studying population transport mobility

To identify passenger flows, distribute them by direction, and collect data on changes in passenger flows over time, studies are conducted. Existing methods of studying passenger flows can be classified by characteristics. According to the duration of the period, systematic and one-time studies are distinguished. Systematic studies are conducted daily throughout the entire period of movement by operation service employees. One-time studies are short-term studies according to one or another program, which is determined by the goals set.

According to the scope of coverage of the transport network, continuous and selective studies are distinguished. Continuous studies are conducted simultaneously across the entire transport network of the served settlement or region. They require a large number of controllers. Based on the results of the studies, issues of the functioning of the transport network, directions of its development, coordination of the work of various types of transport, change of route schemes, selection of types of transport in accordance with the capacity of passenger flows are decided. Selective surveys are conducted in separate traffic areas, conflict points, or some routes in order to solve local, private problems. Traditionally, in practice, the following methods are used to study passenger traffic:

– questionnaire method;
– reporting and statistical method;
– field method;
– automated method.

The questionnaire method of the survey is carried out using questionnaires, the content and number of questions in which depend on the objectives of the survey. During the questionnaire or survey of the population, data on the mobility of the population, the time of movement, the time spent on movement and their structure are obtained. Two methods of conducting surveys prevail. In the first, questionnaires are collected at the place of residence or work and are digitized (the complexity of preparing the questionnaire, depending on its volume, can be from 10 to 30 minutes). The second option involves conducting interviews directly in the rolling stock or at stops. The greatest effect of the questionnaire survey is obtained when surveying the population at the place of work of the main passenger-generating and passenger-absorbing points of the served area (Tarandushka, Kostyan, Tarandushka, 2021).

The reporting and statistical method of the survey is based on data from ticket and registration sheets, the number of tickets sold. In addition to tickets sold, it is necessary to take into account the number of people transported on monthly travel tickets, service cards and people who use the right to free preferential travel, as well as those who did not purchase a ticket.

Field surveys are implemented using coupon, tabular, visual, silhouette and survey methods. The coupon method of surveying passenger flows allows you to have information about the capacity of passenger flow along the length of the route and time of day, about passenger exchange at stops, passenger correspondence, and about the filling of rolling stock. When surveying using this method, preliminary preparation is required, which includes developing a program and calculating the required number of accountants and controllers. The survey program determines the technological sequence of work with an indication of the deadlines. The quality of the information received largely depends on the clarity of the work of the counters and controllers, as well as on the preparedness and awareness of passengers. During the inspection, the counters at each stop, starting from the final one, issue tickets to all passengers who have entered, having previously noted the number of the stop at which the passenger entered. For each direction of movement, their own tickets are used, as a rule, of different colours, with increasing or decreasing stop numbers. When exiting, passengers hand over the tickets, and the counters mark the number of the stop at which the passenger got off. When transferring, passengers tear off the corresponding inscription on the ticket. At the final stops, the counters hand over the used tickets for a specific trip to the controller and receive new ones.

The tabular method of inspection is carried out by the counters, who are located inside the bus near each door. The accountants are provided with survey tables, which, in addition to data on the bus, its departure and change, indicate the trip numbers in the direct and return directions, the time of their departure and the place of stop. For each stop, the accountants enter the number of passengers who entered and exited in the appropriate columns, and then calculate the filling on the route sections. The accounting and registration of passengers moving are carried out separately by each accountant, and the processing of the received data is carried out jointly.

The tabular method can be used for systematic and one-time, continuous and selective surveys. For continuous and systematic surveys, the form of the tables should allow processing of survey data using a PC. For this purpose, the tables are grouped, and then they are divided by days of the week, routes, hours of the day the bus leaves and work shifts.

The visual or survey method of the survey is used to collect data at stops with significant passenger traffic. The accountants visually determine the occupancy of buses according to a conditional point system, and this information is entered into special tables. For example, 1 point is assigned when there are free seats for sitting in the bus cabin; 2 points − when all seats for sitting are occupied; 3 points − when passengers stand freely in the aisles and accumulation areas; 4 points – when the nominal capacity is fully used and 5 points − when the bus is full, and some passengers remain at the stop. Points are entered into the table according to the make and model of the bus. Knowing the number of seats for sitting and the capacity of a specific make and model of bus, you can go from points to the number of passengers traveling. The visual method in the point assessment of occupancy can be used by bus drivers or conductors who are issued a registration table. After the change, the tables are handed over to line dispatchers, and in the operation department they are summarized. This method is more often used in a sample survey.

The silhouette method is a type of visual with the same areas of use. Instead of a point assessment of the filling of buses, a set of silhouettes by bus types is used, which is constantly with the accountants, who select the silhouette number that coincides with the filling of the bus, and enter it into the table. Each silhouette corresponds to a certain number of passengers moving. The interview method of passenger flow survey involves the use of accountants who, being in the bus cabin, interview incoming passengers about the exit point, destination, transfer, purpose of the trip and record this information. This method allows you to obtain data on passenger correspondence, which helps to adjust routes and develop organizational measures to reduce passenger transfer time.

Surveys of bus operations and passenger flow detection are extremely laborious and usually require the involvement of a large number of accountants, which can be high school students, students. In addition, processing the data collected as a result of surveys requires considerable time, and as a result, these data reflect the nature of changes in passenger flows over the past period (Izteleuova et al., 2021).

8.4.4. Automated passenger flow monitoring systems

The use of traditional methods for studying passenger flows for a number of reasons does not allow obtaining a high-quality result. The main disadvantages are: the impossibility of involving a large number of accountants for surveys; significant costs for the labor of accountants and persons who digitize the received data. In this regard, automated methods for surveying passenger flows are being developed and implemented, which provide information in a processed form without involving a large number of people, and are also able to reduce the cost of the procedure for surveying passenger flows. Currently, about twenty different passenger flow accounting systems of domestic and foreign production are offered in our country. For monitoring passenger flows, the most important role is played not so much by the system for managing the collection, processing and transmission of information as by the type of sensors used for passenger registration.

According to the principle of operation, contact and contactless sensors are distinguished (fig. 4.1).

Two types of contact sensors are used: push-button (for counters) and "step" type. With the rapid development of information technology, contactless sensors have become the most widespread. By technological feature, they are of the following types: light, laser, infrared, photo registration, video registration, thermal. Manual counters (clickers) are mechanically driven and electronic. Their principle of operation is based on fixing numbers by pressing the counter key with a finger. Examples of mechanical and electronic clickers offered on the market are presented in fig. 4.2.

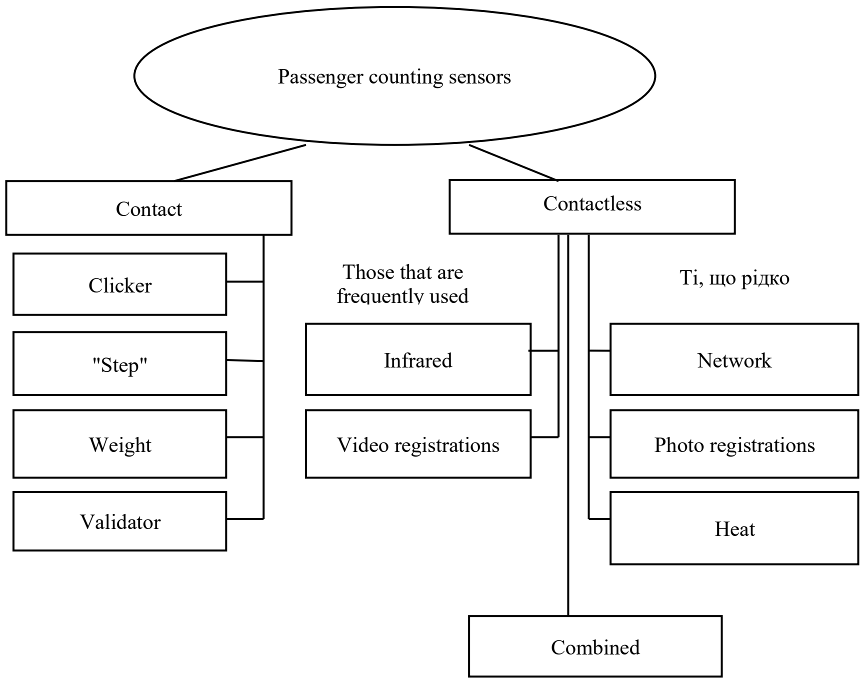

Fig. 4.1. Classification of passenger counting sensors

Source: results of own research.

a) b)

Fig. 4.2. Types of clickers

Source: results of own research.

Abroad, clickers are common when counting passengers, transported. When working, the accountant has one device in each hand. With one clicker, he counts the passengers entering, and with the other, the passengers leaving. This method is advisable to use to count the number of passengers who have travelled during 1 trip or the whole day of transport operation. It is also possible to count the passengers entering and leaving each stop, but in this case, the results should be recorded on pre-prepared accounting forms. In the latter case, clickers are used as an element of the tabular method of counting the number of passengers to reduce the psychological load of the accountant and reduce the influence of the peculiarities of his memory on the results of the studies.

The error of the survey results depends mainly on the human factor and can be 3% – 30%. This accounting system does not allow automatically recording the stopping points, coordinates and time of passenger registration.

The contact sensor of the “Step” type (fig. 4.3) was developed during the Soviet Union (about 40 years ago). These sensors were most widely used on PAZ, “Bogdan”, and “Gazelle” buses. The principle of passenger counting is based on the closing of the contacts of the plate located under the rubber flooring on the first step of the bus. The sensor can be connected to both the local on-board system and used in conjunction with the on-board GPS/GLONASS monitoring terminal.

The "Step" sensor is intended for counting passengers entering or exiting in one row, and it must be located so that passengers cannot stand on it.

That is, it is applicable to buses with narrow doors and short steps, which is typical for suburban and intercity buses, as well as old-style trolleybuses. Counting passengers entering and exiting is possible when two sensors are located on the steps, provided that software is available that allows identifying the sequence of contact closure on both sensors. To eliminate false positives, the analysis of presses is performed only with the doors open. The error of the device is determined based on the characteristics of the daily load of the vehicle and is 5-7%.

Fig. 4.3. Location of the equipment of the "Shodinka" complex on a vehicle

Source: results of own research.

A sensor for determining the total mass of the vehicle (such sensors are called weight sensors) allows you to determine the number of passengers in the vehicle cabin by calculation. The principle of its operation is to record the total weight of the vehicle. Before starting work, the device is calibrated without passengers in the bus cabin (the mass of the empty vehicle is determined). The average estimated body weight of one passenger is taken as 70 kg. Based on these data and indicators from the sensors, the number of passengers in the cabin is calculated. The sensors provide suspension of each of the vehicle wheels. They are connected to both local and network devices. Examples of sensors are presented in fig. 4.4.

These sensors have not received mass distribution in passenger road transport. Since they determine the passenger flow by indirect indicators, the error reaches from 20% to 50%, while they are unable to determine the number of passengers entering and leaving.

a) b) c)

Fig. 4.4. Sensors measuring mass: a) pressure type, b) beam type, c) example of placing a strain gauge on a vehicle cabin support

Source: results of own research.

Validator – a device for controlling and accounting for travel documents made on electronic media. Various systems using magnetic cards and RFID technologies are currently widespread in passenger transport. The latter are contactless means of payment for travel, but work at short distances (up to 50 mm), for reading and recording information on a travel document. The number of passengers is determined by counting the number of activations of their travel documents. Travel document control is carried out using a stationary or portable reading device – a validator (fig. 4.5).

a)

b)

c)

Fig. 4.5. Validators

a), b) – stationary, c) – manual

Source: results of own research.

The disadvantages of using validators include underregistration of passengers who have just entered. This technology is used in cases where there are no tariff zones on city routes and it is not necessary to re-check travel documents when the passenger leaves the vehicle. In addition, such terminals should be used on all city vehicles with a unified fare payment system.

The operation of contactless sensors is based on the use of methods for determining the presence of passengers that do not require direct contact with the human body. The signal of the presence of a passenger is the interruption or reflection of various types of rays directed at a person. Infrared sensors come in three types: beam, passive, active two-beam, active multi-beam, 3D type. The most common infrared sensors with an emitter and receiver manufactured by Autograph and SKP-0371 systems. The principle of operation is based on counting interruptions in the infrared radiation flow when the beam is crossed by a passenger entering or leaving the vehicle (passenger passengers are counted). Passengers are counted and data is stored at time intervals. At the same time, the total number of passengers for a set interval is recorded in the counter's memory with the date and time. Examples of such sensors are shown in fig. 4.6.

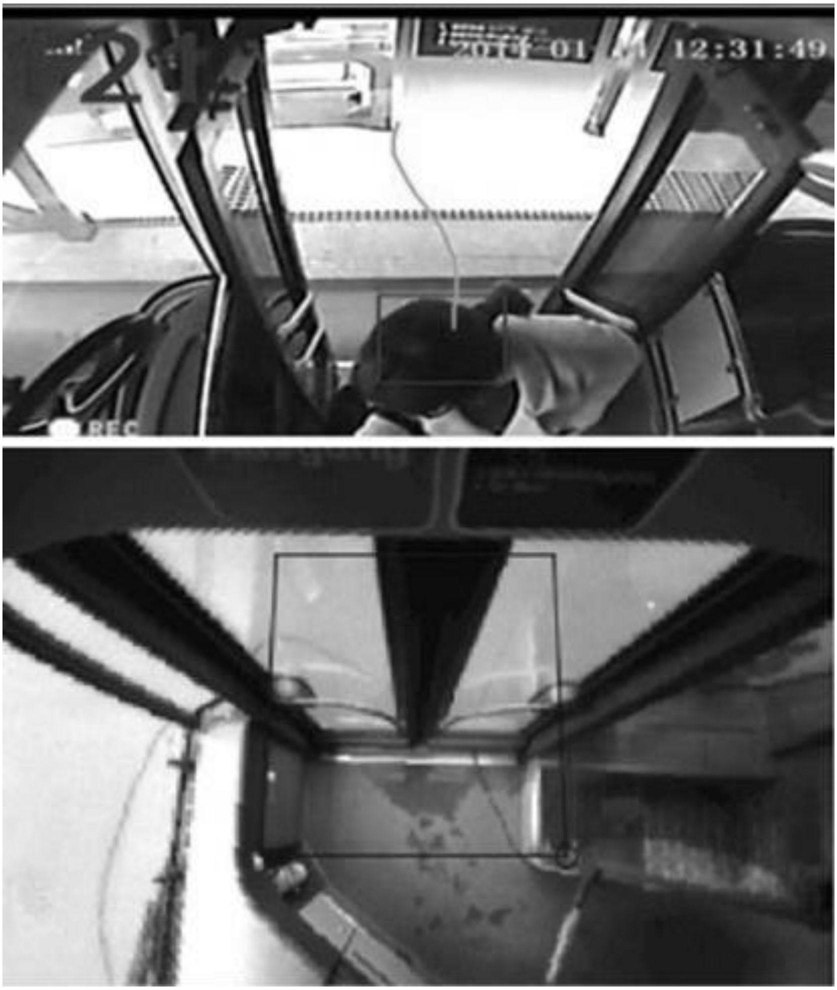

Fig. 4.6. Infrared sensors

Source: results of own research.

Such systems do not allow determining the exact number of passengers entering and exiting at each stop. These sensors can give an error of up to 50%, since passengers entering in a dense stream during rush hours are not taken into account. Also, the temporary exit and return of passengers who let other passengers through when the cabin is crowded are not taken into account. Common passive infrared sensors include the passenger flow counting sensor Sh2 and its analogues (fig. 4.7). The principle of operation of a passive sensor is to detect the entry or exit of a passenger using a combination of volumetric analysis of the object and its thermal radiation. The detection pulse is formed into an information link and transmitted to the analyzing device. The result of the operation of these sensors is similar to beam infrared sensors – they register the number of recognized objects without taking into account the direction of movement and can be used only for trip and daily accounting of passenger flows. To find out the number of passengers transported, it is necessary to divide the obtained number per trip by two. The error in the trip registration of passengers entering and leaving is no more than 10%.

Fig. 4.7. Examples of installation of passive infrared sensors type Sh2

Source: results of own research.

An active two-beam sensor is installed in the vehicle doorway on the ceiling in the area of the door opening mechanism. Active-type infrared sensors work by reflecting rays. Each sensor includes two pairs of emitters-receivers to ensure counting in two directions. Two rays directed at the first and second steps of the door vestibule allow determining the direction of the passenger's movement based on the sequence of intersection of the rays (fig. 4.8).

A feature of two-beam infrared sensors is the ability to count incoming and outgoing passengers. These sensors are installed one for each passage in one direction and two for each passage in both directions. Two-beam sensors "MID-485" use a short wavelength (about 0.5 m), which justifies the error of up to 20%, while the error of counting outgoing passengers is 1.5-2 times greater than that of incoming passengers. Foreign analogues, such as IRMA-S, have an error of up to 10%.

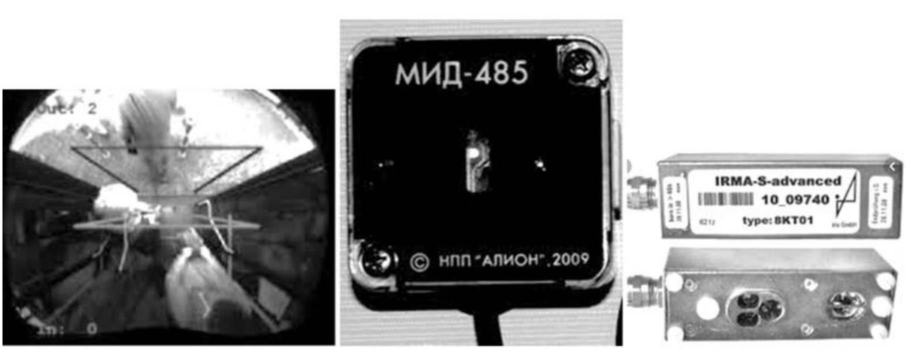

Fig. 4.8. Examples of system sensors: a) "MID-485", b) IRMA – S

Source: results of own research.

The active multi-beam sensor operates in a similar way to the two-beam sensor. Its difference is the presence of a battery of two-beam sensors, which allows for maximum coverage of the required control area (like a “curtain”) and increases the accuracy of passenger counting to 90-95% (fig. 4.9).

Fig. 4.9. Active multi-beam infrared sensors

Source: results of own research.

As practice shows, with proper setup, foreign analogues show 5-7% higher accuracy of results. The 3D (stereo) sensor is based on the technology of active infrared radiation in a three-dimensional format (thermal imager), which allows for the most accurate identification of even passengers traveling together, with subsequent recognition of information (fig. 4.10).

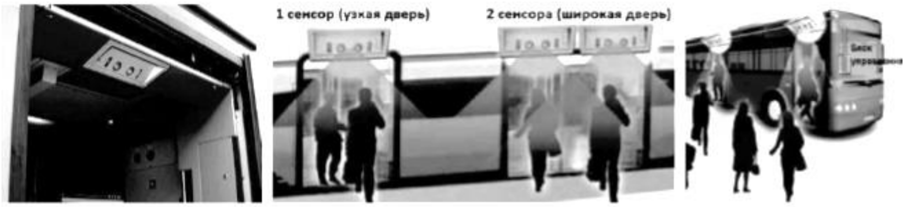

Fig. 4.10. 3D passenger counting sensors

Source: results of own research.

The advantages of the sensor include its high accuracy of operation – the error is no more than 3-5%, and the disadvantages include a significant price. Video recording systems differ in the parameters of the video cameras and the presence or absence of an image recognition system. Most of the systems offered on the market are conventional video surveillance systems with recording of data obtained from the video cameras via a video recorder to a flash card. The recording frequency for 4 video cameras (medium and large-capacity buses) is about 6 frames per second. Some systems use image recognition systems as part of or in addition to them – these are horizontal systems for recognizing a person's figure (by the shape and color of clothing), human face recognition systems and vertical human profile recognition systems. Some video surveillance systems and the results of video recording are presented in fig. 4.11.

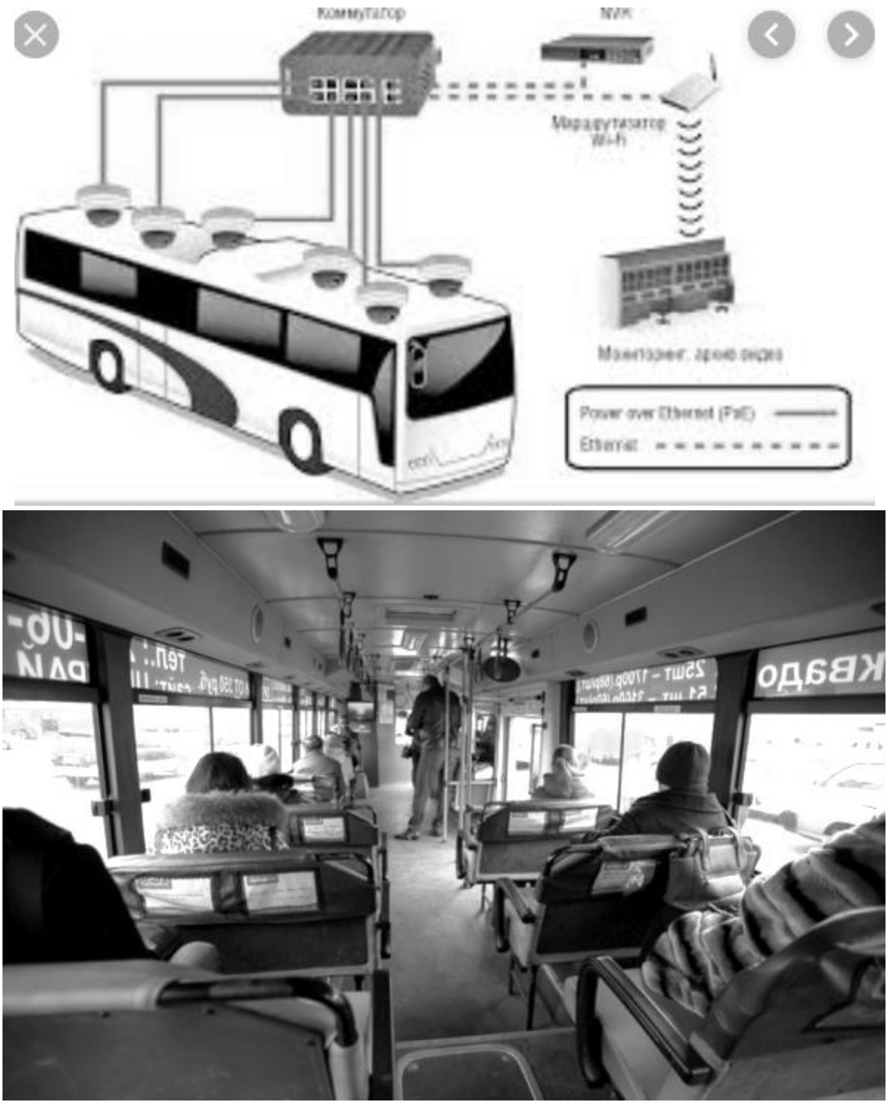

Fig. 4.11. Video equipment options and results of monitoring passengers in urban transport

Source: results of own research.

The advantages of video surveillance systems include the ability to save video data and confirm monitoring results at any time. The disadvantage is the lack of automation of data processing and significant laboriousness of work. The error can be 5 – 20%. When using image recognition systems (some vertical systems take into account the direction of movement of people), automated data processing is carried out, however, depending on the quality of the video material (screen illumination, image blur, etc.), the error in passenger counting results can be 10-80%.

Rarely used sensors include light, photo recorders and thermal sensors. The reasons for their rare use are low accuracy of accounting (error 30 – 60%). The analysis showed that currently different manufacturers offer different devices for automated monitoring of passenger flows. The practical feasibility of using certain systems depends on the financial capabilities of the monitoring entity, the number of vehicles and their design, the need for detailed monitoring results and their required accuracy (Izteleuova et al., 2021).

8.4.5. Methodology for analyzing population demand for transport services

The formation of a matrix of passenger correspondences is the main and most difficult task from a mathematical point of view in all studies related to structural or parametric changes in passenger flows. Mathematical models for evaluating correspondence matrices are based on probabilistic and analytical methods.

With all the variety of mathematical methods for modeling population correspondences, it is possible to clearly divide them into two classes: probabilistic and extrapolative (May, 2016).

In the practice of transport planning, models of the second class are most widely used. This is primarily due to their higher (compared to models of the first class) accuracy.

Probabilistic models are based on statistical analysis of data on actual correspondences. This analysis makes it possible to build relationships, usually linear, between the predicted values of correspondences and such characteristics of the calculation areas as the population and its transport mobility, the total number of workplaces and cultural and household facilities, the level of transport service, etc.

The first mathematical model of correspondence between two transport areas appeared more than 100 years ago, when the Viennese engineer von Lille formulated the law of passenger transport movement. He studied railway passenger transport and derived a mathematical relationship, which later became widespread in the calculations of urban passenger flows and was called the "gravity model". Gravity models got this name due to the fact that they are similar to the law of gravitational attraction. In them, the values of correspondences are directly proportional to the volumes of departures from one transport area and arrivals to another, and inversely proportional to the distance between these areas (May, 2016). The traditional gravitational model is built on the following hypothesis:

$$b_{ij} = K \cdot HO_i \cdot HP_j \cdot f(c) \quad (4.10)$$

where b_{ij} – potential correspondences between districts i and j;

K – calibration coefficient;

HO_i – volume of departure from district i (capacity of the district upon departure);

HP_j – capacity of arrival in district j (capacity of the district upon arrival);

i – number of the district of departure of correspondence;

j – number of the district of arrival of correspondence.

In this case, the following constraints must also be met, which ensure the condition of balance of the correspondence matrix:

$$\sum_{j=1}^{n} h_{ij} = HO_i, i = \overline{1,n} \quad (4.11)$$

$$\sum_{i=1}^{n} h_{ij} = HP_i, j = \overline{1,n} \quad (4.12)$$

where n is the number of transport districts.

The calculation correspondences between transport areas are determined based on the following relationship:

$$h_{ijk} = \frac{HO_i \cdot HP_{ik} \cdot k_{ijk} \cdot d_{ij}}{\sum_{j=1}^{n}(HP_{ik} \cdot k_{ijk} \cdot d_{ij})} \quad (4.13)$$

where h_{ijk} – estimated correspondences between districts i and j at the k -th iteration;

d_{ij} – attraction function between districts i and j;

k_{ijk} – equalizing attraction coefficient of trips from district i to j at the k -th iteration.

The formation of the correspondence matrix in this case is performed using an iterative procedure, which is carried out to the value $k_{ijk} = 1$.

The advantages of the traditional gravity model include the availability of initial information and the simplicity of performing calculations. As a disadvantage, it should be noted that the existing implementation option is not strictly justified from a mathematical point of view, since the calculation formula only reflects the general relationships between the parameters of the model, but does not guarantee a complete analogy of the correspondences between the transport areas of the city and the force of mutual attraction of physical forces (May, 2016).

The entropy model for calculating the correspondence matrix is based on the hypothesis of the analogy of the formation of the value of passenger correspondence with thermodynamic processes. The basis for calculating the value of correspondence according to the entropy model is the value of the average time spent on labor travel. To find the value of the correspondence, it is necessary to optimize the functional:

$$S = \left(-\sum_{i=1}^{n}\sum_{j=1}^{n} h_{ij} \cdot \ln\left(\mathrm{h_{ij}}\right)\right) \rightarrow max \qquad (4.14)$$

where S – entropy of the system; n – number of transport districts in the city, units; h_{ij} – value of correspondences between departure district i and arrival district j, pass.

The disadvantage of the entropy model is the formation of a matrix of passenger correspondences based on only one transport parameter, while the task of determining the demand for movement is multi-criteria. Extrapolation models for calculating passenger correspondences are based on certain a priori logical hypotheses regarding the regularities of the formation of passenger connections between the calculated areas.

The essence of extrapolation methods is that the existing transport flows obtained from survey materials are extrapolated into the future using growth factors.

Growth factors, in turn, are determined from the functions of their dependence on one or more factors that affect the change in transport flows:

- population;
- number of attractions;
- density of the main street and road network;
- uneven distribution of transport flows in time and over a given territory;
- remoteness of areas from the city center.

The following extrapolation methods can be used for forecast calculations: the single growth rate method; the average growth rate method; the Detroit method; the Fratar method; the method of interacting potentials.

The method of a single growth coefficient should be used for an approximate determination of the load on individual elements of the street and road network for the next 3-5 years. The load on the street and road network can be determined in two ways: depending on the availability of data from several surveys of traffic intensity or in their absence. If data from several surveys are available for some sufficiently long period of time, a trend in the growth of traffic intensity on individual main streets (roads) or in concentric zones of the city (central, middle, peripheral) is established in accordance with the change in any interconnected factor (May, 2016).

The method of average growth coefficients is used for an approximate calculation of the load on the street and road network (district) of the city for the next 5-7 years. This method takes into account the development rates of individual zones (districts) of the city and can be used with small errors with minor changes and differences of these coefficients from the average value for the city. The method of average growth rates is based on actual correspondences obtained from statistical data using the growth rate (May, 2016):

$$K_{i(j)} = \frac{P_{i(j)}'}{P_{i(j)}} \tag{4.15}$$

where $K_{i(j)}$ is the growth rate;

$P_{i(j)}$ is the existing traffic volume generated in the transport zone (district);

$P_{i(j)}'$ is the expected traffic volume in the transport zone or district, determined by a number of factors using a multiple regression equation.

When determining the prospective traffic intensity between two transport zones (districts) *i* and *j,* the formula (May, 2016) is used:

$$P_{i(j)}'=P_{ij}\,\frac{K_i+K_j}{2} \tag{4.16}$$

where P_{ij} − existing correspondence;

K_i and K_j − coefficients of growth of traffic volumes in zones (areas) of departure *i* and arrival *j*.

The Detroit method is designed to calculate transport correspondences for a period of 10-15 years by successive approximations to the final results using the average growth rates of the intensity of transport connections of corresponding pairs and the average growth rate of traffic intensity on the entire given street and road network.

The Detroit method is used to determine the intensity of traffic between zones (districts) of the city if data on existing correspondences are available (May, 2016):

$$P_{i(j)}{}'=P_{ij}\,\frac{K_i\cdot K_j}{K} \tag{4.17}$$

where K is the coefficient of growth of traffic intensity on the entire street and road network of the city, determined by the formula (Shibayama, T., 2017):

$$K=\frac{\sum_i P_i\cdot K_i}{\sum P_i} \tag{4.18}$$

Formula (4.18) is intended only for calculating interzonal (interdistrict) correspondences. Intrazonal (intradistrict) movements are determined separately or it is assumed that their specific weight in the volume of traffic in the zone (district) remains unchanged for the calculation period. The accuracy of the forecast according to the Detroit method is quite high, but it requires adjusting the obtained correspondences by successive approximations (iterations) to the given volumes of traffic in the zone (district), which can give a significant error in the case of a large difference in the growth rates of a given zone (district) and the city as a whole (Shibayama, T., 2017).

The Fratar method was developed in the early 50s of the last century in the USA by Professor Thomas J. Fratar. It uses an iterative process of approximation to the final solution. Moreover, the results of the calculation of each intermediate step are the initial data for the subsequent one. This process is carried out until equality is achieved between the predetermined value of the transport turnover of the area and the sum of correspondences obtained as a result of the calculation for this area. The Fratar method has received the greatest distribution among all extrapolation methods for forming the correspondence matrix (Shibayama, T., 2017).

The main assumption used in the Fratar method is that the number of trips from the i-th zone to the j-th for some future moment of time is proportional to the initial number of all trips from the i-th zone, multiplied by the development coefficient of the j-th zone (Shibayama, T., 2017):

$$T_{ij} = t_{ij} \cdot \frac{P_i}{p_i} \cdot \frac{A_j}{a_j} \cdot \frac{\sum_k t_{ik}}{\sum_k \left[\frac{A_k}{a_k}\right] \cdot t_{ik}} \tag{4.19}$$

where T_{ij} − predicted number of correspondences from zone i to zone j;

t_{ij} − number of correspondences from zone i to zone j;

P_i − predicted number of correspondences from zone i;

p_i − number of correspondences in zone i;

A_j − predicted number of correspondences in zone j;

a_j − number of correspondences in zone j;

k − total number of zones.

The method of interacting potentials for calculating transport flows for a period of 15-20 years is based on the obtained matrices of correspondences of freight and passenger transport during an experimental survey. Prospective transport flows are determined through the dependencies between the corresponding calculation zones on the relative magnitudes of changes in these zones and in the city as a whole of several main factors: the city's car fleet, population size and the number of jobs in the calculation zones. The method does not require iterative processes (Shibayama, T., 2017).

8.4.6. Fare payment system in passenger transport

The fare payment system (fig. 4.12) is a combination of the form of concluding a transportation contract and the method of collecting fares and is characterized by: methods of receiving money for travel from passengers, travel documents used, organization of revenue collection, control over the completeness of fare payment, implementation of fare payment benefits, organization of ticket refunds.

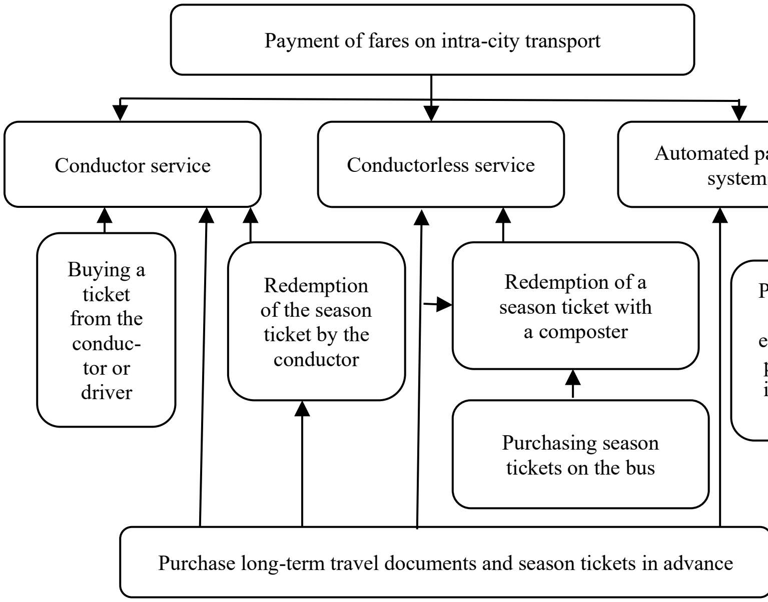

Fig. 4.12. Fare payment system for intra-city transport

Source: results of own research.

In road transport, depending on the types of transport, different fare payment systems are used. Passengers pay for intra-city transport either directly in the vehicle or in advance. With conductor service, the main part of the fare is collected by the conductor by selling tickets to passengers in the bus cabin. Some passengers can purchase season tickets in advance, which are used as tickets. In this case, the season ticket is redeemed at the ticket machine directly in the bus cabin. Long-term travel tickets are presented by passengers to the conductor when entering the bus. Conductor service is most widely used in urban transport.

The advantages of the conductor method include high revenue and the ability to obtain data on ticket sales by trips and stops, which provides information on passenger traffic. The disadvantages of the conductor method are high labor intensity and additional costs for conductors' wages. With a high occupancy of vehicle cabins with passengers during peak hours, the conductor's work is complicated.

Conductorless service allows you to abandon conductors and uses two methods: cash and cashless. With the cash method, which was widely used in cities in the last quarter of the 20th century, the passenger put money into a sealed cash register installed in the bus cabin and tore off the ticket himself. The disadvantages of the cash method are weak control over revenue and the possibility of passengers not paying for their fare in full.

The cashless method is based on the passenger purchasing season tickets in advance, before the trip. A travel ticket is a season ticket, redeemed by the passenger himself using a composter in the bus cabin. The cashless method can be used only if the distribution of season tickets is established in the city. With the cashless method, passengers pay the carrier in advance, which has a positive effect on the financial condition of transport enterprises. However, the absence of a conductor in the bus cabin leads to a decrease in the completeness of the fare payment by passengers. Achievements of scientific and technological progress have allowed in recent years to begin the implementation of automated fare control systems (ASCOP). In large cities, an automated fare control system in urban transport has been put into operation. The passenger's passage into the transport cabin occurs through a turnstile located behind the front door of the bus. The turnstile has a device for controlling magnetic tickets. The main advantage of such a system is the reduction of ticketless people. The disadvantages include increased parking time at stops in connection with the payment of fare. Entry to the bus is through a turnstile mounted in the doorway. To pass through the turnstile, the passenger inserts a magnetic ticket into the reader or walks through the turnstile with a smart card in his pocket. The magnetic ticket is made of thin cardboard with a magnetic strip applied to it, on which information is recorded in encoded form. When passing through the turnstile, information about the redemption of one trip is sent to the magnetic ticket, which does not allow unlimited use of such a ticket. The smart card is made in the form of a plastic card with a microcircuit pressed into it. The information from the microcircuit is read by the turnstile equipment in a contactless manner.

Due to the rapid development of information technologies in transport, traditional fare payment is gradually becoming a thing of the past. The introduction of an automated fare payment system (AFPS) and electronic transport cards, the number of which is constantly growing, is replacing cash payment for travel.

The automated fare payment system is a new stage in the development of passenger transport. It allows you to transfer payments for travel to a cashless form. The large volume of collected data on travel makes it possible to analyze and further optimize the operation of transport. AFPS transfers the work of all participants to an electronic form, provides, in conjunction with other electronic systems (global positioning, scheduling systems, security systems), a greater effect, a modern look and a completely different approach to organizing the work of urban transport. The automated fare payment system consists of a processing center, a network for transmitting these, and system workstations. The processing center includes a database server, where all data generated by the system workstations flow, a data collection server and a WEB server of the system workstations. All this is called the system processing center. The data transmission network is built on the basis of the Internet and the wireless GPRS (3G) transmission network. ASOP workstations include:

- workstations for accessing ASOP database information;
- on-board equipment of vehicles: validators, conductor terminals, GPS devices;
- network for selling and replenishing transport cards;
- subsystem for manufacturing transport cards.

Within the framework of the automated fare payment system, both conductor and conductorless service options can be implemented. With the conductor method, autonomous equipment is used – check or checkless terminals. With the conductorless passenger service scheme, stationary equipment is used – a validator, which is fixed to the handrail, has a screen, sound and light support for paying the fare (fig. 4.13).

a) b)

Fig. 4.13. On-board equipment for fare payment: a) terminal; b) validator

Source: results of own research.

To calculate passengers in transport in the automated fare payment system, plastic cards are used, which are smart cards with an integrated microcircuit that allow storing and processing information in electronic form. The main advantages of smart cards are as follows: large memory capacity (at least 32 KB) allows storing service information and performing necessary operations without connecting to the processing center; the presence of a reliable built-in data protection system; data exchange with the reader in encrypted form; high durability and reliability in operation. Depending on the purpose, smart cards can be made with a microprocessor or only with an integrated memory microcircuit. According to the method of data exchange with the reader, smart cards can have a contact, contactless or dual interface. The block diagram of a smart card is shown in fig. 4.14.

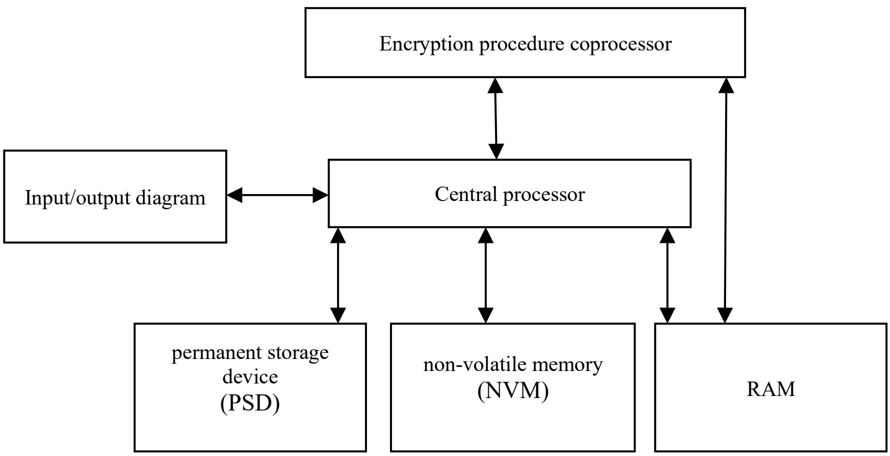

Fig. 4.14. Block diagram of the operation of a smart card with a microprocessor

Source: results of own research.

The central processor controls the reading, processing and storage of data. Permanent data generated during the manufacture of a smart card is stored in a non-volatile memory (NVM), user data and program code are written to non-volatile memory (NVM). For processing, the data is transferred to random access memory (RAM). To relieve the microprocessor of resource-intensive data encryption operations, the coprocessor is entrusted with data exchange with the reader using an input-output circuit.

To pay for a fare, the passenger presents a smart card to a special stationary device equipped with the vehicle (in case of conductor-free service) or to a local terminal located with the conductor. The fare, which is determined by the type of transport and the passenger (adult, student, etc.), is automatically deducted from the amount on the card, and at the same time a record of the payment (transaction) is recorded in the terminal's memory.

A transaction is a record in a database that contains transaction characteristics, including information about the route, direction of travel, date and time of the transaction, and the passenger's characteristics recorded on his smart card (regular passenger or concessionaire). Thus, carriers and APT owners have a tool for collecting information on fare payment and transmitting it to the municipality. Carriers receive funds in accordance with the volume of transportation performed using the electronic card. Passengers – owners of electronic cards – purchase trips by purchasing cards or replenishing them using payment terminals. Payment for travel is made using an electronic card, which is a universal means of payment in any type of public transport, except for taxis (the diagram is given in fig. 4.15).

Fig. 4.15. Diagram of interaction between participants in the passenger transport trip accounting system using electronic cards

Source: results of own research.

For road transport enterprises, the introduction of an electronic ticket means the emergence of transparency in calculations, the ability to receive compensation for the transportation of preferential categories of passengers for the actually performed volumes, the elimination of factors of conductor fraud. For passengers, a commercial ticket is the convenience of calculations, as well as the ability to save money (if there are discount programs).

Electronic fare payment systems and transport cards used within these systems are of great interest to researchers. The emergence of new sources of information about the mobility of the urban population makes it possible to search for new methods of identifying traffic patterns that can be obtained as a result of processing accumulated information about transactions. Thus, traditional methods of surveying passenger flows may be able to be supplemented with information about already known traffic patterns, which will lead to an increase in the accuracy of operating costs and a reduction in research costs.

7.5. Conclusions

The analysis of the regulatory framework and scientific works on the topic of assessment and standardization of quality parameters of transport services by urban passenger transport of general use showed that it is possible to single out a common nomenclature of quality indicators for all works and documents:

- Availability
- reliability;
- Regularity;
- Economy;
- security.

There is a problem of standardization of the quality of general use UPT (Urban Public Transport) and is determined by the fact that the well-known methods of quality assessment contain a list of quality indicators formed on the basis of theoretical experience. The method of determining the values of all the presented indicators is quite complex in application and in some cases not objective. The significance of a separate indicator for the passenger is not taken into account. A nomenclature of quality indicators for its comprehensive assessment is defined, based on the opinion of experts (authors of scientific papers) and the opinion of passengers. To determine the significance of quality parameters for passengers, a questionnaire was conducted, its results showed the most significant factors were for passengers:

- Minimum waiting time for transport at the bus stop
- Regularity

- Minimum travel time
- Direct trip
- The proximity of the house to the stop
- Filling the bus cabin

Therefore, the paper presents a methodology for assessing the quality of transport services, taking into account the significance of parameters for passengers, based on the calculation of coefficients that determine the degree of compliance of the quality parameter with the standard value.

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Appendix A

Questionnaire for passengers

Dear passengers! We ask you to take part in a study aimed at improving the quality of transport services by public urban passenger transport. Your opinion is very important to us. We ask you to take a few minutes and fill out this form.

1. Specify your gender

- Female
- Male

2. Enter your age

- less than 17
- 17-24
- 25-34
- 35-44
- 45-54
- more than 55

3. How many days a week do you use public transport (on average)

____

4. What type of transport do you use most often, please indicate the type and route number

Mode of transport	Never	Sometimes	Often	Route number
Bus				
Trolleybus				
Other (which)				

Source: own work.

5. Specify the purpose of your trips (several answer options are possible)

– Work
– teaching
– Customers
– shopping centers
– health care institutions
– other (specify)

6. How much time do you spend on a one-way trip?

Time to approach the stop __________________

Waiting time ______________________

Travel time _______________________

7. Are you satisfied with the quality of passenger transportation services

1) completely satisfying
2) satisfies faster
3) rather not satisfying
4) Not completely satisfying
5) difficult to answer

8. What does the quality of transport service mean to you personally?

____

____

9. Evaluate the condition of public transport stops on a 10-point scale, where 1 corresponds to "very bad", 10 – "excellent"

Information about traffic (availability, clarity, correspondence to reality)	1	2	3	4	5	6	7	8	9	10
Sanitary Stop Status	1	2	3	4	5	6	7	8	9	10
Equipment of stops (sheds, landing sites, garbage bins, etc.)	1	2	3	4	5	6	7	8	9	10
Transport work evening time	1	2	3	4	5	6	7	8	9	10

Source: own work.

10. Rate the driving conditions on a 10-point scale, where 1 corresponds to "very bad", 10 – "excellent"

Convenience of the vehicle (wide aisles, large storage areas, comfortable seats, etc.)		1	2	3	4	5	6	7	8	9	10
Sanitary condition of transport		1	2	3	4	5	6	7	8	9	10
Thermal regime in the cabin		1	2	3	4	5	6	7	8	9	10
Cabin ventilation, no exhaust odor		1	2	3	4	5	6	7	8	9	10
Information in transport (announcement of stops, availability and clarity of the route scheme, information about the owner of the transport)		1	2	3	4	5	6	7	8	9	10
Appearance of the crew and level of service (polite correct attitude)		1	2	3	4	5	6	7	8	9	10

Source: own work.

11. Your suggestions for improving transport services for the population (several answer options are possible)

1) Renewal of the rolling stock fleet
2) Improve the quality of service
3) Qualifications, appearance and work of the crew

4) Increase the number of rolling stock on the line
5) Increase the level of transportation comfort
6) Improvement of the route network
7) Improvement of bus stations
8) Lower passenger fare
9) Other

12. Evaluate the degree of importance of the presented quality indicators for you personally and how much this indicator is actually implemented according to a scale from 1 to 10, where 1 is not important at all, 10 is very important

Trouble-free operation of transport (no breakdowns)	**Importance**	**Implementation**
Minimal time Waiting Transport At the bus stop		
Reliability (movement is accurate on schedule)		
Environmental safety		
Frequency of movement		
Availability of free seating		
Stop equipment		
Minimum movement time		
Seat softness		
Illumination in the cabin		
Direct trip		
Announcing the names of stops		
The proximity of the house to the stop		
Fares		
External attractiveness of transport		
Timetable information		
Availability of route maps in the cabin		
Interior filling		
Driver's skill		
The width of the doors is clear		

Source: own work.

Chapter 9.

OPTIMIZATION OF PUBLIC TRANSPORT TRAFFIC IN THE CONDITIONS OF THE TRANSPORT SYSTEM

Nataliia Kostian

9.1. Relevance of the research problem

The reason for the significant attention to public urban transport is the need to improve the ecological condition of cities, reduce the carbon footprint of a person, increase the comfort and speed of passenger movement. These tasks are becoming increasingly relevant in the context of a stable growth in the share of the urban population worldwide. Modern urban studies of the problems of population movement within the city (Scott, 2012, Tuli, 2019) pay significant attention to the issues of maximum abandonment of personal cars in favor of other means of transportation. The low level of income of the population and insufficient budget financing of public transport in Ukraine affect the quality of transport services. This leads to trends when the number of traffic jams increases in Ukrainian cities, pollution increases, and parking problems are observed in centers of gravity. All this worsens the conditions for the operation of urban transport. Solving these problems requires new solutions to improve the operation of public transport, including at the local level. The task of developing and gradually increasing the share of public urban transport by reducing the use of private transport should be considered comprehensively both in terms of improving the quality of transport services and in terms of popularizing this type of transport among the most economically active population. However, an important aspect that affects the level of satisfaction of the requirements of disadvantaged categories of the population regarding the quality of transport services is the predictability of travel time by urban transport. Accordingly, the most unpredictable component of such a trip is the waiting time at urban transport stops. On the other hand, for transport operators it is important to determine the frequency of movement at which the maximum load of a route vehicle is achieved. The presence of private carriers on the transport services market has partially solved the problem of insufficient vehicles and improved the quality of service. In terms of the number of regular routes and carriers, the passenger transport network of Cherkasy is redundant, so the level of passenger service is determined by the quality of work of individual carriers. A large number of duplicate bus and trolleybus routes causes simultaneous arrival of transport at stops, creates problems with boarding passengers on the vehicle of the desired route and causes additional time spent waiting for transport on other routes. These factors lead to an increase in the duration of the trip and reduce the productivity of route vehicles. In addition, the safety of passenger service deteriorates. Failure to comply with the city transport schedule causes complaints from passengers. Using a scientific approach to reduce the share of duplicate routes in the city network is one of the ways to optimize it.

The transport network of Cherkasy has a complex structure, in which a larger share falls on small-capacity minibuses. An increase in the intensity of minibus traffic leads to network overload, deterioration of the environmental situation in the city and excessive competition between carriers. To improve the operation of the transport network, it is advisable to rely on current mathematical models: classical optimization, models of mass service systems, simulation and others. In this case, it is necessary to take into account the interests of both carriers and passengers (Izteleuova et al., 2021, Huk, Shkodovskyi, 2009, Koryagin, Katargin, 2016, Koryagin, 2008). In studies (Izteleuova, 2021, Huk, Shkodovskyi, 2009), duplication of routes and the difference in fares in minibuses and trolleybuses were not taken into account. In (Koryagin, Katargin, 2016, Koryagin, 2008, Koryagin, 2014), the process of passenger service is investigated from the point of view of competition between passenger transport enterprises. In these studies, optimization models are based on the application of mass transit systems and game theory. The author of (Koryagin, Katargin, 2016) simulated the flow of minibuses, passenger transport under traffic light regulation, and the behavior of passenger traffic when the vehicle is full. However, when solving the problem of optimizing transport traffic, environmental damage is equated to the cost of transportation. Input information for determining the parameters of the transport network can be obtained using questionnaire survey methods and observation methods. Thus, based on the questionnaire, the authors (Aulin, Holub, 2007) conducted a study of factors affecting the quality of passenger service by public transport. The works are of a computational and analytical nature without identifying optimal modes of transport operation. In work (Horokhovskyi, Oshovska, Shevchuk, 2015), the parameters of passenger flows and vehicles are studied, forecasting methods are used, but the economic and environmental indicators of urban passenger transport are not considered. In (Kara, 2017), a mathematical model for determining passenger flows on urban public transport routes was built based on information about transactions of mobile phone subscribers. However, in Ukraine, institutions interested in optimizing transport networks do not have free access to this information, and citizens can be subscribers of several mobile phone companies at the same time.

In (Mateichyk et al., 2023), it was proven that the number of passengers transported by large-class buses during the day has a significant impact on the efficiency of passenger transport. However, the resulting mathematical models do not take into account the volume of transport flows.

In the process of improving the operation of public transport, it is necessary to take into account the peculiarities of all elements of the transport system in which transport operates. The study (Smieszek et al., 2023) analyzed recent studies on the composition of the urban transport system and identified its four main elements: vehicle, transport flow and environment. The renewal of the public transport fleet and the improvement of urban roads require significant financial investments and are usually planned in the long term. Traffic flow management is possible in real time through intelligent transport systems. Therefore, the search for new approaches and expansion of existing models for optimizing urban transport systems should be implemented by determining the rational size and composition of public transport flows under given conditions.

Despite the large number of studies of public transport traffic patterns, the search for new ways to reduce the impact of bus and trolleybus traffic on the traffic environment and participants in the transport process remains relevant.

The aim of the work is to optimize public transport traffic in the city of Cherkasy by reducing travel time by urban passenger transport and reducing the level of duplication of routes by alternative modes of transport.

To achieve the goal, the following tasks were formulated in the work:

– analysis of the existing transport system serving the population by passenger public transport in the city of Cherkasy;

- studying the population's demand for urban passenger transportation through questionnaires;
- construction of a mathematical model for optimizing the route network of passenger public transport;
- implementation of a mathematical model and analysis of the implementation results in comparison with the existing network of Cherkasy.

Determining the rational number of vehicles on city routes in the process of optimizing the city transport network will ensure a balance between the population's needs for transportation and minimal harm to the city from using the fleet of municipal and private carriers.

9.2 Analysis of the existing public service system by urban passenger public transport

Passenger transportation is carried out on 45 city routes, of which 21 routes are operated by buses and 24 by trolleybuses (1 of which is seasonal). Currently, Cherkasy has a municipal enterprise “Cherkasyelectrotrans” of the Cherkasy City Council and 9 private carriers: SE “CHARZ-avto”; PJSC “Cherkasyavtotrans”; PJSC “Cherkasy ATP-17127”; PE “Medit-Service”; PE “Elit-Trans”; LLC “Avto-TUL”; LLC “Kyytrans-2005”; FOP “Bakashev B.A.”; FOP “Kopievsky E.P.” In the process of studying ways to improve the city transport network of Cherkasy, an analysis of the routes and structure of the transport fleet of 5 major motor transport enterprises providing relevant services was carried out (tab. 1-5).

Table 1. General description of trolleybus routes of the “Cherkasyelectrotrans” municipal enterprise

№	Route No	Starting and ending points of movement	Number of vehicles on the line	Length, km	Movement interval, min.	
					Rush hour ($7^{00} – 9^{99}$/ 15^{00} –19^{00})	Interpeak period
1	1	ChLFZ "Avrora" – sanatorium "Ukraine"	8	25,18	7-10	10-15
2	1A	Patsaeva str. – sanatorium "Ukraine"	4	25,08	15-20	20-30
3	2	Patsaeva str. – ChSHK	2	18,16	30	40-50
4	3	sanatorium "Ukraine" – railway station	3	18	20-30	30-40

5	4	General Momota str. – trolleybus depot	2	26,34	30-40	до 100
6	4A	General Momota str. – railway station	4	18,1	30	до 60
7	7	Mozhaiskogo str. – trolleybus depot	3	17,74	20	30-40
8	7A	sanatorium "Ukraine" – trolleybus depot	10	25,08	8-15	20
9	8	ChLFZ "Avrora" – Rustavi str.	5	27,9	30-40	до 120
10	8P	ChLFZ "Avrora" – airport	3	24,5	30-40	до 100
11	10	river port – Oleny Teligy str.	14	22,26	8-10	до 15
12	14	Onoprienka str. – airport	2	18,4	40	60
13	50	cargo port – airport	2	19,88	30-40	до 100

Source: results of own research.

Table 2. General description of bus routes of PJSC "Cherkasyavtotrans"

№	Route No	Starting and ending points of movement	Number of vehicles on the line	Length, km	Movement interval, min.	
					Rush hour (7^{00} – 9^{99}/ 15^{00} –19^{00})	Rush hour (7^{00} – 9^{99}/ 15^{00} –19^{00})
1	8	Center – Surikova str.	8	13,34	5-6	10-15
1	21	Mytnytsia district – Patsaeva str.	14	25,74	6	14
2	26	Regional Hospital – Bus Station	8	17,6	8-10	12-20
3	27	railway station – Narbutivska str.	4	14,94	20-30	30-40

Source: results of own research.

Table 3. General description of bus routes of PJSC "Cherkasy ATP-17127"

№	Route No	Starting and ending points of movement	Number of vehicles on the line	Length, km	Movement interval, min.	
					Rush hour ($7^{00} – 9^{99}$/ 15^{00} –19^{00})	Rush hour ($7^{00} – 9^{99}$/ 15^{00} –19^{00})
1	4	Regional Hospital – Patsaeva str.	12	23,56	5-6	8-10
2	5	General Momota str. – "Avrora" factory	11	33,48	10	12-15
3	10	Center – Hutory village	3	22,02	30	45

Source: results of own research.

Table 4. General description of bus routes of PE "Elit-trans"

№	Route No	Starting and ending points of movement	Number of vehicles on the line	Length, km	Movement interval, min.	
					Rush hour ($7^{00} – 9^{99}$/ 15^{00} –19^{00})	Rush hour ($7^{00} – 9^{99}$/ 15^{00} –19^{00})
1	7	General Momota str. – cargo port	10	19,18	8-10	10-15
2	22	Sumgaitska str. – 700th Anniversary Square	14	19	5	9-12

Source: results of own research.

Table 5. General description of bus routes of the State Enterprise "Charz-avto"

№	Route No	Starting and ending points of movement	Number of vehicles on the line	Length, km	Movement interval, min.	
					Rush hour ($7^{00} – 9^{99}$/ 15^{00} –19^{00})	Rush hour ($7^{00} – 9^{99}$/ 15^{00} –19^{00})
1	12	Kobzarska str. – Military R&E Office	4	16,42	30-35	40-50
2	20	Rustavi str. – Mytnytsia district	12	23,31	7	8-10
3	25	Sumgaitska str. – "Avrora" factory	14	25,4	6	8
4	31	Dahnivka district – PO «Azot»	10	42,4	10-15	20

Source: results of own research.

The summarized results of calculating the characteristics of the route network of urban passenger transport in Cherkasy are presented in tab. 6.

Table 6. Characteristics of the transport network of Cherkasy city

Types of vehicles	Route network length, km	Average route length, km	Route network density, km/km^2
Trolleybus routes	286,6	22,1	3,7
Bus routes	345,6	21,6	4,4
Together	632,2	21,8	8,1

Source: results of own research.

The density of the route network of urban passenger transport in Cherkasy is 8.1 km/km^2 and significantly exceeds the regulatory values (1.5-2.5 km/km^2). An excessive route network is characterized by a high degree of duplication of routes and, in the case of using small-capacity rolling stock, inevitably leads to an increase in the intensity of vehicle traffic, an increase in accidents, increased air pollution and a decrease in the efficiency of operation of the entire transport infrastructure of the city.

In the urban passenger transport network, routes are divided into those that completely duplicate the routes of other types of urban passenger transport, partially duplicated and independent (Aulin, Holub, 2007, Davidich, 2010). Partial duplication is the most common and occurs when 50 to 75% of the routes of different types of transport coincide in certain sections of the city network. If the coincidence of routes exceeds 75%, duplication is classified as complete (Koryagin, Katargin, 2016). In order to determine the level of duplication of passenger transport routes in Cherkasy, the routes of the trolleybus and bus networks of the city were analyzed. The results of the analysis with the fixation of partial and complete types of duplication of these networks are given in tab. 7, 8.

The highest level of duplication of the trolleybus network is noted on route No. 1, which is partially duplicated by two bus routes and two trolleybus routes, and completely by one trolleybus and one bus route.

In order to study the population's demand for urban passenger transportation, a survey of transport users was conducted over a period of two months and was carried out at stops at different times of the day. Attention was focused on the frequency of transport and its congestion. The number of passengers waiting for transport was recorded three times with an interval of 5 minutes. In addition, the total number of citizens at the stops and the number of vehicles approaching the stop or passing it due to congestion were calculated.

It was noted that 97.5% of all respondents use the services of urban public transport. About 45.5% of respondents expressed their dissatisfaction with its work. The choice of the mode of transport depends on the income of different categories of transport users.

Table 7. Duplication of trolleybus network routes

Trolleybus route number	Number of duplicate routes			Duplicate bus route numbers		Numbers of duplicate trolleybus routes	
	Partial	Complete	Total	Partial	Complete	Partial	Complete
1	4	2	6	25, 31	4	3, 7A	1A
1A	3	2	5	31	4	3, 7A	1
2	-	1	1	-	5	-	-
3	3	1	4	31	26	1, 1A	-
4	1	-	1	-	-	4A	-
4A	-	1	1	-	-	-	4
7	3	2	5	10	31	1, 1A	7A
7A	3	1	4	-	31	7, 1, 1A	-
8	3	1	4	20, 22	25	8P	-
8P	3	-	3	25	-	8, 50	-
10	-	2	2	-	22, 25	-	-
14	1	-	1	5	-	-	-
50	3	1	4	20, 22, 25	-	-	8P

Source: results of my own scientific research.

Table 8. Duplication of bus network routes

Bus route number	Number of duplicate routes			Duplicate bus route numbers		Numbers of duplicate trolleybus routes	
	Partial	Complete	Total	Partial	Complete	Partial	Complete
4	4	-	4	25, 31	-	1, 1A	-
5	1	-	1	-	-	14	-
7	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-
10	2	-	2	31	-	7	-
12	6	-	6	22, 25, 27	-	8, 8P, 50	-
20	2	1	3	22, 25	-	-	8
21	-	-	-	-	-	-	-
22	4	1	5	20	25	8, 8P, 10	-
25	-	1	1	-	22	-	-
26	1	-	1	-	-	3	-
27	1	-	1	12	-	-	-
31	1	-	1	-	-	7A	-

Source: results of my own scientific research.

Privileged categories of the population, as a rule, are people with not very high incomes, and therefore are oriented towards moving around the city using trolleybuses. Passengers who do not have privileges do not pay attention to the mode of transport and board the vehicle that approached the stop first. The advantage of using buses is a higher speed of movement. However, buses are more likely to cause gas pollution in the city than trolleybuses. The distribution of respondents by mode of transport that is more accessible to them is given in tab. 9.

Table 9. Priority of choice of mode of transport

Type of transport	Distribution of respondents
Bus	0,584
Trolleybus	0,296
Bus or trolleybus	0,120

Source: results of my own scientific research.

Thus, traffic optimization in the urban passenger network must be carried out taking into account two categories of passengers (privileged and non-privileged) for both modes of transport.

9.3. Optimization of urban passenger transport traffic intensity taking into account duplication of routes

We present the following classification of criteria by which the route network of urban passenger transport can be optimized:

– − economic indicators, namely, the profit of enterprises and the costs of enterprises for servicing the route network of the city;
– − road structure. The throughput capacity of the city's street and road highways is analyzed depending on the passenger capacity of vehicles;
– − passenger flows (the number of passengers on individual sections of street and road highways);
– − the level of duplication of routes. Namely, optimization by the coincidence of routes of different types of ground passenger transport on individual sections of the city's street and road highways, or their complete overlap.

To optimize the route network of urban passenger transport, the level of route duplication was chosen as a criterion. Since some routes are duplicated by different carriers, this leads to competition on the route, which affects the quality of transport service.

Currently developed mathematical models of urban passenger transport systems do not reflect the conditions of competition in sufficient detail. As a rule, they consider only one criterion for optimizing transport operations with an additional set of constraints. This approach does not allow taking into account the mutual influence of system participants, which can lead to the development of inefficient solutions in practice. It is necessary to use models that would describe passenger behaviour strategies. The relevance lies in the fact that in recent decades, a passenger has a wide range of options for choosing a route (the number of duplicate routes is increasing), as well as a method of transportation (the level of motorization is increasing). Therefore, there is a need to manage public transport based on the interests of passengers in order to ensure the development of the urban transport system as a whole.

In work (Koryagin, Katargin, 2016), the objective function (5.1) of the total losses of passengers and damage to the urban environment from the operation of two modes of transport on the same route was obtained:

$$F(\mu_0, \mu_1) = \frac{\gamma_0 \lambda_0}{\mu_0} + \frac{\gamma_1 \lambda_1}{\mu_0 + \mu_1} + \delta_0 \mu_0 + \delta_1 \mu_1 \rightarrow \min, \quad (5.1)$$

where μ_0, μ_1 – intensities of Poisson flows of trolleybuses and buses moving along the route, respectively;

δ_0, δ_1 – damage to the urban environment from one trolleybus trip and one bus trip on this route, respectively, UAH,

$\delta_0 \leq \delta_1$; λ_0 – intensity of Poisson flow of preferential categories of passengers on this route, passengers/hour;

λ_1 – intensity of Poisson flow of categories of passengers who do not have privileges on this route, passengers/hour;

γ_0 – average cost of one hour of passengers who have privileges when traveling on a trolleybus, UAH/hour;

γ_1 – average cost of one hour of passengers who do not have privileges when traveling on public transport, UAH/hour.

Passenger traffic intensities are calculated using formulas (5.2)-(5.3):

$$\lambda_0 = Q \times 0{,}761 \text{ , pass./hour,} \quad (5.2)$$

$$\lambda_1 = Q \times 0{,}917 \text{ , pass./hour.} \quad (5.3)$$

where Q – the largest passenger traffic value in two directions;

0,761 – share of passengers who have trolleybus travel privileges (Koryagin, Katargin, 2016);

0,917 – share of passengers who do not have a privilege to travel on scheduled vehicles (Koryagin, Katargin, 2016).

A necessary condition for the existence of an extremum (5.1) is that the partial derivatives in all variables at the extremum point are zero:

$$\begin{cases} -\dfrac{\gamma_0\lambda_0}{(\mu_0)^2} - \dfrac{\gamma_1\lambda_1}{(\mu_0+\mu_1)^2} + \delta_0 = 0 \\ -\dfrac{\gamma_1\lambda_1}{(\mu_0+\mu_1)^2} + \delta_1 = 0 \end{cases}, \tag{5.4}$$

The implementation of this optimization problem was performed on the example of the passenger public transport network of Cherkasy. Here are the results of calculating the traffic intensity for the duplicated trolleybus routes No. 1 and bus No. 4.

Intensity for the trolleybus route:

$$\mu_0 = \sqrt{\frac{\gamma_0\lambda_0}{\delta_0-\delta_1}} = \sqrt{\frac{11\times 110}{72-53}} = 8. \tag{5.5}$$

Intensity for a bus route:

$$\mu_1 = \sqrt{\frac{\gamma_1\lambda_1}{\delta_1}} - \sqrt{\frac{\gamma_0\lambda_0}{\delta_0-\delta_1}} = \sqrt{\frac{37\times 278}{53}} - \sqrt{\frac{11\times 110}{72-53}} = 6. \tag{5.6}$$

Let us consider the second case (trolleybus No. 2 and bus No. 5, $\delta_0 \leq \delta_1$,) when the trolleybus trip is cheaper to operate. Since the bus is not used efficiently in this case, the intensity of bus traffic $\mu_1 = 0$.

Then, for a trolleybus route, the intensity is calculated using the formula:

$$\mu_0 = \sqrt{\frac{\gamma_0\lambda_0+\gamma_1\lambda_1}{\delta_0}} = \sqrt{\frac{704+9620}{52}} = 15. \tag{5.7}$$

All calculations using the mathematical model (5.1) for trolleybus routes duplicated by bus routes in Cherkasy are summarized in tab. 10.

Table 10. Mathematical model parameter values for public transport on duplicate routes

No. of duplicate routes	Output data						Optimization parameter (traffic intensity)	
	δ_0	δ_1	λ_0	λ_1	γ_0	γ_1	μ_0	μ_1
Trolleybus №1 – Bus №4	72	53	110	278	11	37	8	6
Trolleybus №2 – Bus №5	52	76	64	260			15	0
Trolleybus №3 – Bus №26	51	50	76	234			14	0
Trolleybus №7A – Bus №31	71	82	69	345			14	0
Trolleybus №8 – Bus №25	79	58	58	379			6	11
Trolleybus №10 – Bus №22	63	43	202	429			11	9

Source: results of my own scientific research.

According to the mathematical model (5.1), it is possible to calculate not only the intensity of flows of different types of transport, but also the intensity of individual transport flows of one type of transport (on sections of routes that overlap with each other). Tab. 11, as an example, shows the results of calculations for two bus routes that overlap.

Table 11. Mathematical model parameter values for buses on duplicated routes

No. of duplicate routes	Output data			Traffic intensity
	δ_1	λ_1	γ_1	μ_1
Bus №12 – Bus №27	37	70	37	13
	34	92		0

Source: results of my own scientific research.

Within the framework of this study, the required number of rolling stock units and the movement interval for each route of the optimized network were calculated based on the obtained values of μ_0 and μ_1. At the first stage of the calculation, the optimized movement interval for the maximum hourly passenger flow is determined for the specified values of vehicle traffic intensity:

$$d_i = \frac{t}{\mu_i}, \tag{5.8}$$

where d_i – movement interval, min.; t=60 min.; μ_i – traffic intensity of the i -th type of public transport. The calculated value μ_i is taken from tab. 10-11.

Based on the specified travel interval, it becomes possible to calculate the number of rolling stock units (A) required to service urban routes using the following formula:

$$A = \frac{t_r}{d_i}, \tag{5.9}$$

where t_r – round trip time of a transport unit on the route taking into account the settling time, min.; d_i – movement interval calculated for each route, min.

The round trip time of the transport unit on a route, taking into account the settling time, is calculated as follows:

$$t_r = \left(\frac{L_r}{V} \times 60\right) + t_{idle}, \tag{5.10}$$

where L_r – route length, km; V – average vehicle speed, km/h; t_{idle} – dwell time at final stops (for urban passenger routes – 5-15 min), we assume the average value t_{idle} = 10 min.

When calculating the round trip time, we assume the average vehicle speed to be 25 km/h for buses and 20 km/h for trolleybuses. The average value of transport speed was determined using the methodology described in the studies (Mateichyk et al. 2023, Śmieszek, Mateichyk, 2021).

The results of the corresponding calculations are presented in tab. 12-13.

Table 12. Results of calculation of the main indicators of improved bus routes in Cherkasy

Type of transport	Route number	L_r, km	Q, pass./hour,	μ_1	d_i, min.	t_{idle}, min.	A, vehicle
Bus	4	23,56	303	6	10	67	7
	5	32,21	284	0	0	87	0
	12	16,42	76	13	5	49	11
	22	19	468	9	7	56	8
	25	25,4	413	11	5	71	13
	26	24,84	255	0	0	70	0
	27	17,6	100	0	0	52	0
	31	36,25	376	0	0	97	0

Source: results of my own scientific research.

Table 13. Results of calculation of the main indicators of improved trolleybus routes in Cherkasy

Type of transport	Route number	L_r, km	Q, pass./hour,	μ_1	d_i, min.	t_{idle}, min.	A, vehicle
Trolleybus	1	25,18	145	8	8	86	11
	2	18,16	84	15	4	64	16
	3	18	100	14	4	64	15
	7A	25,08	91	14	4	85	20
	8	27,9	76	6	10	94	9
	10	22,26	265	11	5	77	14

Source: results of my own scientific research.

In (Koryagin, Katargin, 2016) a more generalized model for *n* optimization parameters is also presented.

9.4. Determination of traffic flow intensity taking into account the level of route duplication and partial passenger flow coefficients by type of transport

In the mathematical model (5.1) the degree of duplication of transport network routes is not taken into account, and environmental damage is equated to the cost of transportation. To eliminate the first drawback, it is proposed to introduce into the formula (5.1) the coefficient ρ, which reflects the degree of duplication of the trolleybus route with the bus. The refined objective function takes the form:

$$F(\mu_0,\mu_1)=\frac{\gamma_0\lambda_0}{\mu_0}+\frac{\gamma_1\lambda_1}{\mu_0+\mu_1-\rho\left(\frac{\mu_0+\mu_1}{2}\right)}+\delta_0\mu_0+\delta_1\mu_1= \\ =\frac{\gamma_0\lambda_0}{\mu_0}+\frac{\gamma_1\lambda_1}{\left(1-\frac{\rho}{2}\right)(\mu_0+\mu_1)}+\delta_0\mu_0+\delta_1\mu_1\to\min. \tag{5.11}$$

$$\rho=\frac{L_{01}}{L_{M0}}, \tag{5.12}$$

where L_{01} is the length of the connected section of two routes, km; determined by measuring on the diagram of the existing route network; L_{M0} is the length of the trolleybus route (tab. 5.1), km.

After differentiating the function F with respect to μ_0 and μ_1 in (5.11), the following dependences are obtained:

$$\begin{cases}\frac{\partial F}{\partial\mu_0}=-\frac{\gamma_0\lambda_0}{(\mu_0)^2}-\frac{1}{1-\rho/2}\times\frac{\gamma_1\lambda_1}{(\mu_0+\mu_1)^2}+\delta_0=0 \\ \frac{\partial F}{\partial\mu_1}=-\frac{1}{1-\rho/2}\times\frac{\gamma_1\lambda_1}{(\mu_0+\mu_1)^2}+\delta_1=0\end{cases}, \tag{5.13}$$

From the second equation of system (5.13) we obtain the expression (5.14):

$$\frac{1}{1-\rho/2}\times\frac{\gamma_1\lambda_1}{(\mu_0+\mu_1)^2}=\delta_1. \tag{5.14}$$

Substituting (5.14) into the first equation of system (5.13), we form an equation with one variable (5.15):

$$-\frac{\gamma_0\lambda_0}{(\mu_0)^2}-\delta_1+\delta_0=0. \tag{5.15}$$

From equation (5.15) we obtain an expression for determining the optimal intensity of trolleybus traffic (5.16):

$$\mu_0=\sqrt{\frac{\gamma_0\lambda_0}{\delta_0-\delta_1}}. \tag{5.16}$$

By performing an arithmetic conversion (5.14):

$$(\mu_0+\mu_1)^2=\frac{2\gamma_1\lambda_1}{(2-\rho)\delta_1} \tag{5.17}$$

and substituting the expression for calculating μ_0 (5.16) into (5.17), we finally determine the optimal intensity of bus traffic along the route that duplicates the first route (5.18):

$$\mu_1=\sqrt{\frac{2\gamma_1\lambda_1}{(2-\rho)\delta_1}}-\sqrt{\frac{\gamma_0\lambda_0}{\delta_0-\delta_1}}. \tag{5.18}$$

In case of constraint $\sqrt{\frac{2\gamma_1\lambda_1}{(2-\rho)\delta_1}}\le\sqrt{\frac{\gamma_0\lambda_0}{\delta_0-\delta_1}}$ it is inefficient to use transport on the second route. Accordingly, the intensity of bus traffic on this route μ_1=0. In this case, trolleybuses (or buses on the first route, if two bus routes that duplicate each other are studied) serve the entire passenger flow with the optimal intensity, which is calculated by the formula:

$$\mu_0=\sqrt{\frac{\gamma_0\lambda_0(2-\rho)+2\gamma_1\lambda_1}{(2-\rho)\delta_0}}=\sqrt{\frac{\gamma_0\lambda_0+\gamma_1\lambda_1}{\delta_0}}. \tag{5.19}$$

To eliminate the second drawback of the mathematical model, it is proposed to calculate δ_0 and δ_1 using the formulas (5.20), (5.21).

$$\delta_0 = L_{r0} K_{R0}, \tag{5.20}$$

where L_{r1} – bus route distance; K_{R0} – tariff rate for damage caused per 1 km of city road by a trolleybus.

The fare rates are given in (Shefter, Triakin, 2007). Since the fare rates for a trolleybus are equal to the rates for large class buses, K_{R0}=2.84 UAH/km.

$$\delta_1 = L_{r1}\left(K_{R1} + K_{EG}\right), \tag{5.21}$$

where L_{r1} – distance of the bus route; K_{R1} – tariff rate for damage caused by a bus to 1 km of a city road; K_{EG} – tariff rate for exhaust gas emissions into the atmosphere, depending on the type of bus engine.

Since the route buses in Cherkasy belong to the small class of buses (except for route No. 22), then K_{R1}=1.48 UAH/km. For diesel engines K_{EG} =0.77 UAH/km [16].

The values of the input parameters of the optimization model (5.11), as well as the results of its implementation on duplicated routes, are summarized in tab. 14 and tab. 15.

Table 14. The values of the optimization model parameters taking into account the route duplication ratio for different types of transport

No. of duplicate routes	Input data						Duplication ratio	Optimization parameter (traffic intensity)	
	δ_0	δ_1	λ_0	λ_1	γ_0	γ_1	ρ	μ_0	μ_1
Trolleybus №1 – Bus №4	72	53	110	278			0,42	8	8
Trolleybus №2 – Bus №5	52	76	64	260			0,55	16	0
Trolleybus №3 – Bus №26	51	50	76	234	11	37	0,37	15	0
Trolleybus №7A – Bus №31	71	82	69	345			0,61	16	0
Trolleybus №8 – Bus №25	79	58	58	379			0,46	6	13
Trolleybus №10 – Bus №22	63	43	202	429			0,37	11	11

Source: results of my own scientific research.

Table 15. The values of the optimization model parameters taking into account the route duplication ratio for the same type of transport (buses)

No. of duplicate routes	Input data			Duplication ratio	Optimization parameter (traffic intensity)
	δ_1	λ_1	γ_1	ρ	μ_1
Bus №12 – Bus №27	37	70	37	0,79	12
	34	92			0

Source: results of my own scientific research.

The results of calculations of transport network indicators, taking into account route duplication ratios, are presented in tab. 16 and tab. 17.

Table 16 Results of calculation of the main indicators of the optimized bus network of Cherkasy city taking into account the duplication ratios of routes

Bus route number	L_r, km	Q, pass./hour,	μ_1	d_i, min.	t_{idle}, min.	A, vehicle
4	23,56	303	8	8	67	9
5	32,21	284	0	0	87	0
12	16,42	76	12	5	49	10
22	19	468	11	5	56	10
25	25,4	413	13	5	71	15
26	24,84	255	0	0	70	0
27	17,6	100	0	0	52	0
31	36,25	376	0	0	97	0

Source: results of my own scientific research.

Table 17 Results of calculation of the main indicators of the optimized trolleybus network of Cherkasy city taking into account the duplication ratios of routes

Trolleybus route number	L_r, km	Q, pass./hour,	μ_1	d_i, min.	t_{idle}, min.	A, vehicle
1	25,18	145	8	8	86	11
2	18,16	84	16	4	64	17
3	18	100	15	4	64	16
7A	25,08	91	16	4	85	23
8	27,9	76	6	10	94	9
10	22,26	265	11	5	77	14

Source: results of my own scientific research.

According to the results of the calculations (tab. 14-17), the following can be stated: taking into account the route duplication ratio in the mathematical model (5.11) ensures a reduction in the optimal number of transport units only on routes of vehicles of the same type (bus route No. 12 and bus route No. 27). This is explained by the fact that the flows of non-privileged category passengers using different modes of transport were evenly divided into equal parts with a share of 0.5 each. If there are statistical data on the distribution of passenger flows moving along these routes (tab. 9), it is appropriate to specify model (5.11) to minimize the level of duplication of trolleybuses with buses. We assume that buses are preferred by respondents who chose this type of transport (58.4%) and half of those who use both buses and trolleybuses (6%). Thus, the calculation of the intensity of transport flows is carried out taking into account the partial coefficients of the passenger flows by type of transport, and the corresponding objective function has the following form:

$$
\begin{aligned}
F(\mu_0,\mu_1) &= \frac{\gamma_0\lambda_0}{\mu_0}+\frac{\gamma_1\lambda_1}{\mu_0+\mu_1-\rho\left[0{,}296\mu_0+0{,}06(\mu_0+\mu_1)\right]}+\delta_0\mu_0+\delta_1\mu_1 = \\
&= \frac{\gamma_0\lambda_0}{\mu_0}+\frac{\gamma_1\lambda_1}{\mu_0+\mu_1-\rho\left(0{,}356\mu_0+0{,}06\mu_1\right)}+\delta_0\mu_0+\delta_1\mu_1 \to \min .
\end{aligned}
\qquad (5.22)
$$

After opening the brackets and bringing together similar terms, formula (5.22) takes the following form:

$$F(\mu_0, \mu_1) = \frac{\gamma_0 \lambda_0}{\mu_0} + \frac{\gamma_1 \lambda_1}{\mu_0 (1 - 0{,}356\rho) + \mu_1 (1 - 0{,}06\rho)} + \delta_0 \mu_0 + \delta_1 \mu_1 \rightarrow \min, \quad (5.23)$$

while L_{r0} when calculating the route duplication ratio ρ corresponds to the length of the trolleybus route, km.

The optimal values of the traffic intensity of trolleybuses and buses on duplicated routes are determined by formulas (5.24) and (5.25), respectively:

$$\mu_0 = \sqrt{\frac{\gamma_0 \lambda_0 (1 - 0{,}356\rho)}{\delta_0 - \delta_1 - \rho(0{,}356\delta_0 - 0{,}06\delta_1)}}, \quad (5.24)$$

$$\mu_1 = \sqrt{\frac{\gamma_1 \lambda_1}{(1 - 0{,}06\rho)\delta_1}} - \frac{(1 - 0{,}356\rho)}{(1 - 0{,}06\rho)} \sqrt{\frac{(1 - 0{,}356\rho)\gamma_0 \lambda_0}{\delta_0 - \delta_1 - \rho(0{,}356\delta_0 - 0{,}06\delta_1)}}. \quad (5.25)$$

For negative values of μ_1, we assume $\mu_1=0$, and the intensity of the trolleybus flow is calculated using formula (5.19).

The input parameters of the optimization model (5.23) and the results of optimizing the movement of trolleybuses and buses, taking into account the duplication ratio of their routes and the shares of passenger flows by mode of transport, are summarized in tab. 18.

The results of calculations of transport network indicators, taking into account the duplication coefficient and shares of passenger flows by mode of transport, are presented in tab. 19.

Table 18 The values of the parameters of the mathematical model taking into account the route duplication ratio and shares of passenger flows by type of transport

No. of duplicate routes	Input data						Duplication ratio	Optimization parameter (traffic intensity)	
	δ_0	δ_1	λ_0	λ_1	γ_0	γ_1	ρ	μ_0	μ_1
Trolleybus №1 – Bus №4	72	53	110	278	11	37	0,42	10	5
Trolleybus №2 – Bus №5	52	76	64	260			0,55	16	0
Trolleybus №3 – Bus №26	51	50	76	234			0,37	15	0
Trolleybus №7A – Bus №31	71	82	69	345			0,61	16	0
Trolleybus №8 – Bus №25	79	58	58	379			0,46	7	9
Trolleybus №10 – Bus №22	63	43	202	429			0,37	12	8

Source: results of my own scientific research.

Table 19 Main indicators of the optimized public transport network of Cherkasy with a guaranteed duplication of routes and the frequency of passenger flows by mode of transport

Type of transport	Route number	L_r, km	Q, pass./hour,	μ_1	d_i, min.	t_{idle}, min.	A, vehicle
Bus	4	23,56	303	5	12	67	6
	5	32,21	284	0	0	87	0
	12	16,42	76	12	5	49	10
	22	19	468	8	8	56	7
	25	25,4	413	9	7	71	11
	26	24,84	255	0	0	70	0
	27	17,6	100	0	0	52	0
	31	36,25	376	0	0	97	0
Trolleybus	1	25,18	145	10	6	86	14
	2	18,16	84	16	4	64	17

	3	18	100	15	4	64	16
	7A	25,08	91	16	4	85	23
	8	27,9	76	7	9	94	11
	10	22,26	265	12	5	77	15

Source: results of my own scientific research.

According to tab. 19, a comparative analysis of the existing and proposed (optimized) networks was carried out (tab. 20).

Table 20. Comparison of routes of optimized and existing passenger transport networks

Type of passenger transport	Route number	Existing network		Optimized network	
		Movement interval, min.	Number of vehicles	Movement interval, min.	Number of vehicles
Bus	4	5-10	12	12	6
	5*	10-15	11	0	0
	12	30-40	4	5	10
	22	5-12	14	8	7
	25	6-8	14	7	11
	26*	8-15	8	0	0
	27*	20-30	4	0	0
	31*	10-20	10	0	0
Trolleybus	1	7-10	8	6	14
	2	30	2	4	17
	3	20-30	3	4	16
	7A	8-15	10	4	23
	8	30-40	5	9	11
	10	8-10	14	5	15

Source: results of my own scientific research.

The symbol "*" in tab. 20 indicates routes whose duplicated sections are proposed to be eliminated based on the optimization results.

After eliminating individual routes, the total duplication in the optimized network is 4 routes. The results of the optimization with the fixation of partial and full types of duplication of the updated transport networks of the city are given in tab. 21 and 22.

Table 21. Duplication of trolleybus network routes after optimization

Trolleybus route number	Number of duplicate routes after optimization			Duplicate bus route numbers		Numbers of duplicate trolleybus routes	
	Partial	Complete	Total	Partial	Complete	Partial	Complete
1	3	2	5	25	4	3, 7A	1A
1A	2	2	4	-	4	3, 7A	1
2	-	-	-	-	-	-	-
3	3	-	3	2	-	1, 1A	-
4	1	-	1	-	-	4A	-
4A	-	1	1	-	-	-	4
7	3	1	4	10	-	1, 1A	7A
7A	3	-	3	-	-	7, 1, 1A	-
8	3	1	4	20, 22	25	8P	-
8P	3	-	3	25	-	8, 50	-
10	-	2	2	-	22, 25	-	-
14	-	-	-	-	-	-	-
50	3	1	4	20, 22, 25	-	-	8P

Source: results of my own scientific research.

Table 22. Duplication of bus network routes after optimization

Bus route number	Number of duplicate routes after optimization			Number of duplicate routes after optimization		Number of duplicate routes after optimization	
	Partial	Complete	Total	Partial	Complete	Partial	Complete
4	3	-	3	25	-	1, 1A	-
7	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-
10	1	-	1	-	-	7	-
12	5	-	5	22, 25	-	8, 8P, 50	-
20	2	1	3	22, 25	-	-	8
21	-	-	-	-	-	-	-
22	4	1	5	20	25	8, 8P, 10	-
25	-	1	1	-	22	-	-

Source: results of my own scientific research.

A comparative characteristic of the existing and optimized level of duplication of trolleybus routes with bus routes is given in table. 23.

Table 23. Comparison of the level of duplication of routes on sections of strategic roads of the existing and optimized network of Cherkasy city, taking into account the duplication ratio

Section of the street and road network	Number of duplicated bus routes	
	Existing network	Optimized network
Strategic roads of the city	8	2
Shevchenko Blvd.	7	3
V. Chornovola Str.	2	0
Smilyanska Str.	3	1
Sumgaitskaya Str.	1	1

Source: results of my own scientific research.

After the elimination of individual bus routes, or their sections, the complete duplication of buses in the optimized network is only 3 routes: bus routes No. 20, No. 22 and No. 25.

The summarized results of minimizing the number of duplicate trolleybus and bus routes are presented in tab. 24 and tab. 25, respectively.

The results of optimizing public transport routes (tab. 24, tab. 25) are clearly shown in fig. 5.1 and fig. 5.2.

Table 24. Number of duplicate routes for trolleybus routes before and after optimization of the transport network of Cherkasy city, taking into account the duplication ratio and shares of passenger flows by type of transport

Trolleybus route number	Number of duplicate routes before optimization	Number of duplicate routes after optimization
1	6	5
1A	5	4
2	1	0
3	4	3
4	1	1
4A	1	1
7	5	4
7A	4	3
8	4	4
8P	3	3
10	2	2
14	1	0
50	4	4
Total:	41	34

Source: results of my own scientific research.

Table 25. Number of duplicate routes for bus routes before and after optimization of the transport network of Cherkasy city, taking into account the duplication ratio

Bus route number	Number of duplicate routes before optimization	Number of duplicate routes after optimization
4	4	3
7	0	0
8	0	0
10	2	1
12	6	5
20	3	3
21	0	0
22	5	5
25	1	1
Total:	21	18

Source: results of my own scientific research.

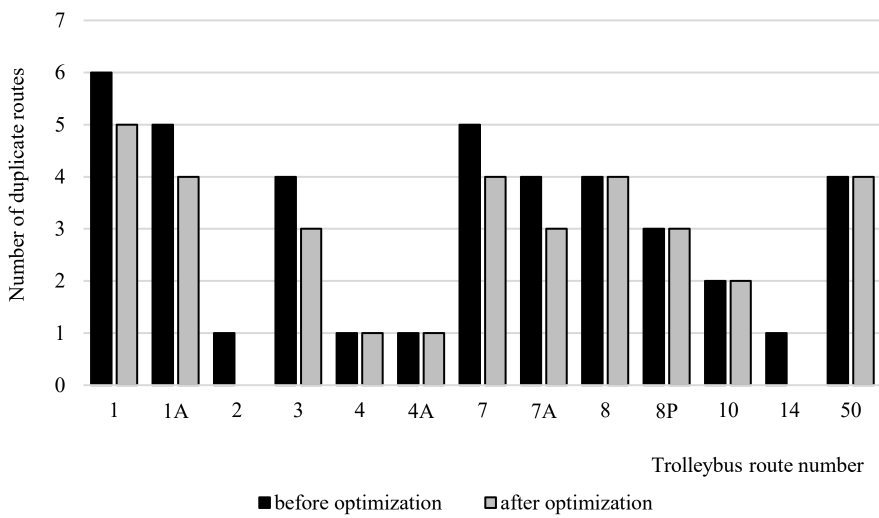

Fig. 5.1. Results of trolleybus route optimization

Source: own work.

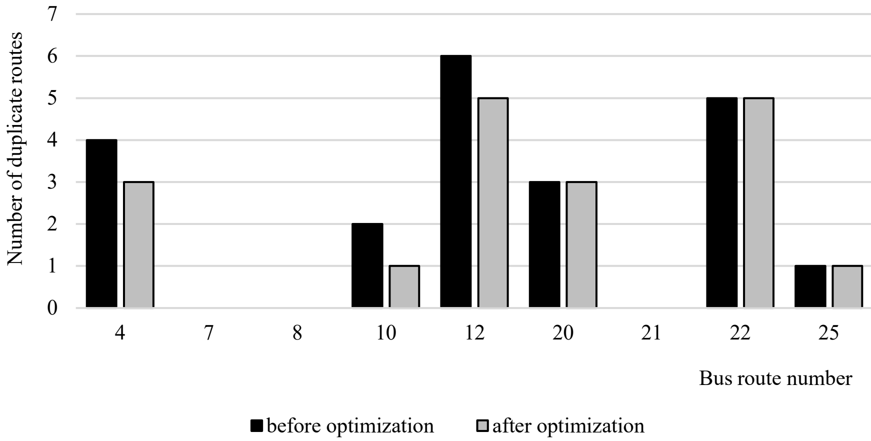

Fig. 5.2. Results of bus route optimization

Source: own work.

9.5. Additional conditions in the model for optimizing the urban passenger public transport network

Urban passenger transport operates in a transport system that is subject to certain restrictions. The optimization task is reduced to improving the quality of passenger service and reducing the negative impact on the environment, taking into account additional conditions and restrictions. One of the significant limitations of the optimization task is the limitation on the passenger capacity of rolling stock. It is recommended to operate vehicles of the same capacity on a separate route. Optimal solutions may lead to violation of standards when loading vehicles, which may lead to a decrease in the quality of passenger service. Another problem is the fact that the passenger flow is random, so it is very difficult to avoid overcrowding of the vehicles involved under such conditions.

When solving the problem of optimizing the urban public transport network, it is advisable to take into account the conditions of the need to maintain stable positions in the passenger transportation market. Any significant changes may negatively affect passengers or transport enterprises. Therefore, municipal authorities are interested in improving the quality of passenger service at an unchanged level of subsidies. In the process of solving optimization problems (5.11) and (5.23), it is proposed to take into account the constraints on the passenger capacity of vehicles (5.26):

$$\begin{cases} g_1(\mu_0,\mu_1)=\dfrac{\lambda_0}{\mu_0}\le q_1, \\ g_2(\mu_0,\mu_1)=\dfrac{\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)}\le q_2, \\ g_3(\mu_0,\mu_1)=\mu_0\ge 0, \\ g_4(\mu_0,\mu_1)=\mu_1\ge 0, \end{cases} \tag{5.26}$$

where q_1, q_2 – maximum passenger capacity on routes I and II, respectively, pas.

To determine the input parameters of the optimization problems of problems (5.11), (5.26) and (5.23), (5.26), the fleet of vehicles of transport operators of Cherkasy was studied.

The optimal values of the intensity of bus and trolleybus flows can be calculated using the generalized method of Lagrange multipliers with given constraints on passenger capacity in the form of a system of inequalities. The algorithm of the generalized method of Lagrange multipliers for this study when the routes coincide will contain the following stages:

Stage 1. The optimal values of the intensity of the transport flow are determined without imposing constraints on passenger capacity. If the obtained solutions satisfy all the constraints of the problem of finding the minimum of total passenger losses and damage to the urban environment, then the calculations are completed, since all the constraints will be redundant. Otherwise, it is necessary to assume k=1 and proceed to stage 2.

Step 2. Any k of the four constraints (5.26) of the optimization problem must be transformed into equalities. Next, the local minimum of the value of the objective function of total losses (5.23) when using two modes of transport, taking into account the ratio of duplication of routes and the distribution of passengers by mode of transport in the presence of k constraints, is found using the Lagrange multiplier method. If the optimal values of the traffic flow intensity satisfy other constraints of the initial problem statement, then the calculations are terminated. The solution found in this way is a local minimum. Otherwise, it is necessary to apply other k constraints from the system (5.26) and repeat this stage. If all combinations of the k applied constraints do not lead to an admissible solution, then proceed to stage 3.

Step 3. If k=4, then the extreme problem has no solutions. Otherwise, it is necessary to perform k=k+1 and go to step 2.

Since the specified algorithm allows finding only a local minimum, to find the global minima of the corresponding objective functions (5.11) and (5.23) the adjusted generalized method of Lagrange multipliers (Taha, 2017) was applied, in which all possible sets of constraints were taken into account. That is, first, individual constraints were activated in turn, then pairs and triples of active constraints were considered. The smallest value of the obtained local minima is global. Based on this, within each problem, 15 optimization subproblems with objective functions in the form of Lagrange functions L_1-L_{15} were solved. Thus, for problem (5.11) and (5.23) the functions L_1-L_{15} take the following form:

$$L_1 = F(\mu_0,\mu_1) - \Theta_1 g_1(\mu_0,\mu_1) = \frac{\gamma_0\lambda_0}{\mu_0} + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \\ + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_1\frac{\lambda_0}{\mu_0} \to \min, \tag{5.27}$$

$$L_2 = F(\mu_0,\mu_1) - \Theta_2 g_2(\mu_0,\mu_1) = \frac{\gamma_0\lambda_0}{\mu_0} + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \\ + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_2\frac{\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} \to \min, \tag{5.28}$$

$$L_3 = F(\mu_0,\mu_1) - \Theta_3 g_3(\mu_0,\mu_1) = \frac{\gamma_0\lambda_0}{\mu_0} + \\ + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_3\mu_0 \to \min, \tag{5.29}$$

$$L_4 = F(\mu_0,\mu_1) - \Theta_4 g_4(\mu_0,\mu_1) = \frac{\gamma_0\lambda_0}{\mu_0} + \\ + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_4\mu_1 \to \min, \tag{5.30}$$

$$L_5 = F(\mu_0,\mu_1) - \Theta_1 g_1(\mu_0,\mu_1) - \Theta_2 g_2(\mu_0,\mu_1) = \frac{\gamma_0\lambda_0}{\mu_0} + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \\ + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_1\frac{\lambda_0}{\mu_0} - \Theta_2\frac{\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} \to \min, \tag{5.31}$$

$$L_6 = F(\mu_0,\mu_1) - \Theta_1 g_1(\mu_0,\mu_1) - \Theta_3 g_3(\mu_0,\mu_1) = \frac{\gamma_0\lambda_0}{\mu_0} + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \\ + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_1\frac{\lambda_0}{\mu_0} - \Theta_3\mu_0 \to \min, \tag{5.32}$$

$$L_7 = F(\mu_0,\mu_1) - \Theta_1 g_1(\mu_0,\mu_1) - \Theta_4 g_4(\mu_0,\mu_1) = \frac{\gamma_0\lambda_0}{\mu_0} + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \\ + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_1\frac{\lambda_0}{\mu_0} - \Theta_4\mu_1 \to \min, \tag{5.33}$$

$$L_8 = F(\mu_0,\mu_1) - \Theta_2 g_2(\mu_0,\mu_1) - \Theta_4 g_4(\mu_0,\mu_1) = \frac{\gamma_0\lambda_0}{\mu_0} + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \\ + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_2\frac{\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} - \Theta_4\mu_1 \to \min, \tag{5.34}$$

$$L_9 = F(\mu_0,\mu_1) - \Theta_2 g_2(\mu_0,\mu_1) - \Theta_3 g_3(\mu_0,\mu_1) = \frac{\gamma_0\lambda_0}{\mu_0} + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \\ + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_2\frac{\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} - \Theta_3\mu_0 \to \min, \tag{5.35}$$

$$L_{10} = F(\mu_0,\mu_1) - \Theta_3 g_3(\mu_0,\mu_1) - \Theta_4 g_4(\mu_0,\mu_1) = \\ = \frac{\gamma_0\lambda_0}{\mu_0} + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_3\mu_0 - \Theta_4\mu_1 \to \min, \tag{5.36}$$

$$L_{11} = F(\mu_0,\mu_1) - \Theta_1 g_1(\mu_0,\mu_1) - \Theta_2 g_2(\mu_0,\mu_1) - \Theta_3 g_3(\mu_0,\mu_1) = \\ = \frac{\gamma_0\lambda_0}{\mu_0} + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \\ + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_1\frac{\lambda_0}{\mu_0} - \Theta_2\frac{\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} - \Theta_3\mu_0 \to \min, \tag{5.37}$$

$$L_{12} = F(\mu_0,\mu_1) - \Theta_1 g_1(\mu_0,\mu_1) - \Theta_2 g_2(\mu_0,\mu_1) - \Theta_4 g_4(\mu_0,\mu_1) = \\ = \frac{\gamma_0\lambda_0}{\mu_0} + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \\ + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_1\frac{\lambda_0}{\mu_0} - \Theta_2\frac{\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} - \Theta_4\mu_1 \to \min, \tag{5.38}$$

$$L_{13} = F(\mu_0,\mu_1) - \Theta_1 g_1(\mu_0,\mu_1) - \Theta_3 g_3(\mu_0,\mu_1) - \Theta_4 g_4(\mu_0,\mu_1) = \frac{\gamma_0\lambda_0}{\mu_0} + \\ + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_1\frac{\lambda_0}{\mu_0} - \Theta_3\mu_0 - \Theta_4\mu_1 \to \min, \tag{5.39}$$

$$L_{14} = F(\mu_0,\mu_1) - \Theta_2 g_2(\mu_0,\mu_1) - \Theta_3 g_3(\mu_0,\mu_1) - \Theta_4 g_4(\mu_0,\mu_1) = \\ = \frac{\gamma_0\lambda_0}{\mu_0} + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \\ + \delta_0\mu_0 + \delta_1\mu_1 - \Theta_2\frac{\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} - \Theta_3\mu_0 - \Theta_4\mu_1 \to \min, \tag{5.40}$$

$$L_{15} = F(\mu_0,\mu_1) - \Theta_1 g_1(\mu_0,\mu_1) - \Theta_2 g_2(\mu_0,\mu_1) - \Theta_3 g_3(\mu_0,\mu_1) - \Theta_4 g_4(\mu_0,\mu_1) = \\ = \frac{\gamma_0\lambda_0}{\mu_0} + \frac{\gamma_1\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} + \delta_0\mu_0 + \delta_1\mu_1 - \\ - \Theta_1\frac{\lambda_0}{\mu_0} - \Theta_2\frac{\lambda_1}{\mu_0(1-0{,}356\rho)+\mu_1(1-0{,}06\rho)} - \Theta_3\mu_0 - \Theta_4\mu_1 \to \min, \tag{5.41}$$

where Θ_i – corresponding Lagrange multipliers, $i = \overline{1,4}$.

In the system of constraints (5.26), correction factors are applied to the traffic intensity indicators, taking into account the ratio of route duplication. Similarly, it is possible to form constraints correcting passenger flows, taking into account the share of passengers distributed by public transport modes:

$$\begin{cases} g_1(\mu_0,\mu_1) = \dfrac{\lambda_0 + 0{,}06(\lambda_0 + \lambda_1)}{\mu_0} \le q_1, \\ g_2(\mu_0,\mu_1) = \dfrac{\lambda_1 - 0{,}06(\lambda_0 + \lambda_1)}{\mu_1} \le q_2, \\ g_3(\mu_0,\mu_1) = \mu_0 \ge 0, \\ g_4(\mu_0,\mu_1) = \mu_1 \ge 0, \end{cases} \tag{5.42}$$

Thus, it is possible to obtain an alternative set of objective functions for finding local minima of the optimization problem.

Based on the results of a study of the fleet of urban carriers, the necessary characteristics of buses and trolleybuses operated on urban routes were determined.

KP "Cherkasyelectrotrans" is engaged in passenger transportation and serves the following city route numbers: 1, 1A, 2, 3, 4, 4A, 7, 7A, 8, 8P, 10, 14, 50. The following vehicles are used on these routes: ZiU-682V − 13 vehicle (7 of which are preserved), ZiU-682V-012 [B0A] − 9 vehicle (4 of which are preserved), Bogdan T70117 − 8 vehicle, BKM 321 − 15 vehicle, ZiU-683B [Б00] − 20 vehicle, ZiU-6205 [620500] − 10 vehicle. On weekdays, 56 trolleybuses are used for city transportation, on Saturdays − 21 trolleybuses, and on Sundays − 16 trolleybuses.

PJSC "Cherkasyavtotrans" is engaged in passenger transportation and serves the following city route numbers: 8, 21, 26, 27. The following vehicles are used on these routes: PAZ-4234 in the amount of 37 buses, PAZ-32054 − 30 buses, LiAZ-5293.60 − 4 buses, Ataman A093H6 − 3 buses.

PJSC "Cherkassy ATP-17127" is engaged in passenger transportation and serves the following city route numbers: 4, 5, 10. Vehicles on these routes: BAZ-A079.14 − 18 buses, PAZ-32054-07 − 13 buses, PAZ-4234 − 13 buses, BAZ-A079.04 − 11 buses, Etalon A079.32 − 5 buses, MAN A10 NL222 − 5 buses, BAZ-A079.19 − 5 buses, Ikarus 250.59 − 4 buses, Etalon A079.34 − 3 buses, Mercedes-Benz Sprinter 312D − 2 buses, Bohdan A09202 − 2 buses, Bohdan A091 − 2 buses.

PE "Elit-trans" is engaged in passenger transportation and serves the following city route numbers: 7, 22. Vehicles used on the routes: Mercedes-Benz O405N2 – 14 buses, Bogdan A091 – 12 buses, Bogdan A09202 – 10 buses, Bogdan A09202 – 7 buses, Bogdan A09201 – 6 buses, Caetano City Gold – 5 buses, Castrosúa CS40 – 4 buses.

State Enterprise "Charz-avto" is engaged in passenger transportation and serves the following city route numbers: 12, 20, 25, 31. Vehicles on the routes: Bogdan A09202 – 37 buses, Bogdan A091 – 34 buses, Bogdan A092H2 – 2 buses, Ataman A092G6 – 2 buses.

The passenger capacity of the indicated trolleybuses and buses is given in tab. 26. and tab. 27.

The values of optimal traffic flows without constraints and with constraints were calculated using the generalized Lagrange multiplier method. The input data for calculating the optimal traffic intensity taking into account constraints on passenger capacity are taken from tab. 5.15, tab. 5.18, tab. 5.26 and tab. 5.27 for trolleybuses and buses, respectively.

A comparison of the optimization results without imposing constraints on the passenger capacity of vehicles and taking into account the specified constraints for the routes of the Cherkasy city network is presented in tab. 28 and tab. 29.

Table 26. Passenger capacity of trolleybuses on the routes of the transport network of the city of Cherkasy

№	Route number	Starting and ending points of movement	Vehicle model	Passenger capacity, pass.
1	1	ChLFZ "Avrora" – sanatorium "Ukraine"	LAZ E183	100
2	1A	Patsaeva str. – sanatorium "Ukraine"	LAZ E183	100
3	2	Patsaeva str. – ChSHK	ZiU-6205	116
4	3	sanatorium "Ukraine" – railway station	ZiU-682 (ZiU-9)	126
5	4	General Momota str. – trolleybus depot	ZiU-682 (ZiU-9)	126
6	4A	General Momota str. – railway station	ZiU-682 (ZiU-9)	126
7	7	Mozhaiskogo str. – trolleybus depot	BMK 321	115
8	7A	sanatorium "Ukraine" – trolleybus depot	BMK 321	115
9	8	ChLFZ "Avrora" – Rustavi str.	ZiU-6205	116
10	8P	ChLFZ "Avrora" – airport	ZiU-6205	116
11	10	river port – Oleny Teligy str.	БМК 321	115

12	14	Onoprienka str. – airport	ZiU-682 (ZiU-9)	126
13	50	cargo port – airport	ZiU-682 (ZiU-9)	126

Source: results of my own research.

Table 27. Passenger capacity of buses on the routes of the transport network of Cherkasy

№	Route number	Starting and ending points of movement	Vehicle model	Passenger capacity, pass.
1	4	Regional Hospital – Patsaeva str.	BAZ A079 «Etalon»	28
2	5	General Momota str. – "Avrora" factory	Bogdan a092	43
3	7	General Momota str. – Cargo port	Bogdan a092	43
4	8	Center – Surikova str.	PAZ 3205	42
5	10	Center – Hutory village	PAZ 3205	42
6	12	Kobzarska str. – Military R&E Office	Bogdan a091	46
7	20	Rustavi str. – Mytnytsia district	Bogdan a092	43
8	21	Mytnytsia district – Patsaeva str.	PAZ 3205	42
9	22	Sumgaitska str. – 700th Anniversary Square	Mercedes-Benz O 405 N2	46
10	25	Sumgaitska str. – "Avrora" factory	Bogdan a092	43
11	26	Regional Hospital – Bus Station	PAZ 3205	42
12	27	railway station – Narbutivska str.	PAZ 3205	42
13	31	Dahnivka district – PO "Azot"	Bogdan a092	43

Source: results of my own research.

Table 28. Vehicle traffic intensity on duplicate bus routes before and after optimization of the transport network of Cherkasy city

Bus route number	Traffic intensity after optimization without taking into account constraints, vehicle/hour	Traffic intensity after optimization with vehicle passenger capacity constraints, vehicle/hour
4	5	8
5	0	0
12	12	14
22	8	11
25	9	12
26	0	4
27	0	0
31	0	2

Source: results of my own scientific research.

Table 29. Intensity of vehicle traffic on trolleybus routes that are duplicated by bus routes before and after optimization of the transport network of Cherkasy city

Trolleybus route number	Traffic intensity after optimization without constraints, vehicle/hour	Traffic intensity after optimization with vehicle passenger capacity constraints, vehicle/hour
1	10	7
2	16	16
3	15	12
7A	16	14
8	7	5
10	12	10

Source: results of my own scientific research.

Thus, it can be argued that reducing the passenger capacity of vehicles increases its impact on the results of traffic flow optimization. Thus, for bus routes in Cherkasy, taking into account constraints on the passenger capacity of vehicles is a necessary condition for optimization. However, by increasing the number of buses on the route compared to the results of optimization without constraints, a reduction in the total number of trolleybuses is achieved, respectively.

9.6. Conclusions

The existing urban passenger transport network of Cherkasy was studied. The parameters of the city's transport network routes were determined, including the intensity of bus and trolleybus traffic on overlapping sections of routes. It was found that the density of the urban passenger transport route network in Cherkasy, Ukraine, significantly exceeds the regulatory value. The optimization of the urban network was carried out by reducing transport flows on bus and trolleybus routes with the coincidence of route routes by at least three quarters of the route length. The constructed optimization model provides an opportunity to determine the optimal mode of operation on an arbitrary route, can be applied for two different types of transport, as well as for duplicate routes of one type of transport. The novelty of the proposed approach lies in the use in the developed models of the route duplication ratio, and statistical information on the distribution of passengers by different types of transport on common sections of different routes. Such an approach refines existing mathematical models of public transport traffic to minimize the negative impact on passengers and the traffic environment.

The main advantage of the proposed mathematical optimization models is the ability to simultaneously determine the optimal operating modes of urban public passenger transport on different routes, taking into account passenger losses. The distribution of passengers by category and public transport by type reflects the presence of socially vulnerable groups of the population. Meeting the interests of these categories of citizens will allow to increase their social level.

The characteristics of vehicles operated on the studied routes were used in the formation of additional constraints imposed on the model, also taking into account the ratio of duplication of routes and partial coefficients that specify the volume of passenger flows on the route by mode of transport.

The implementation of the constructed models can be performed for separate periods of time for which the passenger flow is a constant value, for example, one hour. That is, the optimal number of trips on routes is determined for a specific hour. By analogy, this approach can be used to determine the optimal intervals of transport traffic during the day, taking into account the days of the week and seasons.

The implementation of these models for calculating the optimal intensity of trolleybus and bus traffic allows reducing the total costs of passengers and transport, and as a result, will lead to more effective functioning of transport in the urban environment and its management. The proposed approach can be used in the implementation of transport projects and plans for the reconstruction of the existing transport network of the city.

Further research will be aimed at constructing and solving a problem that is dual to this one, namely the problem of calculating the cost of passenger hours on transport moving along a route with optimal intensity.

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Chapter 10.

CONDITIONS FOR THE DEVELOPMENT OF PASSENGER ROAD TRANSPORT IN POLAND – SELECTED FACTORS

Agnieszka Napiórkowska-Baryła

10.1. Introduction

The TSL sector is one of the most important branches of the economy, accounting for 7% of GDP and creating 6.5% of jobs (GUS 2023). Road transport has the largest share in these results. The degree of development of this sector of the economy reflects the economic level and quality of life of society. Transport is defined as the movement of people and materials and the provision of ancillary services for which a fee is charged. The etymology of this term refers to a technological process involving the transfer of people, objects or energy over a distance. Efficient transport services and transport itself ensure the proper functioning of all sectors of a country's economy.

Road transport (domestic or international), which includes all road journeys performed by an entrepreneur, accounts for the largest share of all types of transport. It can be performed as an ancillary service or in relation to economic activity. It also includes economic activity in the field of freight forwarding[1]. It is playing an increasingly important role in the European economy. This is due to the constant increase in the number of goods and people transported in European countries. Road transport is also a hallmark of the Polish national economy. No other Polish industry has achieved such spectacular success since our country joined the European Union. At the same time, no other industry is so dependent on the European and global economic situation, disruptions in supply chains, the geopolitical situation, armed

[1] https://witd.lublin.pl/podstawowe-definicje/ (April 18, 2025).

conflicts and political decisions. Furthermore, no other industry has such a significant impact on the functioning of both the economy as a whole and its individual sectors (Wroński 2023, p. 4). However, it should be remembered that road transport also causes adverse effects. These include, in particular, noise and pollution, congestion and road accidents, which increase environmental and social costs. The introduction of changes in the latest technology and the development of electric and autonomous vehicles also pose a major threat. Therefore, the direction of transport development, including road transport, must be in line with the principle of sustainable development. This is a priority of environmental policy in Poland and the European Union. The main idea behind the concept of sustainable transport is to minimise the harmful impact of means of transport on the environment, both natural and urban. Sustainable transport is defined as transport that: enables the movement of people/goods in a manner that is safe for people and the environment, enables economic and local development, supports efficient functioning and reduces the consumption of natural resources while minimising land use and noise.

The main objective of the study was to assess the conditions for the development of road transport in Poland, particularly passenger transport. The main objective was achieved through additional objectives, namely:

1. Analysis of road infrastructure and road transport superstructure elements.
2. Analysis of passenger transport volumes.
3. Directions of development resulting from EU environmental policy.

Secondary source material was used in the study. It was obtained from the Subject Knowledge Bases of the Central Statistical Office. The time frame covered the selected period 2010-2023.

10.2. Road transport – advantages and disadvantages

Road transport is one of the most popular modes of transport because it allows you to quickly reach almost any destination. It involves the movement of people or goods on land roads. For this purpose, wheeled means of transport, such as motor vehicles, are used. This branch of transport is operated by road hauliers. In Polish law, it is regulated by the Act of 6 September 2001 on road transport, which divides this activity into commercial and noncommercial. Another division is based on territorial criteria, whereby road transport is divided into domestic and international[2].

Road transport is of key importance in the transport of goods and passengers. Its qualitative and quantitative development has a direct impact on the conditions in which entrepreneurs conduct their business and on the quality of life of residents. In addition to its direct impact, this type of transport also has an indirect impact on economic development. Road transport is the most popular branch of transport. It involves the carriage of goods or persons using motor vehicles (cars). Among all modes of transport, road transport is characterised by the highest reliability of transport and spatial accessibility. Compared to rail and water transport, the cost of this type of transport is relatively high. However, it is lower than air transport. Taking into account criteria such as transport time and security of goods, only air transport has an advantage over road transport, and in terms of transport capacity, rail transport has an advantage (Mendyk 2009; Truskolaski, Bugowski 2018, pp. 266–267).

Road transport (by car) is the most common type of transport and is used in most logistics operations. An extensive road network allows carriers to reach virtually any destination, which means that transport services can be provided to virtually anyone. Due to the low capital barrier to entry into the road transport market, there are a large number of companies providing this type of service. As a result, there is a high availability of services in this field[3]. Another classification is provided by Kautsch (2018, p. 17). According to the author, road transport is divided according to its purpose. This division includes vehicles for the transport of passengers and vehicles for the transport of goods. The first part of the division mainly concerns passenger cars and buses. Passenger cars are involved in the transport process only if they are intended to be used for commercial purposes by the operator. Buses, on the other hand, can be grouped into city buses, intercity buses and tourist buses (coaches). The second part of the road transport classification consists of motorised and non-motorised vehicles. Motorised vehicles intended for the transport of goods are mainly trucks. These types of vehicles can have universal, specialised or special bodies. In addition to trucks, this group also includes tractor units and ballast tractors.

[2]https://www.pkt.pl/artykul/transport-drogowy-definicja-rodzaje-infrastruktura-srodki-transportu-14896 (May 27, 2025).
[3]https://mfiles.pl/pl/index.php/Rodzaje_transportu (May 27, 2025).

According to Sobczak and Wąchała (2017, p. 181), road transport, like any other type of transport, has both advantages and disadvantages. Its main advantage is its accessibility, as compared to rail, sea or air transport, it is able to deliver cargo to its destination. According to Lorenc (2018, pp. 77-78), the basic advantages of road transport include speed and flexibility. Both of these features result from the high availability of point and linear infrastructure. This infrastructure has a dense and coherent network of transport roads, which distinguishes road transport from other modes of transport. This branch of transport is economical for short and medium distances. Figurski and Niepsuj (2021, p. 128) also include high availability of subcontractors, the possibility of additional loads and low service prices among the advantages. The main advantages of road transport include, above all, a large selection of different types of transport and the high availability of basic means of work, as evidenced by the large number of cars on the roads. Another important advantage is the ability to transport cargo and people over short and medium distances and to deliver vehicles to any location, which distinguishes it from other means of transport. The high speed of transport combined with delivery to the customer and the timeliness and punctuality of services should also be taken into account, as these are becoming increasingly important in the world of transport (Kautsch 2018, pp. 16-17).

From the point of view of logisticians, the most important advantage is the attractive cost. It is the most cost-effective type of transport despite high road tolls. This determines its continuing popularity. This type of transport is a great addition to any logistics plan. Even when choosing a different mode of transport, logisticians are unable to completely abandon the use of cars, as there are many places that can only be reached by road. Another strength of road transport is its easy accessibility. The number of companies providing this type of service is growing all the time, which has a very positive impact on prices and delivery times. According to Truskolaski and Bugowski (2018, pp. 267-268), the strengths of road transport include the adaptability of means of transport to the carriage of various goods and the favourable ratio of transport time to transport cost compared to other modes of transport. Another feature to consider is the flexible frequency of services. Another advantage that distinguishes this type of transport from other modes is the possibility of direct transport to the destination. In addition to these advantages, the road transport network is also important, as it is the most extensive, coherent and well-adapted to the location of consumption, production and trade.

The main disadvantages of road transport include its negative impact on the environment, both natural and human (exhaust emissions, soil pollution, noise, landscape change, road incidents and accidents (Sobczak and Wąchała 2017, p. 181).

Lorenc (2018, pp. 77-78) mentions limited load capacity compared to other modes of transport (e.g. rail or sea transport). Travel speed is often dependent on weather conditions. Another problem may be high traffic density, which will cause heavy traffic jams. To avoid such problems, appropriate road transport logistics are necessary in this situation.[4]

Another disadvantage of road transport is the time required to transport people or goods. This is primarily due to the large amount of cargo, which consequently prolongs the execution of the order. Another problem with this type of transport is unpredictability. This is mainly due to costs related to fuel prices, road tolls, insurance and drivers' wages. As a result, rates in the transport industry can change rapidly, which is an unfavourable situation for customers[5].

10.3. Elements of road transport infrastructure

According to Wojdygowski (2018, p. 42), road transport, which enables the smooth and efficient functioning of every economic sector, depends primarily on the existing infrastructure.

The classic definition of infrastructure states that "infrastructure" is permanently located linear and point facilities for public use that have been created by humans. These facilities form the basis of social and economic life due to their functions related to the movement of people and goods. When considering transport alone, it can be said that transport infrastructure is a set of space-related facilities. They enable the transport of people and goods and the performance of activities necessary for the smooth running of the transport process. Infrastructure is an important factor determining economic growth and regional development. Neglecting it will lead to a decline in the efficiency of the entire economy. Adequate point and linear infrastructure determines the level of transport accessibility. This accessibility is one of the most important factors determining the attractiveness or competitiveness of the road transport sector. It has a significant impact on turnover and

[4]https://www.pkt.pl/artykul/wady-i-zalety-transportu-samochodowego-8169 (May 27, 2025).
[5]https://logistykaitransport.pl/logistyka,ac256/zalety-i-wady-transportu-samochodowego,10161 (May 27, 2025).

influences the position in the economy. Within the linear infrastructure, there are two main levels of division, according to function in the road network and according to the degree of accessibility. The first level concerns local, regional, national and international roads. The second level includes public roads, expressways and motorways. Point infrastructure, on the other hand, includes separate places used for transport, cargo or services (Truskolaski, Bugowski 2018, p. 268).

A characteristic feature of infrastructure is its economic and technical indivisibility, which results from its high asset value and capital intensity. It is also characterised by functional and spatial immobility and long-term use. Infrastructure investments require the accumulation of sufficiently high financial resources, often from public sources.

Road infrastructure has certain characteristics that are important for the development of the industry. It is the backbone of every economy. The more a region is saturated with infrastructure elements, the greater its chances of development. Infrastructure investments should therefore precede market needs (Krom et al. 2017, p. 1074).

Road infrastructure requires continuous investment to improve its technical condition. For this to happen, large expenditures are needed for development and to ensure adequate standards to meet market needs resulting from the continuous growth of trade and heavy passenger traffic. Investments in road infrastructure contribute to the construction of motorways, expressways and ring roads. Financial outlays also help to expand the road network and change the road surface to accommodate higher axle loads. This is necessary due to the high volume of heavy goods vehicle traffic. (Targosz, Wiederek 2019, pp. 416-417).

Another criterion concerns technical qualifications. Based on this indicator, five classes of public roads can be distinguished. These include motorways and roads with similar parameters, expressways, and single carriageways with two lanes in each direction. The remaining groups concern roads for intra-regional traffic and narrow lanes intended for local traffic. The last criterion is related to the degree of accessibility and includes public roads, expressways and motorways (Jasińska, Jasiński 2018, p. 147).

Motorways are accessible only to motor vehicles. Traffic on them is collision-free due to junctions intersecting with selected public roads. They are equipped with two one-way carriageways that are permanently separated. Expressways, on the other hand, have junctions and single-level intersections, which can be one-way or two-way. Road sections that include all other public roads accessible to all vehicles are called public roads.

Point infrastructure includes the necessary facilities used for stationary passenger services. The objects found in this infrastructure are also used for loading motor vehicles. This infrastructure mainly includes bus stations with stops, bus stops themselves and technical stations. Another group of these facilities are transhipment and unloading points (Kautsch 2018, pp. 25-26).

According to Karolewski and Roman (2021, PP. 40-41), road transport infrastructure includes motorways and the necessary equipment. These roads are supplemented primarily by bridges, culverts, tunnels, embankments and roundabouts. The condition of the infrastructure is subject to various types of testing. The quantitative condition is measured by the density of the road network and transport points.

Linear road transport infrastructure includes not only roads, but also bridge structures that enable the construction of roads in difficult terrain. These structures can be divided into bridges, viaducts, flyovers, underpasses and footbridges. If a bridge structure is located over several different obstacles, the type of structure is determined by the appropriate order: water obstacle, railway line, road, and only at the very end other obstacles.

According to Pawlak (2018, pp. 937-938), an important factor determining the appropriate level of road transport infrastructure development is the road transport accessibility index. This measure depends on the state of infrastructure development. It is primarily influenced by proximity to the border, distance from the capital or other important centres. Investments in road infrastructure should be carried out in stages. However, priority should be given to sections that bring synergistic effects in many spatial areas. In the case of motorways and national roads, this means priority for entry and exit sections of large urban agglomerations.

In order to increase competitiveness, efforts should be made to connect motorway and national road sections to create a common road network. This will allow positive multiplier effects to be triggered. It is also necessary to connect lower-class roads with the basic "backbone" of the highest-class road network. Properly located junctions on expressways allow for very good communication between centres, which improves transport accessibility. A developed, modern and high-quality infrastructure is very important for sustainable development and economic growth. This infrastructure improves the efficiency of economic activity and allows companies to make investment decisions more easily. In this way, infrastructure contributes to increased competitiveness. Regions with extensive infrastructure have greater development potential.

The effects of motor transport infrastructure development can be assessed in terms of supply and demand. The demand-side approach focuses exclusively on the impact of investments on subcontractors and companies located in the vicinity of the investment. It takes into account social and environmental costs. The supply side, on the other hand, focuses on attracting investment in manufacturing or services. The impact of expanded motorways and expressways affects entrepreneurship and local government budgets. The connection of individual sections of expressways and motorways into a coherent network and the development of road transport infrastructure increase the attractiveness of a given region and improve its transport accessibility.

Infrastructure management is a complex process that covers activities undertaken at every stage of an engineering structure's life cycle. The continuous development of road networks makes it necessary to use new tools and methods that enable sustainable development of the system, along with its assessment and analysis. One concept that addresses this issue is life cycle thinking (LCT). This concept is promoted by the United Nations Environment Programme (UNEP). LCT goes beyond the traditional focus on the manufacturing process. Its main objective is to optimise environmental, social and economic impacts. In summary, it is an approach based on the sustainable development of the analysed object or system.

The Life Cycle Costs (LCC) method is used to assess the functioning of transport infrastructure systems or their components. During the life cycle of a transport system, costs related to design, construction and maintenance are incurred. The LCC method is also a tool for making rational decisions about the choice of the appropriate solution. Considering the life cycle cost of a transport system, the importance of this parameter is evident. It is increasingly recommended when selecting transport options or evaluating tender offers (Gobis et al. 2019, pp. 5-6).

Efficient and safe road traffic is ensured by high-quality linear and point infrastructure. This infrastructure has changed mainly thanks to clear road signs and the absence of pedestrian crossings on expressways. It also owes a lot to an extensive network of safe car parks in convenient locations and user-friendly toll collection systems for expressways. It is also worth mentioning the well-developed road network, which is adapted to the main freight flows. It is part of the priority axes of the TEN-T network (Rucińska, Kędzior-Laskowska 2019, pp. 40-41). Another important element of road infrastructure is the technical condition of roads with specific performance characteristics and high technical parameters. These parameters have been adapted to the needs of local, regional and international transport. In order to maintain good quality infrastructure, it is necessary to invest in city bypasses, which will allow for smooth traffic flow and reduce congestion. Problems related to renovation backlogs and the unsuitability of road and bridge surfaces for heavy vehicle traffic should also be minimised.

The length and quality of roads are of great importance when choosing the type of transport. The development of road infrastructure in Poland is noticeable in every aspect (Table 1).

Table 1. Length of roads in 2010-2023 (km)

Specification	2010	2015	20	2023
Total public roads	406,122.1	419,636.4	430,267.3	428,362.2
Motorways	857.4	1,559.2	1,712.2	1,850.9
Expressways	674.7	1,492.2	2,548.5	3,243.8
Municipal roads with hard surface	112,267.9	127,857.6	149,813.5	155,159.7
Total cycle paths	5,782.8	10,797.2	17,254.6	21,577.5
Length of bus lanes	258.4	276.9	323.2	339.5

Source: own study based on https://bdl.stat.gov.pl/

During the period under review, the total length of public roads increased slightly. However, there was a spectacular increase in the length of expressways. Motorways are accessible only to motor vehicles. Traffic on them is collision-free due to junctions intersecting with selected public roads. They are equipped with two one-way carriageways that are permanently separated. Expressways, on the other hand, have junctions and single-level intersections, which can be one-way or two-way. Road sections that include all other public roads accessible to all vehicles are called public roads.

The latest data from the General Directorate for National Roads and Motorways (GDDKiA) indicate that the length of national roads in Poland is 19,341.8 km, of which 17,821.6 km are managed by the GDDKiA. The total length of expressways is 5,221.7 km (expressways 3,337.1 km and motorways 1,884.6 km), including 465 km of motorway sections under concession. Under the Government Programme for the Construction of National Roads by 2030, 108 projects with a total length of 1,449.9 km are being implemented, 17 projects with a total length of 237.5 km are out to tender, and further projects with an estimated length of 2,261.5 km are in preparation. In addition, as part of the Programme for the Construction of 100 Ring Roads for 2020-2030, 8 projects with a total length of 35.3 km have been completed, 22 tasks with a total length of 176.5 km are under construction, 12 tasks with a total length of 102 km are still in the tender process, and 58 tasks with an estimated length of 555 km are in preparation[6]. Thanks to a number of tasks carried out by GDDKiA, Poland is developing rapidly in terms of the length of motorways and expressways. Thanks to such an extensive motorway network, road transport can reach every important city in Poland, as well as the borders of neighbouring countries. Such a long motorway network allows for the smooth transport of goods and people. The most important motorways in Poland include the A1 motorway, which connects to the Czech border. The A2, A4 and A6 motorways, which have direct connections to the German border, are also important transport routes. The A2 motorway also connects to the Belarusian border, and the A4 to Ukraine.

The accessibility of public roads also depends on their quality. The improvement in quality is particularly evident on municipal roads, which account for approximately 60% of public roads. In 2023, approximately 61% of municipal roads were paved, compared to 44% in 2010.

Due to the widespread promotion of environmentally friendly solutions, including zero-emission transport, local governments in Poland have recently been building cycle paths. During the period under review, the length of cycle paths increased almost fourfold. As a result, in many cities, following the example of other European cities, it is easier to get around by bicycle, avoiding heavy traffic during rush hour. This also has a positive impact on the environment: the fewer cars there are in the city, the cleaner the air and the fewer traffic jams.

The increase in the length of bus lanes is also a positive development. On average, their length increases by about 7% per year. This is aimed at improving the attractiveness and efficiency of urban transport.

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[6] https://www.gov.pl/web/gddkia/generalna-dyrekcja-drog-krajowych-i-autostrad (August 20, 2025)

10.4. Passenger road transport superstructure

Transport superstructure includes the technical and organisational means necessary for the movement of goods and people, such as rolling stock (e.g. trucks, trains, planes, buses), equipment (e.g. cranes, overhead travelling cranes) and the technical facilities for these means and traction systems. Unlike transport infrastructure, which is a system of roads, tracks or ports, superstructure is the equipment needed to carry out the transport process (Rokicki 2020). The road transport superstructure includes not only passenger cars and trucks with trailers. This type of transport also includes mopeds and motorcycles. Buses and various types of special vehicles are also distinguished. This is any type of vehicle registered in the country or registered for the first time in Poland. Road transport, defined as a registered business activity and the provision of passenger or goods transport services, is primarily based on the achievements of the automotive industry, which allow for the mass transport of goods and people in much shorter periods of time.
The number of registered vehicles in road transport is presented in Table 1.

Table 2. Number of road vehicles registered in 2010-2023

Specification	2010	2015	2020	2023
Mopeds	922	1,259,187	1,400,013	1,458,332
Motorcycles	1,013,014	1,272,333	1,669,138	1,923,690
Passenger cars	17,239,800	20,723,423	25,113,862	27,227,691
Mopeds registered for the first time in Poland	81,869	43,258	27,585	n/a
Motorcycles registered for the first time in Poland	43,594	81,831	81,571	93,400
Passenger cars registered for the first time in Poland	873,098	1,145,506	1,179,776	1,202,700

Source: own study based on https://bdl.stat.gov.pl/

The analysis of the data presented in Table 2 shows that the number of road vehicles registered in Poland is constantly growing. Year on year, the popularity of motorcycles and mopeds is increasing. This is mainly due to the increase in the number of two-wheelers with an engine capacity of up to 125 cm^3. This engine capacity is mainly preferred by young people with a moped licence and all persons with a category B driving licence, as these licences allow them to ride motorcycles and mopeds with this engine capacity. The situation is similar for motorcycles. Their number has almost doubled in thirteen years.

The number of passenger cars has increased by one million in thirteen years (from 17 million in 2010 to 27 million in 2023). The continuous increase in the number of passenger cars, reflected in the ratio of cars per 1,000 inhabitants (Table 3), is primarily due to the improvement in the financial situation of Polish citizens. Statistically, there is 1.85 car per household.

Table 3. Passenger cars per 1,000 inhabitants in 2010-2023

Year	Passenger cars per 1,000 inhabitants
2010	451
2015	539
2020	656
2023	723

Source: own study based on https://bdl.stat.gov.pl/

Between 2010 and 2023, a continuous increase in the ratio of passenger cars per 1,000 inhabitants can be observed. However, such a high ratio is not beneficial, as this group of vehicles mainly consists of old cars. There are more and more such vehicles in our country, which mainly causes traffic congestion in a large number of cities, because Polish cities are not fully adapted to such a large number of vehicles. Poland ranks second in the European Union in terms of this measure. The average for the 27 EU countries is 560 passenger cars per 1,000 inhabitants. It can therefore be seen that from 2015 to the end of the period under review, our country exceeded the EU average.

Between 2010 and 2023, there was an increase in the number of passenger cars registered for the first time in Poland. The number of passenger cars registered for the first time accounts for a low share of the total number of vehicles registered in this group. This is mainly due to the purchase of used cars from car dealers and exchanges, while newly registered passenger cars are mainly premium vehicles.

The fleet of electric and hybrid cars is growing quite rapidly. According to the Polish New Mobility Association (PSNM), at the end of October 2024, there were 132,812 electric passenger cars on Polish roads. The fleet of fully electric passenger cars (BEVs) numbered 68,634, and the fleet of plug-in hybrids (PHEVs) numbered 64,178. The fleet of electric mopeds and motorcycles is also growing steadily, with 23,027 units at the end of October, as is the number of hybrid passenger and delivery vehicles, which increased to 904,104 units. This is due to the possibility of co-financing for both individuals and businesses under the "My Electrician" programme. In parallel with the fleet of electric vehicles, the charging infrastructure is also developing. At the end of October 2024, there were 8,184 publicly accessible electric vehicle charging points (4,528 stations) in Poland. Of these, 30% were fast direct current (DC) charging points and 70% were slow alternating current (AC) charging points with a power output of less than or equal to 22 kW. In June 2025, electric cars accounted for approximately 7.6% of new car sales in Poland, reaching a historic record share[7].

A registered motor vehicle is a motor vehicle designed to travel at speeds exceeding 25 km/h. This term includes vehicles registered with vehicle registration authorities, i.e. district offices[8]. The number of passenger cars by age group in 2010-2023 and the percentage structure of age categories are presented in Table 4.

Table 4. Number of passenger cars by age category in 2010-2023

Year	Number of passenger cars by age category:							
	Total	Up to 2 years	3-5	6-10	11-15	16-20	21-30	31 years and older
2010	17,239,800	722,974	1,143,109	2,907,921	4,892,671	3,256,615	2,872,231	1,444,279
2015	20,723,423	885,473	1,047,676	3,024,740	4,278,969	4,710,323	4,064,565	2,711,648
2020	25,113,862	1,321,677	1,494,219	2,674,028	4,653,242	4,924,848	5,917,852	4,127,997
2023	27,227,691	1,252,474	1,524,751	3,566,827	3,512,372	5,445,538	6,534,646	5,418,310

Source: own study based on https://bdl.stat.gov.pl/

7 https://psnm.org/2024/informacja/licznik-elektromobilnosci-polski-rynek-samochodow-elektrycznych-wciaz-na-plusie/ (July 20, 2025)

8 https://stat.gov.pl/metainformacje/slownik-pojec/pojecia-stosowane-w-statystyce-publicznej/310,pojecie .html (January 15, 2025).

Table 5. Share of individual age categories in the total number of passenger cars in 2010-2023

Year	Share of individual age categories in the total number of passenger cars in the year:							
	Total	Up to 2 years	3-5	6-10	11-15	16-20	21-30	31 years and older
2010	100.00	4.20	6.6	16.9	28.40	18.80	16.70	8.40
2015	100.00	4.30	5.00	14.60	20.70	22.70	19.60	13.10
2020	100.00	5.20	5.90	10.70	18.60	19.60	23.60	16.40
2023	100.00	4.50	5.60	13.10	12.90	20	24	19.90

Source: own study based on https://bdl.stat.gov.pl/

An analysis of the data presented in Tables 4 and 5 shows that cars on Polish roads are old. There has been a continuous increase in the share of cars aged 21-30 and 31 and older throughout the entire period under review. This means that Polish households, achieving a high car ownership rate per 1,000 inhabitants (above the EU average), are purchasing older and relatively cheaper cars. Unfortunately, this comes at the expense of the environment and higher vehicle maintenance costs.

Public transport is another term for urban or local transport. It is referred to as a field of management that enables the satisfaction of human needs in terms of movement within a city and its surroundings. The most important group of public transport is urban transport, which includes buses, trolleybuses, trams and urban railways. The size of the public transport fleet is presented in Table 6.

Table 6. Size of the public transport fleet in 2010-2023

Year	Buses	Trams	Trolleybuses
2010	12,098	3,620	180
2015	11,795	3,373	216
2020	12,231	3,106	257
2023	12,500	3,000	233

Source: own study based on https://bdl.stat.gov.pl/

Buses account for nearly 80% of the urban transport fleet. During the period under review, there was an increase in the number of buses and trolleybuses in the public transport fleet and a continuous decline in the number of trams throughout the period. This may be primarily due to the removal of tram lines in some cities. Another reason for this decline is mainly the high failure rate of trams and the increase in electricity prices. The Covid-19 pandemic also contributed to a decline in the number of public transport passengers, which certainly led to a reduction in the number of trams.

A constant trend in urban transport is the replacement of traditional fleets with zero-emission vehicles. Local governments can use EU funds for this purpose, including those launched under the National Recovery Plan. At the end of 2024, the fleet of zero-emission buses in Poland increased to 1,428 (of which 1,348 were fully electric and 80 were hydrogen-powered)[9] .

10.5. Passenger transport by road

Passenger transport is understood as an activity consisting in the provision of services, for a fee or free of charge, resulting in the movement of persons from a point of departure to a point of destination. Due to the organisational aspect, a distinction can be made between regular and irregular passenger transport. Regular transport is characterised by the provision of services on a specific and relatively fixed route. Irregular transport, on the other hand, is carried out on the basis of a prior agreement between the carrier and the customer who requests the transport service. [10]

In 2023, road transport (urban, national and international) carried a total of 3,507.0 million passengers, i.e. 7.0% more than in the previous year. An increase in transport was recorded in interurban transport (by 19.8%), urban transport (by 6.1%) and international transport (by 8.5%). Passenger transport by road (excluding urban transport) is presented in Table 7.

9 https://psnm.org/2024/informacja/licznik-elektromobilnosci-polski-rynek-samochodow-elektrycznych-wciaz-na-plusie/ (July 20, 2025)

10 https://mfiles.pl/pl/index.php/Przew%C3%B3z_os%C3%B3b#cite_note-p1-1 (January 18, 2025).

Table 7. Passenger transport by commercial motor vehicles in 2010-2023 (in thousands of persons)

Year	Total	Domestic transport	International transport
2010	569,652	567,354	2,298
2015	416,774	412,872	3,900
2020	159,700	158,169	1,530
2023	260,220	256,935	3,285

Source: own study based on https://bdl.stat.gov.pl/

In the years 2010-2023, a decrease in the total number of passengers transported by commercial road transport can be observed, especially in 2020. This is due to restrictions introduced as a result of the Covid-19 pandemic. The crisis caused by the outbreak of the Covid-19 pandemic has left its mark on all sectors of the economy, including transport. The restrictions and legal regulations introduced to protect the population from the possibility of infection have had a significant negative impact on mobility (Pomykała 2021, p. 322). Politicians around the world were divided on the use of public transport, and their opinions changed with each passing month of the pandemic. In Poland, a limit of 50% of seats occupied on public transport was introduced, then changed to 30% of seats and standing places (Bryniarska, Kuza 2021, p. 5).

10.6. Sustainable transport development – directions for action

According to the European Environment Agency, approximately 25% of total CO_2emissions in the European Union come from the transport sector (2019 data), of which 71.7% comes from road transport. Transport is the only sector where greenhouse gas emissions have increased over the last three decades (1990-2019) by 33.5%. The European Union emphasises that there are two ways to reduce CO_2 emissions from cars: increasing vehicle efficiency or changing the fuel used. Currently, diesel and petrol are used in most road transport in Europe. Sustainable and responsible development should become an indispensable part of companies' strategies. In order to combat climate change, the European Union is introducing new regulations and requirements in line with the concept of sustainable development. Sustainable transport is a priority of environmental policy. The main idea behind the concept of sustainable transport is to minimise the harmful impact of transport on the environment, both natural and urban. The European Commission defines sustainable transport as transport that:

– enables the movement of people/goods in a way that is safe for people and the environment,
– enables economic growth and local development, supports efficient functioning,
– reduces the use of natural resources while minimising land use and noise.

The main strategy for reducing negative environmental impact is the European Green Deal, which aims to transform the European Union into a fair and prosperous society. EU citizens would live in a modern, resource-efficient and competitive economy. By 2050, the European Union will achieve net-zero greenhouse gas emissions. This will decouple economic growth from the use of natural resources.

The Green Deal also focuses on transport, which accounts for a quarter of greenhouse gas emissions. To achieve climate neutrality, emissions must be reduced by 90% by 2050. Public transport should be improved, which will significantly reduce the negative impact on the environment. The infrastructure and transport system throughout the European Union will be adapted to reduce traffic congestion and environmental pollution (Pomykała, Raczyński 2020, p. 6).

The European Commission's plan provides for special support for electromobility. A continuous increase in low-emission cars is expected. Unfortunately, this necessitates the provision of charging points for this type of vehicle. It is also important to introduce a legislative framework to support the production and distribution of alternative fuels for all means of transport. There are also plans to further tighten emission standards for combustion engines and to intensify measures to reduce traffic congestion, particularly in urban areas.

All the objectives of the European Green Deal are key challenges for European transport policy. A growing number of Europeans are demanding a healthier and better environment. European citizens are concerned about the state and quality of air in cities. They expect changes in mobility models and cleaner means of transport in terms of production and emissions. Many people see an urgent need to decarbonise transport (Adamowicz 2020, pp. 12-13).

In 2021, a legislative package on climate and energy was announced. The "Fit for 55" package introduced by the European Commission aims to reduce greenhouse gas emissions by 55%. The package consists of thirteen legislative proposals. These are new regulations and updates to existing regulations. The update of the regulations is intended to revise the EU emissions trading system and the directive on alternative fuel infrastructure. An amendment to the directive on renewable energy and energy efficiency is to be introduced. The regulation setting CO_2 for passenger cars and light-duty vehicles has also been amended.

New legislative proposals include the introduction of a new European Union forest strategy. Changes were also to be made to the carbon border adjustment mechanism. The European Commission also wants to introduce a social instrument for climate action (Polish Chamber of Chemical Industry 2022, p. 67).

The European Commission's actions under the European Green Deal mainly concern road transport. One of the solutions is to make greater use of multimodal transport. The European Commission has observed that the problem of excessive costs will arise. To prevent this, the Strategy for Sustainable and Smart Mobility was introduced in 2020.

Taking into account regional development, it can be seen that the greatest reference is to transport in cities. Improving transport management at regional and local level must be linked to better spatial planning. It should also depend on better connections with rural and suburban areas, which will be in line with the principles of sustainable development.

Urban transport is at the forefront of the strategy for sustainable and intelligent mobility. According to the European Commission's assumptions, as many as 100 European cities will be climate neutral by 2030. In order to achieve this, it is necessary to increase the role of rail as the main means of passenger transport between cities over short and long distances, as well as for international connections. Another important aspect is that all large and medium-sized cities that are nodes in the TEN-T network should implement their own sustainable urban mobility plans by 2030. These plans should include new targets, such as zero emissions and zero road fatalities. The European Commission also wants to increase the length of cycle paths. They will also consider developing a mission for climate-neutral smart cities. It also wants to help create efficient multimodality and low-emission vehicle procurement (Dulak 2022, pp. 206-208).

In 2020, the European Commission adopted a strategy for the development of hydrogen technologies. According to the strategy, such applications will primarily be used in heavy-duty transport. In line with the actions planned in this strategy, hydrogen is to become an integral part of the energy system. The use of hydrogen will be extended to new sectors over time. According to the European Commission's, the most promising area for transport is heavy road transport. In particular, it refers to city buses and long-distance trucks (Wróbel 2022, p. 54). The hydrogen used for decarbonisation will be produced without carbon dioxide emissions. Currently, this element is used in many sectors of the European economy, but it comes from fossil fuels. Thanks to the use of renewable energy in electricity generation, it is possible to obtain a carbon-free energy source.

The European Commission has also issued a number of documents related to the promotion of the circular economy (CE). In this way, it is forcing Member States to gradually introduce changes. The popularity of the CE is primarily linked to growing consumer awareness. The concept of circular economy mobility offers greater opportunities in the field of transport. The main ones are autonomous vehicles, multimodal solutions, sharing and electrification. This type of mobility would be provided as a service, and increased integration of the transport system would contribute to a significant proportion of journeys being multimodal. These changes mean less use of cars, which will reduce congestion and air pollution (Nowicka 2020, pp. 122-123).

The European Commission's announcement of ambitious climate policy targets under the European Green Deal is accompanied by a preliminary announcement of a reform of the ETS Directive. In addition, a number of other legal acts will be introduced to manage and reduce greenhouse gas emissions. The changes to the ETS Directive are eagerly awaited and are attracting a great deal of interest. The most significant changes will be in the EU ETS itself, and it is this issue that is of greatest interest to the economies of the Member States and the general public. The European Commission is optimistic that the new EU ETS will contribute to promoting low-carbon solutions even more effectively. Greater involvement of various energy transition financing mechanisms is intended to help achieve these goals. These primarily include the Modernisation Fund and the Innovation Fund (Tomasik 2021, pp. 29-30). On 9 December 2020, almost a year after the publication of the main EZŁ document, the European Commission presented its transport strategy entitled "Sustainable and Smart Mobility Strategy – putting European transport *on track for the future*". The strategy envisages that by 2050, EU transport will be sustainable, smart and resilient (Boratyńska-Karpiej, Engel, 2021, pp. 7-12).

Summary

Road transport is one of the key sectors of the economy, with a significant impact on GDP and the labour market. At the same time, it emits around 25% of greenhouse gases. Adequate linear and point infrastructure is essential for the effective functioning and development of this industry. During the period under review, there was an increase in the length of public roads, especially expressways. However, in the context of reducing emissions into the atmosphere, sustainable transport and the development of electromobility, it is necessary to develop infrastructure adapted to electric vehicles. In terms of the condition of vehicles, there is a significant percentage of old cars that do not meet any environmental standards. In addition to environmental requirements, the transport sector will face the introduction of modern technologies. Innovation and digitisation will shape the way passengers and goods are transported.

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