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An analysis of the transport impact of finish building on-ramps and off-ramps from the Dnipro embankment to the Darnytskyi Bridge in Kyiv

Abstract. This study was aimed at assessing the effectiveness of design solutions for the development of Kyiv’s transport infrastructure based on transport modelling and analysis of possible socio-economic effects. To do this, a four-step algorithm for modelling transport demand was used, based on data from sociological surveys, territory plans, and forecasts for 2030. The results of the study showed significant changes in the functioning of the Kyiv transport network as a result of the implementation of the proposed design solutions. The transport modelling helped to estimate quantitative indicators such as traffic volumes on major highways, as well as qualitative changes such as reduced congestion, shorter travel times, and cost savings. One of the key results was that the opening of new exits and entrances to the Darnytskyi Bridge on the left bank contributed to a slight increase in bridge capacity, but the biggest

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effect was seen on the approaches to the bridge. The additional approaches have increased traffic volumes, which indicates improved transport accessibility for drivers using this transport hub. The results related to environmental performance were also important. The reduction in congestion resulted in a reduction in CO₂ emissions, which is a significant contribution to improving the environmental situation in the city. In terms of cost-effectiveness, the results demonstrated significant savings in transport losses, confirming that the implementation of the proposed measures has a positive impact on transport infrastructure, as well as reducing financial losses associated with travel. Thus, the results of the study confirmed that the proposed design solutions have a positive impact on the development of the transport network, increasing capacity and reducing negative environmental impact, which opens up opportunities for creating a more efficient transport system that meets the requirements of sustainable development and improves the overall quality of life of Kyiv residents

Keywords: street and road network; transport modelling; traffic capacity; node congestion; infrastructure development scenarios; social impacts

INTRODUCTION

Ukrainian cities, including the capital, Kyiv, are facing transport issues arising from the rapid increase in car ownership (Semchenko, 2020). The growth of the private car fleet is driven by both the rising demand for personal transport and the relative availability of used cars from Europe and the USA, influenced by national policies. These factors, combined with urban planning policies that typically aim to meet citizens' demands for unrestricted car use, have led to a significant increase in the load on the road network (RN) in Ukrainian cities. The consequences include a deterioration in the level of service (LOS) of the RN, an increase in harmful emissions, higher energy losses, a decline in transport accessibility, and reduced resilience of the transport systems in Ukrainian cities.

The situation is particularly critical in Kyiv. In 2021, the Ukrainian capital ranked third among 404 cities worldwide for congestion levels, according to the Traffic Index (2021), with traffic delays reaching 56%. This indicates that a significant portion of Kyiv's RN, constructed in the 1960s and 1980s, along with RN overall density, is inadequate to meet the growing demand for transportation. Moreover, due to limited resources for maintaining and developing the RN, the city is gradually losing its capacity to modernise, and even maintain, its existing transport infrastructure, further exacerbating the problem of deficiencies (Sidliarenko, 2023). Given these challenges, it is crucial to make decisions aimed at improving the efficiency of the RN. One key area is the modernisation and expansion of important transport hubs and junctions. Conducting a cost-benefit analysis of such projects can facilitate decision-making that aligns with legal requirements and urban planning goals, enabling the achievement of the highest level of cost-effectiveness.

A crucial factor in enhancing the efficiency of RNs is a comprehensive study of the impact of various design solutions on traffic flows using transport modelling. In the research by O. Stepanchuk *et al.* (2022), the effectiveness of transport modelling methods was highlighted, emphasising that such technologies can significantly improve the overall efficiency of RN utilisation. In the study by V. Perlov & I. Kyrystsya (2023), transport modelling was used for

planning and modernising the RN in Vinnytsia, where positive effects of applying such technologies were identified. Furthermore, the article of G. Boeing & W. Riggs (2024) examined the impact of transport systems on traffic optimisation, demonstrating that the use of transport modelling methods can significantly optimise RNs, reducing traffic delays and improving overall network performance. Thus, these results confirm that the application of transport modelling is essential and relevant for the effective management of RN development.

Moreover, transport modelling can provide deeper insights into the impact of specific design solutions on the performance of RNs. In the research conducted by E. Suryani *et al.* (2020), the effectiveness of implementing new design solutions based on transport modelling of various traffic management scenarios was analysed, revealing that optimising traffic management at intersections and road sections can lead to increased capacity of key sections of the RN. The study of E. Zadobrischi *et al.* (2020) focused on the impact of modernising RN elements on the overall efficiency of the transport system, and as a result, revealed that such updates can contribute to a significant transport effect. In the study by W. Wu *et al.* (2020), the emphasis was on the implementation of intelligent transportation systems, where, using transport modelling, it was found that the integration of innovative technologies can improve the overall level of road safety on the RN and yield a transport effect. Nevertheless, even considering the positive results, it is necessary to take into account the limitations and challenges associated with the implementation of such design solutions and, consequently, projects.

Another crucial factor to analyse is the impact of different strategies on RN efficiency through the use of transport modelling. The study of M. Ogryzek *et al.* (2020) conducted detailed transport modelling of scenarios involving both the reconstruction of existing roads and the construction of new transport routes, demonstrating that the reconstruction of key intersections can increase the overall capacity of the RN. The research of C.-Y. Wu *et al.* (2021) focused on assessing the impact of new transport technologies on achieving transport efficiency, revealing through





transport modelling those new technologies contribute to reducing congestion duration at intersections on the RN. The article of P. Wang *et al.* (2020) used transport modelling to investigate the transport effect of measures to restrict the use of private transport, including the development of cycling infrastructure and increasing the amount of public transport. However, despite these results, it should be noted that when implementing new design solutions in an existing RN, it is necessary to consider not only technical but also socio-economic aspects, ensuring a balance between efficiency and the system's resilience, which requires further monitoring and adjustment as projects are developed.

This study aimed to assess the transport impact of design solutions for intersections on the RN, using the left-bank on-ramps and off-ramps of the Darnytskyi Bridge in Kyiv as a case study. To achieve this goal, several key tasks were defined and implemented, including an analysis of the impact of the proposed design solutions on the overall efficiency of the RN, including changes in capacity, and delay times, as well as an assessment of socio-economic and environmental impacts such as savings in transport losses and expected reductions in CO₂ emissions, allowing for a comprehensive evaluation of the consequences of implementing changes to the RN.

MATERIALS AND METHODS

The research was conducted at the Department of Urban Construction and Architecture (KNUCA), which specialises in the analysis and development of urban planning solutions. A digital twin of Kyiv's mobility, developed by the university, was used for the analysis. One of the key tools used for transport modelling was the academic version of the PTV Visum software. To forecast the development of Kyiv's regional network (RN) and its suburbs under conditions of uncertainty, a two-stage expert survey was conducted in the field of urban planning. The survey aimed to gather insights and professional assessments on potential development paths, considering the current challenges and resources available. The experts who participated in the survey had significant professional experience in urban and transport planning, ranging from 10 to 25 years, which ensured a high level of expertise in evaluating the feasibility and implications of proposed projects.

The survey was conducted in Kyiv, Ukraine, in 2024, using an absentee format to accommodate the participants' schedules while maintaining ethical and procedural integrity. During the first stage, five experts participated, primarily representing academic institutions and consulting firms. Their involvement focused on identifying critical issues and proposing preliminary solutions. In the second stage, six additional experts joined the survey, including specialists from local government bodies and design organisations. This diversified the perspectives and enriched the analysis by incorporating practical and institutional knowledge alongside academic insights. To ensure transparency and adherence to ethical standards, all participants

were informed in advance about the principles of ensuring their anonymity. They received comprehensive information about the study's objectives, the procedures for using the data they provided, and the potential risks associated with their participation. Ethical standards were strictly observed throughout the research process. The study conformed to the recommendations of the American Sociological Association's Code of Ethic (1997), Guidance Note of the European Commission "On Ethics and Data Protection" (2021), and adhered to the ethical principles outlined by the academic institution overseeing the research.

During the first stage, experts were asked to identify infrastructure projects and urban development projects in Kyiv and its suburbs that were likely to be implemented or in the final stages of implementation by 2030. Projects were classified into three categories: infrastructure (including the construction or redevelopment of highways, bridges, intersections, and streets), public transport (new routes and rapid transit lines), and development (new residential areas, business centres, industrial enterprises, shopping and entertainment facilities, educational institutions, and cultural institutions). Given that experts provided a more detailed list of projects in the first two categories, it was decided to focus on these areas. In the second stage of the study, the assessment of the likelihood of implementation only concerned infrastructure projects and public transport development projects.

The finalised list from the second stage was provided to 6 experts to assess the likelihood of implementation for each project. The experts were asked to assess the likelihood of the implementation of the following projects by 2030 on a scale from 1 to 7, where 1 indicates the project will definitely not be implemented, and 7 indicates the project will definitely be implemented by 2030. To assess the development of the RN by 2030, the analysis area was divided into over 500 transport zones. For each of these transport zones, data on population and other socio-economic indicators were collected based on materials from the Kyiv General Plan (2020). This data was used to calculate transport demand, which in the digital twin of Kyiv's mobility is implemented using a fourstep algorithm.

The first step in the transport modelling involved a representative sociological survey, based on which the main purposes and volumes of daily trips between transport zones were determined, as well as the distribution of trips by different modes of transport. The analysis also considered data on the duration and distance of trips, which allowed for the calculation of transport demand for each step of model creation. Four main matrices of inter-zonal trips were then formed: for private transport, public transport, pedestrians, and cyclists. Subsequently, the matrices, except for the pedestrian one, were distributed across the RN. For calibration, data from passenger flow surveys on public transport routes and data on traffic volume at key intersections and segments of the RN were used.

The transport demand model used in this study included data from 2019, i.e., the period before COVID-19 and the



full-scale war in Ukraine. In the calculations of the forecast scenarios for 2030, a constant value of projected transport demand was used for all scenario variants. Additional important factors were the limitations and assumptions considered when constructing the digital twin, as well as in the process of calculating the transport effect of implementing the proposed scenarios for the development of the RN.

RESULTS

The development of a digital twin of Kyiv's mobility and its suburban area has revealed that one of the primary

issues in urban mobility is the uneven planning and development of urban territories. Kyiv exhibits a significant imbalance in the spatial distribution of population and jobs. According to Figure 1, the left-bank districts of the city – Desnianskyi, Darnytskyi, and Dniproviskyi – account for 36% of the city's population (approximately 1.05 million people), yet these areas host only 18% of the total number of workplaces (Sustainable urban transport for Kyiv..., 2016), as illustrated in Figure 2. This mismatch creates significant challenges for the RN, hindering movement and increasing delays.

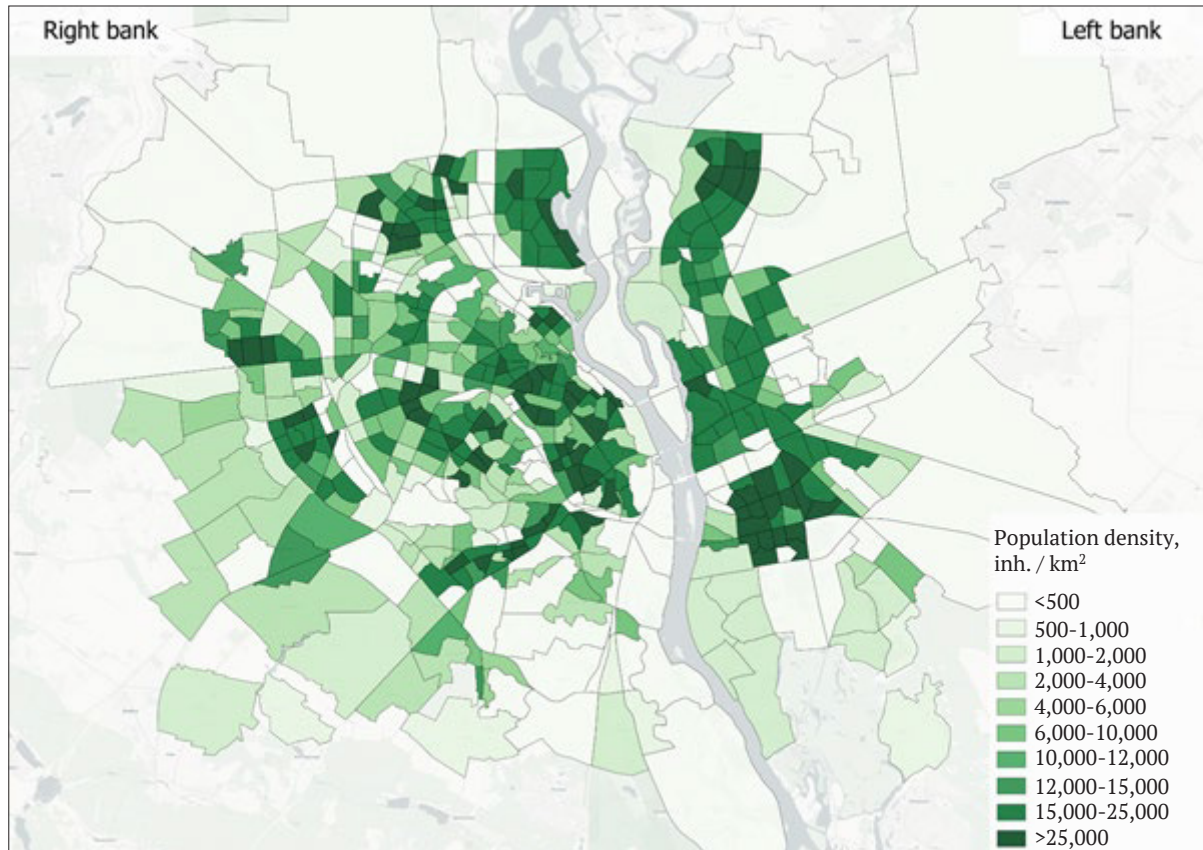


Figure 1. Distribution of population in the spatial settlement structure of Kyiv and its suburban area

Source: developed by the authors based on Sustainable urban transport for Kyiv: Towards a sustainable and competitive city built upon the legacy system and innovations (2016)

Movement between both banks of the Dnipro River in Kyiv is facilitated by both private and public transport. The capital has a fairly extensive public transport system, but its capacity and quality of service remain insufficient to fully meet the city's demand for transportation and effectively curb the growth of car ownership. In 2016, approximately 320 buses, 430 trolleybuses, and 212 trams operated on Kyiv's routes. However, according to a World Bank report (Sustainable urban transport for Kyiv..., 2016) published the same year, to optimise the transport network and adequately meet transport demand, it was necessary to

invest in the purchase of at least an additional 230 buses, 420 trolleybuses, and 72 trams to supplement the existing fleet. Despite expert recommendations and the declared priority of developing public transport in Kyiv's strategic plans, the city's public transport system has not undergone significant improvements since 2016. One of the significant blows to public transport was COVID-19 (Gkiotsalitis & Cats, 2021). During the quarantine restrictions, transport operated in a reduced mode and with a limited number of passengers, leading to the loss of some users who previously preferred public transport.



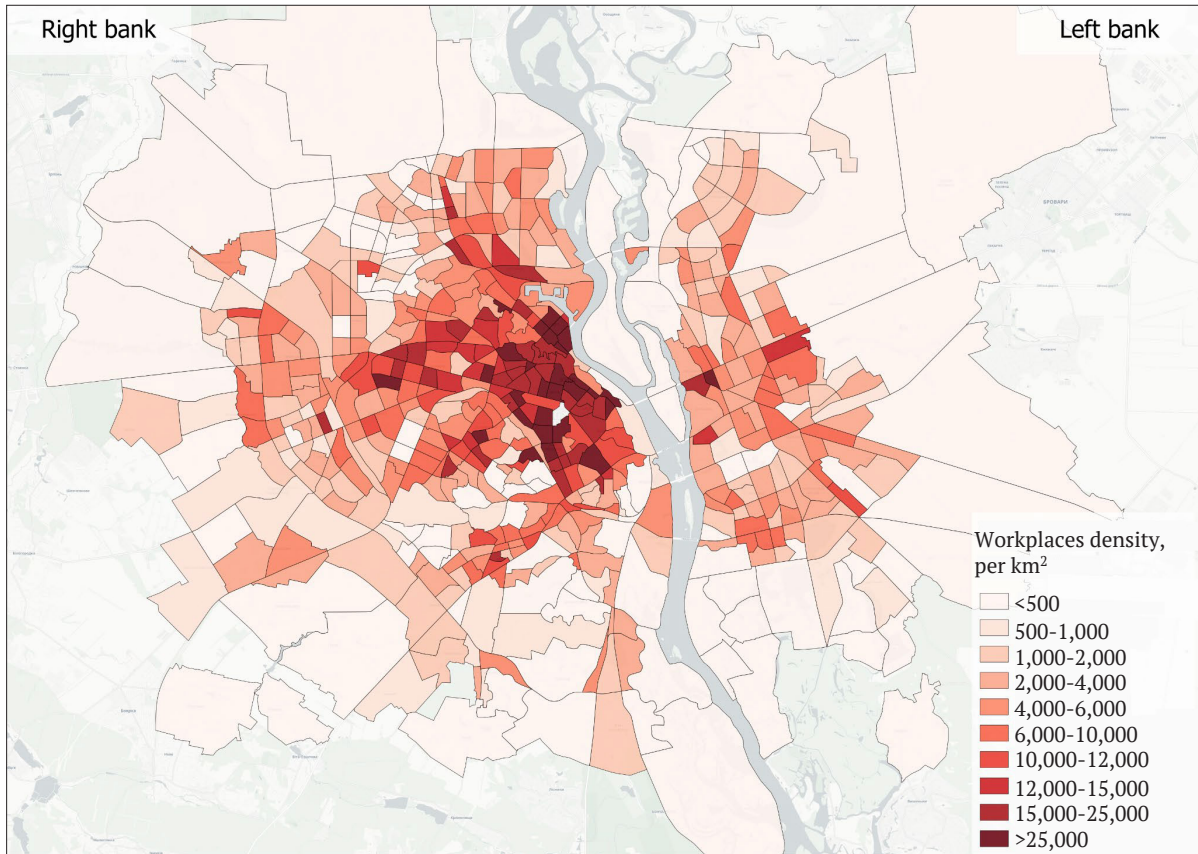


Figure 2. Distribution of workplaces in the spatial settlement structure of Kyiv and its suburban area

Source: developed by the authors based on Sustainable urban transport for Kyiv: Towards a sustainable and competitive city built upon the legacy system and innovations (2016)

Since the beginning of the full-scale Russian invasion of Ukraine in 2022, the situation for public transport has deteriorated even further. The number of vehicles on public transport routes has decreased significantly. For example, in September 2022, only 180 buses, 165 trolleybuses, and 97 trams were operating on the routes, which is 44, 62, and 54% less, respectively, than in 2016 (Ivanets, 2022). This reduction significantly decreased the reliability and accessibility of public transport for Kyiv residents, which, in turn, could be one of the reasons for the increase in car ownership and the more frequent use of private cars for urban trips. The lack of stable and high-quality public transport pushes residents to choose personal transport (Li & Xu, 2020), which puts additional pressure on the RN and worsens the overall transport situation in the capital (Kramskiy *et al.*, 2023).

In 2017, the Decision of the Kyiv City Council No. 7/4071 (2018) was developed and officially approved in 2018. This document envisages the construction of over 1,000 km of bicycle routes throughout the city. However,

as of 2021, the total length of existing bike paths and lanes in Kyiv was only 202.2 km (Bicycle infrastructure in Kyiv, 2022), of which 27.8 km falls on public transport lanes where cycling is experimentally permitted. However, despite the stated length of the cycling network, its main problem remains its connectivity. As of 2024, Kyiv has only one fully-fledged cycling route “Residential Area Troieshchyna-Centre”. Other sections of cycling infrastructure are mostly made up of separate and unconnected fragments (Fig. 3). Most bike lanes or paths have appeared as a result of major repairs to individual streets and do not form a single network, which significantly complicates safe and convenient cycling in the city.

Due to the lack of adequate transport supply, including the insufficient development of public transport and cycling infrastructure, as well as the uneven distribution of the population within Kyiv and its suburban area, the demand for private car trips is growing (Ceder, 2021). This leads to the overload of existing bridge crossings over the Dnipro River (Fig. 4), which creates significant problems for the RN.

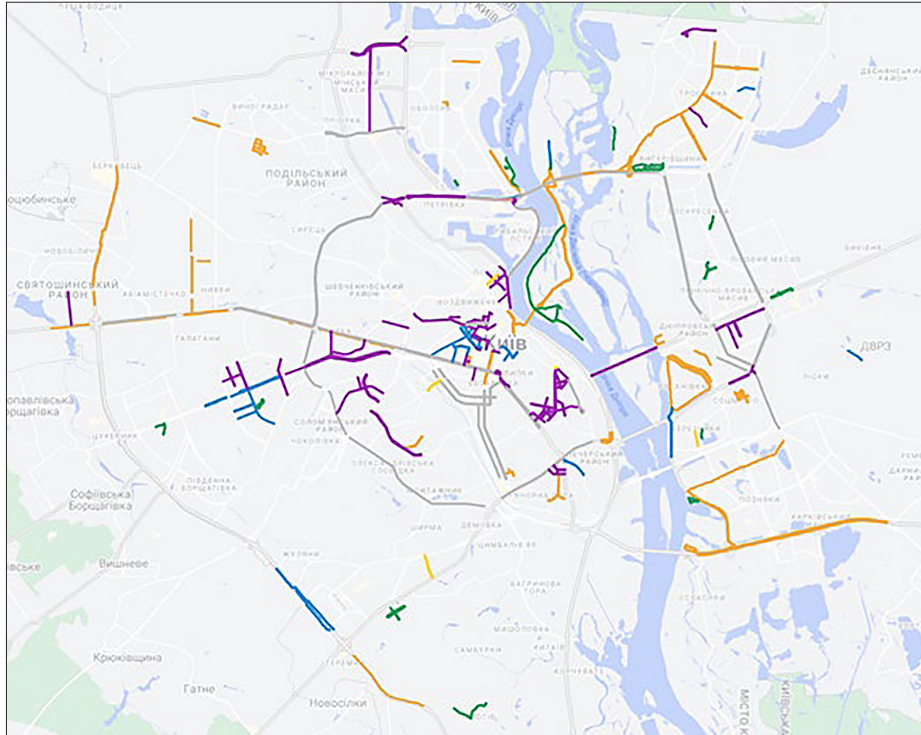


Figure 3. Map of bicycle lanes and cycle paths in Kyiv as of 2022

Source: developed by the authors

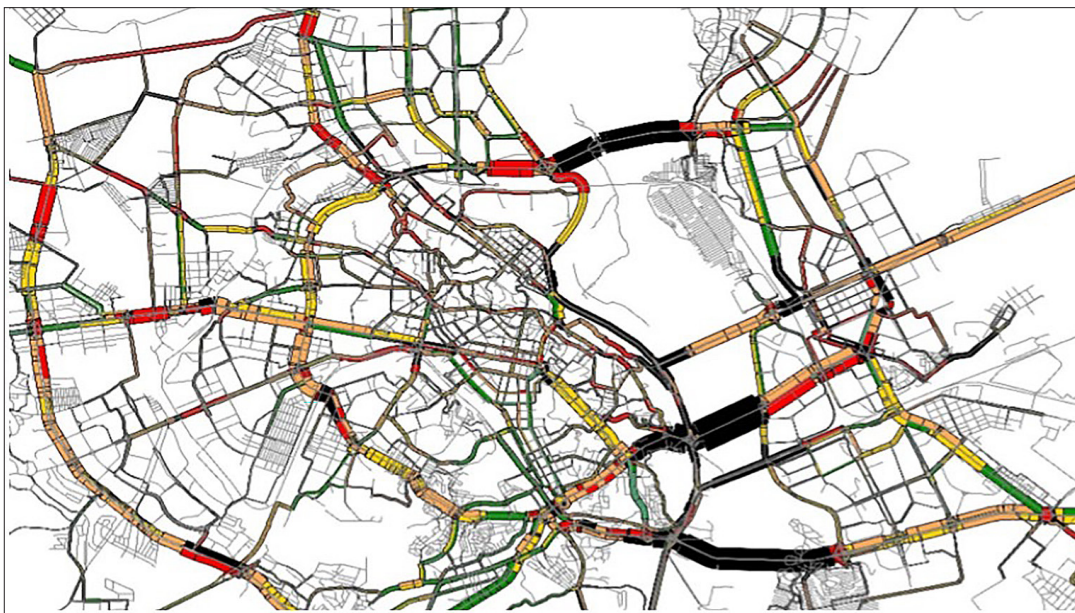


Figure 4. Map of the volume/capacity ratio on the Kyiv RN

Source: developed by the authors based on M. Osetrin *et al.* (2015)

Overloaded bridges become “bottlenecks” in the RN, affecting its overall efficiency. In case of emergencies, such as the sudden closure or repair work on any of these structures, the resilience of the RN is significantly reduced. This, in turn, jeopardises not only the safety but also the defence capability of the Ukrainian capital, as the reliable functioning of the RN is critical for ensuring the mobility

of the population, logistics of goods, and prompt response to various challenges.

Of the five operational road bridges across the Dnipro River in Kyiv, two bridges – the Metro Bridge and the Paton Bridge – are in a non-operational state (Ministry of Infrastructure..., 2023). This creates an additional load on the other bridges and significantly affects the overall capacity





of the RN. In such a situation, when assessing the effectiveness of design solutions, special attention should be paid to bridge crossings as critical elements for the resilience of the RN. The efficiency of these bridges largely depends on the quality of the functioning of pre-bridge intersections on the RN. They are key points that play a decisive role in the distribution of traffic flows (Osetrin & Tarasiuk, 2014), and their operation is determined by factors such

as transport demand, location, and purpose of the intersection (Bekenovet *al.*, 2020). One of the important objects of Kyiv's RN is the Darnytskyi Road and Railroad Bridge, along with its approaches. This bridge performs a crucial transport function as it connects the left and right banks of the capital, providing for the movement of both road and rail transport. The road part of the Darnytskyi Bridge has 3 lanes in each direction, as shown in Figure 5.

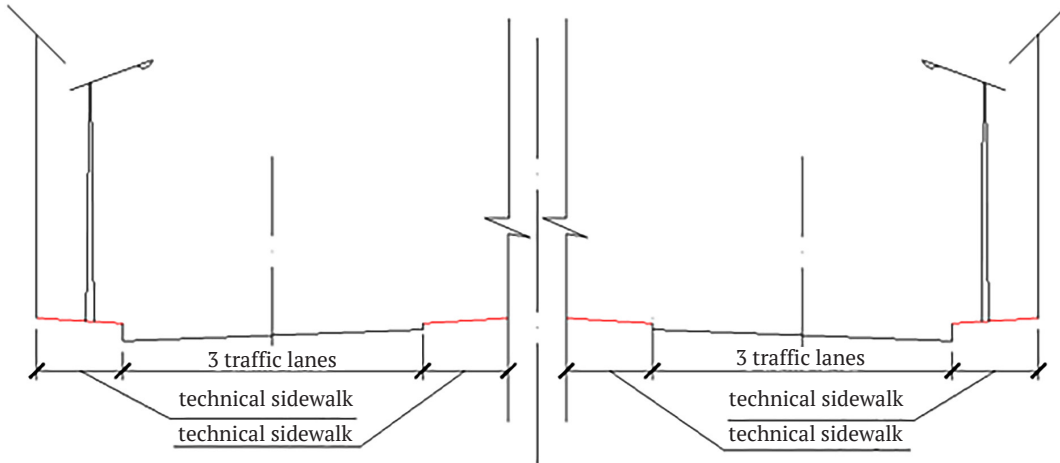


Figure 5. The cross-section of the road section of the Darnytskyi Road and Railroad Bridge in Kyiv

Source: developed by the authors

On the right bank of the Dnipro River, to effectively connect the Darnytskyi Road and Railroad Bridge to the RN, an interchange with flyover was built, which provides access to the Naddniprianske Highway. This interchange is an important part of the RN, which allows for reducing delays as a result of the assignment of traffic flows. On the left bank, the main approach to the Darnytskyi Bridge is Petro Radzina Street, which connects to the intersection of Pryvokzalna Street and Kharkivske Shose, providing the main transport link for cars moving to-

wards or from the bridge. In addition, to integrate the Darnytskyi Bridge into the existing RN, part of Sortuvalna and Yuriy Shumskiy Streets were additionally built, improving access to the bridge and the capacity of its approaches. In Figure 6, these new sections created for better connection of the Darnytskyi Bridge with the RN are marked in blue. In red, in turn, are the key exits of the Darnytskyi Bridge, which play an important role in ensuring the movement of cars between different parts of the bridge.

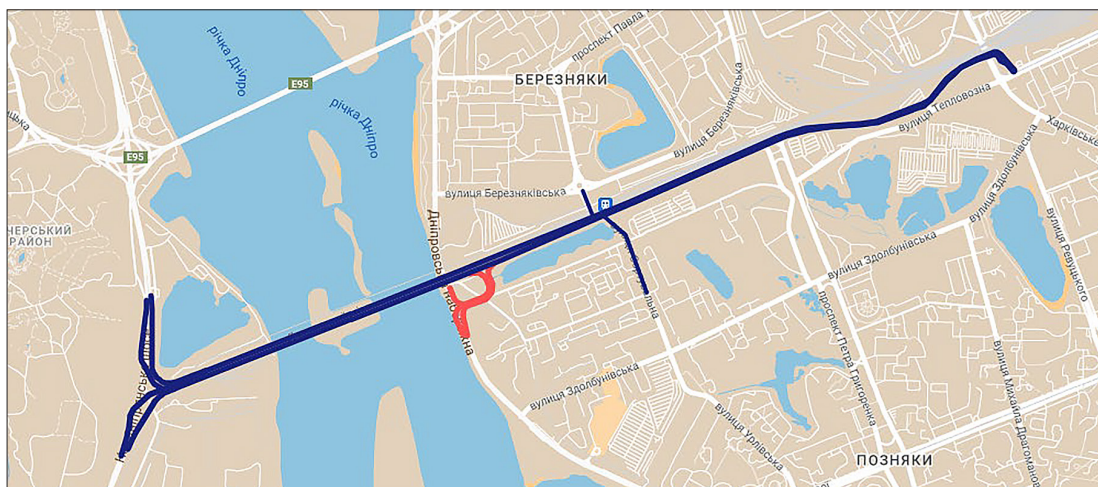


Figure 6. Darnytskyi Bridge with right-bank and left-bank approach routes

Source: developed by the authors



The foundational urban planning document in Ukraine is the General Plan of a city, which defines the strategy for the development of a settlement, including its transport infrastructure, development planning, and socio-economic development. This document is a crucial tool for regulating the development and the evolution of urban space and also determines the main directions of spatial planning for the city over a long period. For Kyiv, a General Plan (2020) was approved which was valid until 2020. However, as of 2024, this document has already lost its relevance and does not take into account modern challenges, such as population growth, increased levels of car ownership, and the need for modernisation of transport infrastructure (Buil *et al.*, 2016). In this regard, there has been a need to develop a new General Plan that could reflect the current realities and formulate the prospects for the city's development in the future. As of 2024, attempts are underway to create a new General Plan for the city of Kyiv, which will cover the period up to 2040. However, the process of developing this document faces several difficulties, and therefore it has not yet been approved. The absence of an up-to-date General Plan significantly complicates the planning and development of urban infrastructure, including the RN, as there are no clear

guidelines for making design solutions regarding the future development of the capital (Nenastina *et al.*, 2024).

In the section concerning the RN, the draft of the new General Plan for Kyiv continues to follow the principles laid down in previous versions. The main concept is focused on the extensive development of transport infrastructure, which involves large-scale investments in the expansion of the RN. In particular, the project envisages the construction of multi-level intersections, which, according to the developers, should contribute to the optimisation of traffic flows and reduce delays at key intersections on the city's RN. In addition, significant attention is paid to transforming many existing streets into continuous-flow highways, which is expected to increase the speed of movement around the city. This decision is aimed at improving connectivity between city districts and ensuring greater capacity for vehicles. One of the most ambitious elements of the project is the planned construction of three new bridges across the Dnipro River, aimed at significantly easing traffic between the right-bank and left-bank districts of the capital. These new bridges should become important transport arteries, capable of reducing the overload of existing bridges and providing additional routes for motorists (Fig. 7).

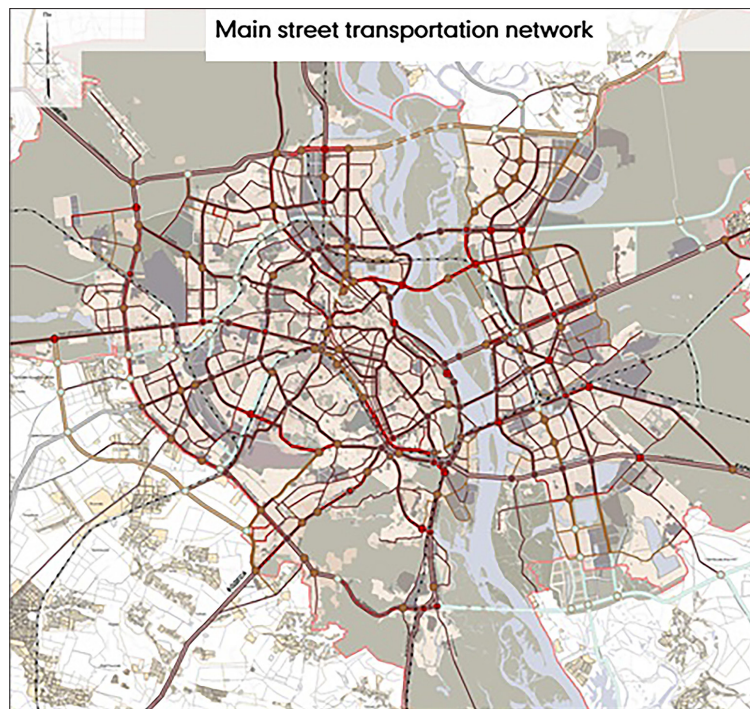


Figure 7. Development of the urban RN as outlined in the draft of Kyiv's new General Plan

Source: developed by the authors based on the Kyiv General Plan (2020)

It should be noted that the implementation of all the measures envisaged in the draft of the new General Plan for the city of Kyiv and its suburban area is unlikely. A significant number of the declared projects require large investments and long implementation periods, which calls into question their full implementation.

Given these limitations, within the framework of this study, it was decided to consider a more realistic scenario for the development of the RN. For this purpose, as noted before, a two-stage expert survey in the field of urban planning was conducted, which made it possible to assess potential development paths, taking into account



the expert assessment of current resources and capabilities. The results of this assessment of the probability of implementing urban planning projects are partially presented in Table 1.

Table 1. Partial results of expert assessment on the feasibility of urban development projects for Kyiv

Category	Project	Experts share	Average score
Bridges	Off-ramps from Darnytskyi Bridge	1	5.9
	Reconstruction or restoration of the Metro Bridge	1	4.6
	Restoration of the Paton Bridge	0.8	4.5
	Completion of the Podilskyi Bridge	0.7	4.4
Highways/streets	Finish building of Medova Street (near Zhulyany Airport)	0.8	5.3
	Dovbusha Street extension from DVRZ to Brovarskiy Avenue	0.5	3.8
Pedestrian	Pedestrianisation of Kontraktova Square	0.8	5.3
	Pedestrian bridge at Obolon	0.5	4.6
	Bessarabska passage	0.5	4.2
	Reorganisation of Lvivska Square	0.5	3.8
	Replacement of 30 underground crossings with surface-level crossings	0.5	3.7
Public transport	Extension of the metro line to Vynohradar	0.8	5.3
	Urban electric railway line Vyshhorod-Obolon-Pochaina	0.8	4.1
	The new urban railway station at Obolon	0.7	4
	The new urban railway station at Lybidska	0.5	3.8
	Extension of the Borshchahivka rapid tram line to Vokzalna station (via Petliura Street)	0.5	3.8
	Opening of the Lvivska Brama metro station	0.5	3.7
Intersections	Development of a rapid transit line from Troieshchyna to the city centre	0.5	3.5
	Bohatyrska/Poliarna intersection	0.7	4.4
Squares	The intersection at Vernadskyi/Palladina (near Akademmistechko)	0.7	3.7
	Reconstruction of Halytska Square (Peremohy Square)	0.7	4.2

Source: developed by the authors

To include in the digital twin of Kyiv’s mobility (projected state), those projects that received the support of most experts were selected. Of all the proposed projects, only two – the construction of off-ramps for the Darnytskyi Bridge and the reconstruction of the Metro Bridge –

received the consolidated support of all survey participants. All experts without exception expressed confidence that these projects would be implemented within the specified timeframe. The location of all objects supported by experts, including these two critical projects, is shown in Figure 8.

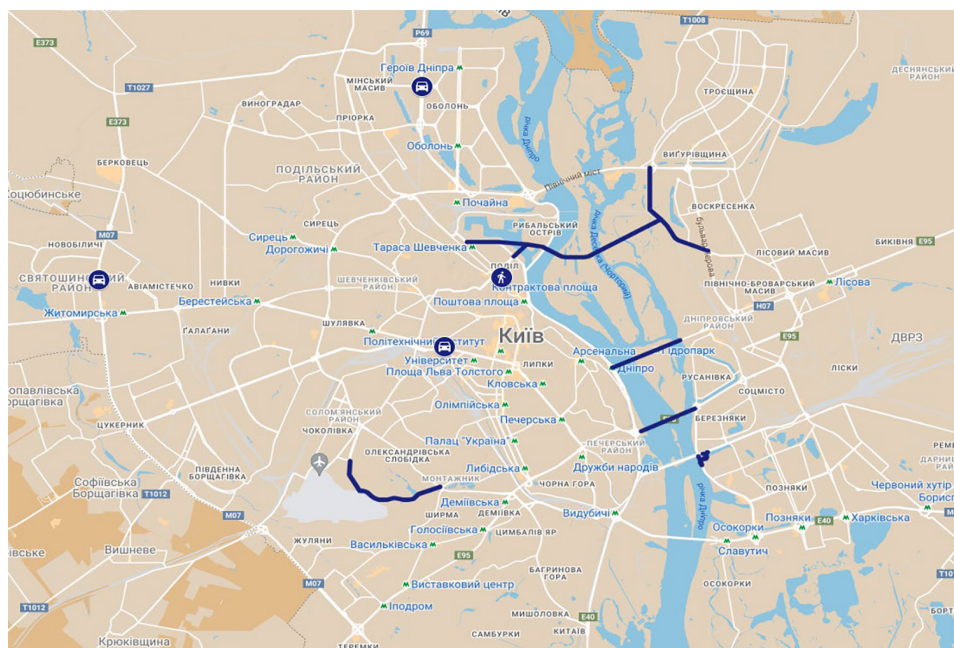


Figure 8. Projects with a high probability of implementation by 2030 according to the assessment of surveyed experts
Source: developed by the authors



During the calculation of forecast scenarios in the digital twin of Kyiv's mobility, an assignment of the expected transport demand, which was forecast for 2030, was carried out. It is important to note that this transport demand remained constant for all considered scenarios, which allowed for the comparability of results and the assessment

of the impact of various infrastructure projects under the same conditions. In addition, to create a baseline version of the digital twin of Kyiv's mobility and to calculate the transport effect of each of the forecast scenarios, several assumptions were used, a list of which is presented in more detail in Table 2.

Table 1. Assumptions for the creation of the baseline version of Kyiv's digital mobility twin

Assumption	Value
The base year for mobility data within the analysis area	2019
Projected population in the analysis area for 2030	4,478,738
The projected level of motorisation in the analysis area for 2030	556 vehicles per 1,000 people
The average occupancy of a private car	1.7
Analysis period	Average annual daily period
Cost of 1 hour in 2022, UAH	127.1
Average CO ₂ emissions from a private car, g/km	130

Source: developed by the authors based on Main Department of Statistics of Kyiv (2024), European Environmental Agency (2024)

Within this study, 14 forecast scenarios were formed for transport modelling. These scenarios were created by comparing 7 basic development options for the RN in 2030 in two versions: the first – without off-ramps from the Darnytskyi Bridge to the Dnipro embankment, and the second – with their commissioning. Scenario 1 is the baseline and includes all projects selected based on the results of the expert survey, as well as forecast data on

the socio-economic development of Kyiv in 2030. This scenario serves as a basis for comparison with other options. Scenario 2 is based on the data of Scenario 1 but additionally assumes the commissioning of new exits from the Darnytskyi Bridge to the Dnipro embankment, which could potentially significantly change the transport demand in this part of the RN. Scenarios 1 and 2 are demonstrated in more detail in Figure 9.

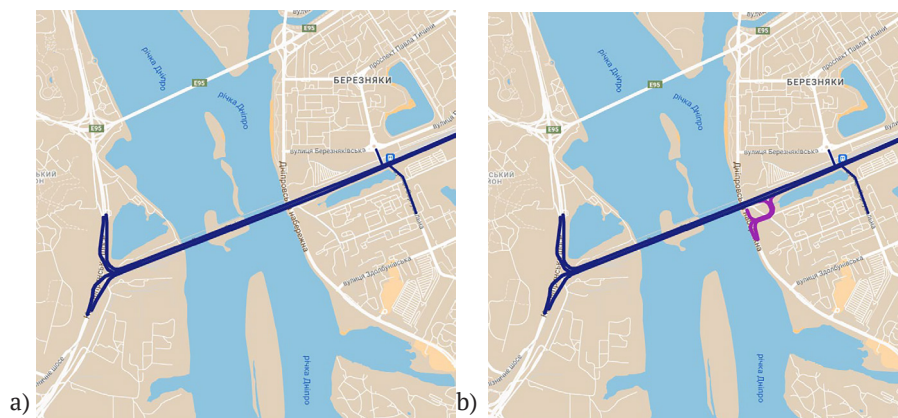


Figure 9. Baseline forecast of transport modelling for the study

Notes: a) – Scenario 1; b) – Scenario 2

Source: developed by the authors

Comparing forecast Scenarios 1 and 2 enables an assessment of the impact of introducing exits for the Darnytskyi Bridge on the overall efficiency of the RN. This comparison provides a clear indication of how new crossings in the RN could enhance the throughput of the RN, reduce delays, and optimise the distribution of traffic flows, which is critical for the city's future development (Medina-Salgado *et al.*, 2022). The following forecast scenarios allow for a detailed evaluation of the impact of introducing exits for the Darnytskyi Bridge, assuming the construction of a new tunnel on the right bank of the Dnipro River. This

helps identify how the integration of new elements into the RN may influence traffic distribution and the overall effectiveness of the RN.

Forecast Scenario 3 is based on the data of forecast Scenario 1 but includes additional changes. Specifically, this scenario assumes the commissioning of a tunnel through Busova hora, which will exit onto the intersection of M. Boichuka and Zaliznychne Shoes streets. In addition, within the framework of this scenario, it is also planned to reorganise traffic on Saperno-Slobidska and Zhylianska streets, which will allow to reduce delays and improve the



connection between the main highways. Forecast Scenario 4 expands the previous one, providing for the simultaneous commissioning of both the tunnel on the right bank and the exits for the Darnytskyi Bridge on the left bank. This allows for an analysis of the combined transport effect of both elements of the RN, which can increase the throughput of the RN, reduce delays, and optimise the distribution

of traffic flows in the city. More details of forecasted Scenarios 3 and 4 are shown in Figure 10.

The following forecast scenarios, presented in Figure 11, are based on the data of forecast Scenario 1 and involve the sequential closure of bridges across the Dnipro River, both without and with the opening of the Darnytskyi Bridge exits, respectively.

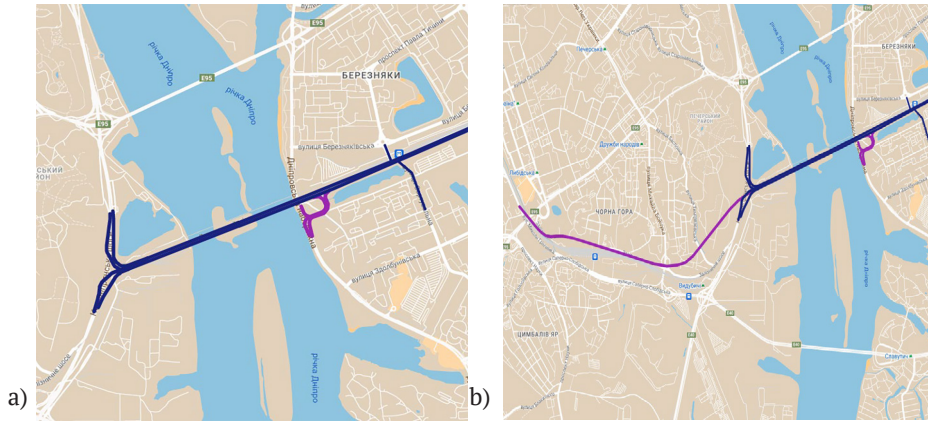


Figure 10. Forecasted transport modelling for the study

Notes: a) – Scenario 1; b) – Scenario 2

Source: developed by the authors



Figure 11 . Forecast Scenarios 5-14 of transport modelling for the study

Notes: a), b) – forecast Scenarios 5 and 10 (closure of the Pivnichnyi Bridge); c), d) – forecast Scenarios 6 and 11 (closure of the Podilskyi Bridge)

Source: developed by the authors



Figure 11. Continued

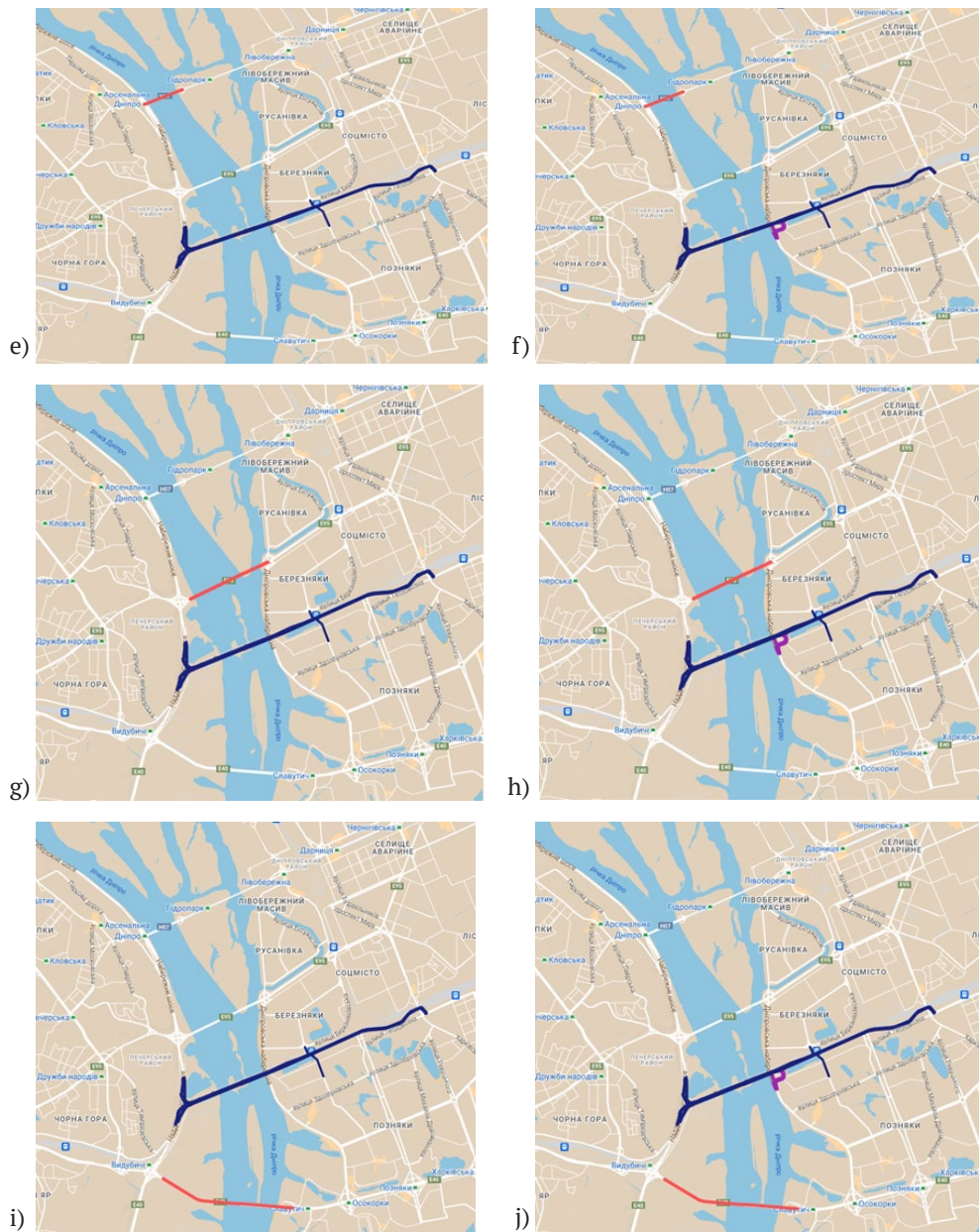


Figure 11 . Forecast Scenarios 5-14 of transport modelling for the study

Notes: e), f) – forecast Scenarios 7 and 12 (closure of the Metro Bridge); g), h) – forecast Scenarios 8 and 13 (closure of the Paton Bridge); i), j) – forecast Scenarios 9 and 14 (closure of the Pivdennyi Bridge)

Source: developed by the authors

Forecast Scenarios 5-14 aim to provide a detailed assessment of the impact of introducing off-ramps for the Darnytskyi Bridge on the resilience of the RN. These forecast scenarios consider various options for the implementation and modernisation of intersections on the RN, allowing for an analysis of how additional exits for the Darnytskyi Bridge can affect the overall stability and reliability of the RN in the event of potential emergencies or repair work. The results of the calculations

carried out in the digital twin of Kyiv's mobility and its suburbs are presented in the form of cartograms illustrating the volume of private transport and the load on the RN. These maps clearly visualise the level of traffic loads as a result of assignment for different forecast scenarios. An example of visualisation for the baseline scenario is shown in Figures 12 and 13. The performance indicators for the RN across all forecasted scenarios are presented in Table 3.

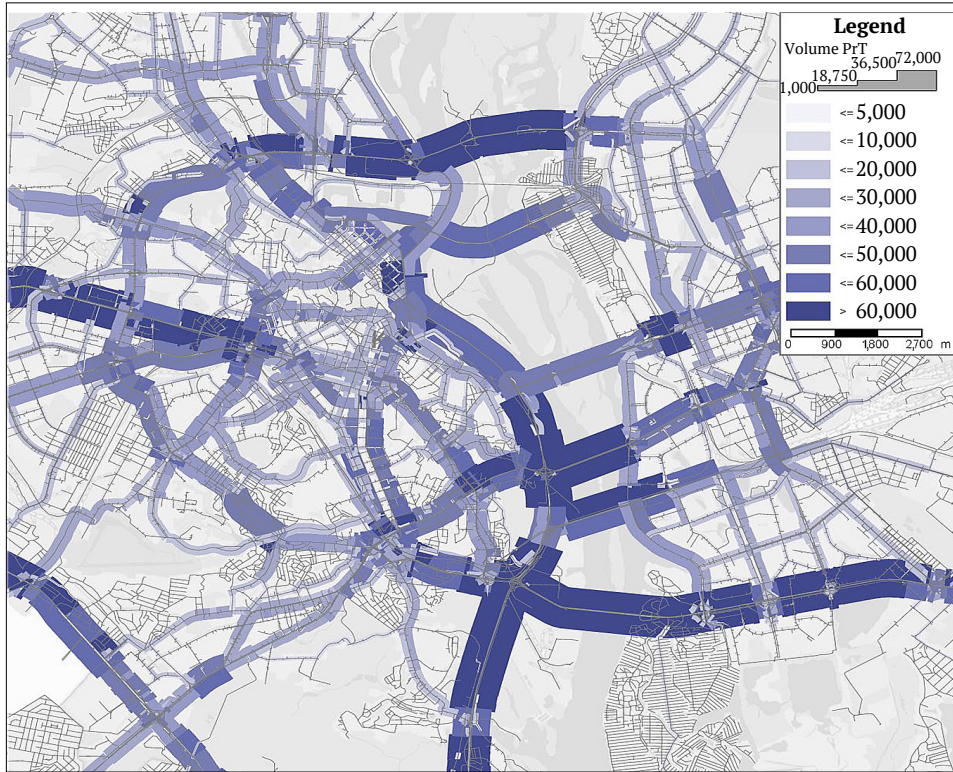


Figure 12. Traffic volume map for the RN of Kyiv city for the base scenario

Source: developed by the authors

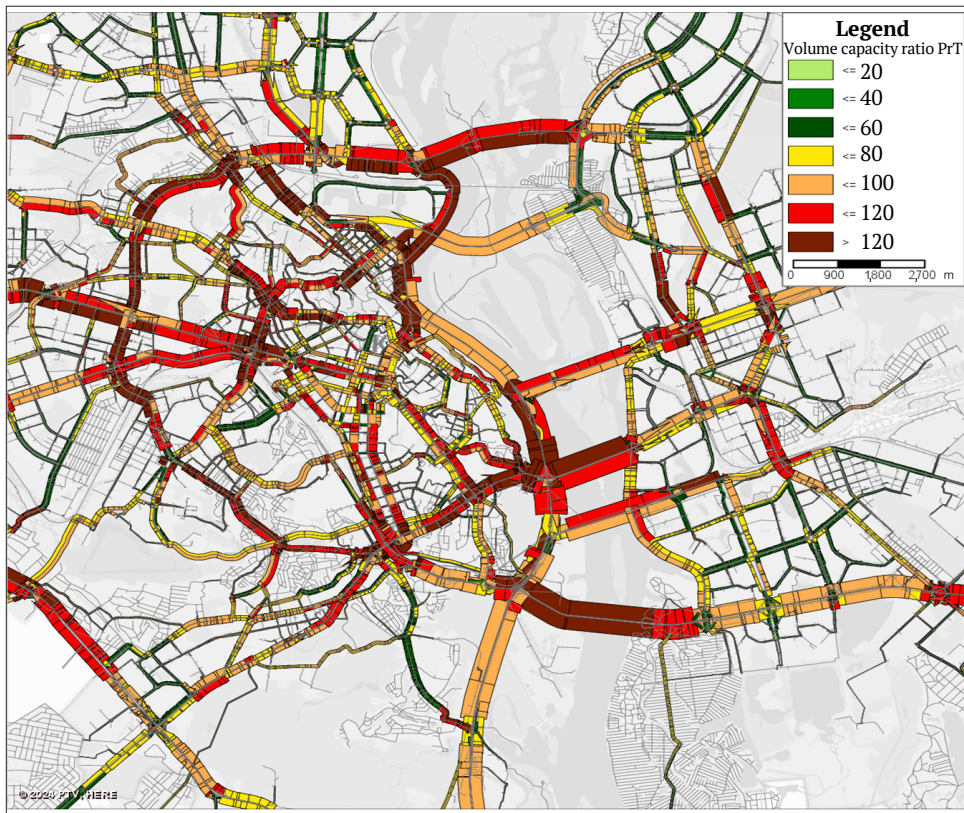


Figure 13. Map of the volume/capacity ratio for the RN of Kyiv city for the base scenario

Source: developed by the authors

**Table 3.** Performance indicators for the RN of Kyiv city for forecasted scenarios

Compared scenarios		Change in daily mileage of private transport, km	Change in travel time for correspondences, hours	Change in average trip duration, sec	Change in annual transport loss, UAH	Change in CO ₂ emissions, kg
1	2	-9,461	-5,642	-7.90	261,741,000	1,514
3	4	-9,924	-7,791	-10.91	361,436,000	1,590
5	10	-5,136	-5,380	-7.53	249,586,270	822
6	11	-8,878	-4,693	-6.57	217,715,310	1,421
7	12	-10,802	-6,775	-9.48	314,302,410	1,730
8	13	-47,979	-25,307	-35.43	1,174,029,690	7,680
9	14	-24,229	-11,130	-15.58	516,337,400	3,880

Source: developed by the authors

The assessment of changes in CO₂ emissions into the city's atmosphere is based on the product of the projected changes in the daily mileage of private transport, which are predicted within the framework of the calculated scenarios, and the average amount of CO₂ emissions from one vehicle per kilometre of its mileage (Liu *et al.*, 2023; Yang *et al.*, 2023). For an accurate calculation of annual transport losses, changes in the time of correspondence realisation and the value of time, determined by the average wage within the study area, are taken into account. For example, in 2022, the average salary in Kyiv was 127.1 UAH/hour

(Minfin, 2022). In addition, it is assumed that on average a passenger car in Ukraine emits about 160 grams of CO₂ per kilometre of mileage (Buberger *et al.*, 2022).

The opening of the off-ramps from the Darnytskyi Bridge to the Dnipro embankment (without considering other changes in the RN) does not directly affect the capacity of the bridge itself. However, it significantly changes the capacity of the approaches to the bridge on the left bank. Changes in transport demand that arise as a result of these changes for all forecast scenarios were compared to the baseline forecast scenario and are presented in Table 4.

Table 4. Changes in traffic intensity in Kyiv compared to the baseline forecast scenario

Compared scenarios		Scenario name	Change in Darnytskyi Bridge load, %	Load of Darnytskyi Bridge off-ramps, %			
			On the left bank	The off-ramp from the bridge	To Berezniaky	To Osokorky	On-ramps to the bridge
1	2	Baseline + offramps	1.8%	42.5%	28.8%	51.9%	9.5%
3	4	Tunnel + offramps	3.3%	57.8%	56.8%	53%	6.6%
Bridge closures							
5	10	Pivnichnyi	1.4%	51%	39.1%	57.8%	7.4%
6	11	Podilskyi	1.5%	49.6%	37.5%	56.7%	7.5%
7	12	Metro	2.5%	54.9%	46.5%	57.7%	6.3%
8	13	Paton	7.7%	96.7%	128%	55.8%	2.9%
9	14	Pivdennyi	7%	65.9%	13.3%	112%	12.2%

Source: developed by the authors

Thus, in the baseline forecast scenario with the addition of off-ramps, the load on the Darnytskyi Bridge increases by 1.8%, indicating a slight increase in transport demand. However, the off-ramps demonstrate significant variation in load. Specifically, the off-ramps from the bridge to Berezniaky and Osokorky have loads of 42.5 and 28.8% respectively, while the on-ramp to the bridge has a load of 9.5%. In the forecast scenario with the tunnel and offramps, the load on the Darnytskyi Bridge increases by 3.3%, and the load on the off-ramps also increases. Specifically, the off-ramps to Berezniaky and Osokorky have loads of 56.8 and 53% respectively, while the on-ramp to the bridge decreases to 6.6%. When considering forecast scenarios with the closure of other bridges, the results show more variations in the impact on the load of the Darnytskyi Bridge. The closure of the Pivnichnyi Bridge leads to an increase in the load on the

Darnytskyi Bridge by 1.4%, while the closure of the Podilskyi and Metro bridges causes an increase of 1.5 and 2.5% respectively. The most significant impact on the load of the Darnytskyi Bridge is observed in the scenario with the closure of the Paton Bridge (7.7%) and the Pivdennyi Bridge (7%).

The load on the off-ramps in the case of the closure of the Paton Bridge and the Pivdennyi Bridge reaches critical levels, in particular, the off-ramps from the Darnytskyi Bridge to Berezniaky and Osokorky have loads of 128 and 112% respectively. This indicates a potential overload of infrastructure in such scenarios, which requires additional measures to improve capacity. Thus, the obtained results provide valuable information for further planning and optimisation of the RN, including the possibility of adapting infrastructure to ensure effective operation under conditions of traffic assignment.





DISCUSSION

Within this study, the use of transport modelling in a digital twin allowed for a detailed assessment of the impact of design solutions on Kyiv's RN. Thanks to the capabilities of transport modelling, it was possible to forecast changes in demand and assignment on the RN and predict their transport effects, impact on the RN's capacity, and environmental aspects. Transport modelling allowed for the evaluation of the transport effect of implementing design solutions, such as the construction of off-ramps for the Darnytskyi Bridge, as well as analysing potential forecast scenarios for the assignment of traffic flows. Moreover, this research helped identify critical points that require additional intervention or correction of design solutions. The use of a digital twin made it possible to evaluate various options for the development and reconstruction of intersections on the RN, providing a scientific basis for making management decisions and increasing the efficiency of transport infrastructure under conditions of uncertainty (Matsiuk *et al.*, 2023). In the study by J. Li *et al.* (2021), transport modelling was also used to evaluate the effectiveness of urban transport system planning, allowing for the consideration of numerous RN development scenarios. The study of D. Alobaydi *et al.* (2020) focused on researching the impact of increasing the capacity of intersections on the RN and changes in traffic flows on the RN's capacity using transport modelling methods, which allowed for achieving a transport effect. In the study by R. Lovelace *et al.* (2020), in turn, attention was paid to analysing the transport effect of introducing new intersections on the RN using transport modelling, focusing on improving mobility and reducing travel time for the population. Thus, this study, compared to the mentioned research, covers a more comprehensive approach, combining transport demand modelling with the analysis of the transport effect, making it more scalable and suitable for broader practical application.

A crucial part of the research was the formation of 14 forecast scenarios, allowing for a detailed study of potential changes in the distribution of traffic flows and the identification of the transport effects of design solutions, particularly the off-ramps for the Darnytskyi Bridge to the Dnipro embankment in Kyiv. The research results showed that the implementation of the off-ramps for the Darnytskyi Bridge would significantly impact the distribution of traffic flows and reduce delays on the RN. A comparison of the forecast Scenario 1 (baseline) with the forecast Scenario 2, which envisages the implementation of the specified design solutions, showed that the new off-ramps could significantly impact delays on the RN and improve its capacity. The introduction of a tunnel through Busova hora and the reorganisation of traffic on major streets within the framework of forecast Scenario 3 may also have a positive impact on reducing delays and improving connections between major highways. Forecast Scenario 4, which combines both of these elements, may have even greater benefits, providing a comprehensive approach to the development of the RN. Forecast Scenarios 5-14 enabled an assessment of how

different implementation options for new intersections on RN can affect the resilience and stability of the RN. In the research of Z. Liu *et al.* (2022), a similar approach to analysis was used, including the creation of various scenarios to assess the dynamic stability of a multimodal public transport network for sustainable transport development. In the study of P.-C. Xu *et al.* (2024), a similar methodology was applied to assess social aspects, creating scenarios to analyse the impact of new transport solutions on public transport accessibility. In the article of W. Yue *et al.* (2021), transport modelling was used to study traffic efficiency, developing scenarios to assess the impact of new infrastructure solutions on highway congestion levels. However, this research, in comparison to the mentioned studies, is unique in that it is focused on the specific conditions of the city of Kyiv and includes a comprehensive approach to transport modelling of traffic flows, allowing for obtaining more detailed and specific information about the impact of specific design solutions on the capital's RN.

The results of the analysis of various forecast scenarios, presented in this study, have provided an opportunity to comprehensively assess the impact of different RN development options on key performance indicators. Forecast scenarios that included new off-ramps for the Darnytskyi Bridge, as well as other infrastructure changes, showed a significant reduction in daily vehicle kilometres travelled, indicating a decrease in delays and improved conditions for drivers. In particular, forecast Scenario 13, which envisaged the greatest number of changes, demonstrated the most significant results in all key indicators: daily vehicle kilometres travelled decreased by 47,979 km, correspondence completion time decreased by 25,307 hours, and the average trip duration decreased by 35.43 seconds. This was accompanied by a significant reduction in annual transport losses and CO₂ emissions, confirming the high efficiency of the design solutions of this forecast scenario. Forecast Scenarios 2 and 4 also showed a significant transport effect, reducing daily vehicle kilometres travelled by 9,461 and 9,924 km, respectively, as well as reducing correspondence completion time and trip duration. Although forecast Scenario 4 showed the most significant positive effect in all aspects, forecast Scenario 2 also demonstrated a significant reduction in annual transport losses and CO₂ emissions. Other forecast scenarios, such as 10, 11, 12, and 14, also showed positive results, albeit less significant compared to the most comprehensive scenarios. While they still provided reductions in transport costs and improvements in environmental indicators, the differences compared to the most effective scenarios were smaller. In the study of X. Xiao & H. Duan (2020), a comprehensive approach to transport modelling of traffic flows was also used, including an assessment of the effectiveness of implementing new intersections on the RN and changes in urban infrastructure. In the article of L.M. Hilty & R. Meyer (1996), in turn, the impact of different transport infrastructure development scenarios on environmental indicators, in particular, pollutant emissions, was studied. However, compared



to the mentioned studies, this research is distinguished by the fact that it includes a detailed assessment of the impact not only of infrastructure changes but also of scenarios that take into account the real socio-economic conditions of the city, as well as their long-term consequences for the RN.

Additionally, this study provided detailed results on the impact of various forecast scenarios on the traffic load of the Darnytskyi Bridge and its off-ramps. Forecast Scenario 2 showed a moderate impact on the traffic load of the Darnytskyi Bridge and its off-ramps. The introduction of new off-ramps led to a significant increase in the load on offramps to the left bank (42.5%) and to Berezhniaky (28.8%), as well as a significant increase in the capacity of the bridge entrance (up to 9.5%). This forecast scenario provided a reduction in the load on the main traffic flows but did not significantly change the overall traffic load picture. Forecast Scenario 4 demonstrated greater changes in the traffic load of the RN. The introduction of the tunnel along with the off-ramps led to a significant increase in the load on the off-ramps, in particular in the directions to Berezhniaky (56.8%) and Osokorky (53%). Forecast Scenarios 5-12 with bridge closures showed varying levels of impact on the traffic load of the Darnytskyi Bridge. For example, forecast Scenario 10 (Pivnichnyi Bridge closed) and forecast Scenario 11 (Podilskyi Bridge closed) demonstrated a moderate increase in the load on the off-ramps up to 7.4 and 7.5%, respectively, while forecast Scenario 12 (Metro Bridge closed) showed a high load on the new off-ramps up to 54.9%. Forecast Scenarios 13 (Paton Bridge closed) and 14 (Pivdennyi Bridge closed) showed a significant increase in traffic load, especially on the off-ramps, up to 128 and 65.9%, respectively. Overall, the analysis showed that forecast scenarios with bridge closures can create additional load on other sections of the RN, while forecast scenarios with new off-ramps and tunnels can more effectively distribute traffic flows and reduce the load on some intersections of the RN. In the study by P. Bindzar *et al.* (2021), a transport modelling method was also used to assess the impact of new intersections on the load on highways. The research of M.Z. Serdar *et al.* (2022) aimed to assess the impact of various infrastructure reconstruction scenarios on the overall capacity of the RN. In the article by R. Suryadithia *et al.* (2021), in turn, the possibility of integrating new transport technologies that improve the efficiency of the transport system was considered. However, the results of this study, compared to the results of the mentioned works, differ in that it offers more accurate and specific data on the impact of the proposed design solutions on traffic flows and socio-economic aspects in the conditions of the Darnytskyi Bridge in Kyiv, which allows for a clearer understanding of the potential benefits and risks of implementing the design solutions.

Such studies are crucial for the effective planning and development of the RN. They allow for a detailed assessment of the impact of various design solutions on traffic flows, socio-economic indicators, and environmental aspects. The creation of digital twins and the

use of transport modelling methods enables accurate forecasting of the consequences of introducing new elements to the RN, helps to optimise costs and improves the efficiency of the transport system. The results of such studies also assist in the formation of strategies for sustainable development, which is critical for ensuring a high quality of life in megacities.

CONCLUSIONS

Through the use of transport modelling, this study conducted a detailed analysis of the impact of design solutions on the functioning of Kyiv's RN. This allowed for the consideration of several factors, such as the intensity and composition of traffic flow, design solutions, and traffic organisation. Based on the obtained data, quantitative and qualitative indicators of the RN's performance were formed, including the intensity of movement of various participants, time costs, distance travelled, and environmental indicators.

The evaluation of design solutions, particularly the off-ramps for the Darnytskyi Bridge, showed that the implementation of these design solutions will lead to an increase in traffic demand on the bridge towards the left bank by 1.8%. This is also accompanied by a reduction in transport losses, which will amount to 261.7 million UAH per year, and a decrease in CO₂ emissions by 1,500 kg per day. These results confirm that the implementation of design solutions with off-ramps can positively impact the transport situation in the city, specifically by reducing costs and improving environmental indicators, thus creating a positive transport effect. The study also established that the additional commissioning of a tunnel on the right bank to the Darnytskyi Bridge, along with the completion of off-ramps from the Dnipro embankment, has an even greater impact on the performance indicators of the RN. In this scenario, the demand for the bridge towards the left bank increases by 3.3%, indicating a higher efficiency of the implemented solutions. The annual savings in transport costs in this case will amount to over 361.4 million UAH, and the reduction in CO₂ emissions will reach 1,590 kg per day. This demonstrates a better transport effect for the RN.

Overall, the conducted research confirms that the implementation of the proposed design solutions can significantly improve the efficiency of Kyiv's RN, particularly in terms of reducing transport losses and environmental impacts, which underscores the importance of planning and implementing design solutions considering all possible impacts on the city. It is important to note that the approach applied to the evaluation of design solutions for urban RNs is focused on indicators obtained from a digital twin exclusively within the framework of transport modelling, which may affect the accuracy and detail of the assessment. For further research in this direction, it should be considered to integrate detailed transport modelling, which allows for a more detailed study of the impact of design solutions at the level of individual elements of the RN, which will enable a more accurate assessment of the transport effect.





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CONFLICT OF INTEREST

None.

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Аналіз техніко-економічної ефективності добудови з'їздів/заїздів з Дніпровської набережної на Дарницький міст у м. Києві

Анотація. Дане дослідження було спрямоване на оцінку ефективності проєктних рішень для розвитку транспортної інфраструктури Києва на основі транспортного моделювання та аналізу можливих соціально-економічних ефектів. Для цього було використано чотирикроковий алгоритм моделювання транспортного попиту, що базується на даних соціологічних опитувань, планів територій та прогнозних показниках на 2030 рік. Результати проведеного дослідження показали суттєві зміни у функціонуванні транспортної мережі Києва в результаті впровадження запропонованих проєктних рішень. Завдяки застосуванню транспортного моделювання вдалося оцінити кількісні показники, такі як інтенсивність транспортних потоків на основних магістралях, а також якісні зміни, такі як зменшення заторів, скорочення часу поїздки та економію витрат. Одним із ключових результатів стало те, що відкриття нових з'їздів та в'їздів на Дарницький міст на лівому березі сприяє незначному зростанню пропускної здатності мосту, однак найбільший ефект був помітний на під'їздах до нього. Завдяки додатковим підходам зросла інтенсивність руху, що свідчить про поліпшення транспортної доступності для водіїв, які користуються цим транспортним вузлом. Також важливими були результати, пов'язані з екологічними показниками. Внаслідок зменшення заторів було досягнуто зниження викидів CO₂ у повітря, що є значним внеском у поліпшення екологічної ситуації в місті. Щодо економічної ефективності, результати продемонстрували значну економію транспортних витрат, підтверджуючи, що впровадження запропонованих заходів має позитивний вплив на транспортну інфраструктуру, а також зменшуючи фінансові втрати, пов'язані з поїздками. Таким чином, результати дослідження підтвердили, що запропоновані проєктні рішення мають позитивний вплив на розвиток транспортної мережі, підвищуючи пропускну здатність та зменшуючи негативний вплив на довкілля, що відкриває можливості для створення більш ефективної транспортної системи, яка відповідає вимогам сталого розвитку та підвищує загальну якість життя мешканців Києва

Ключові слова: вулично-дорожня мережа; транспортне моделювання; пропускна здатність; завантаженість вузлів; сценарії розвитку інфраструктури; соціальні наслідки