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Planning of bicycle infrastructure for urban sustainable mobility: Kharkiv case study

The paper presents a comprehensive approach to strategic planning of bicycle infrastructure as a key element of sustainable urban mobility. The research integrates spatial planning analysis, bicycle traffic modelling, and an objective assessment of infrastructural solutions (Kharkiv case study). The approach focuses on developing technological principles for a rational bicycle infrastructure scheme that balances spatial constraints with residents' mobility needs and contributes to an inclusive urban environment. Special attention is given to dynamic bicycle traffic modelling using PTV VISSIM and to the evaluation of effectiveness using the intersection hazard index. Based on traffic flow analysis, a survey of local residents, existing national regulations, and international best practices, the study substantiates the social, environmental, and economic benefits of integrating cycling infrastructure. Results show that combining cycle lanes along the main highway with protected tracks at intersections reduces the traffic safety indicator (from 0.699 to 0.577), decreases average transport delays by over 106 seconds, and provides a significant environmental benefit. The positive economic effect and investment payback period confirm the feasibility of the proposed solutions. The findings are practically relevant for local authorities, design organizations, and civic initiatives involved in sustainable urban mobility planning.

Keywords: *bicycle infrastructure, sustainable urban mobility, transport planning, safety, ecological effect*

Introduction. In the context of post-war reconstruction of Ukrainian cities, the priority of developing sustainable cycling infrastructure is growing, as a modern, safe bicycle network is a key element in creating resilient, inclusive urban spaces. Cycling is recognized as one of the most efficient and environmentally friendly components of sustainable urban mobility. It helps reduce traffic loads on the street-road network, decrease CO_2 emissions, and promote a healthy lifestyle among the population [1]. A developed, integrated, and safe cycling infrastructure in cities contributes to a gradual shift in citizens' daily mobility patterns, as demonstrated by the experience of European cities [2-3]. This role becomes strategically significant within the framework of the European Green Deal [4], the EU's main roadmap for achieving climate neutrality by 2050. As part of the "green transition", the European Union is actively implementing policies to increase the share of active modes of transport. The European Strategy for Sustainable and Smart Mobility [5] emphasizes that doubling cycling volumes across Europe by 2030 is particularly important. The urgent need to rebuild the transport system aligns with the European agenda of minimizing congestion, reducing environmental impacts, and decarbonizing the transport sector [6]. The European Sustainable and Smart Mobility Strategy and its key component, Sustainable Urban Mobility Plans (SUMP), highlight the need to prioritize active modes of travel as the foundation of a healthy, resilient, and energy-efficient city.

Analysis of the latest research and problem statement. In the period of post-war reconstruction of cities and the implementation of European transport policies into national legislation, the insufficient development of cycling transport and infrastructure can be transformed into an advantage through strategic planning aligned with the documents that define the overall vector of sustainable transport development, which Ukraine follows in the process of European integration. When designing a rational cycling infrastructure, it is crucial to adhere to the principles of sustainable development to reduce energy and environmental costs, improve urban quality, and create conditions for safe and convenient movement for all road users. The EU Directive Guidelines for Developing and Implementing a Sustainable Urban Mobility Plan [7] defines a comprehensive approach to urban transport planning that prioritizes pedestrians and cyclists.

At the national level, the sustainable development system for communities has been aligned with the Ukrainian national standardization system through the National Standard ISO 37101:2019, "Sustainable development in communities". The obligation to plan cycling networks is established by the State Building Standards (SBS/DBN). These regulations define technical parameters related to safety and usability. An analysis of deviations between regulatory requirements and the actual condition of infrastructure (e.g., insufficient lane width or non-compliant turning radii) enables the identification of problematic sections. This serves as the basis for prioritizing modernization work, allowing the identification of which inconsistencies pose the most significant risk to user safety. However, an analysis of the current Ukrainian regulatory framework (in particular, DBN) indicates that it primarily governs design standards for individual segments of cycling infrastructure, thereby encouraging the separation of cycling flows from motor traffic. The standards are oriented toward existing demand (e.g., cycling lanes are required when traffic intensity exceeds 50 units/hour) and do not consider cycling transport as an integrated system, nor do they provide for strategic planning of a unified, coherent network, which contradicts the goal of increasing the cycling modal share [8].

International experience in cycling network planning (the Netherlands, Denmark, Germany, the USA) highlights key principles necessary for an effective network: maximum route directness, network connectivity, orientation toward trip purposes and user types, consideration of physical effort, and ensuring a high level of safety. These approaches can be reduced to two major strategies: the principle of spatial separation (Denmark, the Netherlands), which prioritizes safety by physically separating flows, and the principle of integration (Germany), which integrates cycling transport into the urban network through a combination of measures.

All national approaches rely on scientifically grounded principles for developing cycling networks. Based on recent scientific research, several actively studied directions can be identified: the design and resilience of cycling networks, interactions between cycling and public transport, factors influencing bicycle choice, and the specifics of cycling infrastructure development in Ukrainian cities.

Authors [9-10] consider cycling transport at the strategic planning level as an integral part of a multimodal system, integrated into the urban environment through the development of SUMPs. In this case, cycling is prioritized over private cars (the Modal Shift principle). In the research [11], safety is emphasized as a key factor in increasing cycling volumes. This is achieved through physical separation of cycling paths and the implementation of the Vision Zero concept, which underpins European directives. Researchers devote considerable attention to designing methodologies and evaluating the effectiveness of cycling networks. The models proposed in [12-13], developed using graph-theoretic and network analysis methods for route optimization, consider not only shortest distance but also safety, comfort, and route continuity. Authors [14] use GIS technologies and data on urban topography, building density, and attraction points to automate the selection of optimal corridors for constructing cycling paths. Studies [8, 15] focus on developing transport models to predict potential cycling demand based on infrastructure quality and its integration with public transport.

Ukrainian researchers have also intensified studies in this direction in recent years. They analyze the specifics of cycling transport planning in Ukrainian cities and factors influencing bicycle choice [8, 16-17]. However, an unresolved part of the overall problem remains the development of a comprehensive and adapted methodology for large Ukrainian cities - one that simultaneously considers the challenges of post-war reconstruction (speed, economic efficiency), ensures integrity and safety of the network in accordance with European directives, and provides practical tools for demand modelling and optimal placement of cycling infrastructure within the existing car-oriented urban structure.

This shortcoming is critical for large cities in Ukraine, particularly Kharkiv. Despite the existence of general strategic documents such as SUMP (2024) and the Concept for the Development of Cycling and the Creation of Cycling Infrastructure in Kharkiv (2016), the task of developing practical tools for implementing these strategies at the local, engineering, and planning levels in the context of urban reconstruction remains unresolved. The lack of such methodologies complicates the informed choice of rational planning solutions based on the principles of sustainable development for individual streets in conditions of limited space. Thus, the development and testing of such a methodology, using a specific section of Kharkiv as an example, has significant scientific and practical value.

The purpose and objectives of the research. The purpose of the research is to develop an approach to planning cycling infrastructure in cities that is grounded in sustainable development principles. To achieve this purpose, the following tasks must be accomplished: to analyze existing strategic and regulatory documents; to determine development and implementation stages of a rational cycling infrastructure option on sustainable development principles; to determine effectiveness criteria for evaluating alternative options for developing bicycle infrastructure; to conduct a sociological survey of the resident's needs, preferences; to conduct an experimental study; to analyze the results of the research and select a rational option for cycling infrastructure; to determine effectiveness of solutions.

Research materials and methods. The object of the research is the process of forming a rational option for urban cycling infrastructure. The subject of the study is the influence of street and road network parameters on the sustainability of bicycle-based population movement. The development of cycling infrastructure requires detailed planning to support a comprehensive analysis of all its components, given the multifaceted nature of the process, which encompasses not only the physical construction of cycle paths and parking facilities but also regulatory and legal frameworks, planning, financing, information support, and community engagement.

In addition to the direct construction of bicycle routes, strategic planning that accounts for the urban environment's spatial, social, and functional characteristics is a critical component. Efficient cycling infrastructure should meet the needs of different user groups (local residents) and ensure safe travel, even in areas with heavy traffic. It also requires accompanying navigation, bicycle storage facilities, convenient transfer hubs, and information support to promote cycling as a fully-fledged mode of transport. Only a combination of physical, organisational, regulatory, social, and technological solutions can create an effective cycling system that complies with the principles of sustainable mobility. Each structural element has its own specifics and implementation requirements, which must be considered when developing specific projects and development programmes.

The type of cycling infrastructure and the technical parameters of each cycle path (width, surface, colour, markings) are determined by the project (plan) individually for each street, taking into account local conditions and the requirements of state standards, and can be implemented in the following forms: cycle lanes; one-way cycle path; two-way cycle path; one-way cycle and pedestrian path; two-way cycle and pedestrian path.

When designing cycling infrastructure, it is crucial to make an informed choice between these types of cycling arrangements, particularly between carriageway cycle lanes and separate cycle paths. Cycle lanes have the advantage of being easy to implement in limited space and at minimal cost. Still, they are inferior to cycle paths in terms of safety, conflict, and comfort. Separate cycle paths provide a higher level of safety and better integration with the urban transport system, but require more space and resources to implement. The final decision should be based on a balance between the spatial, financial, and functional constraints of the implementation site in accordance with approved strategic concepts for the development of sustainable urban mobility.

Urban development concepts, in particular the Cycling Concept [18], provide a strategic framework for analysis. They define key performance indicators such as the planned length of cycle paths, implementation deadlines, and expected results. For example, comparing actual construction rates with planned rates can reveal systemic problems in project management, such as insufficient funding or poor coordination between services.

State building regulations establish technical parameters for safety and usability. An analysis of discrepancies between regulatory requirements and the actual state of the infrastructure (e.g., insufficient lane widths or inappropriate turning radii) enables the identification of problem areas. This provides a basis for prioritizing modernization work by identifying nonconformities that pose the most significant risk to user safety.

DSTU standards detail the requirements for individual infrastructure elements. They cover aspects such as road surface quality, road sign visibility, and parking space ergonomics. A systematic comparison of actual indicators with regulatory ones enables not only the identification of shortcomings but also the proposal of technically sound solutions. For example, if measurements show that the road surface has insufficient grip, this may be grounds for replacing it with a higher-quality material.

Traffic rules and traffic management instructions form the legal basis for analyzing the behavior of road users. Research on compliance with these standards (e.g., the frequency with which cyclists ride on the carriageway in the absence of cycle paths) enables us to assess the effectiveness of existing infrastructure and identify areas for improvement. Such data is particularly valuable when planning new routes or adjusting existing ones.

The integration of the regulatory framework into the study ensures its scientific validity and practical relevance. It allows us to move from general observations to specific recommendations, each supported by official requirements. This is particularly important when justifying the need for change to local authorities or potential investors. For example, references to specific points in DBN or DSTU significantly increase the weight of arguments for reconstructing a particular section. One of the key factors in the success of bicycle infrastructure planning is compliance with national standards and requirements, particularly DSTU 8906:2019, which establishes design standards for cycle paths and other infrastructure elements. According to this standard, the design of cycling infrastructure should provide safe and convenient conditions for cyclists, including dedicated cycling lanes, bicycle parking, and maintenance. In addition, the infrastructure should be integrated into the city's overall transport network, ensuring convenient access to key locations and connections to other modes of transport. At the international level, a key focus is the application of urban planning principles to bicycle infrastructure, particularly in medium- and large-sized cities. The success of bicycle transport development there is based on a systematic design approach that includes safety, comfort, connectivity, and social and cultural change.

The results of public discussions and the opinions of all stakeholder groups in the city should guide the development of cycling infrastructure. Taking into account the views of cyclists, pedestrians, drivers, business representatives, local authorities, and relevant public organizations is essential to designing effective, high-quality infrastructure that is well-received. Ignoring the views of even one of these groups can lead to conflict, inefficient resource use, and low facility utilization.

Studying the opinions of different participant groups allows us to determine the population's needs for cycling infrastructure at the district, street, intersection, and city levels, and to identify key interrelationships among these aspects and develop practical solutions. For example, surveys can reveal not only desirable locations for bicycle parking near metro stations or shopping centers, but also less obvious needs for safe crossings at complex transport junctions and for integrating bicycle routes with pedestrian areas. Understanding these interrelationships is critical to a systematic approach to bicycle infrastructure development, rather than just addressing individual issues.

Figure 1 presents a diagram of the relationships among participants (stakeholders) in the decision-making process for creating bicycle infrastructure based on sustainable mobility principles, from public initiatives through the implementation of the finished facility.

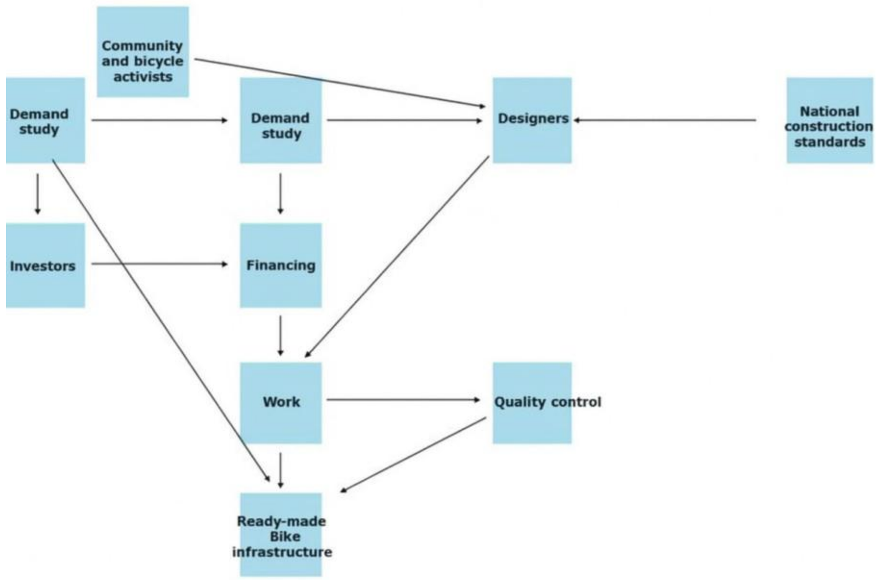

Fig. 1. **Scheme of interaction between participants in the cycling infrastructure planning process**

The diagram covers the participants and all the main stages of developing and implementing cycling infrastructure based on the principles of sustainable development: demand analysis, design, financing, construction, quality control, and commissioning, and shows the interaction between key participants (the public, local authorities, investors, designers, builders, and quality controllers), which are shown in Figure 2. The structure allows you to follow the sequence of stages in detail and analyse the potential influences among different participants, from public initiatives and cycling activists to established cycling infrastructure.

The first step is to study demand based on feedback from city residents and active bicycle users. Based on these data, local authorities engage designers who, in turn, adhere to state construction standards.

At the same time, funding is sought from investors and local authorities. Once the design phase is complete and funding has been secured, implementation of the project begins. Quality control ensures the project complies with standards and requirements, thereby guaranteeing the durability and safety of the infrastructure. At the end of this process, a rational version of the cycling infrastructure is formed, the result of coordinated cooperation among the public, government agencies, investors, and technical specialists. This sequence of stages enables a comprehensive study of the project, accounting for both technical and social factors.

Among the methods for developing a rational bicycle infrastructure option in cities, the following can be highlighted: physical modeling, mathematical modeling, simulation modeling, and statistical modeling. Based on an analysis of the advantages and disadvantages of these methods, it was determined that comprehensive modeling that integrates physical analysis and statistical data enables assessment of critical areas. Compliance with standards, consideration of public opinion, and adaptation of international experience will ensure the high-quality development of the bicycle network.

The choice of a rational option should be based not only on technical feasibility but also on the maximization of social, transport, and environmental benefits. A safe environment is a prerequisite for the development of cycling. In urban areas with high car traffic density and congested street and road networks, safety levels determine residents' willingness to switch to cycling. Where cyclists feel vulnerable or isolated, the use of this mode of transport declines, regardless of other advantages such as route accessibility, travel speed, or cost savings. If the cycling conditions are safe, even a less convenient or longer route becomes attractive to users.

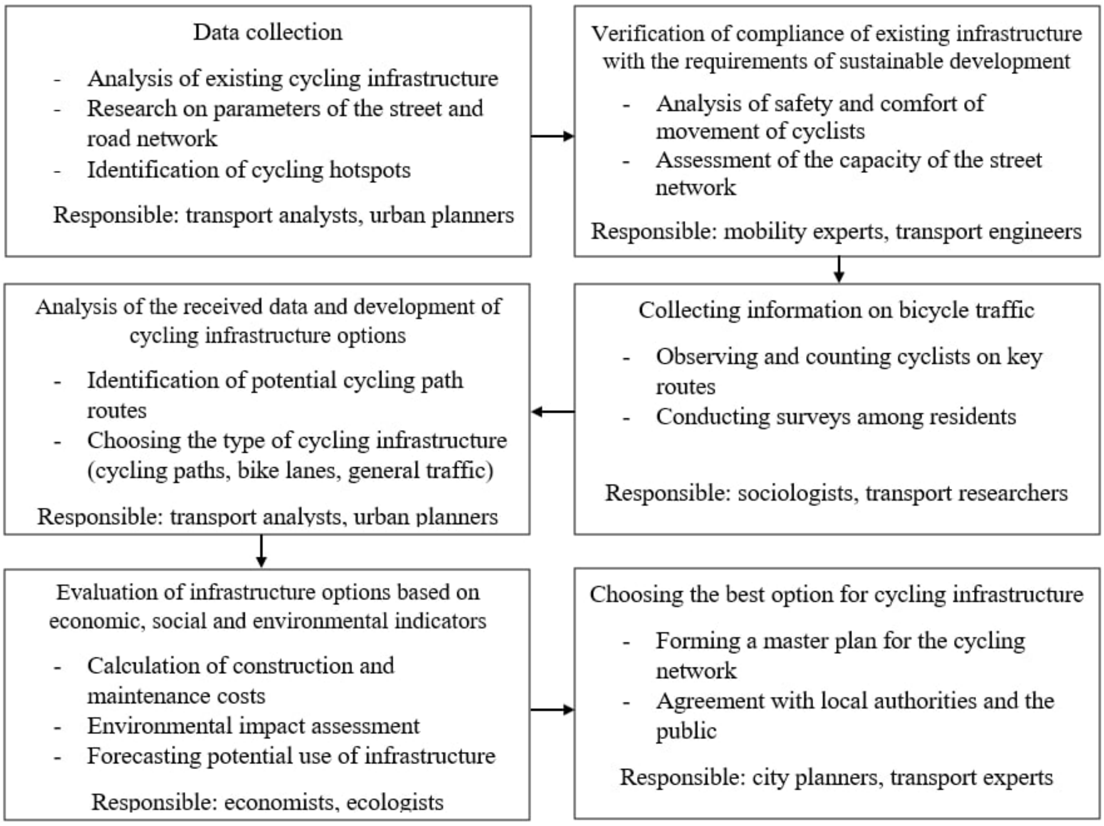

Fig. 2. **Development and implementation stages of a rational cycling infrastructure option on sustainable development principles**

According to 2024 statistics from the Ukrainian Patrol Police, the proportion of road traffic accidents (RTAs) involving cyclists was nearly 6%. Planning the development of cycling infrastructure from the perspective of user safety has a long-term impact in the form of:

- a reduction in CO_2 emissions and other pollutants due to a decrease in the proportion of cars in urban traffic as some residents switch to bicycle transport. However, these changes will be effective only if the infrastructure ensures the safety of bicycle use;

- rational infrastructure decisions can be more cost-effective in the long term, even if the initial implementation costs are higher. This can be achieved by increasing the appeal of bicycle transport as a cheap and efficient mode.

- safe cycling infrastructure, especially at intersections, allows the city to avoid significant economic losses from the consequences of traffic accidents.

- the availability of a safe environment for travel stimulates sustainable tourism, urban initiatives, and the attractiveness and development of the city.

The rationale for the safety criterion also reflects the contemporary philosophy of human-centered urban design. This approach has become the basis for many transport policies worldwide and is enshrined in Ukraine's national regulatory documents. It enables the creation of infrastructure that not only fulfils a technical function but also shapes a new transport culture in which bicycles are perceived as a fully-fledged and safe means of transport.

Therefore, as a criterion of effectiveness, we propose considering the traffic safety indicator, which accounts for accident risks and characterizes the level of danger at intersections

$$K_a = \frac{G \cdot K_P \cdot 10^7 \cdot k_r}{(M+N)\cdot 25} \to min, \tag{1}$$

where G is the theoretically probable number of accidents at an intersection in one year;
K_P is the coefficient of annual traffic unevenness (we assume Kr = 0.12); M is the traffic intensity on the main road, vehicles per day;
N is the traffic intensity on the secondary road, vehicles per day.

This indicator is the basis for creating a safe, sustainable, convenient, and attractive urban space where cyclists feel like equal participants in traffic. All further technical and economic justifications and project decisions will be made with this criterion in mind.

The organization of safe and efficient bicycle traffic in the urban street and road network is impossible without proper intersection design, areas with high accident rates, and dense interactions among all road users. In this context, special attention should be paid to the analysis of the interphase period—the interval between the end of one traffic light signal and the start of another—which plays an essential role in ensuring safety when changing direction, particularly when vehicles turn and cyclists cross paths.

A variety of methods are used to determine the risk of accidents at intersections. We suggest using the conflict point method [18], based on the analysis of the points of intersection between the trajectories of conflicting vehicles, primarily to assess safety in urban areas

$$q_i = \frac{K_i \cdot M_i \cdot N_i \cdot 25 \cdot 10^{-7}}{k_H \cdot K_p}, \tag{2}$$

where i is the number of conflict points;
M_i, N_i are the intensities of traffic flows interacting at this point, vehicles/hour;
K_i is the coefficient of relative accident rate of the conflict point, accidents/10^7 vehicles.

The overall danger level of an intersection is an additive indicator, determined as the sum of the danger levels of all conflict points at the intersection.

The task of comprehensively assessing traffic safety is addressed in several stages for each alternative intersection design: in the absence of bicycle infrastructure, with the introduction of a cycle lane, and with the construction of a full-fledged cycle path. In the first stage, accident rates are determined for each potentially conflict point at the intersection, based on the nature of interactions among road users (pedestrians, cyclists, and vehicle drivers) and traffic intensity. At the second stage, using the obtained coefficients, a generalized traffic safety indicator (K_a) is calculated for each option under consideration. The K_a value is used to assess the danger at the intersection. If $K_a \leq 3$, the intersection is safe; if $3 < Ka \leq 8$, the intersection is almost safe; if $8 < K_a \leq 12$, the intersection is dangerous; if $K_a > 12$, the intersection is perilous. Next, to justify the most rational engineering solution, an alternative comparison is conducted using the generalized traffic safety indicator. When developing a rational bicycle infrastructure option for a city, one key task is to assess the effectiveness of the proposed solutions. Accurate quantitative forecasting of the reduction in private car trips following the introduction of bicycle infrastructure is difficult because it requires accounting for all the factors that influence changes in the population's transport behavior. In this regard, it is best to focus not on the absolute reduction in car traffic, but on the potential environmental impact by analyzing changes in pollutant emission levels, and on the possible social effect by reducing vehicle delays at intersections. To model these indicators for alternative bicycle infrastructure options, we propose using PTV VISSIM traffic modelling software, which enables the reproduction of traffic patterns of all road users at a microscopic scale and the simulation of the impacts of traffic light phases, congestion, queues, waiting times, and pollution intensity [1].

We assess the social effect of implementing a rational bicycle infrastructure option using the indicator of annual transport time spent on the section

$$\Delta T_{з}^{рік} = \frac{365 \cdot N_{sum} \cdot \Delta \bar{t}_{\Delta H}}{3600 \cdot k_H}, \quad (3)$$

where N_{sum} is a total traffic intensity of all vehicles at the intersection, cars/hour;
$\Delta \bar{t}_{\Delta H}$ is the change in the average delay of vehicles at the intersection after the implementation of the proposed measures, s;
k_H is the coefficient of transition from hourly traffic intensity to daily traffic intensity (it is recommended to take k_H=0,1).

The annual socioeconomic effect of reducing vehicle delay time on the section under consideration is estimated using the cost of 1 hour of driver/passenger time (assumed to be 40% of the current year's hourly wage rate).

To conduct a quick comparative assessment of the ecological effect per hour of vehicle movement per 1 km of road, based on modelling harmful emissions volumes, it is advisable to use the methodology [19]

$$\Delta E_i = \left[\sum_{i=1}^{n} C_i \cdot (g_{i\,exist} - g_{i\,rational}) \cdot k_i \cdot N_i \right] \cdot 10^{-6}, \quad (4)$$

where C_i is the damage from the emission of one tonne of the i-th pollutant, UAH/tonne;
$g_{i\,exist}$, $g_{i\,rational}$ is specific emissions of the i-th pollutant by the main car models in comparable road traffic conditions, g/km;
k_i are a correction coefficients for the transition from basic car models to those studied during the calculation of harmful emissions and fuel consumption;
N_i is the number of cars of the specified model passing through a section of road within an hour.

As is well known, developing cycling infrastructure requires significant capital investment. The average payback period for capital investments in cycling infrastructure depends on the scale of the project, local conditions, the volume of use of cycle lanes, and the methodology used to assess the effect. However, the experience of EU countries shows that, in most cases, the average payback period for cycling infrastructure is between 3 and 10 years.

The payback period for cycling infrastructure on the section of the street-road network under consideration is determined by the ratio of total investment costs to the annual economic effect, including socio-economic and ecological effects

$$T_{PB} = \frac{K}{\sum E} \quad (5)$$

where K is the capital investment for the establishment of 1 km of cycling infrastructure.

The implementation of the proposed approach is illustrated by the example of the street-road network of Kharkiv (a section of Silikatna Street). The city authorities, guided by international experience and national standards, incorporate European approaches into their bicycle transport development concept, particularly through public information and support for sustainable mobility. The area's characteristics are conducive to the development of pedestrian and micromobility traffic. Pedestrian traffic is popular among Kharkiv residents. At the same time, micro-mobility is primarily undertaken by the population on bicycles for domestic and recreational purposes. According to open data, walking accounts for approximately one-third of the modal split in Kharkiv. Analysis of cycling intensity data shows that most cyclists use it as a full-fledged individual mode of transport. The priority direction for the development of cycling in Kharkiv is to connect the most densely populated areas of the city and the largest centers of attraction. Given the remoteness of residential areas from the city center, it is necessary to ensure that routes are as short and direct as possible, with minimal disruption to bicycle traffic.

Silikatna St. is located in the Osnovyanskyi district and reflects the district's typical mixed urban structure. The Osnovyanskyi district is located in the southern part of the city and combines historical development, industrial areas, and modern residential neighborhoods. The district is centered on the historic area of Osnova. It is distinguished by distinctive natural and landscape features, owing to its location at the confluence of the Lopan and Kharkiv rivers. This creates a well-developed network of recreational spaces. Elevated risks for road users - typical for streets in this district are driven by intense motor vehicle traffic, insufficient systems for transport prioritization, suboptimal traffic light operation, and the absence of informational signage for micromobility users, including cyclists. These risks increase further at night due to inadequate lighting on both the roadway and the sidewalks. Typical streets in this district exhibit a diverse development pattern, combining multi-storey residential buildings with low-rise private housing. Such a layout increases demand for convenient, safe, and efficient transport solutions, including cycling routes as alternatives to car travel (Fig. 3). The varying density of development generates demand for cycling routes as an alternative to motorised transport, as well as the potential to develop local bicycle paths that are comfortable for residents of the private housing sector. This requires adapting infrastructure solutions to the specific characteristics of each zone.

Fig. 3. **Current condition of the road surface on Silikatna St. (Kharkiv)**

Silikatna St. in Kharkiv has basic public transport connections to other parts of the city. Bus services connect the metro station to the recreational area and provide convenient connections between different parts of the city; however, bus intervals exceed 30 minutes. A trolleybus route additionally covers this part of the city, providing an alternative to bus services. The tram line is far from the area. Thus, this street lacks adequate transport connections, as it is served primarily by bus and trolleybus routes. The development of cycling infrastructure on this street could significantly improve transport accessibility for residents of neighboring areas, reduce congestion, and enhance the urban environment.

An alternative route for cyclists is often the sidewalk, which is not designed for bicycle traffic. This situation results in frequent conflicts between cyclists and pedestrians, particularly in areas with high pedestrian traffic. This once again highlights the lack of a well-thought-out and balanced transport policy at the district level.

In addition to the lack of cycle paths and lanes, the district lacks supporting infrastructure to promote bicycle use and convenience (e.g., bicycle parking areas, navigation and information signs). This significantly limits the use of bicycles as a daily means of transport for a wide range of residents and exacerbates social inequality across segments of the population, including children, young people, the working population, the elderly, people with disabilities, and people on low incomes. In addition, the complete lack of conditions for bicycle transport adversely affects the overall mobility of the population, contributes to motorization, exacerbates environmental problems, and contradicts the principles of urban mobility development grounded in sustainable development, which modern European cities strive to achieve.

To research the population's needs for cycling infrastructure on Silikatna St., a survey was conducted among residents and visitors to the area. Forty-one respondents of different ages, statuses, and modes of transportation were interviewed. The results allowed us to assess the current situation and identify residents' problems and expectations. Most respondents (42%) consider the current situation dangerous for cyclists and express support for the creation of safe, separate cycle paths, bicycle parking facilities, and appropriate markings. A significant proportion of respondents (63%) are also willing to use bicycles more often if high-quality infrastructure is available. These results demonstrate the importance of designing bicycle infrastructure as part of comprehensive street and neighbourhood development, thereby promoting sustainable mobility for the population.

The intersection of Silikatna St., Kamianetskyi v'izd, and Rudynska St. in Kharkiv was selected for research due to its strategic location and characteristic features that reflect typical problems of bicycle traffic organization in urban areas. This intersection connects a residential area with industrial and recreational areas, resulting in dynamic traffic from various groups of road users, including pedestrians and cyclists. In addition, the availability of spatial reserves in street cross-sections creates opportunities for implementing bicycle infrastructure elements. That is why this intersection is a good example for analyzing the impact of the street network's geometric parameters on the feasibility of integrating sustainable solutions to organize bicycle traffic.

Based on field survey data, the intensity and composition of traffic flow (vehicles, bicycles, and pedestrians) at this intersection were obtained to support a comprehensive safety assessment of two alternative options for bicycle infrastructure development: constructing cycle paths and constructing cycle lanes.

To comprehensively assess the safety of each intersection design option, a step-by-step calculation was performed using the proposed methodology. At the first stage, accident rates were determined for each potentially conflict point in the intersection based on the nature of interactions among traffic participants (pedestrians, cyclists, and vehicle drivers) and traffic intensity. Next, based on the results, a generalized traffic safety indicator was determined for each of the considered options. Based on the selected efficiency criterion, it was determined that, under the existing option (without bicycle infrastructure), this intersection is classified as very dangerous ($K_{a\ exist}$=15,4). According to the option of equipping this section of the street with a cycle path, the intersection is classified as very dangerous ($K_{a\ path}$=12,7). In contrast, with the installation of a cycle lane, the level of danger increases to ($K_{a\ lave}$=13,1). However, the overall level of danger at the intersection measured by conflict points decreases from 0.6997 to 0.595 when cycle lanes are set up and to 0.577 when cycle paths are set up. This demonstrates that implementing cycle paths at intersections will be more effective.

The results confirm the hypothesis that integrating cycle lanes not only improves safety but also does not create significant obstacles to the overall operation of traffic light control. Taking into account the current regulatory documents on the design of traffic light systems, a rational option for developing bicycle infrastructure on such typical streets is to combine cycle lanes along the main route with cycle lanes within intersections. This approach is justified because the street's width does not permit the construction of full-fledged cycle paths along the entire length of the route without significant interference with existing buildings or a reduction in motor-vehicle traffic lanes, which is contrary to the regulations. Cycle lanes within the carriageway are an acceptable and recommended solution for streets with limited space. At the same time, at intersections where the intensity of conflict between road users increases, it is advisable to allocate separate cycle lanes to improve cyclists' safety and to implement distinct traffic zoning.

Therefore, the most rational option for cycling infrastructure on Silikatna St. is a combined option: constructing a cycle line and installing cycle paths at intersections, which will reduce traffic congestion without compromising road-user safety and minimize environmental impact. The proposed solution, grounded in sustainable mobility principles, underscores the need for an approach to developing a sustainable urban bicycle network.

As part of the research, simulation modelling was conducted using PTV VISSIM. Two transport models were developed for the typical intersection in the Kharkiv case study: one without a dedicated bicycle space (Fig. 4) and one with a dedicated bicycle infrastructure (Fig. 5).

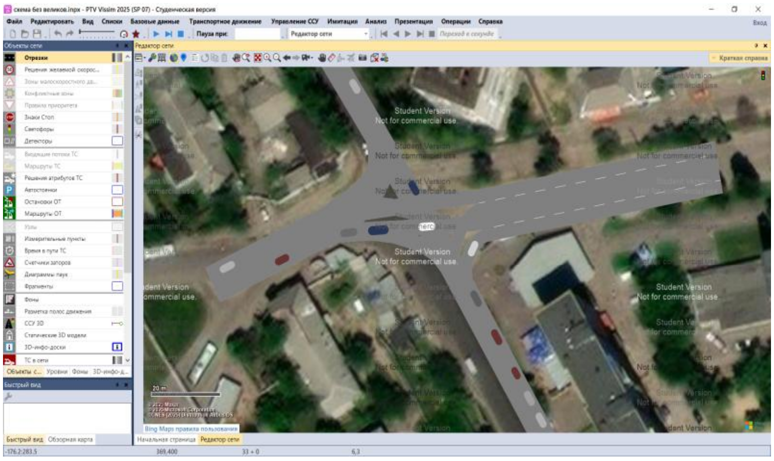

Fig. 4. **Transport model of the intersection without a separate space for cyclists in the PTV VISSIM software**

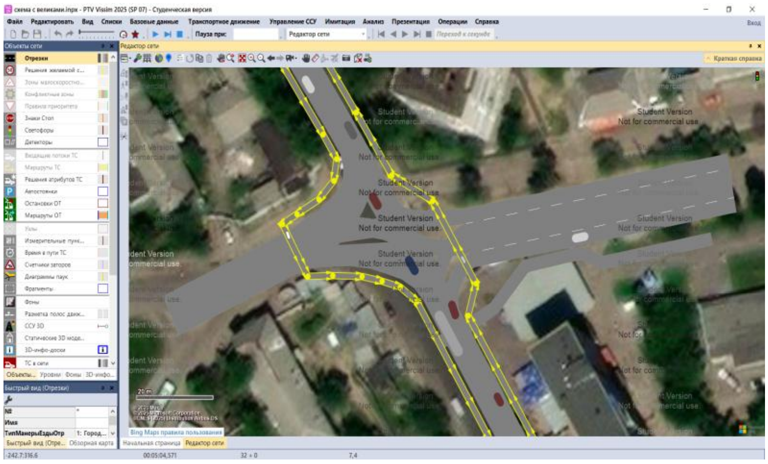

Fig. 5. **Transport model of the intersection with a separate space for cyclists in the PTV VISSIM software**

The modelling was based on established quantitative and qualitative characteristics of vehicle traffic, derived from hourly intensity and composition data on Silikatna St. The simulation results yielded values for 17 indicators across 17 segments, including vehicle delays, pollutant emissions, and fuel consumption per 1 km travelled. The statistical characteristics of the simulated parameters are presented in Table 1.

Table 1. **Results of the estimation of statistical characteristics of simulated parameters**

Name of indicator	Value of the indicator			
	Mathematical expectation		Mean squared deviation	
	Existing	Rational	Existing	Rational
Vehicle delay time, s/km	149,55	43,67	318,85	12,06
Total emissions of pollutants per hour, g/km	17,65	8,20	49,22	4,56

As a result of transport process modeling, it was established that introducing bicycle infrastructure on Silikatna St. would reduce average transport delays by more than 106 seconds and reduce harmful emissions by 50%. The results of annual environmental damage calculations indicate that passenger cars have the most significant adverse ecological impact among all vehicle types, with annual damage from their operation amounting to 4.5 thousand UAH/km, owing to their considerable share (537 units) of total traffic. The total yearly ecological effect of implementing a rational bicycle infrastructure option on Silikatna St. for a 1 km section considered in the modeling is 2,900 UAH/km.

The annual socio-economic effect of reducing vehicle delay time is 4.019 thousand UAH, estimated based on the cost of 1 hour of driver/passenger time. The total economic impact of implementing a rational bicycle infrastructure option is 4024.9 thousand UAH per 1 km, with a 5-year payback period, which corresponds to the average payback period for investments in bicycle infrastructure development in European Union countries and demonstrates the effectiveness and feasibility of the proposed solution.

Conclusions. In this paper, an approach to planning bicycle infrastructure in cities based on sustainable development principles was proposed. The study focused on a detailed examination of the planning process for bicycle infrastructure as an integral component of sustainable urban mobility. Special attention is paid to the justification of bicycle traffic modeling methods, which enables not only the identification of critical areas but also the objective assessment of the effectiveness of the proposed solutions. The integration of statistical analysis, consideration of community needs, theoretical approaches, and physical modeling practices has established a scientifically grounded basis for planning bicycle infrastructure that accounts for current regulations and standards.

The analysis of stakeholder interaction across all stages of planning and implementation shows that the effective operation of bicycle infrastructure is impossible without well-established cooperation among local authorities, project organizations, investors, construction companies, community activists, and residents.

The proposed approach is examined using a typical section of Kharkiv’s street-road network as an example (on Silikatna St.). The assessment of the current state of the network, particularly in the city's residential and industrial areas, indicates fragmentation and a critical shortage of bicycle infrastructure. Primarily, this increases risks at intersections for all road users, particularly cyclists and micromobility users. Therefore, there is an urgent need to develop approaches for planning justified, safe, and functional infrastructure solutions.

Safety is a key factor that encourages the use of bicycles as an everyday mode of transportation, which defines the choice of the efficiency criterion. The road safety indicator assesses the risk of traffic accidents in planning bicycle infrastructure, employing a systemic approach that focuses on objective performance indicators and residents' needs to create a sustainable, comfortable, and safe urban environment.

Based on the efficiency criterion, it was determined that, when developing alternative options for bicycle infrastructure at the intersection, the overall level of danger decreases from 0.6997 to 0.577 when a bicycle lane is implemented. However, given the current regulatory documents and spatial planning for a typical section of the network, the most rational option for bicycle infrastructure is a combination of bicycle lanes along the main street corridor and bicycle paths within intersections. Bicycle lanes, as part of the roadway, are an acceptable and recommended solution for streets, particularly in situations with limited space. At the same time, at intersections where the intensity of conflict points between road users increases, it is advisable to allocate separate bicycle paths to enhance cyclist safety and to implement distinct traffic zoning.

The proposed planning approach, based on analyses of the transport situation, spatial planning, and the assessment of the effectiveness of the proposed solutions, enabled justification not only of the technical feasibility but also of the social, environmental, and economic benefits of integrating a bicycle component into the urban transport system. The positive results of the financial impact assessment confirm the effectiveness of the solutions proposed in the research.

The results of this study could inform a new urban transport policy focused on inclusiveness, environmental sustainability, and improved residents' quality of life.

REFERENCES

1. Kholodova, O., Buhaiova, M. (2025). *Modeling and Evaluation of the Effectiveness of Modern Methods of Traffic Management in Urban Street and Road Networks: monohrafiia /red. prof. I. S. Nahliuka.* Kharkiv. [in Ukrainian].
2. Qiu, L.-Y., He, L.-Y. (2018) Bike Sharing and the Economy, the Environment, and Health-Related Externalities. *Sustainability* 2018, 10, 1145. https://doi.org/10.3390/su10041145.
3. Zhao, C., Carstensen, T.A., Nielsen, T.A.S., Olafsson, A.S. (2018) Bicycle-friendly infrastructure planning in Beijing and Copenhagen - between adapting design solutions and learning local planning cultures. *Journal of Transport Geography*. 2018, 68, 149–159. https://doi.org/10.1016/j.jtrangeo.2018.03.003.
4. European Commission. (2019). European Green Deal.
5. European Commission. (2020). Sustainable and Smart Mobility Strategy – putting European transport on track for the future.
6. Potaman, N., Orda, O., & Orda, O. (2024). Analysis of Sustainable Urban Mobility Planning Aspects in the Context of European Integration Reforms in Ukraine. *Central Ukrainian Scientific Bulletin. Technical Sciences*, 10(41(2)), 188-195. https://doi.org/10.32515/2664-262X.2024.10(41).2.188-195. [in Ukrainian].
7. European Commission. (2019). Guidelines for developing and implementing a Sustainable Urban Mobility Plan (2nd ed.).
8. Ukrainian State Standard ISO 37101:2019. Sustainable development in communities. Management system. General principles and requirements with guidance for use. (2019). International Organization for Standardization. [in Ukrainian].
9. Ministry of Regional Development, Construction, Housing and Communal Services of Ukraine. (2018). DBN V.2.3-5:2018. Streets and roads of settlements (With Amendment No. 1). Official publication. [in Ukrainian].
10. Ministry of Regional Development, Construction, Housing and Communal Services of Ukraine. (2015). DBN V.2.3-4:2015. Highways. Part I. Design. Part II. Construction. Official publication [in Ukrainian].
11. Ministry of Economic Development and Trade of Ukraine. (2019). DSTU 8906:2019. Planning and design of bicycle infrastructure. General requirements. [in Ukrainian].
12. Chernyshova, O. S. (2019) Development of cycling network in cities with low level of cycling. *Doctor's thesis*. Kharkiv', 207 [in Ukrainian].
13. Litman, T., 2021. Evaluating Public Transit Benefits and Costs: A Best Practices Guidebook, *Victoria Transport Policy Institute*. Canada. https://coilink.org/20.500.12592/fc5jt2.
14. Torrisi, V., Garau, C., Ignaccolo, M., & Inturri, G. (2020, July). "Sustainable urban mobility plans": key concepts and a critical revision on SUMPs guidelines. In *International conference on computational science and its applications* (pp. 613-628). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-58820-5_45.
15. Pucher, J., & Buehler, R. (2017). Cycling towards a more sustainable transport future. *Transport Reviews, 37*(6), 689-724. https://doi.org/10.1080/01441647.2017.1340234.
16. Barati, H., Yazici, A., & Almotahari, A. (2024). Graph Neural Networks Model to Generate Transportation Test Networks. *Transportation Research Record*, *2678*(10), 435-448. https://doi.org/10.1177/03611981241233569.
17. Miah, M. M., Mattingly, S. P., & Hyun, K. K. (2023). Evaluation of bicycle network connectivity using graph theory and level of traffic stress. *Journal of transportation engineering, Part A: Systems*, *149*(9), 04023080. https://doi.org/10.1061/JTEPBS.TEENG-7776.
18. Özkan, S. P., Şenol, F., & Özçam, Z. (2020). Bicycle Route Infrastructure Planning Using GIS in an Urban Area: The Case of İzmir. Planning, *Planlama*, *30*(2), 313-327. https://doi.org/10.14744/planlama.2020.41275.
19. Oskarbski, J., Birr, K., & Żarski, K. (2021). Bicycle Traffic Model for Sustainable Urban Mobility Planning. *Energies*, *14*(18), 5970. https://doi.org/10.3390/en14185970.
20. Fomenko H.R. (2024) Bicycle Transport And Its Development In Urban Centers. *Vcheni zapysky TNU imeni V.I. Vernadskoho. Seriia: Tekhnichni nauky*, *35*(74(6)),. 288-292 [in Ukrainian].
21. Prokopchuk, I., & Gladkykh, V. (2022). Cycling in the context of state transport policy: Modern challenges. Naukovi perspektyvy, *5*(23), 127–142. https://doi.org/10.52058/2708-7530-2022-5(23)-127-142. [in Ukrainian].
22. Concept of development of cycling and bicycle infrastructure in Kharkiv.
23. Barhoumi, O., Zaki, M. H., & Tahar, S. (2024). A formal approach to road safety assessment using traffic conflict techniques. *IEEE Open Journal of Vehicular Technology*, *5*, 606-619. https://doi.org/10.1109/OJVT.2024.3387414.
24. Lynnyk, I., Lezhneva, O., Dorozhko, Ye., Vakulenko, K., Sokolova, & N., Afanasieva, I. (2020). *Ecological aspects of the road transport complex: monohrafiia*. Kharkiv.

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Планування велосипедної інфраструктури для сталої міської мобільності: тематичне дослідження Харкова

Анотація. *У контексті повоєнної реконструкції українських міст пріоритетність розвитку сталої велосипедної інфраструктури зростає, оскільки створення сучасної та безпечної веломережі є ключовим елементом формування стійких і інклюзивних міських просторів. У статті представлено комплексний підхід до стратегічного планування велосипедної інфраструктури як важливої складової сталої міської мобільності. Дослідження охоплює аналіз просторових умов, моделювання велосипедного руху та оцінювання ефективності інженерних рішень в місті Харкові (на прикладі вул. Павла Тичини). Запропонований підхід передбачає обґрунтування раціонального варіанту велоінфраструктури з урахуванням наявних обмежень вуличного простору та потреб мешканців у безпечному та комфортному пересуванні, що дозволить зменшити залежність населення від приватного автотранспорту. Особливу увагу приділено застосуванню динамічного моделювання у середовищі PTV VISSIM та використанню індикатора рівня небезпеки перехресть для кількісної оцінки ефективності. Результати аналізу транспортних потоків, соціологічного опитування та адаптації зарубіжних практик підтверджують значний соціальний, екологічний і економічний ефект від впровадження запропонованих рішень. Зокрема, поєднання велосмуг уздовж основного маршруту з облаштуванням велодоріжок у межах перехресть дозволило зменшити показник небезпеки перехрестя, скоротити затримки транспорту та отримати екологічний ефект. Отримані результати можуть бути використані органами місцевого самоврядування, проєктними організаціями та громадськими ініціативами під час планування сталої міської мобільності.*

Ключові слова: *велосипедна інфраструктура, сталий міський транспорт, транспортне планування, безпека, екологічний ефект*