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REVEAL OF CRITICAL POINTS OF THE URBAN TRACK-BASED PUBLIC TRANSPORT NETWORKS WITH NETWORK SCIENCE METHODS

A VÁROSI KÖTÖTTPÁLYÁS KÖZLEKEDÉSI HÁLÓZATOK KRITIKUS PONTJAINAK FELTÁRÁSA HÁLÓZATUDOMÁNYI MÓDSZEREKKEL

SZILÁGYI, Győző Attila

(ORCID: 0000-0002-3294-6760)

szilagyi@strategiakutatas.hu

Abstract

The aim of this research was to explore the topological characteristics of the public transport network of the examined big cities and to show the vulnerabilities, on the basis of this, to take strategic decisions, which increase the robustness of the network. In this frame five big cities, Washington, London, Paris, Vienna and Budapest track-based community networks were compared, with network analysis method. The research drew attention to an interesting thing. It can be thought that the most important points in the urban public transport are always the central big stations, where a great number of lines meet. The research points out that these are not necessarily the most crowded nodes from robustness point of view, and the involvement of the urban railways into the urban public network would increase the robustness of the network. If those urban railway lines played an active role in the urban transport system, the load of the central lines would drop significantly and along with that the robustness of the whole system would rise not only against targeted terror attacks but against accidental technical disturbances as well.

Keywords: *public transport, network topology, network robustness, critical infrastructure protection*

Absztrakt

Jelen kutatás célja az volt, hogy feltárja a vizsgált nagyvárosok közösségi közlekedési hálózatainak topológiai tulajdonságait és megmutassa azok sebezhető pontjait, hogy erre alapozva olyan stratégiai döntéseket lehessen hozni, amik növelik a hálózat robosztusságát. Ennek keretében öt nagyváros Washington, London, Paris, Bécs és Budapest kötöttpályás közösségi hálózata lett összehasonlítva, hálózatelméleti módszerekkel. A kutatás érdekes dologra hívta fel a figyelmet. Azt gondolhatnánk, hogy a legfontosabb pontok egy város közösségi közlekedésében mindig a centrumban lévő, nagy állomások, ahol több vonal találkozik. A kutatás rámutatott, hogy robosztusság szempontjából nem feltétlen ezek a legfrekventáltabb pontok, és hogy a városi vasútvonalak bevonása a városi közösségi közlekedésbe növeli a hálózat robosztusságát. Ha ezek a városi vasúti vonalak aktív szerepet kapnának a városi közlekedésben, akkor jelentősen csökkenne a belső vonalak terheltsége és ezzel együtt nőne a teljes rendszer robosztussága is, nem csak a célzott terrortámadásokkal szemben, de a véletlen műszaki zavarokkal szemben is.

Kulcsszavak: *közösségi közlekedés, hálózati topológia, hálózati robosztusság, kritikus infrastruktúra védelem*

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INTRODUCTION

Today it is increasingly common, that the public transport junctions of the big cities become targets of terror attacks. These junctions are typically crowded areas of the urban public transport network, where many lines meet, provide transfer opportunity for the passengers. In this kind of junctions can also be found typically the stations of the track-based transport. If this kind of junction is a target of a terror attack, temporary shutdown does not only involve the given line and the stations that are directly affected [1]. The track-based transport is particularly sensitive to the terror attacks, what can be traced back to their technical characteristics. Attacks can be coordinated more easily in place and time, like in the case of other vehicles. Such terror attacks were in Madrid on the 11th of March 2004 and in Mumbai on the 11th of July 2006. In both cases the urban track-based network was attacked. The different lines and stations of the public transport linked to a complex joint network [2], in such network a drop out of certain hubs may have severe impact on faraway not directly connected lines as well. These spillover effects can be modeled by network analysis methods [3]. Having obtained these results it is possible to reduce the risk of closing down the whole system, to increase the capability of resistance of the whole network, the so-called robustness. For transport network, this means from the point of view of operational safety, the whole public transport system's operational safety can be increased by better protection of crowded places. An attack against the track-based transport of a big city may affect the operation of the whole country and can cause confusion in the whole society [4]. Though the video surveillance of stations and track sections can be technically solved, but the examination of the personal belongings of passengers is not feasible. Although technical devices are available, they are not ideal neither passenger traffic nor in economic terms to control so many passengers. Based on the results of the research and knowing the topological characteristics of the track-based network such kind of network development can be created using network science methods that consequentially increases the network's resistance against targeted attacks.

RESEARCH GOALS

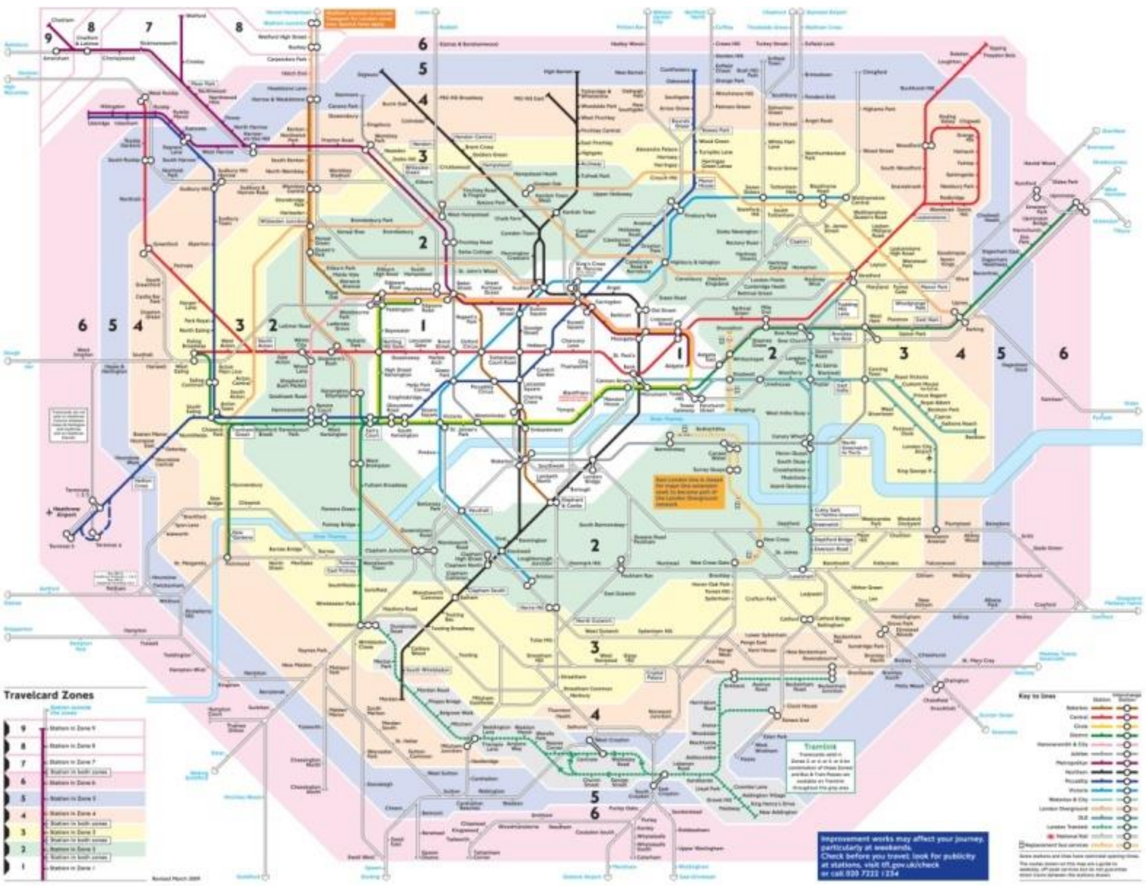
How resistant is the public transport network of a big city for the intentional failures or random attacks? What are the key elements of the network from the perspective of network robust? How does the loss of the parts of transport change the topological features of the network?

The behavior and the growth of the network to the intentional or accidental disturbance can be deduced from the topological characteristics of a network [5]. The aim of the research was to explore the topological characteristics of the urban track-based public transport network of the examined big cities and to show the vulnerabilities, on the basis of this, to take strategic decisions, which increase the robustness of the network. The research also aimed to reveal topological similarities and differences on urban track-based public transport network of the big cities of different areas, population and transport culture. Besides revealing characteristics features of the urban track-based public transport network of different cities, the comparison was made between the quantitative characteristics of certain networks. The aim of the research by this was to reveal that different network analysis provide different safety information in case of transport network analysis, so it is worth taking into consideration more network indicators in case of safety developments. Therefore the aim of the present study is to contribute to the development of the domestic risk management methodology of the track-based transport networks.

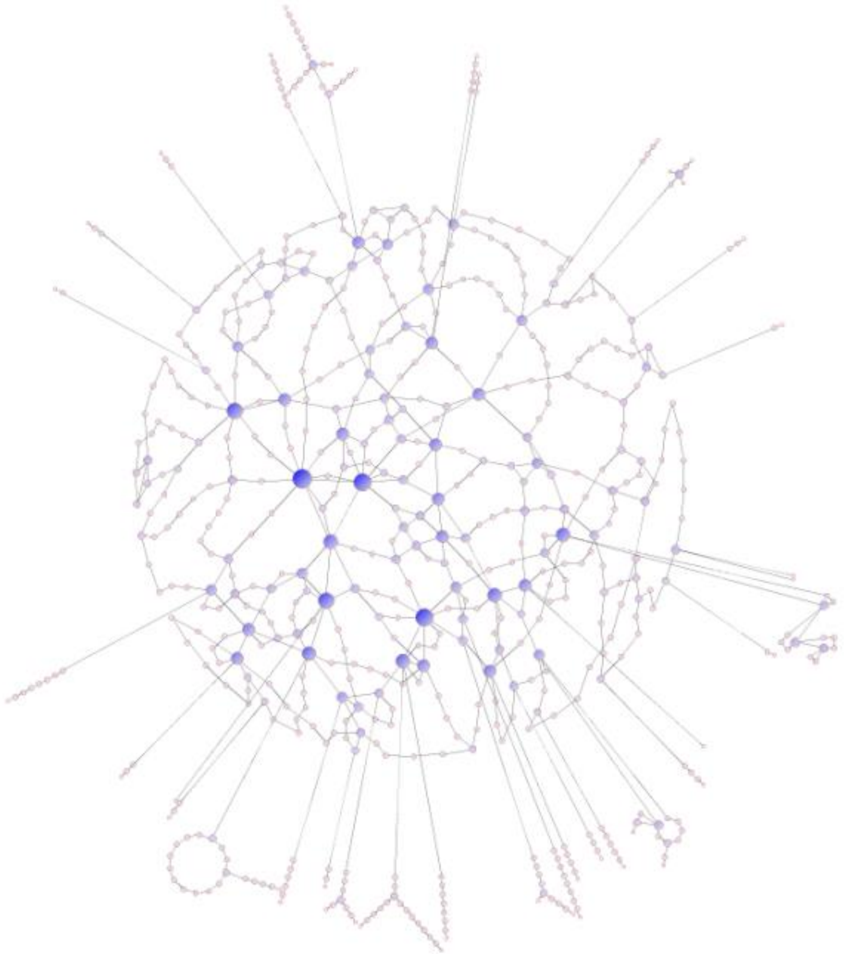
EXAMINED CITIES AND DATA

In the research five big cities, Washington, London, Paris, Vienna and Budapest track-based community networks were compared. The criteria for the selection included comparing public city networks of different size, area and population. The research was focused exclusively on the track-based public transport network. In this case, urban transport network refers to the network of transport routes, namely the tracks. The reason why the research was confined to this subset of the whole public transport network was that the track-based and bus network are different from the aspect of vulnerability. In the case of an attack affecting a part of the bus network, bus routes can be replaced easily and quickly by operating routes on other streets of the city and as a result of this, the service of the system can be partly restored [6]. Fast and partial restoration in the event of track-based network disruption may require a much longer time period, hence the track-based network is more vulnerable to attacks than the bus network [7]. The mapping included all the stations and lines of the track-based network located within the city's administrative boundaries in the research, accordingly also the tram, the subway and the rail network parts within the city. If the line stretched beyond the administrative boundaries, only the stations within the administrative boundaries were taken into account.

The track-based community transport network of the examined big cities was mapped on an undirected graph. The mapping was based on the public maps issued by companies operating the network by using network diagram and analyzer software (Figure 1).



(a)



(b)

Figure 1. The guide of based-track public transport network of London (a) [20] and the network mapping of it (b) (Own made figure.)

At the mapping the tracks that run parallel or on the same line between two stations were considered as only one edge. At the connection of different routes the station was mapped as an only one node, if the stations were not located directly next to each other, but according to the official map they can be reached in a few minutes' walk. These possibilities are marked on the guide, the certain stations are connected by an edge used for that.

Typically there are lines in the examined cities, where it is possible to travel in both directions between the adjacent stations. There are also solutions where it is possible to travel only in one direction on the route in a large number of stations. Example for that is one part of the Madrid subway system. Therefore the research involves only the analysis of the community transport system of the cities, where such stages are not typical, or only some stations at the end of the line are affected, so the network indicator values are only negligibly modified by them.

RESEARCH METHODOLOGY

Network analysis methods were applied in the research. The tracked-based public transport network was mapped into a network model, whose elements are the stations and the tracks sections between the stations. The nodes of the network are the stations and the tracks between them are the edges. At the mapping it was not considered which stations have turning back possibility therefore the mapping is the simplified model of the real network. The analysis was carried out in these networks.

The quantitative analysis

Firstly, the generally typical quantitative indicators were revealed for the given network. The number of the nodes is equal to the number of the stations, the number of the edges shows how many tracks connect the stations. The average degree shows how many direct connections a node has with neighbor nodes in average [8]. The greater this number is, the more complex the network is. In this case, it may be interpreted how many track connections a station has to other stations in the given city on average. The diameter of the network is the longest path of the shortest paths between the nodes [9]. The topological characteristics may be concluded from the diameter of the network by comparing the real diameter to the calculated diameter. It can be shown whether the network is random network or small world [10] topology network by calculated diameter. If the real diameter and the calculated diameter have almost the same value, it indicates that the network has a small-world topology. If the real diameter is much bigger than the calculated diameter it indicates that it is a random network. To obtain the calculated diameter the number of vertices *(N)* logarithm with the average degree number *(k)* logarithm (1) were contrasted.

$$d_{calc} \approx \frac{\ln N}{\ln\langle k \rangle} \tag{1}$$

Density is the indicator of the network complexity (2). The density describes the portion of the edges in the network and the edges in the complete graph of the given network, namely how close the network is to complete graph [11]. The number of possible edges in the complete network is *N(N-1)*. The higher the D density is the more complex network we have.

$$D = \frac{2E}{N(N-1)} \tag{2}$$

Modularity is the indicator of the communities within the network [12]. With the help of it the modularity of the network can be pictured. The higher modularity signs that there are more edges in the modules than between the modules. The calculation of the modularity of the network shows the equation (3) where the e_{ii} is the possibility of an edge in i module, and a_i is the possibility that an edge connects the given module with other modules.

$$Q = \sum_{i=1}^{k}\left(e_{ii} - a_i^2\right) \tag{3}$$

The average clustering coefficient [13] indicates how embedded a node is in their neighborhood. This is also an indicator for topological characteristics of the network. The local clustering coefficient C_i of a node gives the density degree of the edges E_i between i node and its neighbor k_i. (4). If this value is *0*, it means there are not any connections between the node's neighbors. If this value is 1, it means that any neighbors of the i node are connected to each other. The average clustering coefficient is the average of the network nodes, the local clustering coefficient. The greater value the average clustering coefficient has, the more similar to the small-world type network is.

$$C_i = \frac{2\langle E_i \rangle}{k_i(k_i - 1)} \tag{4}$$

The average path length (5) measures the average shortest lengths between the nodes in the network [14], namely how many steps away are two randomly selected nodes from each other on average.

$$l_{ave} = \frac{1}{N(N-1)} \cdot \sum_{i \neq j} d(v_i, v_j) \tag{5}$$

The average path in the random networks is higher than in the small-world type networks therefore this quality indicator refers to the type of the examined network.

The topological analysis

In the course of the topological analyses, one of the parameters of the examined public transport network was the betweenness-centrality [15]. This indicator shows that how many shortest paths of the total paths go through a specific node in the network. The equation (6) shows the calculation of betweenness-centrality.

$$C_b(v) = \sum_{i \neq k} \frac{p_{ij}(v)}{p_{ij}} \tag{6}$$

In the topological analysis, the degree distribution of the networks [16] was examined. The concept of degree-distribution was introduced by Erdős and Rényi in the course of random graph examination [17]. Knowing this, the topological nature of the network can be concluded, therefore this is one of the most important indicators in the field of the network research. It shows the frequency of occurrence of the different degree nodes N_k in the network (7).

$$p_k = \frac{N_k}{N} \tag{7}$$

The degree distribution of the random, the scale-free and the small-world networks are different. The random networks follow the Poisson distribution, the degree-distribution of the scale-free and the small-world network can be described by a power function.

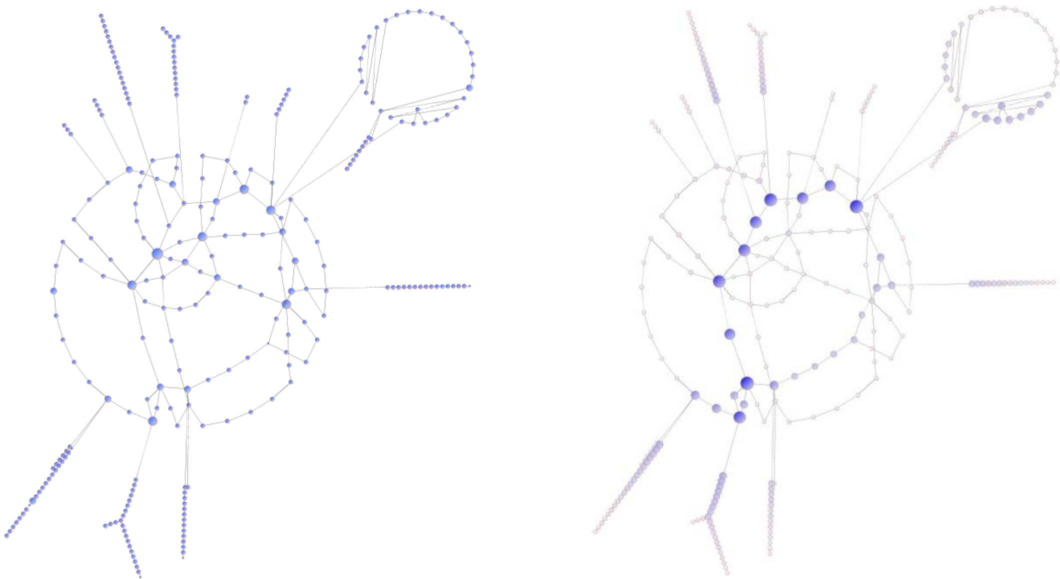
RESULTS

Among the quantitative indicators of the examined public networks it can be seen in the case of average degree that all cities' values are greater than *2*, but less than *2,5* (Table 1). This indicates that the track-based public networks typically comprise many chain subgraphs. All the nodes between the two last nodes in the chains have degree *2*. In fact, these are tracks without branches connecting many consecutive stations. This is a typical characteristic of the track-based networks. From the perspective of network theory, this with the low clusters indicates that the examined network has greater similarity to random networks than to scale-free networks topologically.

	Budapest	London	Paris	Wien	Washington
area (km2)	525,2	1572	105,4	414,6	177
nodes	378	609	436	270	115
edges	434	736	460	293	137
average degree	2,296	2,417	2,11	2,17	2,383
real diameter	34	34	41	51	32
calculated diameter {d}	7,14	7,27	8,14	7,23	5,46
density	0,006	0,004	0,005	0,008	0,021
modularity	0,82	0,835	0,869	0,828	0,73
average clustering coeff.	0,002	0,036	0,004	0,003	0,05
average path lenght	11,355	12,63	17,034	16,631	10,133

Table 1. The quantitative results of the examined public transport networks

Comparing the real diameter of the networks it can be seen that different cities' transport networks show great resemblance also in this index number with the values between *32-41*. An exception is Vienna, where the value is *51*, resulting from that the proportion of the branch lines is much higher and more complex in Vienna networks than in other cities compared to central component (Figure 2).

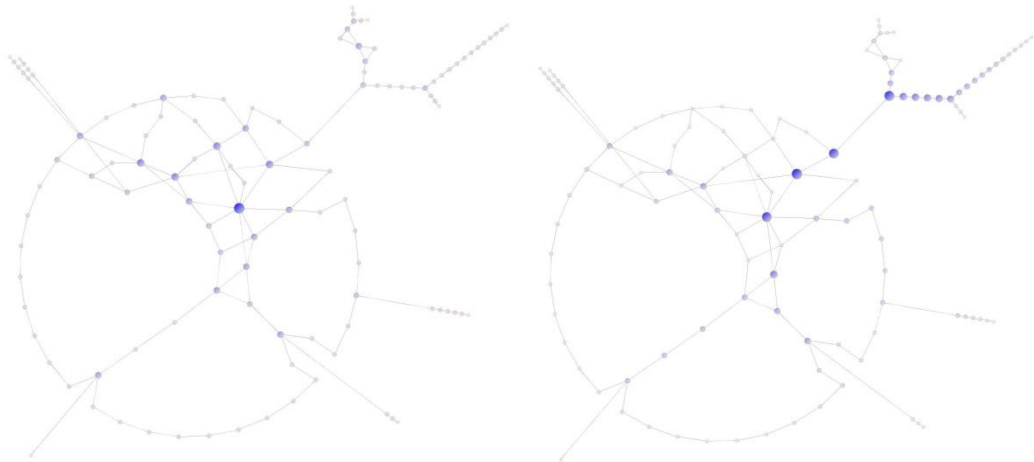


(a) (b)

Figure 2. Public transport network of Wien by degree-centrality (a) and betweenness-centrality (b) (Own made figures.)

Comparing the real and the calculated diameter, it can be seen that there are significant differences between them. This result also confirms that the examined networks are not scale-free type networks. The same may be concluded from the low cluster coefficient as well, as greater cluster coefficient is typical in the scale-free type networks. The values of the average path length show in that direction also. From this point of view, we obtain the same values in national power electronics network, which rather shows a random network topology than a scale-free type. From the quantitative analysis of the examined networks it can be concluded that the tracked-based public transport networks of the examined cities typically have random network topology. From the aspect of safety operations, the random networks behave differently than the scale-free networks [18]. The scale-free networks are robust against accidental disturbance, but if the attack is targeted to the biggest hub, the scale-free networks collapse quickly. The collapse of a random network, dissolution into separate parts does not happen gradually. Removal of some nodes has very little impact on the network.

On the other hand, when the number of attacked and eliminated nodes reaches the threshold, the networks fall apart immediately into many isolated, small-sized subgraphs, where the connection between them ends. Therefore it is worth taking the topological characteristics into consideration in the defense strategy against intentional attacks to the urban transport network. One of the most important and frequent indicators of the network theory analysis is the degree-centrality, that shows how many connections the given node of the network has with the other nodes. However an other indicator was applied in the research, the betweenness-centrality. If we carry out both analyses on a network, the importance of the nodes will be different.



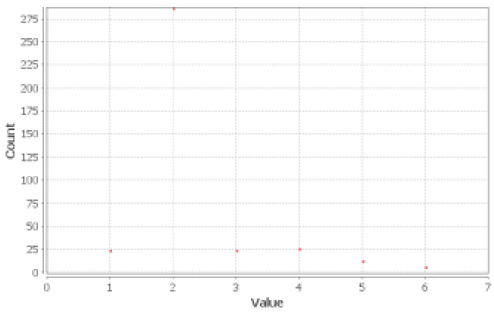
(a) (b)

Figure 3. In a network the degree-centrality (a) and the betweennees-centrality (b) of nodes can be different. (In the picture the network of Washington can be seen.) (Own made figures.)

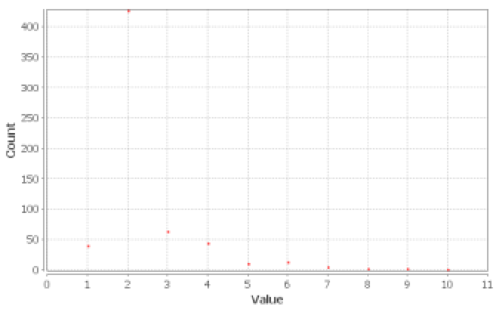
It is clearly visible in the Figure 3 that other nodes have greater centrality value in the network as a result of the two analyses; other nodes have greater centrality value if the degree centrality is examined and other nodes have greater centrality value if we examine the robustness. If we find nodes, that have great centrality referring to both, those are the nodes that play particularly important roles from robustness point of view.

As the betweenness-centrality based on the shortest way passing through the nodes gives the weight of the nodes, this analysis shows which nodes are important from the aspect of flow. While the degree-centrality provides useful information about the static network structure, the betweenness-centrality weights the nodes according to possible flow aspects. The flow of people and the possible flows in a city urban transport give the real weight of a node in the network. That was the reason that betweenness-centrality analysis was carried out in the analysis.

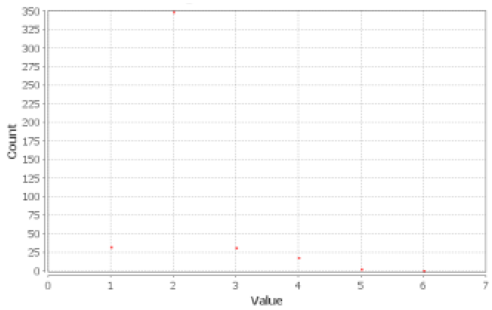
The degree-distribution analysis showed similar results in the case of every city. The degree-distributions of networks show Poisson-distribution what confirms that we have random topology networks (Figure 4). Namely in the scale-free networks the degree-distribution shows power-low distribution.



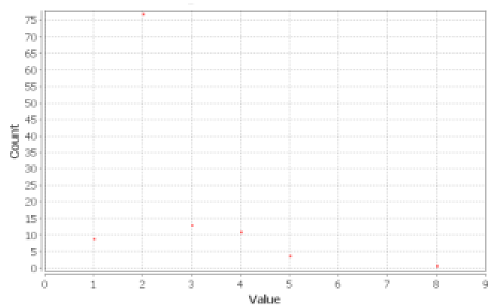
(a) Budapest



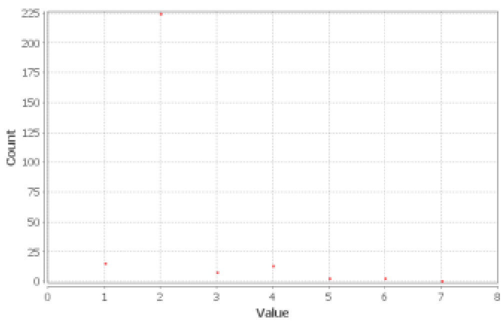
(b) London



(c) Paris



(d) Washington

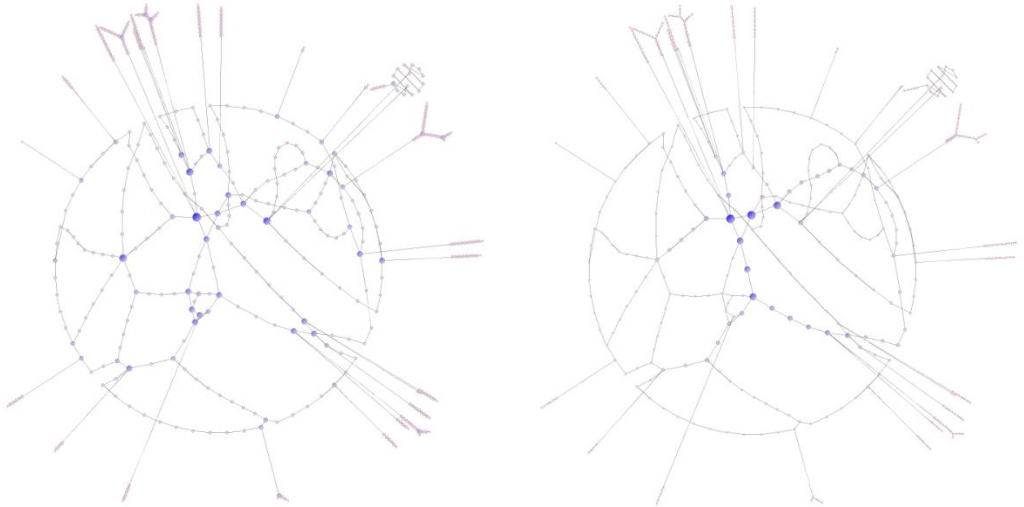


(e) Wien

Figure 4. The degree-distributions of the different city public transport networks.

The research drew attention to an interesting thing. At the examined tracked-based public transport networks railway hubs operating within the city appeared as high centrality node. Accordingly, the track sections between the suburban districts and the track sections between the city center and the suburban districts play an important role from the perspective of the flow and robustness. We may think that the most important hubs in the urban public transport are always the central big stations, where a great number of lines meet. The research points out that these are not necessarily the most crowded nodes from robustness point of view [19]. Although, in the case of attack the loss of these nodes may cause a severe disturbance in the network, but the network could operate, the flows would be replaced, in a longer way, though, but the lost nodes would be avoided.

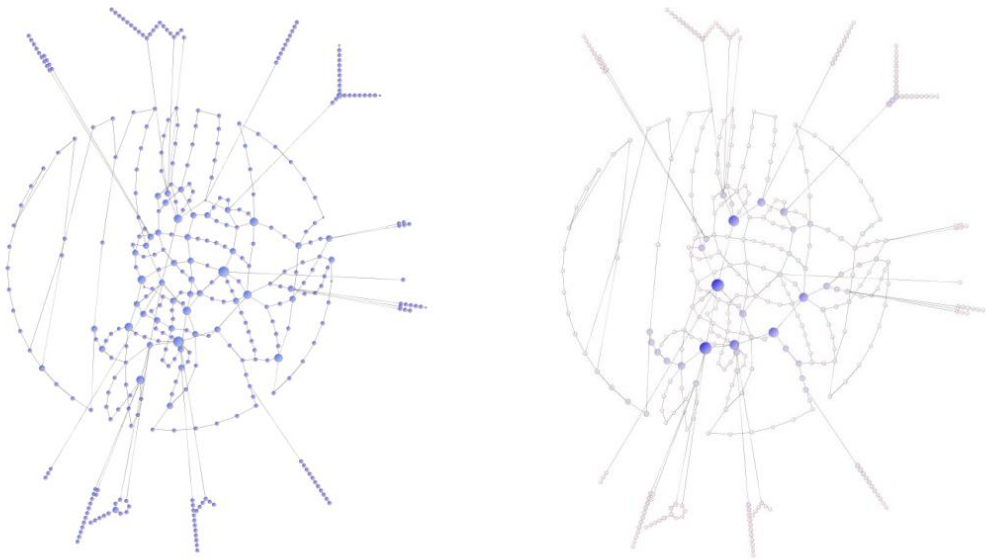
In this regard the public transport network of Paris is very interesting. The station with highest degree-centrality and betweenness-centrality in Paris is the Gare du Nord rail station in the city centre. From security and safety aspects it means that the Gare du Nord station is the most important station because a targeted attack against this station could cause a high level of chaos in the whole network in itself (Figure 5).



(a) (b)

Figure 5. Public transport network of Paris by degree-centrality (a) and betweenness-centrality (b) (Own made figures.)

The other result of the analysis is that the involvement of the urban railways into the urban public network would increase the robustness of the network. In the cities where the railway network became the active part of the public transport, the load of junction stations of the center decreases, or the load is dispersed evenly in the whole network. This can be seen in the case of Budapest on Figure 6.



(a) (b)

Figure 6. Public transport network of Budapest by degree-centrality (a) and betweenness-centrality (b) (Own made figures.)

The greatest centrality nodes are not the central subway stations, where more lines meet, but the railway stations in the suburb. For example the biggest city station Deák Ferenc tér is only the 36th. The Ferencvárosi pályaudvar has the highest betweenness-centrality and the first three on the list are also rail stations. In the first ten the three biggest rail stations of Budapest can be found (Table 2).

	Station	Betweenness-centrality
1	Ferencváros vasútállomás	0.34
2	Kőbánya-Kispest	0.33
3	Kelenföld vasútállomás	0.27
4	Kőbánya alsó	0.23
5	Zugló vasútállomás	0.23
6	Nyugati pályudvar	0.21
7	Déli pályaudvar	0.16
8	Szél Kálmán tér	0.15
9	Határ út	0.13
10	Keleti pályaudvar	0.12

Table 2. The highest betweenness-centrality stations of Budapest

If those urban railway lines played an active role in the urban transport system, the load of the central lines would drop significantly and along with that the robustness of the whole system would rise not only against targeted attacks but against accidental technical disturbances as well.

CONCLUSIONS

During the research the vulnerability points of the public transport networks of the cities were revealed with network analysis methods. In the examination the quantitative and topology indicators were useful. The research revealed that the topological characteristics of the track-based urban public transports show the feature of the random network. It follows that the track-based city public transport networks are more robust against the targeted attacks than the scale-free networks. The knowledge of the topological characteristics of the urban public networks can be used in the area of indirect protection. To this end attention should be paid also to the betweenness-centrality analysis in the analysis of the urban public transport networks. Knowing the betweenness-centrality the points of the public transport networks that are the most important from security and safety aspects can be identified. Knowing the crowded hubs which are important from the flow point of view may help in the urban transport development, and indicates, that the higher degree involvement of the intramural railway transport into the system improves the operational security and decreases the traffic-flow loads on the central stations.

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