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Formation of an Optimal Road Network in Large Cities and Agglomerations

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ABSTRACT: Poor development of the urban transport network, its low capacity and inaptitude of the topology, formed in Soviet Russia, do not fully meet the needs of the economic development of the urban area in modern realities and significantly constraint the economic development of most cities in the country. The poor condition of the Russian road network and non-optimal organization of traffic in cities are one of the main reasons of a huge (by the standards of developed countries) number of road accidents claiming a significant amount of human lives each year and causing considerable harm to economic activity. Currently, in order to contribute to further development of most cities in Russia, it is necessary to resolve the issue of the urban transport systems and their functioning in conditions of a continuously growing traffic flow. Accordingly, technical, economic and organizational solutions are required to optimize existing opportunities of providing infrastructural assistance to the socio-economic development of the city. This research is devoted to theoretical and methodological analysis of these opportunities.

Keywords: City; Economic Development; Traffic Flow; Transport System; Restrictions.

I. INTRODUCTION

Numerous studies and the author's observations allow concluding that the main "hubs" of the urban transport network problems are crossroads and intersections.

The functioning of the urban transport network requires socio-ecological-economic and technical-technological efficiency. This requirement is to be applied to all parts of the urban transport network, including crossroads and intersections [1-4].

The presence of road junctions and intersections is an integral part of the transport system of any city and almost any transport network (with the exception of pipeline transport networks). Nevertheless, the following problems should be solved:

1. Defining the function of junctions' location;
2. The number of levels in a junction;
3. The presence of a turn to the left in the middle of the road/highway and the optimal mode of its operation.

The formal finding of answers to the questions posed will depend essentially on the specific conditions.

In order to develop proposals for optimizing the organization of traffic in this case, it is necessary to calculate the probability of a traffic jam at each intersection organization graph and build an algorithm for making decisions about optimizing urban transport network – an algorithm that depends on this probability and the importance of this junction for the entire transport network of the city (at least for roads and streets intended for road transport) and takes into account the distribution of the main traffic flows in the city in the context of cargo and passenger components [7-10].

II. METHODS

The synergy of the cumulative actions of the regulator of the urban transport system development as a managing agent can be expressed by the classical function of describing managed systems. In our case it will be:

$$U = \{u_1, u_2, \dots, u_n\} \quad (1)$$

where $u_1, u_2, \dots, u_n$ stand for constituent elements of the transport policy of the city, as well as targeted elements of the transport system development.

Next, we need to develop an information-mathematical model for managing the transport development of the territory through the development of its differential infrastructure:

$$y = y(x, \dot{x}, \ddot{x}, t) \quad (2)$$

Accordingly, in our case, based on the provisions of the control theory, the model will look like this:

$$Y = f(t, x, U) \quad (3)$$

$$x(t_0) = x_0 \quad (4)$$

where t is time parameter of the controlled system;

x_0 – initial vector characterizing the initial dynamics of socio-economic system of a large city;

U – vector of controlling actions.

The criterion of the control action effectiveness is the total change in the basic indicator of the state of the system by an amount exceeding the total cost of resources:

$$\Delta \text{ GRP} >> \sum_{i=1}^{n} R_i \quad (5)$$

where R_i is the cost of the i-th kind of resources.

Thus, analyzing an effective management system for the transport development of a large city from the point of view of resource expenditure, we conclude that it should be pronounced super additive – a positive effect should substantially exceed the expenditure of resources for achieving this effect [14, 15].

Accordingly, the potential for achieving the effectiveness of the entire urban transport system consists of the effectiveness of private projects aimed at forming an optimal road network in large cities and agglomerations.

In accordance with the provisions of functional cost analysis and project management, the final effectiveness of a project depends primarily on the initial parameters of the project and the mechanism of coordination with all interested parties [16, 17].

III. RESULTS AND DISCUSSION

Considering the procedure for coordinating the project parameters with the city leaders, government of a region or a number of neighboring cities, we assume that the authorities involved in the procedure are guided by the interests of the national economic benefits and personal gain.

Getting personal gain is considered in the following aspects:

1. Formation of a positive image of regional or territorial authority representatives of the electorate of the relevant territory. At the same time, the positive effect in monetary terms should substantially exceed the costs of the formation of this effect (in the ideal case, there are no separate costs for the image within the framework of the project).
2. Issues related to the solution of the problem of urban development and the transfer of land from a category for construction to a category on which it is possible to build transport infrastructure facilities.
3. A question also arises with the owners of the land plots on which future transport infrastructure facilities should be located. To simplify the model, let us suppose that the owner of the land is interested in the immediate financial result that the infrastructure project, the so-called "rent", will bring to him. Accordingly, in this case, the condition for the coordination of interests is the level of "rent" not exceeding the value critical for the project, on the one hand, and, on the other hand, not lower than the acceptable "rent" for the owner of the land or the objects located on it – that makes the project implementation possible.

Formally, it will look like this:

Option 1: "Rent" is associated with the revenue stream generated by the infrastructure project:

$$C_r = EA_{pr} \times N_{r1} \quad (6)$$

Option 2: "Rent" is related to the amount of budget resources allocated for the implementation or budget support of the project:

$$C_r = ERb_{pr} \times N_{r2} \quad (7)$$

Option 3: "Rent" is associated with both options proposed above:

$$C_r = EA_{pr} \times N_{r1} + ERb_{pr} \times N_{r2} \quad (8)$$

where C_r is the costs associated with the rental aspects of the project;

EA_{pr} – revenue stream generated by the infrastructure project;

N_{r1} – the rate of deduction of the income stream ("rent") associated with the project;

ERb_{pr} – the amount of budget funds allocated for implementation or budget support of the project;

N_{r2} – the rate of deductions of budget funds ("rent") associated with the implementation of the project.

The rate of land "rent" in the project must be compensated by some source related to the project. Theoretically, in an infrastructure project that does not involve other activities other than construction, modernization and maintenance of infrastructure, there may be two such sources:

1. Reducing the quality of project work.
2. Improving the (technological) efficiency of the project operation.

The next question related to the implementation of the infrastructure project is the issue of budget constraints in case of project funding from the federal (in the case of federal funding) and / or (in the absence of federal funding) the regional budget. In both cases, the project budget should not go beyond budget constraints:

$$R_b \geq \sum_I C_i \quad (9)$$

where R_b is budget constraints;

C_i – the cost of the i-th activity of the project;

i – the main directions of the costs of the infrastructure project, including the cost of "informal coordination".

However, let us consider the situation when, as a result of the transport network restructuring, it becomes possible to reorganize the transport space of the city and to reallocate land previously used for transport infrastructure or transport infrastructure objects as free. In this case, from the point of view of mathematics and economics, there will simply be a decrease in the project's need for new land resources, both in physical and monetary terms.

Further, given that the regional and city authorities, at least formally, should take care of the state of economic life in the region, we get the next level – the coordination of the infrastructure project being designed for implementation with the needs of the population and business entities in the transport infrastructure [5, 6, 11, 12, 13].

In this case, when identifying the level of conformity of the network infrastructure with the economic needs of the region and its constituent territories, we propose to use the analysis of the territory traffic flows graph by the method of successive iterations.

We propose to use the coefficient of spatial conformity of the network to the national economic needs in road capacity as an indicator characterizing the adequacy of the existing network to the infrastructure needs of the city or region (territory).

When deriving this coefficient (conformity coefficient) as the initial base, we take the real existing need of the territory economy for infrastructure services.

When assessing the need for upgrading the infrastructure network and calculating the coefficient, one should proceed from whether it is an edge or a graph, or a part of the transport system (or the transport system on the whole) of the corresponding level. If the capacity of a separate edge of the graph is estimated in relation to the real transport demand that occurs on this edge, we will proceed from the model of the load flow distribution in the series circuit (using the analogy of the electrical network nodes and incompressible fluid flows).

We use the model of parallel flows of incompressible fluid for calculating the level of capacity on two conjugated levels of the edge of the graph,

Formally, for successive connections of edges of a graph of decreasing level, the conformity coefficient will be:

$$Cc_{\Sigma} = Cc_1 \times Cc_2 \times \ldots \times Cc_{n-1} \times Cc_n \quad (10)$$

$$Cc_n = \mu pr_n / \mu r_n \quad (11)$$

where μpr_n is practical real need for capacity of the edge of the graph;

μr_n – available (real) capacity of the edge of the graph.

As a rule, the graph of urban and regional infrastructure is a network of series-parallel connections, so it is reasonable to apply the weighted average method to calculate the conformity coefficient of the whole network level by analogy with networks of freely flowing incompressible fluid:

$$Cc_n = (z_{n1} \times C_{n1} + z_{n2} \times C_{n2} + \ldots + z_{nk-1} \times C_{nk-1} + z_{nk} \times C_{nk}) \quad (12)$$

$$(z_{n1} + z_{n2} + \ldots + z_{nk-1} + z_{nk})$$

$$z_{nk} \times = \mu r_{kn} \quad (13)$$

$$\mu r_{\Sigma n}$$

where μr_{kn} isthe actual capacity of the edge k of the level n of the transport network of the region (territory);

$\mu r_{\Sigma n}$ – total capacity of branches of level n of the region's transport network graph;

$$C_{nk} = \mu pr_{nk} / \mu r_{nk} \quad (14)$$

where μpr_{nk} is practical real need for capacity of the edge k of level n of the infrastructure network graph;

μr_{nk} – available (real) capacity of the edge k of level n of the infrastructure network graph.

IV. SUMMARY

Obviously, in the case of the ideal functioning of all the edges of all levels of the infrastructure network and their full compliance with the current national economic needs for infrastructure services, the compliance rate is equal to one. However, it is necessary to take into account that the economic development of territories, especially in large cities, does not stand still. Accordingly, it is necessary to evaluate this coefficient on the basis of forecasts of the territory (region) development for the medium term (road transport infrastructure) period. Therefore, when coordinating interests in the process of developing and implementing an infrastructure project, this indicator should be multiplied by the coefficient of perspective development (C_p), equal to the forecast increase in demand for transport infrastructure services in the relevant period.

Also, the parameters of the function should be set in the analysis and coordination of interests in terms of the city and regional (territorial) authorities interests:

$$GRP = f\,(F \quad (15)$$

where F is some parameter characterizing infrastructure security of the territory.

Since the coefficient of the network density per square meter of territory, the Engel coefficient and the Vasilevsky coefficient are traditionally used to characterize the infrastructure security of the territory, we suggest using them as the parameter F.

Accordingly, in the limiting (marginal) expression, the criterion of the infrastructure project effectiveness in terms of the regional authorities interests will be:

$$\begin{cases} (\Delta\, GRP / \Delta\, F) \rightarrow max \\ (\Sigma\, (\Delta\, GRP) / C_b) \geq 1 \\ (\Sigma\, (\Delta\, GRP) / C_b) \rightarrow max \\ C_b \rightarrow min \quad Cc_{\Sigma} \rightarrow 1 \end{cases} \quad (16)$$

V. CONCLUSIONS

This model has a number of significant drawbacks, which arise due to the fact that:

Within the framework of this model, it is assumed that the calculation is carried out within the framework of the infrastructure of any one type of transport. However, at present in a real large city, as a rule, several types of transport function. Consequently, it is necessary to take into account that in passenger traffic the capacity of various types of transport and transport networks accordingly differ significantly, and the passenger route may include the usage of various types of transport. To bring them to a single model, it is necessary to introduce the appropriate conversion factors, and therefore, it is possible to use the reduction factors of the road capacity of various transport networks (for example, obtained as a result of field studies) to modify this model by eliminating the disadvantage mentioned above.

1. It should be taken into account that from the point of view of economic and technological efficiency, the most effective solution would be to avoid using private transport – and this result is also implied in this model – since the capacity of public transport and its efficiency of transport space usage (rail transport especially) is many times higher than the ones of private passenger transport. However, in modern conditions, this solution seems to be low inclusive, utopian, and attempts to implement it will certainly lead to a significant increase in social tension.

In addition to our model, there is, in particular, a variant of the SWOT analysis of the development of transport systems of large cities and agglomerations, on the basis of which the following options for transport system data optimizing can be distinguished:

1. Transformation of the traffic management system with the allocation of separate lanes for urban public transport – this solution is already used in many cities of the country, but insufficiently – in extreme terms, it boils down to the development of urban passenger transport types with its own transport space and the formation of their effective interaction among themselves and with road transport.

2. Introduction of intracity toll highways system, interacting with the system of “capillary” roads, stops and passing points.

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