“Green” principles of sustainable development of road and transport infrastructure of the cities of Ukraine

N V Vnukova, G M Zhelnovach and O V Kozlovskyi

Department of Ecology, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine

vnukovanv@ukr.net

Abstract. The paper is devoted to the development of criteria for the implementation of the principles of “green” and sustainable development of road and transport infrastructure of the cities of Ukraine on the basis of world experience, as well as own research. It is established that the world experience offers a number of systems for assessing environmental friendliness and sustainability of the development of transport infrastructure, which cannot be applied unambiguously and without adaptation in the cities of Ukraine. Therefore, environmentally significant criteria for assessing compliance with the requirements of “green” standards for the development of the city’s transport infrastructure in the context of assessing its life cycle stages, which in the future will help the environmentally balanced development of the city’s transport system were developed and proposed in the paper. As an example of the practical application of the criteria for "green" construction and assessment of environmental sustainability for the development of the road network, a mechanism was developed and proposed to assess the environmental efficiency of the development of the urban bicycle transport network based on estimates of reduced fuel consumption, pollutant emissions and noise levels by replacing motor work with cycling.

1. Introduction

Among the global challenges that humanity now faces, one of the most urgent is to ensure the sustainable development of society in the global context in accordance with the Sustainable Development Goals [1]. They are a kind of call for action aimed at improving well-being and protection of the planet. At the same time, states recognize that measures to eliminate poverty should be taken in parallel with efforts to increase economic growth and solve whole host of issues in the field of education, health, social protection and employment, as well as combating climate change and environmental protection. The analysis of global environmental issues showed that for the world community the problem of urbanization is very acute [2]. According to forecasts, by 2030, more than 60 % of the world's population will live in cities [3], which maximizes the need to develop effective measures for the implementation of Goal 11 “Sustainable cities and towns”. This problem is relevant for the most cities of Ukraine. The state has not developed a targeted integrated strategy for sustainable development of cities and settlements, being the integral part of the national document "Strategy for Sustainable Development of Ukraine until 2030" [4]. The analysis performed showed that the key criterion for ensuring sustainable, multi-vector and balanced development of urbanized areas is the sustainable development and operation of their street-road network in accordance with the criteria for "green” construction [5–6].
The purpose of this paper is to develop approaches to the implementation of the principle of sustainable development of cities through the optimization of their road transport infrastructure by introducing standards for the "green" construction of the road network and assessing the environmental efficiency of the development of the bicycle transport network.

2. "Green" standards for sustainable development of the urban road network

In recent years, green construction has become increasingly relevant, which is being implemented in the context of sustainable urban development.

The main objective of the "green" construction is the greening of design and construction technologies, which can significantly reduce operating costs, contribute to the implementation of innovative technologies and encourages the search for innovative solutions.

To unify the requirements for “green” construction, “green” standards were developed containing specific requirements (criteria) for the construction of buildings, structures, transport infrastructure and rating system for their implementation.

The most common certification systems for green or ecological building in the world are the British Environmental Assessment Method (BREEAM) – UK, Demarche Haute Qualité Environnementale (HQE) – France, Leadership in Energy and Environmental Design (LEED) – USA, EcoProfile – Denmark, German Sustainable Building Council (DGNB) – Germany, Comprehensive Assessment System for Built Environment Efficiency (CASBEE) – Japan, Green Building Initiative (GBI) – Canada [7].

In the area of ensuring sustainable environmentally-oriented development of the transport infrastructure of cities of the EU countries, “green” criteria and standards are applied according to the series of guides “Transport and Environmental Reporting Mechanism” (TERM), in particular: TERM 01 Total energy consumption in transport depending on its type; TERM 02 GHG emissions in the transport sector, depending on type; TERM 03 Air pollutant emissions in the transport sector depending; TERM 04 Exceeding air quality requirements; TERM05 Exposure to traffic noise and irritation from it; TERM 06 Fragmentation of ecosystems and habitats by transport infrastructure; TERM09 Number of fatal accidents and serious injuries (caused to soil, air and the marine environment); TERM 11a Generation of waste from end-of-life vehicles; TERM 11b Oil waste and used tires from vehicles [8].

In the USA, almost the same approaches are used to assess the environmental friendliness and sustainability of the development of transport infrastructure in the context of "green" construction. Section 502 of the U.S. Federal Clean Water Act defines green infrastructure as "... a set of measures that use plant or soil systems, permeable coatings or other permeable surfaces or substrates, the collection and reuse of rainwater, or landscape design for storage, infiltration or evaporation of storm water and reduce flows to sewers or surface waters [9].

The Sustainable Highway Construction project, implemented in the context of the “Joint Research Program” of the Transport Research Council, defines modern practice in the field of sustainability of road construction and provides a guide for practitioners to help inform, implement and evaluate effective sustainable highway construction [10].

The US Federal Highway Administration (FHWA), the US Environmental Protection Agency (EPA), other federal transportation and environmental agencies, industry, trade associations, academics and contractors to promote ecological, sustainable and green road construction are implementing partnership in the ranks of the Green Highways (GHP) program is an alliance [11].

The Asphalt Research Consortium (ACR) research program, created in collaboration with FHWA with private institutions and several universities, is exploring potential ways to make asphalt pavements more environmentally friendly and sustainable. In the future, it is expected to lead to increased road safety and reduced environmental impact at the stages of the construction life cycle [12].

It has been established that in foreign countries principles and approaches for the practical implementation of the “green” and sustainable development of the road transport infrastructure of cities are actively developing, although unified approaches and criteria for implementing such activities have not been developed.
Based on our own studies, it was found that the application of the principles of "green" development of transport infrastructure in Ukrainian cities is most effective when taking into account the life cycle of its constituent parts in the context of taking into account environmentally significant criteria for its construction and operation. The developed system of criteria according to the groups of the environmental management system and quality management, material and energy conservation, quality and comfort of the living environment is given in Table 1. [13–16].

**Table 1.** Environmentally significant criteria for assessing compliance with the requirements of the "green" standards of the transport infrastructure of the city in the context of assessing its life cycle.

| Criterion                                                                 | Life Cycle Stage |
|---------------------------------------------------------------------------|------------------|
| Implementation of the environmental management system (ISO 14001: 2004)  | D    | C   | O   |
| Environmental management systems. Requirements with guidance for use       | +    | +   | +   |
| Implementation of the quality management system (ISO 9001: 2015 Quality management systems. Requirements) | +    | +   | +   |
| Informing the public about the implementation of the object construction project | +    | +   | –   |
| *Rational nature management and landscape arrangement*                     |                  |
| Selecting a site (highway) for the construction of the facility           | +    | +   | –   |
| Reclamation, sanitation and rehabilitation of the territory, landscape arrangement and conservation and / or restoration of soil and vegetation cover | +    | +   | +   |
| Integrated storm water management systems                                 | +    | +   | +   |
| Rational water use: reducing the consumption of drinking water for domestic use | +    | +   | +   |
| Prevention of surface and groundwater pollution during construction and operation | +    | +   | +   |
| Waste management and recycling                                            | +    | +   | +   |
| Development and implementation of solutions to ensure animal migration routes | +    | +   | +   |
| Development and implementation of the solution to preserve and / or provide landscape attractiveness | +    | +   | +   |
| Use of the best available technologies from the list (register) of innovative technologies | +    | +   | +   |
| *Material and energy saving*                                               |                  |
| Energy Efficiency Solutions Developed and Implemented                     | +    | +   | +   |
| Use of materials mined, processed and produced in the region where the facility is located | +    | +   | +   |
| Use of recycled materials generated in the process of construction, reconstruction, overhaul, repair and maintenance of roads | +    | +   | +   |
| Assurance of the excavation work balance                                   | +    | +   | –   |
| Use of the best available technologies from the list (register) of innovative technologies of State Highway Service of Ukraine | +    | +   | +   |
| Availability of energy efficiency certificates for the applied technologies and equipment | –    | +   | +   |
| Use of warm mix asphalt technology                                          | +    | +   | +   |
| Quality and comfort of the living environment                              |                  |
| Creation of forest shelter belts along roads of resistant species of trees and shrubs | +    | +   | +   |
| Use of materials with a low level of emission of harmful substances and the non-use of asbestos-containing materials | +    | +   | +   |
| Ensuring minimization and monitoring of the level of air pollution in residential areas | +    | +   | +   |
| Ensuring minimization of the level of pollution of water bodies            | +    | +   | +   |
| Ensuring minimization of soil pollution in residential areas              | +    | +   | +   |
| Provision of regulatory noise levels in residential areas                 | +    | +   | +   |
| Assurance of the reduction of vibration level                              | +    | +   | +   |
| Use of the best available technologies from the list (register) of innovative technologies | +    | +   | +   |

**Note.** D – design stage, C – construction stage, O – operation stage.
The application of the proposed approach to ensure the sustainable development and operation of the road network of Ukrainian cities according to the “green” standards and criteria in the context of the stage assessment of its life cycle taking into account regulatory and legislative requirements in the long term can lead to the integrated reduction in the technogenic load generated by the road network.

3. The mechanism for assessing the environmental efficiency of the development of the bicycle transport network of cities

In the framework of the integrated sustainable development of the transport infrastructure of urban areas, the important factor is the development of cycling. It helps to redistribute passenger and traffic flows, reduce operating costs, reduce exhaust emissions and improve the acoustic climate, as well as improve overall fitness and improve public health [17].

The key criterion for the possibility of mass development of bicycle traffic in cities is the formation of the optimal bicycle transport network that ensures safe, comfortable and encouraged use of bicycle transport as an alternative to car trips.

The main tasks of the development of the bicycle transport network include the following:
- improving the convenience of movement over distances of up to 10-15 km;
- increasing the accessibility of territories;
- the solution for transport, environmental and social problems;
- reduction of health care costs;
- improving the quality of the environment by reducing the number of trips by car at distances of up to 10-15 km.

The generally accepted approaches used in the design of bicycle infrastructure include the following activities:

1) Identification of opportunities to use the territory of the settlement, urban district to ensure the movement of cyclists, including:
   - improving the layout through the reorganization and reconstruction of existing transport infrastructure facilities to increase their capacity (including reducing or increasing lanes, reconstructing intersections, creating separate streets, intersections at different levels);
   - the search for redistribution of cycling and pedestrian traffic using territories located off-road (including green areas, exclusion lanes along railway lines).

2) Improving the efficiency of trips by differentiating cycling by distance, speed, time; combining and dividing the movement of cyclists; development of intermodality; reorganization of traffic.

3) Introduction of new transport solutions and types of transport services for the population.

4) Analysis of existing conditions and prospects for the development and deployment of bicycle transport infrastructure, assessment of the regulatory framework necessary for the functioning and development of bicycle transport infrastructure, and assessment of the volume of financing of transport infrastructure, taking into account the development of bicycle transport [18].

The legislation of Ukraine establishes a number of criteria and requirements for the development of the urban bicycle transport network [19–20], the main of which are given below.

Bicycle paths and bicycle lanes should be arranged on the territories of residential and industrial areas, communal and warehouse areas, on main roads and streets of continuous and regulated traffic, streets and local roads, settlement and rural streets (roads), which provide access for cyclists to residential, public buildings, industrial enterprises, public visiting facilities, open parking lots and garages, etc.

Bicycle lanes are designed only for one-way traffic, and bicycle lanes should be arranged primarily one-way on both sides of the street. If there is a building on one side of the street, a two-way bicycle path on the built-up side should be arranged. If there is cycling on one-way streets, it should be provided in both directions, including using the oncoming bike lane.

The values of indicators and the main calculated parameters of bicycle paths for settlements should be determined in accordance with table 2.
Table 2. Parameters of bicycle paths in Ukraine.

| Estimated speed, km/h | Minimum radius of the curve in plan, m | Minimum radius of the convex curve, m | Minimum radius of the concave curve, m | Maximum longitudinal slope, % | Braking distance on the wet surface, m |
|-----------------------|----------------------------------------|--------------------------------------|----------------------------------------|-----------------------------|---------------------------------------|
| 20                    | 10                                     | 15                                   | 40                                     | 25                          | 15                                    |
| 30                    | 20                                     | 35                                   | 80                                     | 50                          | 40                                    |
| 40                    | 30                                     | 70                                   | 150                                    | 100                         | 40                                    |

Note: The speed of 40 km/h is used when calculating the movement on the slopes.

Under the conditions of historically developed urban development, the longitudinal slope of bicycle paths can be increased to 60 ‰, and in hilly and mountainous areas - up to 100 ‰. In areas with the longitudinal slope of more than 60 ‰, it is necessary to avoid double-sided bicycle lanes and provide for the extension of one-sided bicycle lanes and tracks by 0.5 m. On sections of slopes with a longitudinal slope of more than 60 ‰ it is recommended to use bicycle lanes on sections of slopes - bicycle or bicycle-pedestrian paths.

The selection of the form of organization of cycling, depending on the categories of streets and roads, is carried out in accordance with table 3.

Table 3. Forms of organizing cycling.

| Street category | Forms of organizing cycling |
|-----------------|----------------------------|
|                 | Bike path | Bike lane | Bike and pedestrian path | Mixed traffic on the roadway |
| Trunk roads     |           |           |                           | X                           |
| Main streets of municipal significance | Continuous motion | X | X | X |
| Main streets of district significance | Adjustable movement | X | X | X |
| Streets and local roads | Residential streets | X | X | X |
|                     | Departmental streets and roads | X | X | X |
|                     | Pedestrian streets | X | X | X |
|                     | Driveways | X | X | X |

Note: Joint bicycle and pedestrian path is arranged according to the total traffic intensity of not more than 75 units/h.

Within the framework of landscape-recreational territories (parks and forest parks), as well as along water bodies and railways, bicycle and bicycle-pedestrian paths are provided mainly with two-way traffic. At the same time, measures should be taken to separate the flows of cyclists and pedestrians in accordance with the requirements (Table 4).

Table 4. Minimum width of bicycle lanes and paths.

| Forms of organizing cycling | Minimum width, m |
|-----------------------------|------------------|
|                             | With new construction | Under reconstruction |
| Bike lane                   | 1.85             | 1.5              |
| One-Way Bike Lane           | 1.85             | 1.5              |
| Bike lane with two-way traffic on both sides of the street | 2.5 | 2.0 |
| Bike lane with two-way traffic on one side of the street | 3.0 | 2.5 |
| Joint bike and pedestrian path | 3.0 | 2.5 |
The main criterion for the development of the bicycle transport network, which is a network of bicycle transport routes, is its effectiveness, based on the principles of:

1) Safety – the cycling infrastructure should provide a minimum risk of injury or traumas, as well as a sense of safety among cyclists.

2) Consistency – the bicycle transport infrastructure should be a unified system linking the main places of the start of trips and destinations, be continuous, uniform in terms of movement, have information signs, and allow you to choose options for the route of movement.

3) Straightness and uniformity of movement – the cycling route should have a minimum number of sections with a change in direction. Cyclists should not linger at intersections with traffic flows. Cyclists must be able to move at maximum speed

4) Attractiveness – the bicycle transport infrastructure should provide lighting, aesthetics, integration with the surrounding space, access to service and trade facilities.

5) Comfort – the bicycle transport infrastructure must ensure the quality of coverage, minimal deviations, the exclusion of complex maneuvers, minimizing the need to dismount, minimal interference from vehicles and pedestrians [21].

The analysis of the above criteria for the development of the bicycle transport network carried out in the work indicates the impossibility of their systematic accounting for the integrated implementation of such activities, including in the context of ensuring the environmental safety of urban areas. Therefore, to assess the potential effectiveness of the development of the bicycle transport network, it is advisable to use the method of convolution into the integral criterion (indicator) of single indicators characterizing the impact of bicycle transportation on the functioning of the urban transport system, the environment and public health. The integral criterion P is determined by the formula:

$$P = \frac{S_1 \alpha_1 + S_2 \alpha_2 + \cdots + S_n \alpha_n}{\alpha_1 + \alpha_2 + \cdots + \alpha_n} \to \max,$$

where \(\alpha_1, \alpha_2, \ldots, \alpha_n\) – weighting factors of the \(i\) performance indicator; \(S_1, S_2, \ldots, S_n\) – the relative values of the performance indicators of the certain scenario of the development of military-technical cooperation compared with the base, score [22–23].

As basic indicators for assessing the expected environmental performance from the implementation of the set of measures for the development of cycling it is advisable to consider:

– reduction of pollutant emissions (pollutants) by motor vehicles when it is replaced by cycling (\(S_1, \text{t/year}\));

– reduction of fuel consumption by vehicles when it is replaced by cycling (\(S_2, \text{t/year}\));

– reduction of traffic noise in the residential area due to the development of cycling (\(S_3, \text{dBA}\)) [22, 24].

As one of the input parameters for carrying out such comprehensive assessment, it is recommended to consider the rate of decrease in motor transport work performed by all types of urban transport, primarily personal automobile transport, on cycling according to the formula:

$$\Delta Z = \frac{\delta K_c W(T)}{K_c} = N \cdot \Delta L,$$

where \(\delta\) is the proportion of cyclists who previously used a personal car; \(K_c\) – regional coefficient of passenger capacity of cycling vehicles, pass/bicycle; \(K_c\) is the coefficient of filling the passenger compartment, pedestrian/car; \(N\) is total number of personal cars, auto.; \(\Delta L\) is change in the average annual mileage of 1 car associated with the replacement of part of road trips by bicycle rides, km; \(W(T)\) is the volume of cycling work performed at the time \(T\), bicycles / km, calculated by the formula:

$$W(T) = k_u \cdot \sum_{i=1}^{n} L_i \cdot \int_{t=0}^{T} S_i(t) \cdot dt,$$

where \(L\) is length of the \(i\) section of bicycle transport network, km; \(S_i(t)\) is dependence of traffic on \(i\) section of bicycle transport network from time to time slot under consideration, bicycle/min.; \(T\) is the time interval for which the transport work is calculated, hour; \(k_u\) is the uncertainty coefficient, taking into account the proportion of movements of cyclists outside the considered bicycle transport network; \(n\) is the number of sections of the bicycle transport network [17].
For the calculation of $S_1$ must use a technique [25], which allows to calculate the pollutant emissions during starting and warming up the motor vehicle, as well as running exhaust emissions which magnitude inversely to bicycle transport work done $ΔZ$. Expressing the magnitude of the reduction in total emissions of pollutants from vehicles through $ΔZ$, we obtain the following formula:

$$\Delta m_i = \sum_i \left| \sum_j \sum_k \sum_l \sum_m \frac{δl(W(T))_{ki}}{K_{c100}} \cdot (m_{1ijk} \cdot l_{kl} \cdot m_{2ijn} \cdot t_{cr} \cdot n_j \cdot α_j \cdot N_{jkl}) \right|,$$

where $m_{1ijk}$ is the mileage emission of the $i$ pollutant of a vehicle of the $j$ design type when driving along streets and roads of $k$ category, g/km; $l_{kl}$ is length of the $l$ section of streets and roads of the $k$ category, km; $N_{jkl}$ is traffic intensity of the $j$ design type on the $l$ section of streets and roads of the $k$ category during the day, thousand cars/day; $m_{2ijn}$ is emission of $i$ pollutant when starting and warming up the engine of the motor vehicle of $j$ design type for $n$ period of the year, g/min; $t_{cr}$ is the warm-up time of the engine, min; $p_l$ is the number of cold starts per day of the vehicle of $j$ design type; $α_j$ is the exit coefficient of the vehicle of the $j$ design type [25].

The reduction in fuel consumption ($S_2$) consumed by the vehicle is calculated according to the methodology [26].

The value of the efficiency indicator $S_1$ is advisable to determine the value of the noise characteristics of traffic flows according to the formula [27]:

$$L_{7,5} = 9.5 \cdot \log(N_0) + 12.64 \cdot \log(v) + 7.98 \cdot \log(1 + P_r) + 11.39,$$

where $N_0$ is the estimated maximum traffic intensity, car/h; $R_s$ is the share of freight vehicles and buses, $%; v$ is speed, km/h.

From formula 5 it follows that the value of noise characteristics of traffic flows will be affected by the intensity, speed and composition of the traffic flow, which depend on the adopted architectural and planning decisions and the conditions for organizing traffic.

Typical measures for urban areas are the following measures to limit the use of cars in the city:

– redevelopment of the typical city street into the bicycle-pedestrian zone – there is no motor noise in this case, and the noise is taken equal to the background;

– limiting the speed of vehicles to 30 km/h with the organization of combined automobile-bicycle traffic, while the value of noise characteristics of traffic flows can be calculated by the formula:

$$L_{7,5} = 9.5 \cdot \log(N_0 - N_i) + 12.64 \cdot \log(v - v_i) + 7.98 \cdot \log(1 + P_r) + 11.39,$$

where $N_i$ is the estimated maximum traffic intensity after the creation of the bicycle transport network, car/h; $v_i$ is speed after restrictive measures, km/h;

– the structure of the bike path (or bike lane) instead of the rightmost lane of the driving way on the streets with a different number of lanes of the driving way, while the value of noise characteristics of traffic flows can be calculated by the formula:

$$L_{7,5} = 9.5 \cdot \log(N_0 - N_i) + 12.64 \cdot \log(v) + 7.98 \cdot \log(1 + P_r) + 11.39 - ΔL_{\text{dis}},$$

where $ΔL_{\text{dis}}$ is the correction taking into account the attenuation of traffic noise with distance (the magnitude of the cylindrical divergence), dBA, which is of the greatest importance when implementing the measure and is calculated by the formula:

$$ΔL_{\text{dis}} = 10 \cdot \log \left( \frac{R_e + L_e}{R_0} \right),$$

where $L_e$ is the width of the created bike lane, m; $R_0 = 7.5$ m.

The value of the weighting coefficients for these criteria, determined by the method of expert estimates, are given in table 5 [17].
Table 5. Coefficients of weighting indicators.

| Weight indicator                        | Name   | Significance factors, options |
|-----------------------------------------|--------|-------------------------------|
|                                        | 1      | 2    | 3     | 4     | 5     | 6     |
| Pollutant emission reduction            | $\alpha_1$ | 0.05 | 0.025 | 0.075 | 0.025 | 0.5   | 0.05  |
| Fuel economy                            | $\alpha_2$ | 0.1  | 0.15  | 0.5   | 0.025 | 0.125 | 0.2   |
| Noise level reduction                    | $\alpha_3$ | 0.05 | 0.025 | 0.025 | 0.5   | 0.075 | 0.05  |

Thus, all three of the above-mentioned measures contribute to improving the environmental situation in large cities, potentially formed by the development of the bicycle transport network and the noticeable motor transport work on the bicycle transport. The proposed integral indicator of the ecological efficiency of the development of the municipal bicycle network helps to combine the above criteria for objective management decisions to ensure sustainable development of urban areas.

4. Conclusions

Based on the goal of the article, which is to develop approaches to implementing the principle of sustainable development of cities through the optimization of their road transport infrastructure by introducing standards for the green construction of the road network and assessing the environmental efficiency of the development of the bicycle transport network, a general approach was proposed for such works, based on the stage assessment of the stages of the life cycle of objects taking into account regulatory and legislative requirements. In prospect, when implementing this approach, the integral decrease in the technogenic load formed by the street-road network is expected. To detail the practical approach to the implementation of the principle of sustainable or “green” construction, the paper proposed the criterion for the environmental efficiency of the development of the municipal bicycle transport network, based on the replacement of motor transport work with bicycle transport and the subsequent reduction in fuel consumption, pollutant emissions and acoustic load. The proposed indicator can be recommended for use for the objective adoption of managerial decisions to ensure the sustainable development of urban areas.

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