IOP Conf. Series: Journal of Physics: Conf. Series **803** (2017) 012165 doi:10.1088/1742-6596/803/1/012165

General topologic environment of the Russian railway network

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Abstract. Basic structural properties of Russian railways are explored through the complex network scope. We imply ontology where railway stations portray nodes, while links are represented by trains plying among stations. The information L- network model founded on route is built and its topology is compared with Indian and Pakistan analogues. The network model demonstrates small world properties and its assortative nature. Structural vulnerability is assessed for random attacks, and those on degree and strength targets. Taking into account series of the node centralities, the most important sites are identified as those that could help in clarifying the sensitive points in the network. These sites should be in the focus of pre-protection and post hazard recovery. Also, a P-model is touched and an S- and H- model idea is proposed for further analysis of transportation networks.

Introduction
Based on the complex network theory, a topological analysis of transportation systems becomes a common tool and has been applied for airlines, metro, bus-lines and others in many countries [1-3]. The network analysis provides a platform for development of national and global mobilities to support effective economies and democratic governance. However there is a lack in such studies concerning Russian transportation systems, i.e. the Russian railway (RR) system. Now Russia has about 128000 kilometers of the common-carrier railway network. The Russian railway average length of haul is estimated second on the planet; only the US tied with Canada are behind it. As neither statistics is available for private transportation, nor the amount of passenger traffic that is transferred by rail, nor the known number of stations. In its population, Russia is of the same order as Pakistan. If we compare it with Pakistan railway network, the latter is a moderate one with over 620 stations and a 7791-kilometer track [4]. India, which is more numerous in people, has a railway network with the dense structure of more than 8000 stations where the number of trains plying in this network is close to 10 000 [5].

Models and methods
The study proposes a description of Russian Railways in the form of complex network models. Similar to [5], all the models of the RR network are represented as undirected graph G: $G = \langle V, E \rangle$

The set of vertices (nodes) reflects the stations: $V = \{v_1, v_2, ...v_i\}$.

A neighborhood of adjacent stations in the identified routes serves as a set of edges (links):

$$E = \left\{ L_{ij} = (v_i, v_j) \middle| v_i, v_j \in V \right\}.$$

For charting, we use Matplotlib package. For data composition in a network form and calculation of the network metrics, the igraph package is utilized. To render the network, the graph-tool has been found as an effective instrument .

The following metrics were calculated for each node.

Connectivity - the number of links a node.

Strength - each node (station) strength is measured by its traffic volume in terms of the total number of trains that originate or terminate at that node.

Closeness centrality is

$$C(x) = \frac{1}{\sum_y d(y,x)},$$

where $d(y,x)$ is the shortest distance from current node x to any other node y .

Betweenness centrality is

$$C_B(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}},$$

where σ_{st} is the shortest distance between nodes s and t, and $\sigma_{st}(v)$ is a portion of them passing through current node v .

Eigenvector centrality is a relative score assigned to each node in the network, so that the score is higher when the node connections correspond to highly connected nodes.

For given graph $G := (V, E)$ with a $|V|$ number of vertices, let $A = (a_{v,t})$ be the adjacency matrix, i.e. $a_{v,t} = 1$ if vertex v is linked to vertex t and $a_{v,t} = 0$.

One defines the relative centrality score of vertex v as

$$x_v = \frac{1}{\lambda} \sum_{t \in M(v)} x_t = \frac{1}{\lambda} \sum_{t \in G} a_{v,t} x_t \ ,$$

where $M(v)$ is a set of the neighbors of v, and λ is constant. In addition, this can be rewritten in a vector notation as the eigenvector equation: $Ax = \lambda x$

The relative size of the maximum cluster (maximum connected component) has been applied to assess damage initiated by attacks or failures (untargeted attacks) .

According to [6], transportation networks are often described either in L-space or in P-space configuration formats. In both formats, node sets remain equivalent, for example, bus stops, metro or railway stations, whereas the patterns of the link sets are different. In the L-space format, each pair of sequential neighboring nodes lying along a route is considered to be connected by a link. Contrary P-space envisages that all nodes belonging to the same route are connected by links and thus compose a clique. Thus, the L-space format is effective in understanding the relationship between the stations (nodes) in general, and P-space promotes studying the transfers between different routes in the transportation system (Figure 1).

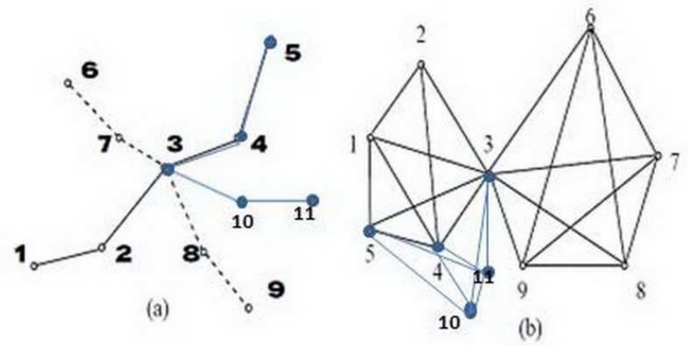

Figure 1. L-(a) and P- (b) configuration formats

Results

To construct the network models, we collected (in the Internet) publicly available data about the passenger train routes for RR. The model networks (L- and P-) contain 2271 stations – nodes and 3467 trains, of the 85300-kilometer track. The total number of 784 routes is analyzed.

2.1. L-space model.

The model gives assortativity: 0.162599573212.

Visualization of the network model presented in Figure 2 is done with the line layout. We calculate community distribution (Figure 3) according to the algorithm [7].

Figure 4 presents the distribution of RR network connectivity. The figure shows that the network nodes include hubs with high connectivity and the network obeys somewhat to a well-known power law with the preferred attachment process [8]. In Table 1, there are selected nodes of 25 highest connectivity. All other calculated metrics (strength; closeness , betweenness , and eigenvector centralities) also are given. These nodes should be in the focus of pre-protection and post hazard recovery from structural damage attacks. .

Figure 5 shows the results of calculating the relative size of the maximum cluster network model of railways under targeted attacks taking into account 3 various strategies. The strategy indicated in the chart legend as the "Random" is due to removal of 5 nodes randomly at every step. Similarly, other strategies, such as "Degree" were selected and excluded nodes with highest connectivity (hubs), the "Strength" legend reflects sites with the most traffic volume. "Strength" is defined with the idea that the traffic volume may be a useful metric for understanding damage and for further ranking nodes to provide effective recovery. As the graph portrays, removal of hubs ("Degree" strategy) is the most effective strategy on the side of the attack. Researchers have already drawn attention to the fact that many real-world networks are vulnerable to such targeted attacks, and this is in line with their scale-free nature [8]. It might be inferred that in case of limited available resources, hubs should be protected primarily.

Also, we compare our results with the data for the Indian railway network containing the important trains and stations in India. The latter was built for the system of L=5579 trains covering N=5587 stations [5].

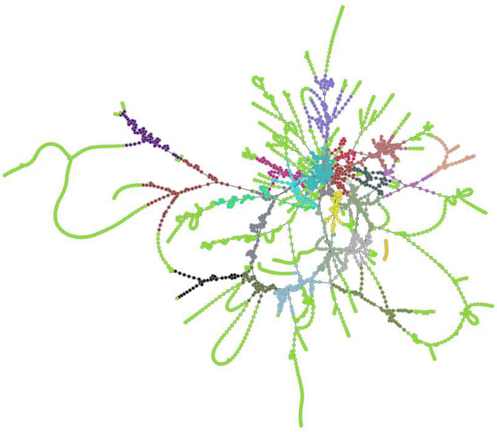

Figure 2. The line layout of the Russian railway network in the L-space model.

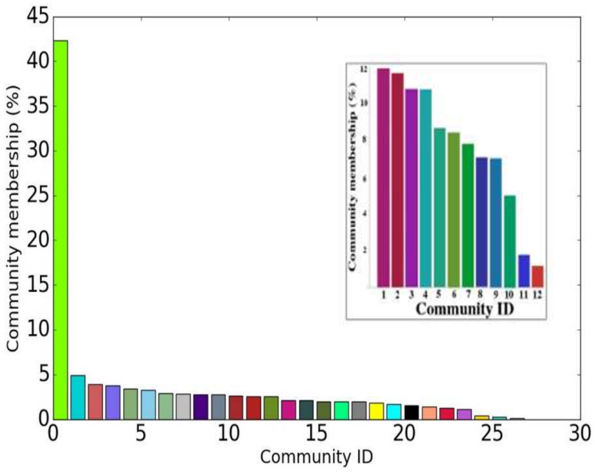

Figure 3. Connectivity distribution in the L-space model of the RR network in comparison with that of India [5] (in the window).

Table 1. Characteristics of 25 nodes with the highest connectivity within the L-space model of the RR network

#	Node	Degree	Strength	ClosenessCentrality	Betweenness Centrality	EigenvectorCentrality
1	Moskva	49	426	0.07408987	0.52649223	0.512069006
2	Rjazan'	19	127	0.071504546	0.139893783	0.281376821
3	Syzran'	17	126	0.067321406	0.067705246	0.024491918
4	EkaterinburgPass.	17	126	0.065939615	0.223597415	4.82268E-05
5	ArzamasGorod	16	59	0.068016783	0.009759882	0.048125639
6	Tjumen'	16	106	0.064220939	0.224626434	1.32235E-05
7	Samara	15	118	0.066034356	0.141881498	0.013049924
8	Krasnodar	15	157	0.053749151	0.004395171	0.000756683
9	Ruzaevka	14	44	0.06864916	0.14625009	0.07954355
10	Uzunovo	14	44	0.070587879	0.035770914	0.215260703
11	Rostov	14	210	0.05669064	0.040608564	0.001178662
12	Voronezh	13	146	0.064702513	0.056088366	0.037247557
13	Omsk	13	110	0.060132858	0.222383731	4.16991E-07
14	Kanash-1	13	56	0.066394519	0.023840455	0.019383898
15	Cheljabinsk	13	112	0.06197979	0.093593493	7.47357E-06
16	Syzran'-1	13	69	0.067112757	0.044425468	0.023329617
17	Novosibirsk	12	113	0.056426441	0.099336188	2,62982E-07
18	Rjazan'-2	12	90	0.070632157	0.023894976	0.232870495
19	Bogojavlensk	12	60	0.067283191	0.002339082	0.156282421
20	Novosibirsk-Glavnyj	12	113	0.055838826	0.057502664	2.54897E-07
21	Barabinsk	12	99	0.058147061	0.144444166	2.57547E-07
22	Rossosh'	12	184	0.059566633	0.097034861	0.00214152
23	Rostov-Glavnyj	12	183	0.056687786	0.039603345	0.001097373
24	Tihoretskaja	12	130	0.053799228	0.033740629	0.000467988
25	Bologoe-Moskovskoe	12	87	0.066285083	0.018267561	0.055634464

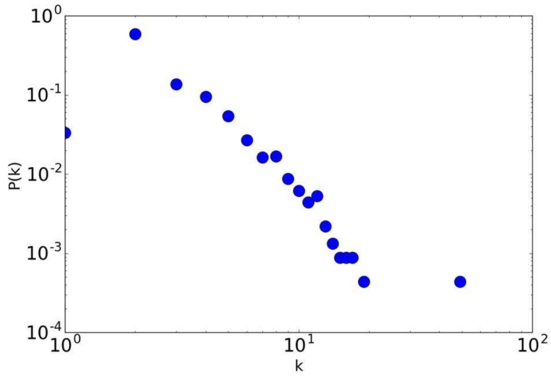

Figure 4. Connectivity distribution in the L-space model of the RR network.

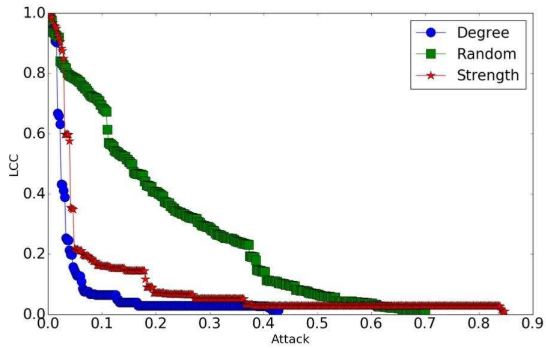

Figure 5. Topological change of the L-space model under attacks (failures).

2.1. The P-space model

The model gives negative assortativity value: -0.033095085101. Visualization of the network cluster which includes 2699 nodes and Edges, 171905 edges (links), is presented in Figure 6.

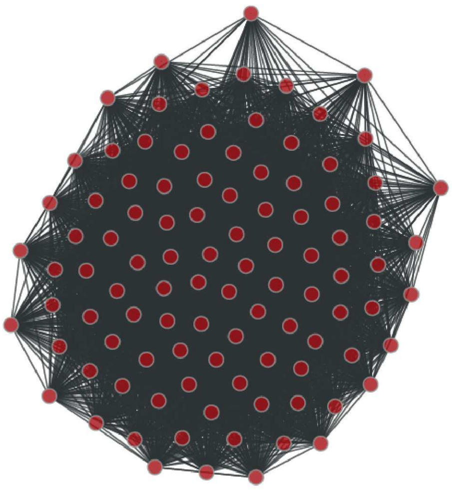

Figure 6. Visualization the RR network in the P-configuration format

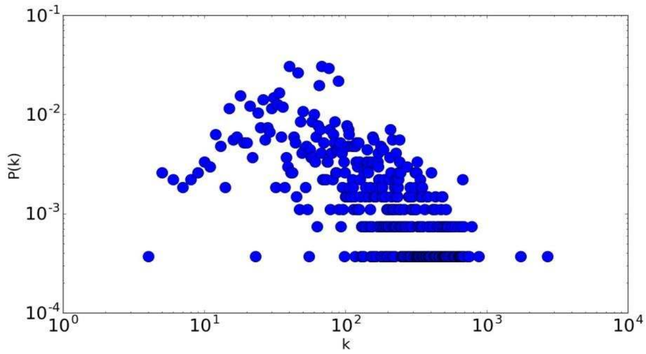

Figure 7. Connectivity distribution in the P-space model

Discussion

The modern transportation network is composed of different means/ways of transportation: railroads, roads and highways, air and sea routs by different types of transportation: trains, trucks, pipes, ships and planes, balloons, airfoil boats and other modern air platforms.

These are hybrid transportation networks. Instead of L- or P-space models, an S-space model, which consists of the stem network [9], might be useful for analysis of the transportation systems of the same nature. Plying in the hybrid transportation system might be covered by combined stem network models [10] in H-space. It is of value that both approaches envisage line changes i.e. to other railway line within S-space or to airline within H-space.

Conclusion

This network ontology and topological analysis are of value per se, but it will also stimulate to invent organization schemes and devices (carriages, facilities) to make changes easier or seamless. The present study builds a new platform for the efficient transportation network designing, planning, protecting, and recovering.

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