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OVERVIEW OF THE MASS TRANSIT NETWORK'S PROPERTIES IN REGARD TO THE TERRITORY FUNCTIONS ASSURED

Mass transit networks are the ones that cover the urban space and lead to social - economical development of the areas. The intensity of the activities in the areas irrigated by mass transit must be the one determining network's design and location of the terminals, leading to accessibility and attractiveness growth. Bucharest metro network nodes are characterized using Shimbel nodality indexes (generalized nodality index and Shimbel nodality index) that are correlated with socio – economical characterization of the covered areas. The analyzed spatial – temporal correlation is studied by nodal accessibility; every path has associated a transport time value. Then, the pole of the network is determined and conclusions regarding the covering of the areas with high capacity transport network are formulated. The study is achieved for the present transport network and also for the designed transport network of the year 2030 and conclusions about future network orientations and developments have been formulated.
Keywords: mass transit, network topology, mobility, territory functions, ubiquity, vulnerability.

Prolegomena

In regard to the infrastructure and operating technologies, spatial differences of territory functions assured by mass transit networks are emphasized, capable to determine further land use and transport planning actions [5, 9, 11].

Mass transit networks' properties

Ubiquity

Ubiquity stands for the network's property of being accessible in more points in the same time/for a certain period.

The spatial covering of the network is reflected by the degree of ubiquity. Underground network's ubiquity, like for the others networks of terrestrial transportation, is strictly determined by stations' locations. On a continuous space, it is obvious that increasing the degree of ubiquity for the network by increasing stations density has a direct consequence on decreasing passengers average travel speed on the entire network. One of the main reasons for limiting the number of stations for the underground network (except the total investment costs) is the decreasing efficacy induced by stops, stationing times and frequent start ups. Smooth disparities can be noticed between the present underground network and the one arising from the projected developments.

While the existing network has an average distance between the stations, $\overline{d}$ = 1.40 km, with a dispersion σ_2 = 0.19 km^2, the projected network for 2030 will have $\overline{d}_1$ = 1.15 km, with a dispersion σ_{12} = 0.20 km^2.

In the above mentioned hypothesis of a continuous space, the average ubiquity of the network, $\overline{u}$, can be defined as ratio between the number of stations, n and the total length of the network, $\sum L_r$:

$$\overline{u} = \frac{n}{\sum L_r}, \text{ or } \overline{u} = \frac{1}{\overline{d}}, \tag{1}$$

expressed in number of stations for network's length unit (for example, km). The average ubiquity value $\overline{u}$ has a dispersion:

$$\sigma_u^2 = \frac{1}{n\overline{d}^2} \sum \left(\frac{\overline{d}}{d_i} - 1 \right)^2 . \tag{2}$$

The existing metro network has $\overline{u}$ = 0.71 stations/km and σ_u^2 = 0.10 while the extended network of 2030 has $\overline{u}_1$ = 0.87 and σ_{u1}^2 = 0.18.

The following conclusions can be drawn by comparing the values of ubiquities and their dispersions in the two hypotheses (existing network and the developed/extended one):

- an ubiquity increase and so a better served area is supposed to be obtained by developing the underground network,
- the structural specificity of the area is emphasized by the significant values of ubiquity dispersion (and also for the distances between the stations),
- the extended network would be more adapted to the specificity of the served urban area ($\sigma_{u1}^2 > \sigma_u^2$).

Connexity

Network's property of assuring connexions among the considered points/areas is defined as connexity.

The representation of the planar graph associated with the network (only with the points/areas connected on the network) shows that connexity is assured. Infrastructure connexity must be extended to service connexity for main lines/routes of the underground network. Admitting the possibility that in all the junction points of the main underground lines one can pass from one main line to another (even passengers' travelling from one platform to another, on the same level or from one station to another one situated on different levels), we can conclude that the network is connex (figure 1) both in the present and the 2030 perspective.

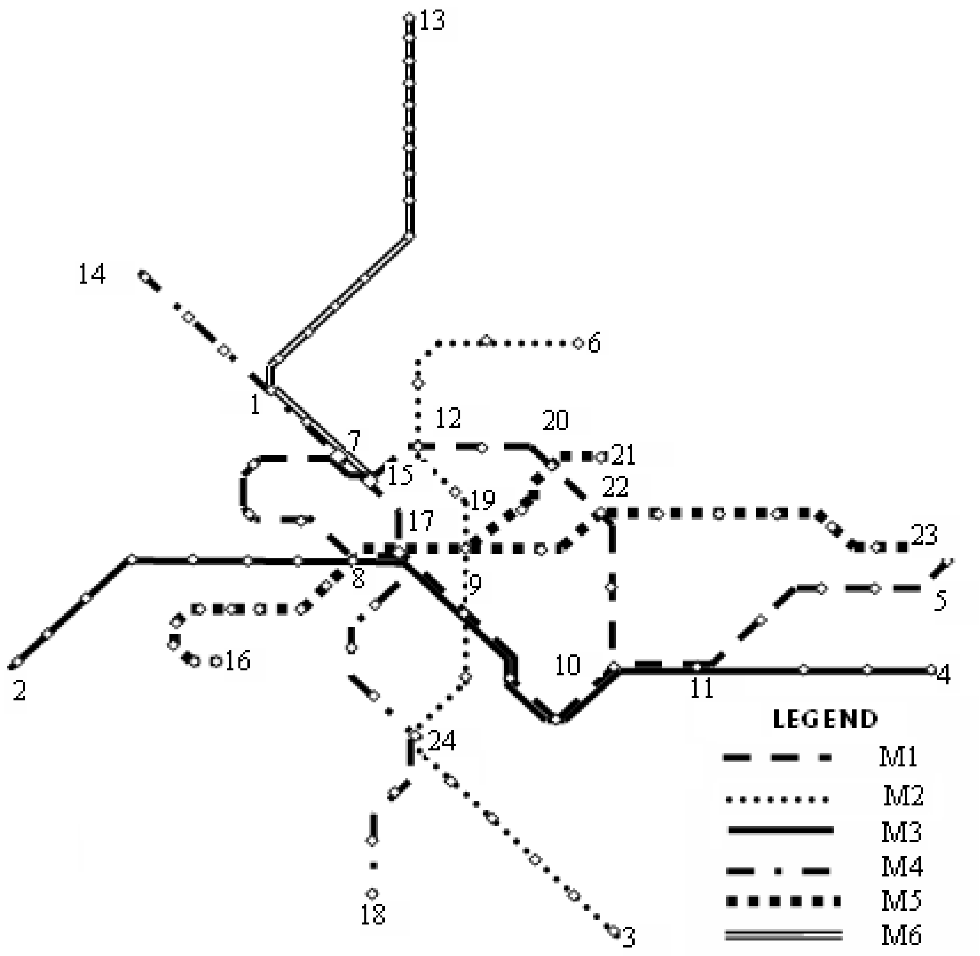

Figure 1 – Underground network (present and 2030 extensions)

Connectivity

Connectivity is represented by the multiplicity of the connexions within a network. The possibility of choosing an itinerary between two nodes appears by comparing some alternatives on a connective network.

Commonly, transport infrastructure networks haven't got maximal connectivity (corresponding to a complete graph in which any node has direct connexion with all the other nodes) and so, different indexes are used to reflect the network connectivity level. Among these, [6] for the actual study we have used α and γ indexes.

The α index is defined as ratio between the number of independent circuits of the graph associated to the network and the maximum possible number of independent circuits of the graph with the same number of nodes.

The cyclomatic number of the graph provides the number of independent circuits in a graph:

$$\mu = A - N + G, \tag{3}$$

where A is the number of links,

N – number of nodes,

G – number of connected components,

and maximum number of circuits of the planar graph is 2N – 3, so:

$$\alpha = \frac{\mu}{2N - 5} \tag{4}$$

For the existing network $\alpha = 0.015$ and for the extended one $\alpha_1 = 0.021$. The γ index is determined as ration between the number of links of the graph associated to the network and the maximum number of links of the graph with the same number of nodes.

For the planar graph:

$$\gamma = \frac{A}{3(N - 2)} \tag{5}$$

The existing network has a γ index of 0.166 while the extended one of 2030 has a γ_1 of 0.1.

Vulnerability

Low values of connectivity both for the existing network and for the extended one can be notice (reflected by α and γ indexes) meaning that the network (with almost a tree structure) is more vulnerable to losing the functionality of one or more links between the nodes than a complex network (following accidents or hyper congestion) [1-4, 8, 12].

The lack of functionality might even mean losing connexity for many of the links associated to the network's graph. This links (connecting marginal nodes and also the links 1-7, 7-15 and 10-11) are critical to network functioning.

To the other links of the network a different vulnerability index can be credited in correlation with the consequences of prolonging the travel time necessary to assure all the connexions within the network while, successively, one link loses functionality.

The total length of the shortest paths between the nodes of the network (table 1) in case of all links functioning is $\sum L = 5978.9$ km and in case of links successively losing functionality (figure 2) the sum of the shortest paths among the nodes of the network is $\sum L_d$ presented in table 2.

Table 1 – The shortest path among the nodes of the underground network

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Shortest path	530	290	226	178	167	168	280	192	170	171	272	153	153	172	393	314	203	297	359	158	203	229	384	320

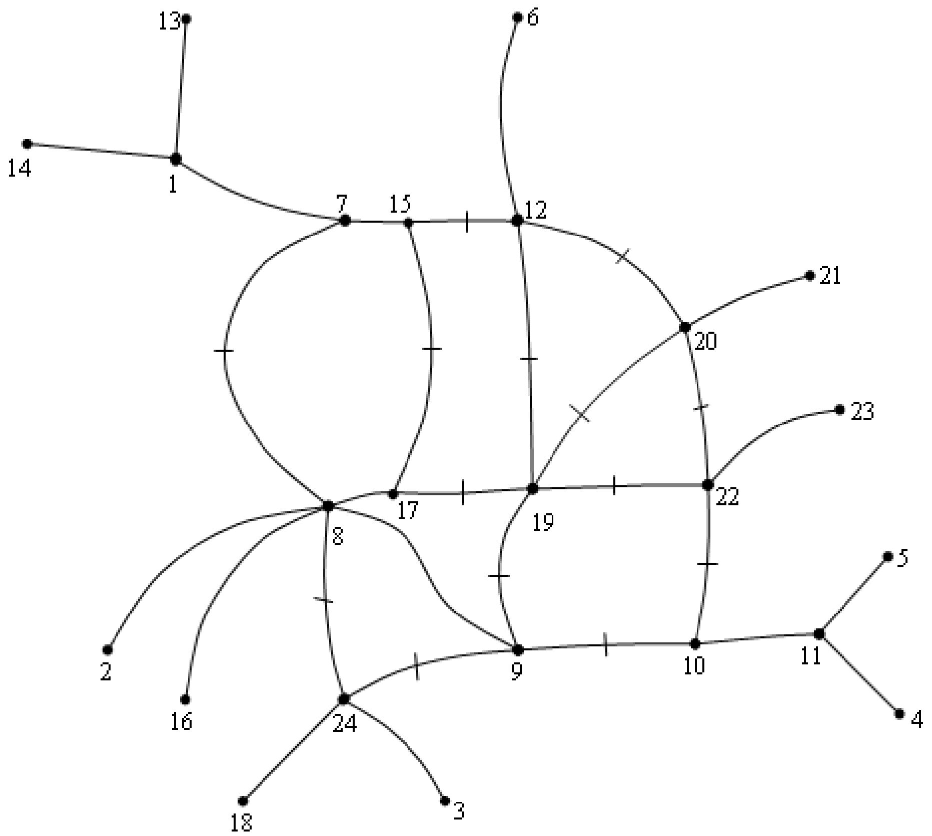

Figure 2 – Simplified representation of the links of the underground network (the case of links losing functionality)

Table 2 – Sum of the shortest links among the nodes in the hypothesis of losing the functionality

Link that loses functionality	7-8	15-17	17-24	24-9	9-19	19-17	9-10	19-22	10-22	20-22	19-20	19-12	15-12	12-20
Sum of minimum paths, $\sum L_d$	5978.9	6152.28	5996.96	6084.38	6023.2	6165.72	6065.82	6018.5	6161.02	6154.22	6006.86	6029.74	6241.3	6086.5
$\varepsilon = \dfrac{\sum L_d}{\sum L} - 1$	0	0.029	0.003	0.018	0.007	0.031	0.015	0.007	0.030	0.029	0.005	0.009	0.044	0.018

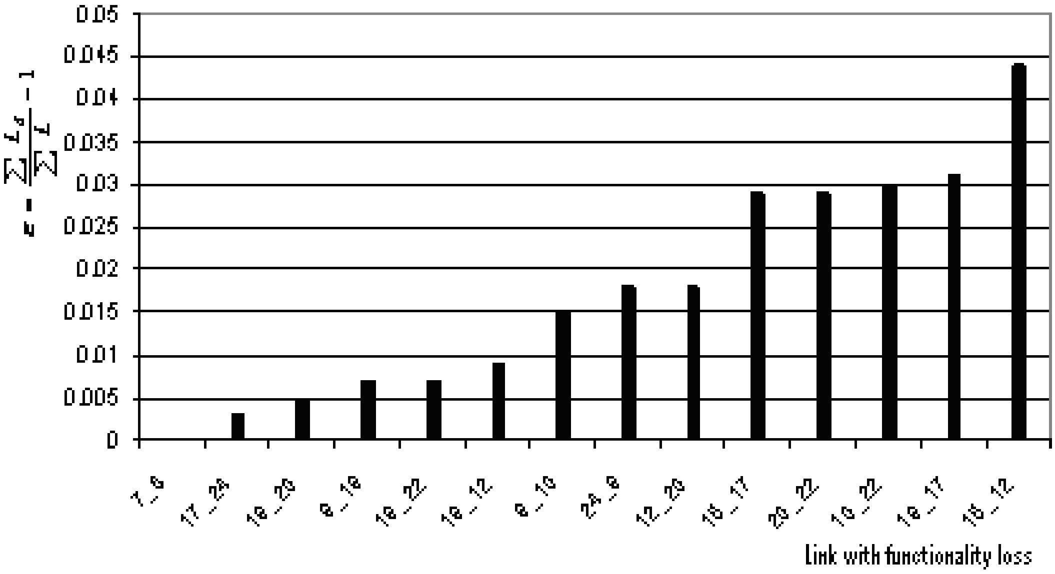

Figure 3 – Vulnerability of link with functionality loss

The ε ratio gives a measure of the vulnerability of the network's links in relation to the considered criterion. The links of the network are differentiated by ε values that could become scale marks for a hierarchy of the links' importance in relation to network vulnerability. Bigger values of ε signify links with high vulnerability (except the ones defined critical to the network as the loss of their functionality would bring network connexity loss too).

The results present links 15-12 and 15-17 as being the most vulnerable in the whole network.

Homogeneity and isotropy

In the strict way of definition [5] these aspects are idyllic network properties, untouchable for any of the networks designed for material flows transfer.

In a wider approach, topological/geometrical/technical/functional characteristics of the network can be identified, that would allow the use of attributes like homogeneity/no homogeneity or isotropy/anisotropy for a transport network.

The previous references regarding ubiquity and vulnerability of the present and extended underground network revealed no homogeneity under the aspect of distances between stations and importance of the different links in assuring space-time correlations for the network. The links disparities from the vulnerability point of view can be interpreted as anisotropy, as they reveal the fact that not all the network's links are equivalent under the aspect of the relations assured among the network's elements. Actually, like properties of the networks, homogeneity and isotropy must be correlated to the relations assured among the elements of the network and not to irrelevant characteristics about those functioning links that the network assures for the use of the territory system. That is way, the homogeneity of the underground network, under the aspect of the technical characteristics of infrastructure, transport means, technologies and even tariffs is not presented as it is not relevant for network's homogeneity and isotropy from the functions to be assured point of view.

Relevant for the global characterization of the space-time correlations assured by the underground network we have considered to be the average transfer speed, $\overline{v}_i$ [7, 9], from each i node to all the others, j (j$\neq$i),

$$\overline{v}_i = \frac{\sum_j d_{ij}}{\sum_j t_{ij}} \qquad (5)$$

where d_{ij} is the distance from node i to all the others, j,

t_{ij} – travel time from node i to node j (including passengers' changing the line time in underground junction stations).

After grouping the $\overline{v}_i$ values of the extended network of 2030, the izoaccesibility chart from figure 4 shows no homogeneity and anisotropy of the network.

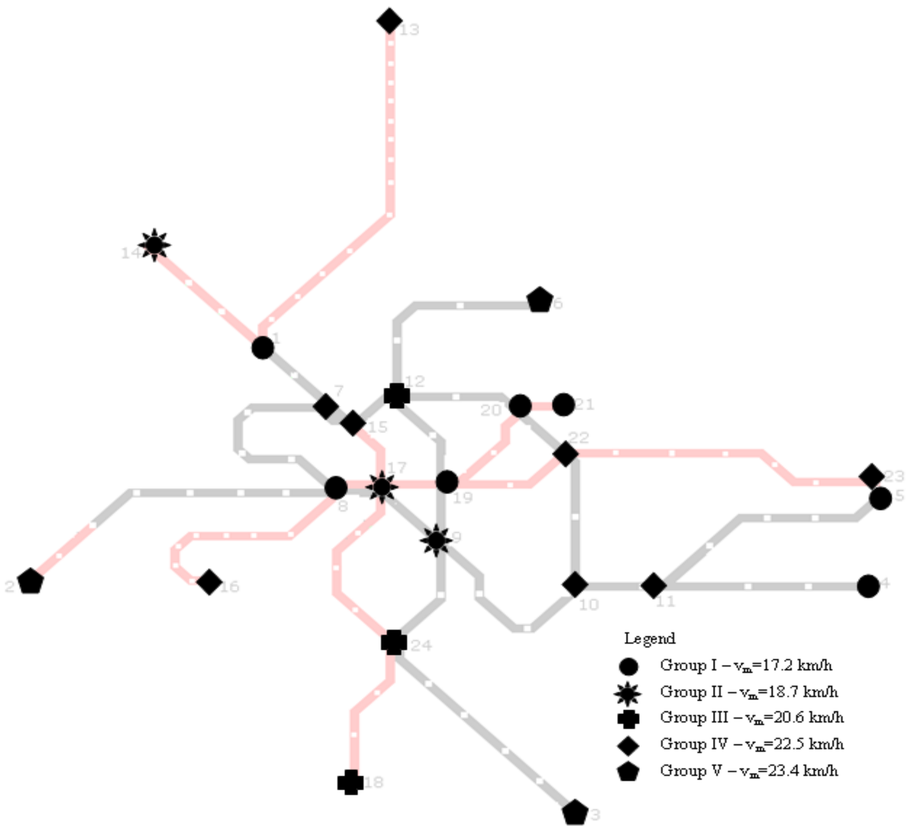

Figure 4 – Izoaccessibility (for $\overline{v}_i$ values)

Generalized accessibility

As a measure of the relative importance of the nodes given by network's topology, the generalized accessibility [5, 7, 9], together with the other quantitative measures of network properties, completes the studied network characterization. Starting from the direct accessibility matrix, M, for the existing network, $M^2, M^3, \ldots, M^p$ and nodal vectors, direct accessibility vectors N_1 and N_i, for $i = \overline{1,5}$ were determined ($p = 5$, network's diameter). Adding them (N_i) gave us the generalized accessibility vector N_g (table 3) and n_g values, obtained by dividing N_g to $N_g^{max} = 420$, for the existing and the extended network.

Both for the existing and for the projected network one can see that the hierarchy of the nodes within the network is clearer as the nodal vector has a higher rank. The expected changes in network's configuration modify nodes' hierarchy. If in the present situation 9 and 12 nodes hold the best positions, in the future network they would be gained by 17 and 19 nodes.

2.7 Shimbel accessibility

Unlike generalized accessibility, the Shimbel accessibility takes into account only the direct links between the nodes [5, 7, 9]. Redundant links with repeated returns at origin and/or destination node are eliminated.

Shimbel accessibility vector (signifying the number of sequences – links involved in the connexion from that node to all the other nodes of the graph) emphasizes the dominant positions of the nodes 9, 10 and 12 for the present situation and nodes 17 and 19 for the projected network (table 3).

Table 3 – Shimbel accessibility and generalized accessibility indexes

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
N_i (2010)	35	35	31	37	37	31	25	25	**21**	**21**	27	**21**												
N_i/N_g^{max} (2010)	0.23	0.23	0.34	0.15	0.15	0.34	0.66	0.66	1.00	0.84	0.43	1.00												
N_i (2030)	90	86	89	108	108	89	72	64	*58*	68	86	67	112	112	62	86	*54*	89	*59*	66	88	69	91	67
N_i/N_g^{max} (2030)	0.09	0.11	0.15	0.04	0.04	0.18	0.28	0.38	0.79	0.43	0.14	0.65	0.03	0.03	0.50	0.11	0.89	0.15	1.00	0.68	0.19	0.63	0.17	0.55

2.8 Nodal accessibility

The generalized and Shimbel accessibility took into account only network's topology while the nodal accessibility [5, 7, 9] differentiate network's nodes from the point of view of length, travel time and transfer cost for all the links between nodes' graph associated to the network (the links of the graph have geometrical and technical-functional characteristics associated, which integrates infrastructure aspects and technology performances of the network). Both for the existing and the projected network, the nodal accessibility, determined in relation to the transfer time between the nodes, led to the nodal accessibility vectors from table 4.

Table 4 – Nodal accessibility vectors

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Travel time (present)	520	480	536	566	566	409	433	369	351	286	304	278												
Travel time (2030)	772	993	921	1284	1284	725	485	618	499	545	599	489	1428	922	440	841	502	853	525	571	637	456	720	597

Conclusions

For the actual case of a large city, it was proven that the correlations between high capacity public urban transport and urban area can be quantitative characterized.

Focused both on the accessibility given by the infrastructure and on the one assured by the global offer of the public transport system (including operating technologies of different operators), the research can be further developed with attractiveness evaluations (as an expression of the specificity of the potential need for population mobility in a certain urban area) in relation to a certain development stage of high capacity public urban transport.

The results, by the discrepancies emphasized in covering the territory with high capacity public transport offer, are appropriate to developing infrastructures and/or transport technologies and also for land use planners that aim spatial development with consequences in modifying the need for social mobility within urban territory.

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