Modelling the Bottlenecks Interconnection on the City Street Network

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Abstract. The results of a questionnaire survey of Kyiv residents regarding their traffic to work places are considered and analyzed, taking into account the administrative-territorial division of the city territory. The traffic model of Kyiv city residents between its districts has been developed, on the basis of which the model of "bottlenecks" interconnection on the city street network is proposed, which allows to identify possible alternative routes of distribution of traffic flows on the network in case of failure of some of its elements.

Keywords: City · Traffic system · Traffic flow · Bottleneck · Traffic of inhabitants · Traffic route

1 Introduction

The vehicular traffic affecting significantly the living conditions of people and the further territorial and economic development of settlements has become a vital problem in many cities of Ukraine. Nowadays, the main aspects of such traffic problem are both the road network overload and inadequacy of road capacity at the certain road network sections to the traffic needs that cause the congestions and delays. Providing the required capacity for a certain road sections or junctions of a road network is a major indicator of creating the necessary conditions for the effective functioning of the entire city transport system [1–3].

2 Modelling the Bottlenecks Interconnection

The passenger traffic volume depends on the size of a settlement. As the population of the city grows, the territory and the volume of traffic increase. And as the size of settlement increases, the pedestrian traffic reduces and the number of trips by transport increases. The increase of passenger traffic depends mainly on the number of city inhabitants. Therefore, at this stage of the study, we are interested in the influence of the city's life structure on its transport network, in particular, on the distribution of transport and passenger flows, and what methods of traffic management are used to increase the traffic effectiveness. The peculiarity of major and largest cities is that the considerable proportion of inhabitants uses mainly the certain number of transport

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routes connecting chiefly the peripheral districts and city center zone of the city. Although in a modern cities with a developed division of social and production areas, such factor as a living place is less and less tied to the workplace. The volumes and directions of passenger traffic routes depend from both the volume of housing stock of residential districts and the number of jobs available in other districts. Therefore, the passenger traffic formation is quite spontaneous, but the process of this formation can be governed by analyzing the collected objective data on the volume and routes of work trips. It is the work trips of urban residents that are the most stable in real practice and are especially obvious in peak hours. It is also necessary to pay special attention to the traffic of the city inhabitants, taking into account the volumes and directions of their trips within the territory of a particular settlement. This allows identifying the directions of passenger traffic and main routes of transport vehicles to find out the most loaded traffic directions and the transport network sections [1].

In order to carry out the further surveys for obtaining the required information necessary for revealing the certain regularities in passenger traffic within city territory, the existing administrative-territorial division of Kyiv was used. The surveys were carried out for the entire city of Kyiv taking into account the existing administrative division. The city of Kyiv has ten administrative districts, among which there are adjacent links: Shevchenkivskyi district borders with five districts; Holosiivskyi, Dniprovskyi and Pecherskyi districts border with four districts; Obolonskiy, Podilskyi and Solomenskiy districts border with three districts; Darnytskyi, Desnyanskiy and Svyatoshinskiy districts border with two districts. The data on population and area of administrative districts of Kyiv are represented in Table 1 [2]. Considering that each administrative district of the city actually completely meets the necessary consumer services of its population, we analyze the passenger traffic caused by labor and education needs that is the most widespread in the morning time. It is this approach that will enable to find the location of employment gravity centers and reveal the passenger traffic regularities that will allow establishing the characteristic traffic routes for the population of each area and building the required transport infrastructure, which provides this traffic process, in particular, the correspondence of transport demand to its supply. According to the data [2] it is accepted that percentage of the employed population of Kyiv is 50.7%, and taking into account 8.3% of full-time students the total number is 59.0%.

The study mentioned above was performing in the city of Kyiv, by interviewing its inhabitants to identify the number of the district residents travelling to work only within the district territory, as well as between adjacent and remote districts. The questionnaire results are represented in Table 2. As a result of the surveys performed, the principles of district gravity centers distribution according to the administrative-territorial division were found, which characterize the peculiarities of mutual location of work and educational places in relation to the living places (Table 3). To find out the peculiarities of workplaces and determine main gravity centers of workplaces for residents of every district, the corresponding surveys were performed also. Such approach allows to identify the main stable traffic routes for the majority of residents of each district [4–7].

Table 1. The population and area of administrative districts of Kyiv.

The name of city district	The area of district, km^2	The population number, thousands of inhabitants	The working population number, thousand people	The proportion of the district population in the whole city, %	The Population density, inhabitants/km^2
Holosiivskyi	156	247.6	146.1	8.6	1584
Darnytskyi	134	314.7	185.7	10.9	2480
Desnyanskiy	148	358.3	211.4	12.5	2421
Dniprovskyi	67	354.7	209.3	12.3	5294
Obolonskiy	110	315.5	186.1	11.0	2868
Pecherskyi	27	152	89.7	5.3	5630
Podilskyi	34	198.1	116.9	6.9	5826
Svyatoshinskiy	110	340.7	201.0	11.8	3097
Solomenskiy	40	364.8	215.2	12.7	9120
Shevchenkivskyi	27	230.2	135.8	8.0	9208

Based on the volumes of passenger traffic for each administrative district obtained during peak periods of the whole transport system operation, the main traffic routes of population were found, which allowed revealing the regularities in traffic of Kyiv city residents to their workplaces and developing the methods of such traffic distribution depending on the traffic routes established.

Table 2. The trips of Kyiv city inhabitants from home to workplaces or educational institutions in accordance with its administrative-territorial division.

The name of city district	The area of district, km^2	The population number, thousands of inhabitants	The working population number, thousand people	The proportion of the district population in the whole city, %	The Population density, inhabitants/km^2
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Analyzing the possible traffic routes of the population within the city territory, the main traffic directions of the population are clearly traced, i.e., the routes of main inter-district passenger traffic flows within every administrative district.

The data obtained in the paper shows that transport connections between all districts of Kiev exist, but their volumes differ significantly, depending on their mutual territorial location, availability of jobs and location of city gravity center objects (Fig. 1). The obtained diagram of transport connections between the districts of Kiev forms a certain graph that has 10 vertices and 90 edges. However, the connections between the remote districts having no common boundaries pass through the territory of the adjacent districts and the districts through which the transport network is laid to provide the appropriate connection. The traffic between remote districts passing through the territory of other districts is characterized mainly by additional transit traffic on the street network (transit traffic flows). After analyzing the data obtained as a result of the experiment, you can determine the passenger traffic volume between districts (transport work) and, accordingly, define the volume of relationship between them as a percentage of any passenger traffic route volume of certain district with respect to the total volume of all city passenger traffic routes.

Table 3. The distribution of passenger traffic flows of Kyiv between its administrative districts.

The name of city district	The area of district, km^2	The population number, thousands of inhabitants	The working population number, thousand people	The proportion of the district population in the whole city, %	The Population density, inhabitants/km^2
Holosiivskyi	156	247.6	146.1	8.6	1584
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Using the diagram (Fig. 1), which demonstrates the fact that the traffic between remote districts pass through the other city districts, and the percentage of city residents traffic between its separate districts (Table 3), we can create the model (Fig. 2), which illustrates the relationship of traffic flows between administrative districts in the Kyiv city.

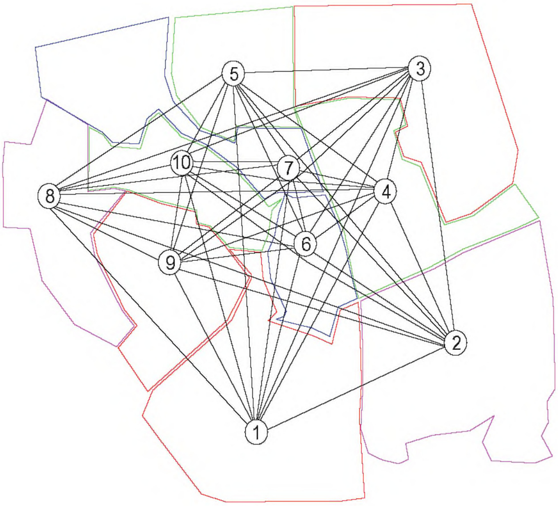


Fig. 1. The diagram of transport connections between all districts of Kyiv.

The obtained data concerning the city population traffic between administrative districts can be presented in the form of a weighted graph which can be used for further analysis and calculations (Fig. 2). The weighted graph is determined by the four variables:

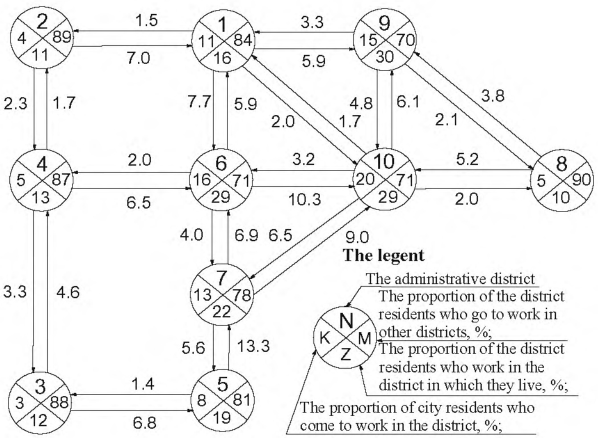
$$G = (V, E, X, C), \tag{1}$$

where

V = {vi}, i = 1,2,…,n are the graph vertices;
E = {ei}, i = 1,2,…,n are the edges;
X = {xi}, i = 1,2,…,n are the characteristics of the graph vertices;
C = {ci}, i = 1,2,…,n are the characteristics of the graph edges;

In this case, the city districts (vertices of the graph), the traffic directions (the graph edges), the number of residents moving from one area to another, as well as those who move within only one district (characteristics of the graph vertices), the number of residents moving in the directions between city areas (graph edges characteristics).

The weighted graph represents the inputs and outputs of residents' traffic for work trips and their percentage distribution by direction of movement between districts, which makes it possible to characterize the volume of inter-district traffic.



1- Holosiivskyi district;
2- Darnytskyi district;
3- Desnyanskiy district;
4- Dniprovskyi district;
5- Obolonskiy district;
6- Pecherskyi district;
7- Podilskyi district;
8- Svyatoshinskiy district;
9- Solomenskiy district;
10- Shevchenkivskyi district.

Fig. 2. Model of Kyiv residents' traffic between districts of Kyiv (for work trips).

The obtained model makes it possible to define and evaluate the transport and passenger demand, to determine the transport dependence of a district taking into account the directions of passenger flows and their volume. The corresponding model at this stage is a simple graph that shows only one connection between adjacent areas, which is in fact incorrect. But it does provide general information about city traffic, which allows you to determine the volumes and directions of traffic in the corresponding district.

In order to manage such traffic, it is necessary to determine the possible traffic routes between the certain city districts, and the maximum number of possible routes that can be formed between two gravity centers. This largely depends on the number and type of street network elements (bridges, overpasses, signalized intersections, etc.) that provide transport links between adjacent or remote districts and concentrate traffic flows around gravity centers within each district. Actually these elements determine the number of possible traffic routes between certain gravity centers.

By considering possible traffic routes between the administrative districts of a city, it is possible to select some number of street network centers through which you can travel from one district to another, that is, a certain number of possible traffic routes for inter-city and transit traffic.

Thus, each district has the k inputs and the n outputs. Each input has a link with any output. So that, you can create a graph of traffic routs for every district of any city. As an example, we selected locations of possible transport routs between the administrative districts of Kyiv. When analyzing the existing routs between administrative districts, all possible streets, roads and other elements of the street network were considered, regardless of their category and technical-planning characteristics. The number of traffic routs between the administrative districts of Kyiv is represented in Table 4.

A matter of particular importance in any city street network providing city traffic between administrative districts are so-called "bottlenecks" in each city district's territory, which affect, sometimes significantly, the formation of traffic routes for not only the inter-city and transit transport, but also for intra-district one. Such problem is solved by developing the model of the city's street network, based on the number of its nodal points ("bottlenecks"), through which traffic flows naturally pass, because any redistribution of traffic flows along the city street network require special attention to the traffic capacity of bottlenecks and their number. The number of bottlenecks and their traffic capacity affect the effectiveness of the decisions being made concerning the organization and management of city network traffic because bottlenecks are those critical elements through which traffic flows are to go.

According to our surveys there were identified 99 "bottlenecks" in the Kyiv city street network (Fig. 3):

– bridge crossings - 5 places;
– overpasses that cross over railway, subway or express trams - 36 places;
– traffic intersections on the arterial roads at different levels - 24 places;
– signalized intersections (located at or near the administrative district boundaries) – 23 places;
– entrances and exits from the city - 11 places.

Table 4. The number of traffic routs between the administrative districts of Kyiv.

The city district	The number of traffic routs between the administrative districts of Kyiv									
	Holosi-ivskyi	Darnyt-skyi	Desnyan-skiy	Dniprov-skyi	Obolon-skiy	Pecher-skyi	Podil-skyi	Svyatoshin-skiy	Solomen-skiy	Shevchenkiv-skyi
Holosiivskyi	–	1	0	0	0	7	0	0	6	4
Darnytskyi	1	–	0	3	0	0	0	0	0	0
Desnyanskiy	0	0	–	7	1	0	0	0	0	0
Dniprovskyi	0	3	7	–	0	3	0	0	0	0
Obolonskiy	0	0	1	0	–	0	9	0	0	0
Pecherskyi	7	0	0	3	0	–	1	0	0	3
Podilskyi	0	0	0	0	9	1	–	1	0	9
Svyatoshinskiy	0	0	0	0	0	0	1	–	3	2
Solomenskiy	6	0	0	0	0	0	0	3	–	6
Shevchenkivskyi	4	0	0	0	0	3	9	2	6	–
Total	18	4	8	13	10	14	20	6	14	23

In this case, it is suggested to consider the city's traffic route system as the "bottlenecks" interconnections system.

Such approach allows to describe the city transport route system in the form of a graph [3, 4], on which each vertex characterizes a "bottleneck" through which vehicles are driving to a selected vertex. This model clearly exhibits a certain number of alternative routes and possible alternative streets that will allow redistribution of traffic flows when any difficult situation occurs in one of the traffic routes. This approach enables to remove some number of streets and intersections from traffic management system that do not have a significant impact on the traffic flows. Important in the study are only those nodes where traffic routes for a significant number of vehicles are changed or those road network elements where the main number of transport routes go along.

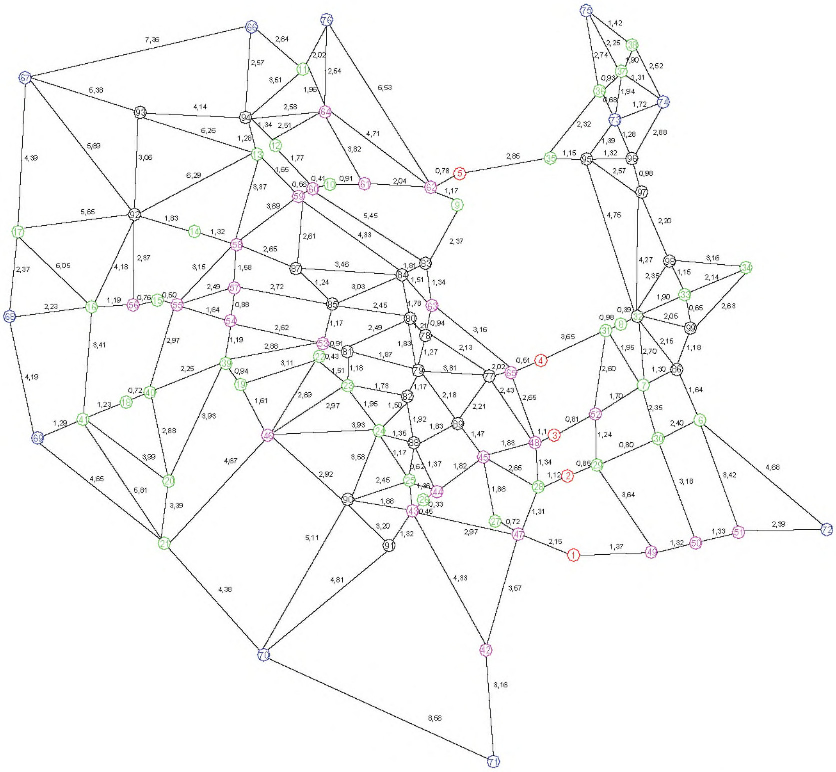


Fig. 3. Model of interconnections between “bottlenecks” of Kyiv city transport route system.

Such model of bottlenecks on the city’s street network is based on the selection of its optimal sections to ensure the most effective transit traffic to the required district under conditions of minimal time and expenditures. Each edge of the model’s graph can be characterized by the value t_{ij}, which corresponds to the total travel time on a given section of the street network.

The application area of the model is very broad: transport tasks, optimization tasks of street networks and transportation systems. One of the well-known optimization tasks is finding the shortest paths in a graph with weighted arcs. Also, assuming that the vertices of the graph are the source and purpose of population traffic, based on the data, you can solve the network problem of optimal flow, maximum flow and minimum cut, as well as build a model of interaction between different modes of transport.

Employing the Ford-Falkerson algorithm [5] to the model of bottleneck interconnections on the city's road network we can find the maximum flow in the network and determine the possible saturation flow of the entire network on the base of given traffic capacity of the vertex ("bottleneck") and not the arcs.

For this purpose, any oriented edge f: (a, b) is matched by the flow f (a, b) passing along the edge, provided that the flow value is less than or equal to the throughput of the edge z (a, b).

$$f : (a, b) \to f(a, b) \leq z(a, b) \tag{2}$$

At such condition, the conservation law is met for any vertex b, that does not belong to vertices S and T, that is, the magnitude of the flow coming along the edge f (a, b) must coincide with the magnitude of the flow originating from the vertex b on the edge f(b,c).

$$\sum\nolimits_{a;(a,b)\in E(G)} f(a, b) = \sum\nolimits_{c:(b,c)\in E(G)} f(b, c) \tag{3}$$

The traffic capacity of the cut

$$z(S, T) = \sum\nolimits_{z(S,T)\in R(S,T)} z(a, b) = G \tag{4}$$

Maximum flow in the network

$$Q \leq z(S, T) \forall R(S, T) \tag{5}$$

This method enables to reveal possible alternative routes of traffic flows distribution over the network at the time of failure of one or more of its elements, which provide transport connectivity and reliability of the city street network operation as a whole.

3 Conclusion

Having obtained data on the traffic capacity of the road network elements, it is possible to determine the correspondence of these elements to the city transport needs and define whether the construction of additional elements in the street network is needed, as well as identify possible unloaded alternative traffic routes, which is essential in creating an intelligent traffic management system that will allow effectively distribute traffic flows over the street network.

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