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Procedia Engineering 134 (2016) 276 – 283

Procedia Engineering

www.elsevier.com/locate/procedia

9th International Scientific Conference Transbaltica 2015

# Peculiarities of City Street-Road Network Modelling

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**Abstract**

It's discussed the peculiarities of graph theory application for modeling of city road-street networks. It's represented the example of dividing the territory of Pereyaslav-Kheknytskyi city of Kyiv region into transportation sub-districts.


Peer-review under responsibility of the organizing committee of Transbaltica 2015

*Keywords:* motor vehicle; traffic flow; road-street network; graph theory.

## 1. Actuality of the subject matter

Historically the street network of cities and character of their residential buildings layout were formed without taking into account such powerful anthropogenic factor as a motorcar. The last caused the especially adverse conditions in central part of cities where density of road network and residential buildings is too high. The traffic in such areas is characterized by frequent stops before traffic lights and uncontrolled road intersections. All that leads to traffic speed decrease, loss of passenger transportation time, decrease of passenger transport productivity, negative psychological climate for traffic participants, growing quantity of traffic accidents and loss of lives on roads.

Solution of such problems is quite complicated task due to growing increase of motor car quantity in conditions of significant leg in construction and reconstruction of intersections, streets and roads in the settlements.

Nowadays solution of such problems requires transport means traffic optimization in city street-road network (RSN) though the certain set of scheduled, technical, management and organizational measures.

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Peer-review under responsibility of the organizing committee of Transbaltica 2015
doi:10.1016/j.proeng.2016.01.008

## 2. Problem solution

It's obvious that all mentioned above motorization problems cannot be eliminated completely. Therefore it's necessary to develop some effective measures reducing their negative impact on city environment.

There are three ways to solve such problems:

- heavy capital investments – method based on reconstruction and construction of highways and roads with grade-separated intersections. (Such method shortcoming is its realization complexity in conditions of city RSN);
- middle capital investments – method based on reconstruction of existing RSN. (Such method shortcomings are similar to the first method, i.e., the complexities concerned with existing development of city);
- low capital investments – based on method of traffic organization (TO).

The most economically effective way in current conditions is realization of measures directed of road traffic management and organization, i.e., the traffic optimization on city RSN of Ukraine.

The idea of such approach is to solve the problem without changes in current city development and observing the maximum safety level.

Methods of traffic organization are realized by using technical means of traffic organization (TM TO).

Methods of traffic organization are the most effective approach. There are seven methods of traffic organization within city territory (Reitsen, Stepanchuk 2004):

- one-way traffic;
- self-regulating traffic;
- unregulated traffic with road signs;
- isolated traffic light direction;
- green time on highway;
- system control by using automated traffic control system (ATCS);
- distributing control system of grade-separated interchange traffic.

The most effective one, from our point of view, is traffic management by means of ATCS. The important place in the general problem mentioned above occupies the implementation of automated traffic control systems and automated dispatching systems (ADS) based on modern means of automatics and computer engineering.

Automated traffic control systems operate in 13 cities of Ukraine: Kyiv, Dnipropetrovsk, Kharkiv, Donetsk, Odessa, Zaporizhia, Zhitomir, Lugansk, Mykolayiv, Khmelnytskiy, Poltava, Cherkassy, Mariupil.

The main purpose of ATCS implementation is to increase the effectiveness of city road-street network operation without significant capital investments.

Nowadays ATCS is the most perfect complex of technical devices and software which shortens maximally the possible time of traffic delays and increases the highway capacity and road safety.

But nowadays, structure of traffic management is the outdated one and not able to influence the processes causing traffic jams. Of 568 traffic light objects operating in Kyiv today, only 124 (21.8%) are connected to existing ATCS.

The experts state that proper level of traffic management requires 85–90% of traffic light objects connected to ATCS. But existing ATCS is out of date morally and physically (Stepanchuk, Bieliatynskyi 2013). Existing ATCS is primitive prototype of modern systems and therefore can't respond on-the-fly onto changes of traffic intensity which usually differ from the design traffic intensity.

To overcome the such problem it's required to solve the complex of scientific, technological, technical and organizational tasks dealing with designing, construction and organization of ATCS operation. Organization of traffic management should be realized on the base of traffic flow modeling methods.

The especially important question in modern conditions is the one concerned with improving methods dealing with prediction and planning of transport system development including all questions of its own infrastructure development. The great importance in this way is development of complex evaluation technique of street-road network state in cities as well as the traffic organization system.

It depends first of all from existing state of traffic management in transport district of city. Analysis of street-road network as geometrical object is necessary to develop rational measures for improvement of traffic management state on RSN.

There is currently no uniform method which enables to define sub-districts on the base of criteria insuring optimal traffic flow management. To obtain qualitative information about size of city traffic flows, it's necessary, first of all, to structure the city territory.

It is known that formation of any territorial system and structure describing the traffic network matrix are based on determining some set of vertex (Rihter 1983):

$$M_o = \{O_1, O_2, \ldots, O_p\}. \quad (1)$$

The elements of this set represent the territorial units where certain traffic starts or ends. Such territorial units are considered as endpoints of transport objects when they change their spatial and time location. Let's consider the traffic links matrix H which elements are determined in following way:

$h_{ij} = 1$, when direct link from vertex $O_i$ to vertex $O_j$ exists;

$h_{ij} = 0$, if not.

It's obvious that matrix H is square matrix with elements equal either 1 or 0. Traffic networks and their matrices can of different structures. For instance, the set

$M_o = \{O_1, O_2, O_3, O_4\}$, containing four vertexes, can determine the following types of traffic network and corresponding matrices (Fig. 1).

The specified above traffic networks matrix coincides with vertex matrix of oriented graph considering in graph theory. Oriented graphs represented on Fig. 1–7 correspond to traffic network and traffic networks matrix.

Let's examine some network and its oriented graph having set of vertices $U$ and set of arcs $S$. There are the following relations between elements of network and graph:

| Network | Graph |
|---|---|
| Vertex | Vertex |
| Link | Arc |

Matrix is the representation of certain real traffic network or in other words, it is a high abstraction degree model of traffic network.

Different traffic network models correspond to different abstraction degrees:

0 corresponds to real traffic network;

1 corresponds to geographical map;

2 corresponds to map of network (highways, railways);

3 corresponds to graph (mathematical model);

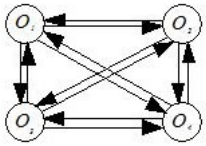
4 corresponds to matrix (mathematical model).

On the example of Pereyaslav-Kheknytskyi city of Kyiv region we propose the technique of its territory structuring by using the graph theory elements to insure the possibility of its separate sub-districts modelling in a future. For this purpose, we model the cellular partition procedure of city territory (Lukanin, Buslaev, Trofimenko, Yashyn).

Analysis of RSN characteristics in separate districts are performed to reveal "trouble spots" in the whole city RSN. The traffic management is more expedient for RSN with highest characteristics. Therefore, first let's describe the procedure of dividing RSN into parts. The territory dividing can be performed by a few methods.

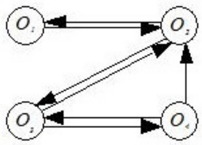
Our method is based on centered binary distribution that enables embedding of every next level into previous one. That allows to:

- compare the characteristics of whole square with characteristics of its components;
- find the appropriate level of square size decrease during dividing the territory, i.e., find the such threshold when characteristics of square become almost constant and independent from RSN geometry.



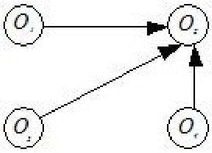
$$H_{FS} = \begin{pmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix} \quad (2)$$

Fig. 1. Two-way exchange network.



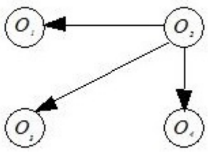
$$H_{TS} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix} \quad (3)$$

Fig. 2. Exchange network with the partial blocking.



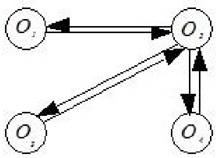
$$H_{S} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \quad (4)$$

Fig. 3. Collecting network.



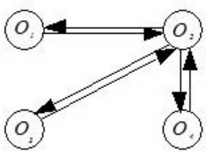
$$H_{V} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad (5)$$

Fig. 4. Separating network.



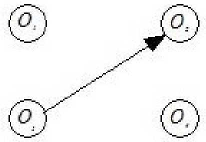
$$H_{P} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \quad (6)$$

Fig. 5. Pendulum network.



$$H_{R} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{pmatrix} \quad (7)$$

Fig. 6. Ring network.



$$H_E = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad (8)$$

Fig. 7. Single link.

As it was mentioned above, the Pereyaslav-Kheknytskyi territory was divided into 17 squares measuring 1.5 × 1.5 km each, i.e., area of each square accounts for 2.25 km$^2$ (Fig. 8). Transport interchanges of first, second and third class were numbered. The total quantity of transport interchanges accounted for 57. The first class of transport interchange corresponds to intersection of general city arterials roads between each other, the second class corresponds to intersection of general city arterials roads with district arterials roads, and third class corresponds to intersection of district arterials roads between each other.

Oriented graph was built in accordance with 57 transport interchanges found above (Fig. 9).

Ribs of the graph can contain different information such as allowed traffic directions, number of traffic lanes in each direction, the most traffic accident parts on roads, etc.

To obtain possibility of further modelling of RSN traffic within each square it's rational to divide the city territory into separate sub-districts with minimal number of external links. Then if value of input traffic flow is known and its distribution within every internal interchange is specified, traffic modelling is possible.

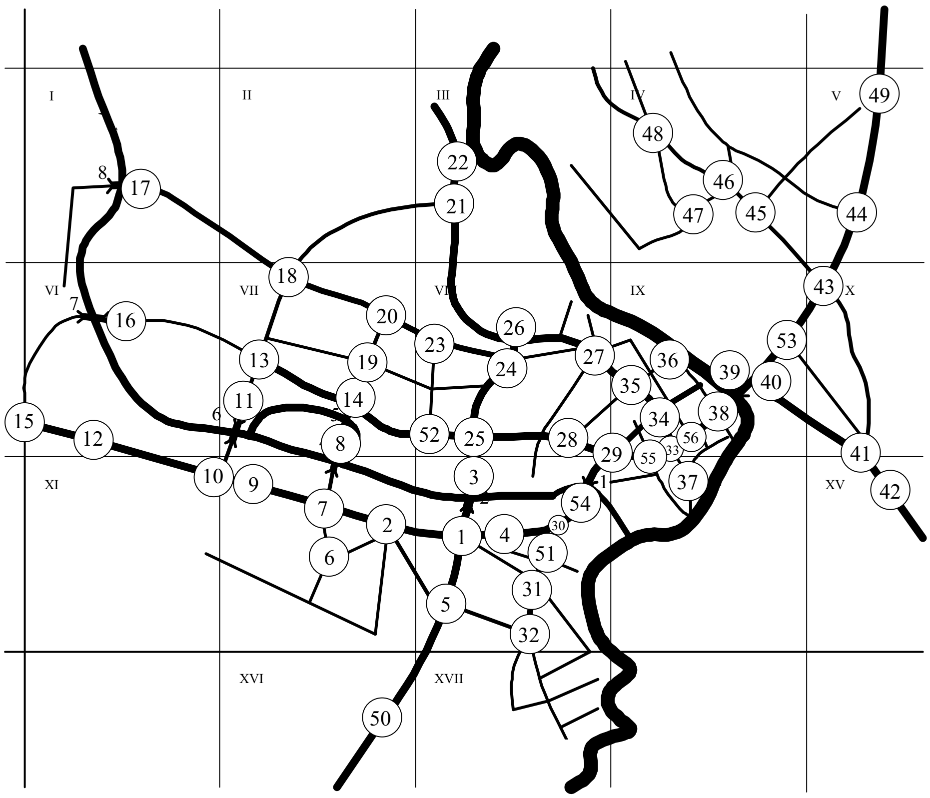



Fig. 8. Dividing of Pereyaslav-Hmelnytsky territory into squares.

To solve such type tasks, the graph theory (Stepanchuk et al. 2013) introduces some numerical characteristics enabling to describe the following qualitative characteristics of network:

- reliability;
- stability;
- accessibility of network with minimal traffic density;
- accessibility of network with maximal traffic density.

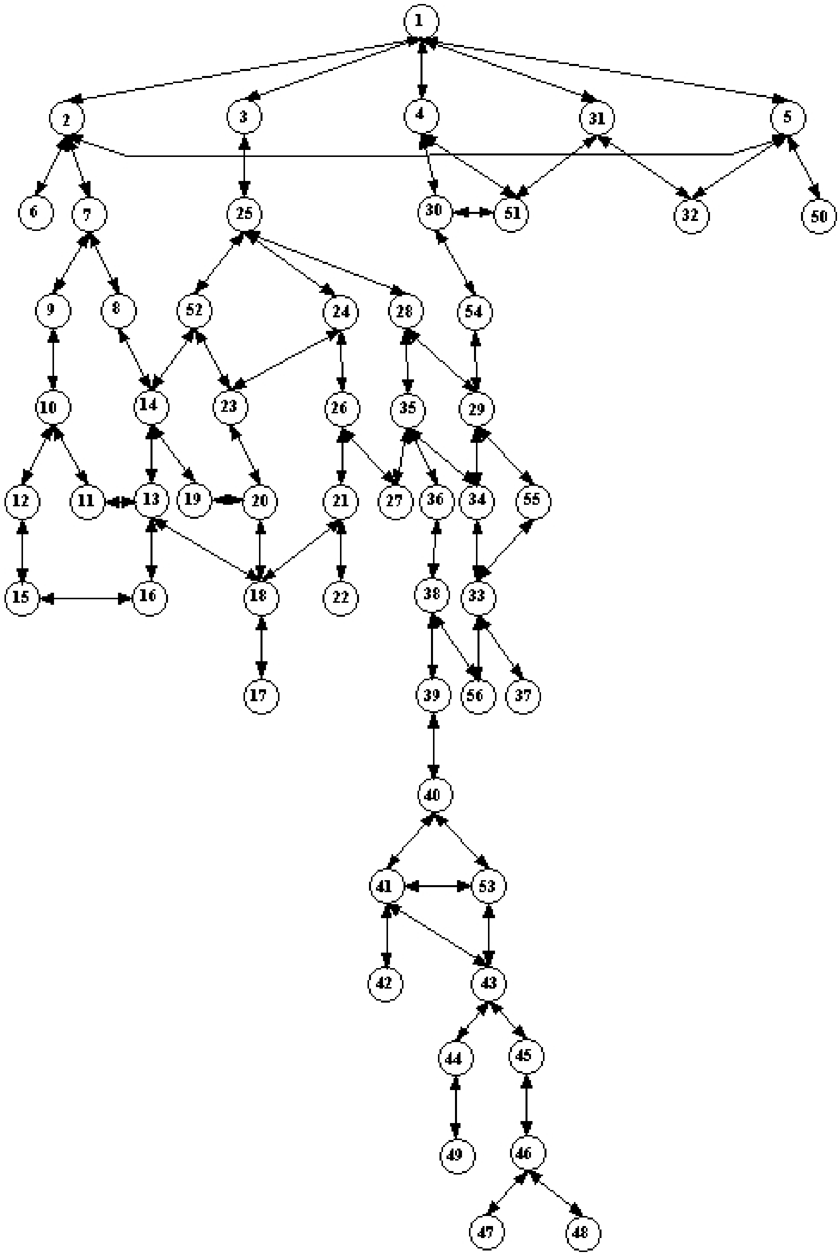



Fig. 9. Directed graph of Pereyaslav-Hmelnytskyi RSN.

Methods of network optimization taking into account the road conditions can be proposed on base of analysis of these qualitative characteristics.

The planning RSN layout of practically any city can be divided into certain structures (squares) with 3 or 4 external entrances. That is represented on the example of Pereyaslav-Hmelnytskyi city. You can see that square IX (Fig. 10) contains 9 sub-districts (Fig. 11).

Using the technique of RSN modelling and dividing city into planning traffic elements (when any city can be divided into “M” separate districts), the area necessary for traffic and parking vehicles can be determined by the formula (Reitsen, Kaddakh 2000; Stepanchuk et al. 2009):

$$S_{ci} = \frac{I_i W(1+P)}{C} q_{ci} + \frac{S_p q_{ci}}{\mu}, \tag{9}$$

where $S_{ci}$ is the area, necessary for traffic and parking of vehicles within traffic flow $q_{ci}$; $I_i$ is average traffic distance of single vehicle in sub-district $i$; $\mu$ is the inverse value of average idle time for single vehicle.

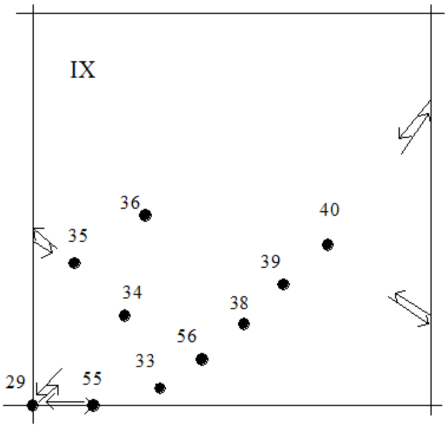



Fig. 10. Square IX.

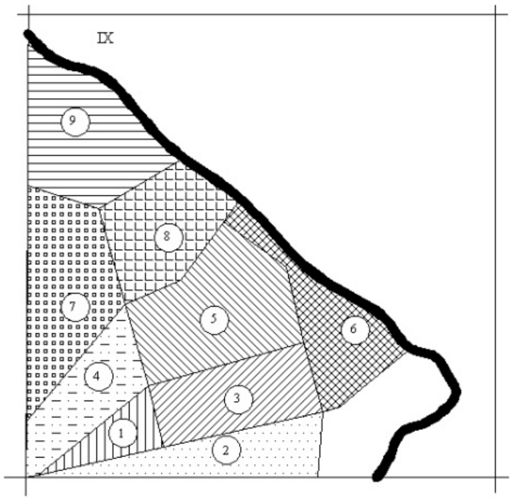



Fig. 11. Dividing of a certain square into sub-districts.

In addition to flow of vehicles with destination point located in sub-district $i$ ($q_{ci}$), there are two more flows of vehicles in sub-district $i$. One of them is a flow of vehicles with start point in a given sub-district $i$. The another one is the transit flow of vehicles driving through sub-district $i$ to another sub-districts.

$q_{bi}$ represents the sum of these two mentioned above traffic flows.

The area $S_{bi}$, necessary for traffic of $q_{bi}$ flows can be calculated by the formula

$$S_{bi} = \frac{I_i W(1+P)}{C} q_{bi}. \tag{10}$$

The following inequality should be observed as well:

$$S_{ci} + S_{bi} < S - S^{\wedge}, \tag{11}$$

where $S$ is total area of district; $S^{\wedge}$ is a part of district area where different buildings and installations are located.

The maximum value of traffic flow within sub-district territory of city RSN can be calculated by the formula:

$$q = \frac{S - S^{\wedge}}{\left\{ \frac{IW(1+P)}{C} + \frac{S_p \gamma}{\mu} \right\}}, \tag{12}$$

where $I$ is average traffic distance of single vehicle; $W$ is width of one traffic lane; $P$ is ratio between widths of sidewalk and traffic lane; $C$ is traffic lane capacity; $S_p$ is area necessary for parking of single vehicle; $\gamma$ is a coefficient accounting for the part of vehicles located in parking area in total quantity of vehicles taking part in traffic.

Modelling of road-street network on the base of graph theory enables to solve a whole series of tasks such as calculation of unit rates of road traffic, substantiation of road traffic organization patterns with redistribution of traffic flows within RSN, adding of pedestrian zones, evaluation of given measures expediency, and creation of expert systems.

## 3. Conclusions

The effectiveness level of road traffic management system depends on its speed of reacting to current traffic situation in RSN. Such system should be reliable and sensitive to all factors characterizing road traffic situation. Reliability is essential requirement for successful operation of RSN.

The traffic problem solution is to redistribute traffic flows in such manner to insure free traffic along working parts of RSN.

Analysis of all mentioned above factors enable to propose optimization methods of RSN operation in cities of Ukraine by its modelling on the base of graph theory.

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