TECHNOLOGY, CREATIVITY, IMPLEMENTATION

EFFICIENCY EVALUATION OF INTERSECTIONS AND INTERCHANGES OF THE URBAN STREET NETWORK IN UKRAINE USING TRANSPORT MODELING

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Summary

The article examines the current problems of transport modeling using to evaluate the efficiency of intersections and interchanges in a saturated by traffic flows urban street network in conditions of limited resources. It was found out that current urban planning documentation in Ukraine is oriented towards working with unsaturated by traffic flows urban street network, and the main efficiency indicator now is the capacity. It has been proven that the efficiency of the urban street network depends on the efficiency of its components – intersections, interchanges, and links. Due to the permanent redistribution of the traffic flows, intersections and interchanges have a greater impact on the urban street network efficiency. In turn, the efficiency of the intersections and interchanges is determined by their project solutions. It was concluded that it is possible to evaluate the efficiency of the intersections and interchanges on the urban street network using the total delay time for cars. Accordingly, the criterion for evaluating the efficiency of the intersections and interchanges is the reduction of this indicator. The computer experiment showed that the reduction of delay time for cars at intersections and interchanges in saturated by traffic flows urban street networks does not necessarily mean a decrease in the total delay time for cars. At the same time, a decrease in the total delay time for cars may stimulate demand for additional car trips, which will lead to an increase in the total delay time for cars due to an increase in the number of cars in the urban street network. It is justified that the choice of efficiency criteria should be approached responsibly and carefully especially in conditions of limited resources.

Key words: urban street network, intersection, interchange, project solution, efficiency criteria, efficiency evaluation, delay time for cars, transport modeling.

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1. Introduction

In the cities of Ukraine, there are a number of transport problems caused by urban planning aspects, in particular, the imbalance of settlement and jobs; and transport policy, for example, softness of parking policy, insufficient attention to the development of urban passenger transport (PT), etc. This is reflected in the constant growth of demand for car trips.

Most of the transport infrastructure or so-called transport supply in Ukraine, was built in the 60–80s of the last century and is designed for lower loads in terms of the number of vehicles that use it daily.

Domestic and foreign scientists dealt with the problems of efficiency evaluation of intersections and interchanges on the urban street network using transport modeling. For Ukraine in particular this are Mykola Domin, Mykola Osetrin, Volodymyr Tarasiuk, Valerii Huk, Petro Horbachov, Roman Zubachyk, Olena Chernyshova, Ihor Mohyla, Yevhen Liubyi, Mykhailo Krystopchuk and others. However, due to the circumstances in which Ukraine currently finds itself, related to the attack on it by the Russian Federation, this problem remains is gaining momentum, so this research is relevant and scientifically expedient.

The purpose of the article is to suggest a basic approach to efficiency evaluation of intersections and interchanges on the urban street network in Ukraine in conditions of limited resources and uncertainty using transport modeling.

2. Transport problems of Ukrainian cities

In the cities of Ukraine, due to excessive loads from vehicles, violations of infrastructure maintenance regulations, including different transport facilities, as well as exceeding the regulatory time of their operation, transport infrastructure facilities fail, or their capacity is artificially limited for preventing this (Fig. 1).

Fig. 1. Restriction of traffic on the two edge lanes of the Paton Bridge in Kyiv due to its poor technical condition

Source: tsn.ua

Now the trend is only accelerating. For example, according to the report of the government commission on the assessment of the condition of bridges, almost 1/4 of all bridge structures in Ukraine are in a critical condition – they are inoperable or only partially operable *(Mininfrastruktury, 2023)*. For example, out of 5 main bridges for car traffic over the Dnipro River in Kyiv, 2 bridges (the Metro Bridge and the Paton Bridge) are in an inoperable condition. However, despite this, hundreds of thousands of cars travel through it every day. One of the structural units conditions of the transport facility in the capital of Ukraine can be assessed in Fig. 2.

Fig. 2. Layering of the upper belt of the main beam of one of the transport facilities in Kyiv due to corrosion

Source: State Agency for Reconstruction and Development of Infrastructure of Ukraine

The increase in transport demand for car trips against the background of the preservation or even reduction of transport supply due to insufficient development, restriction or even destruction of transport facilities causes the traffic saturation of urban street network in Ukrainian cities. Saturation means a certain value of traffic flow density and corresponds to level of service (*Highway Capacity Manual 2010: Transportation Research Board of the National Academy, 2010*) from D to F, when the traffic flow becomes unstable, fills all available space, and the speed varies spontaneously and mostly unpredictably.

Based on the definition of level of service D, E, F, it follows that the saturation of urban street network with traffic flows carries the risk of increasing the delay time for cars, which is one of the main consequences of Ukraine's urban planning problems. This fact is confirmed by the city of Kyiv, which in the TomTom Traffic Index ranking for 2021 ranked 3rd in the number of traffic congestion among 404 cities in the world with the delay for cars of 56% *(TomTom Traffic Index, 2021)*. Delay is expressed in % means the number of the average daily ratio of delay time for cars to the total travel time.

Therefore, to change the negative trend and ensure the sustainability of the urban street network of the cities in Ukraine, it is necessary to use modern approaches to assessing the effectiveness of the urban street network and its components. That is to determine the ratio between the achieved result and the used resources (*ISO 9000:2015-11, 2015*) at all stages of planning of its development.

3. Intersections and interchanges as a main area in need of improvements

Intersections and interchanges together with links are the components of the urban street network system. Traffic flow is redistributed at intersections and interchanges, and it's delivered to the next intersection or interchange by the links. Since, due to the redistribution of traffic flow at intersections and interchanges, their capacity mostly lower than at links, the consequences of transport problems are usually concentrated at intersections and interchanges in saturated by traffic flows urban street network: delay time for cars increased, and as a result, the deterioration of road safety, worsening of ecology, etc. Therefore, the efficiency of the urban street network, first, depends on the efficiency of the intersections and interchanges.

Typical modern situation for the city of Kyiv: the saturated traffic flow at one of the interchanges on the urban street network can be visually assessed in Fig. 3.

Fig. 3. An example of an interchange saturated with traffic flows on the urban street network: the interchange of Beresteyskyi Ave., st. Hetman and st. Oleksandr Dovzhenko in Kyiv

Source: tsn.ua

4. Standard Ukrainian approach of a transport problems solving

According to the Law of Ukraine "On the Regulation of Urban Planning" (*zakon.rada.gov.ua/laws/show/3038-17, 2011*), a multi-level approach to planning, including planning for the development of transport infrastructure, was established in Ukraine.

For the entire urban street network, the general principles of its development are established at the level of development and approval of the Community Development Strategy (*zakon.rada.gov.ua/laws/show/156-19, 2015*), which are then reflected in the Master Plan of the settlement and its supplementary document on transport – the Integrated Transport Scheme (*DBN B.1.1-15:2012, 2012*). At this level, in relation to the entire urban street network, intersections and interchanges on it, the categories of highways should be chosen, the types of intersections and interchanges, traffic organization schemes should be established, and the territory for them should be reserved.

The main directions of the Master Plan and the Integrated Transport Scheme was to increase the capacity of urban street network in the city of Kyiv, planning the construction of additional transport facilities. Fig. 4 shows dozens of new planned transport facilities at intersections and interchanges on the urban street network in Kyiv.

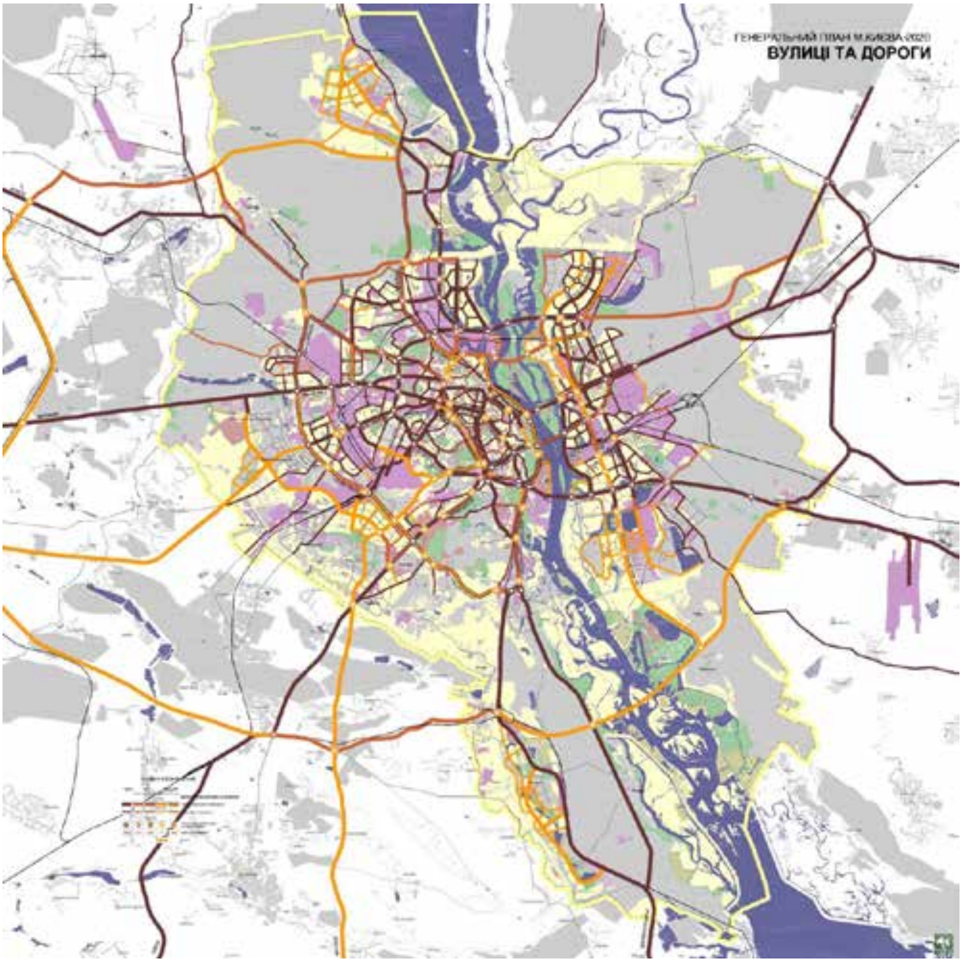

Fig. 4. Master Plan of the city of Kyiv until 2020 with the development of urban street network

Source: http://kyiv-landuse.com/content/genplan-kieva-do-2020-r-diyuchiy

Obviously, this was a response to growing motorization and its consequences due to increasing delay time for cars, deterioration of road safety and ecology, first, at intersections and interchanges on the urban street network. According to the developers of these documents, increasing the capacity of the urban street network by arranging dozens of additional interchanges with flyovers should increase the efficiency of its work.

It is likely that it would have happened, but there were 2 nuances:

1) the increased capacity of urban street network would eventually cause additional trips by cars, once again demonstrating the induced demand *(Horem, 2011)*;

2) in the cities of Ukraine, including its capital, there were and are extremely limited resources for the entire transport infrastructure, which are not enough even to maintain and keep the existing facilities on the urban street network in proper condition.

As a result, instead of dozens of new transport facilities on the urban street network, only a few of them were built in Kyiv over the past years, which obviously did not solve the main consequence of the capital's transport problems – increasing delay time for cars.

The next level of urban planning in Ukraine after the strategic, which significantly affects project solutions of intersections and interchanges, is the level at which issues of the direct operation of intersections and interchanges on the urban street network are considered. It begins with the preparation of technical terms of reference for conducting open tenders on the national tender procurement system ProZorro for project solutions on new construction, reconstruction, or repair of intersections and interchanges on the urban street network. At this level, it is necessary to define the tasks for the development of project solutions for intersections and interchanges on the urban street network.

Project solutions for intersections and interchanges on the urban street network is a set of proposals for organizing the redistribution of traffic flow at the intersection or interchange. The requirements for them are established by current regulatory documents and are provided by engineering assessment based on calculations and include the determination of spatial parameters of their geometry, elements of engineering arrangement, etc. However, although the Ukrainian State Building Regulations (abbreviated as DBN) have established a list of requirements for intersections and interchanges on the urban street network, which could be used to obtain efficiency criteria for comparing different project solutions with each other, these requirements do not always have a numerical value or recommendations for its establishment. This somewhat complicates the process of proving the compliance of project solution of intersection or interchange with exact requirement of the DBN.

It can be said that the step of preparing the terms of reference for design make a link between the strategic and tactical level of urban planning. This is followed by the standard for Ukraine stages of transport facilities design: feasibility study, Project stage, Working documentation stage. For simpler intersections on the urban street network, which have a lower so-called class of consequences and do not require a three-stage design process, a change in the project solutions to improve the efficiency could be planned at the stage of developing the Project of the traffic organization scheme.

The conducted analysis of the efficiency evaluation of intersections and interchanges on the urban street network showed that the standard urban planning sequence for Ukraine can work effectively regarding the selection of project solutions unsaturated by traffic flows. So, it means with the level of service (LOS) up to C.

To be able to adopt effective project solutions, according to the Ukrainian DBN, means of transport modeling must be used. In DBN (*DBN B.2.2-12:2019, 2019*), (*DBN V.2.3-5:2018, 2018*) the requirements for the use of this tool are regulated, but the principles, methods, requirements for initial data, structures, and quality checks of transport models for efficiency evaluating of intersections and interchanges on the urban street network are not given.

All the above-mentioned problems need to be solved, since the adoption of ineffective project solutions regarding intersections and interchanges on the urban street network not only increases the consequences of transport problems in the cities of Ukraine, but also poses a threat to the safety of people in the conditions of armed aggression from the Russian Federation.

It is important to establish an efficiency indicator for intersections and interchanges on the urban street network to compare their project solutions and determine its impact on it.

5. Determination of the efficiency indicator

Intersections and interchanges on the urban street network, depending on the project solutions, have certain initial indicators. Project solutions determine the base speed V_0 for a single vehicle, the base speed V_0 and the distance determined by the route *R* of the vehicle through the intersection or and interchange, determine the base time t_0.

For one vehicle trip on the scale of the entire urban street network, the base intersection or interchange time t_0 is only a part of the total base time T_0 for the vehicle trip between the starting point of the trip and the point of its termination in a conditionally empty network. Base time t_0 exists separately for intersections and interchanges and for links.

Project solutions of intersections and interchanges are characterized by a certain ability to provide capacity for individual maneuvers *M*. The problem is that in urban street network saturated with traffic flows, the value of the intersection or interchange capacity will depend on both the project solution and the volume of traffic, the volume of maneuvers and the composition of the traffic flow. That is why, in the urban street network saturated with traffic flows, the intersections and interchanges capacity cannot be considered the main criterion for the efficiency of its work as a dependent and unstable quantity.

Consequently, cars are constantly being redistributed (changing the routes *R*) in the urban street network saturated with traffic flows. The volume of traffic interacts with the capacity, and instead of indicators of the basic speed V_0 and basic time t_0, the indicators of the active speed V_{act} and, as a result, the active time t_{act} is formed.

In this case, the delay time for cars at the intersection or interchange on the urban street network t_{delay} can be determined by the formula:

$$t_{delay} = t_{act} - t_0 \qquad (1)$$

A change in the project solutions at intersections and interchanges on the urban street network should lead to a change in the speed V_0 and time t_0 first, and then, as a result of the redistribution of the traffic flow due to the saturation of the urban street network, the active speed V_{act} and the active time takt change and, accordingly, the delay time for cars t_{delay} will be changed too.

The total delay time for cars T_{delay} for the entire urban street network can be found using a similar formula:

$$T_{delay} = T_{act} - T_0 \qquad (2)$$

It is likely that due to the redistribution of the traffic flow to find equilibrium, the increase in the delay time for cars t_{delay} due to the change of project solution does not necessarily mean an increase in the total delay time for cars T_{delay} for the entire urban street network. However, this hypothesis needs to be tested, which can be done using transport modeling.

6. Transport modeling for the efficiency evaluation

Transport modeling for efficiency evaluating of intersections and interchanges on the urban street network on the example of the transport model of the city of Kyiv and its suburban area (*Tselovalnyk, 2015: 22.1–22.7*) is a combination of special software PTV Visum and databases on the mobility of citizens, which are established using sociological surveys of mobility, or Big Data, dependencies, are calculated according to mathematical formulas and reflect the load on the components of the urban street network.

The transport model of the city of Kyiv and its suburban area is multimodal and consists of two main sub models – the model of transport supply and the model of transport demand.

The model of transport supply is a tool that reproduces the urban street network and various parameters of the transport infrastructure that shape the possibilities and volumes of public transport services. It helps to analyze and forecast transport accessibility, capacity, and other important characteristics, but its main function is to create a realistic representation of the city's transport infrastructure for the further distribution of transport demand (Fig. 5).

Fig. 5. Transport supply model of the Transport model of the city of Kyiv and its suburban area

A transport demand model is an analysis tool that helps predict and understand how people will use the transport supply and which transport services they will prefer – cars or public transport. It considers various factors that influence the mode choice of trips by citizens.

As a result of the interaction of transport supply and transport demand models, OD-matrices are calculated according to the defined algorithm of the classic 4-step transport model, which are further redistributed to the urban street and the public transport networks. The result of this is the indicators of traffic volumes, passenger flow on public transport and indicators of travel time, i.e., the total base time T_0, the total active time T_{act}, which makes it possible to establish the total delay time for cars T_{delay}.

After the transport modeling of the entire urban street network to evaluate the efficiency of intersections and interchanges, and compare its project solutions, it is advisable to make a traffic simulation on this intersection or interchange. It is possible to use the indicators obtained because of traffic simulation to set the base time t_0 of the intersection or interchange and the active time t_{act}, which allows to set the delay time for cars t_{delay}.

To test the assumptions and hypotheses formulated above, it is necessary to conduct a computer experiment.

7. The computer experiment

Let's choose one of the intersections on the urban street network in Kyiv. This is a complex regulated intersection saturated with traffic flows (Fig. 6).

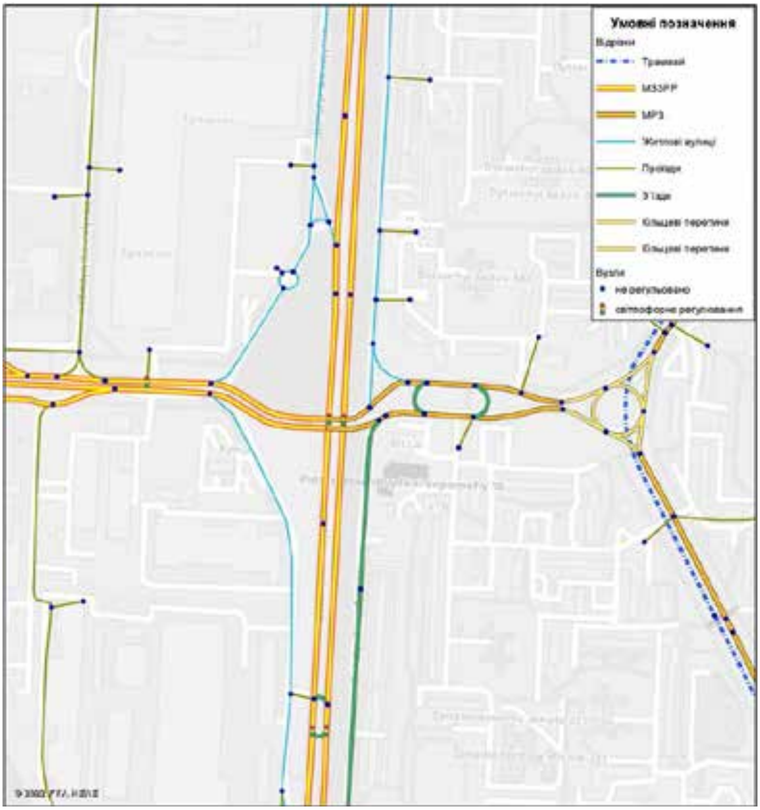

Fig. 6. A fragment of the urban street network of Kyiv with the investigated intersection

It is believed that increasing the capacity of this intersection can improve the situation on the urban street network in Kyiv. Project solutions to increase the capacity of this intersection is to create the interchange with a semi-cloverleaf or with a roundabout (Fig. 7).

Fig. 7. Project solutions for the intersection to establish an interchange: semi-"clover leaf" (left) and the roundabout with flyover (right)

Traffic simulation performed in PTV Vissim software in accordance with the requirements (*DBN B.2.2-12:2019, 2019*), (*DBN V.2.3-5:2018, 2018*), (*MR – B.2.2-37641918-928:2022, 2022*) established that within the intersection under the semi-cloverleaf project solution, the delay time for cars t_{delay} decreases from **261.47 seconds** (corresponds to LOS F) to **14.53 seconds** per vehicle (corresponds to LOS A), and for the project solution roundabout – up to **8.68 seconds** per vehicle (corresponds to LOS A).

However, transport modeling performed in the Transport model of the city of Kyiv and its suburban area, also done in accordance with the requirements (*DBN B.2.2-12:2019, 2019*), (*DBN V.2.3-5:2018, 2018*), (*MR – B.2.2-37641918-928:2022, 2022*), showed that total delay time for cars T_{delay} for the urban street network did not change: Tact for urban street network remained **1080900 hours** for basic situation without interchange and for both project solutions.

That is, money spent on increasing the capacity of one of the intersections can really reduce the delay time for cars t_{delay} locally at this intersection. However, transport modeling shows that the entire urban street network will not start to work more efficiently from the point of view of the criterion for reducing the total delay time for cars T_{delay}.

8. Conclusions

1. Urban planning documentation in Ukraine is focused on working with unsaturated traffic flows on urban street network in conditions of LOS A – C, and the main indicator of efficiency is the capacity.

2. Efficiency i.e., the ratio between the achieved result and the used resources, in relation to urban street network depends on the efficiency of its components – intersections, interchanges and links.

3. Due to the redistribution of traffic flow, intersections and interchanges have a greater impact on the efficiency of urban street network operation. In turn, the efficiency of the

intersections and interchanges is determined by its project solutions, which is an engineering method of solving the consequences of transport problems of modern cities.

4. The indicator capable of evaluating the efficiency of the intersections and interchanges on the urban street network is the total delay time for cars T_{delay}, and the criterion for evaluating the efficiency of the efficiency of the intersections depending on the goals of transport planning is, accordingly, the reduction of total delay time for cars T_{delay} for the entire urban street network.

5. Transport modeling makes it possible to count the delay time for cars t_{delay} at intersections and interchanges, and the total delay time for cars T_{delay} on urban street network for comparing different project solutions. This requires a certain configuration of initial data, formulas for calculation, sequence of calculations and regulations for checking the quality of the transport models, which requires further integration into the Ukrainian DBN.

6. The computer experiment showed that the reduction of the delay time for cars t_{delay} at the intersections and interchanges in the urban street network saturated with traffic flows does not necessarily mean the reduction of the total delay time for cars T_{delay}.

7. At the same time, a decrease in the total delay time for cars T_{delay} can lead to a more frequent choice of cars for trips by users over other modes of mobility, which will inevitably lead to an increase in the total delay time for cars T_{delay} due to an increase in the number of cars on urban street network. This is called induced demand. Therefore, the choice of efficiency criteria and determination of their weight should be approached responsibly and carefully, especially in conditions of limited resources and uncertainty.

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