METHOD OF FINDING SOLUTIONS TO ENLARGE RAILWAYS

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ABSTRACT

The author justifies the rationality of changing of the exisiting Russian network of interconnected railways [branches of JSC Russian Railways – *ed. note*] by enlarging certain of them under conditions when the level of their technical equipment, automation of management processes and possibilities to consolidate production resources are growing thanks to the advancement of transport and logistics system of globalization of network technologies. The proposed method of rank positioning of railways, selection of optimizing criteria evaluation is tested on systemic and provable examples.

Keywords: *modernization, scientific and technical progress, automated control systems, enlarged railway, methodology, approaches.*

Background. *The trend of reforming the railways in the world [e.g., 1] has been implemented in numerous changes based on rapidly progressing computing facilities and automated systems [e.g., 2], focused on enhancement of competitiveness by developing infrastructure [e.g., 3], optimizing railway network and capacity, and transportation logistics nodes with the account for accessibility [e.g., 4–9]. For Russian railways, the problem of reforming railway network, by means of their enlargement has become in the opinion of the author topical.*

Objective. *The objective of the author is to consider a method of finding solutions of a problem of possible enlargement of some interconnected railways.*

Methods. *The author uses general scientific and engineering methods, comparative analysis, evaluation approach, mathematical apparatus.*

Results.

Problem formulation

Let there be N railways and they are sequentially numbered from 1 to N. Inter-railway correspondence is described by the average matrix $B = ((b_{ij}))$ of train flows per day, where i is the departure railway number, j is the destination railway number, b_{ij} is the average value of train flows from the departure railway i to the destination railway j. The task is to enlarge the railways for more efficient management of train flows. The material basis of reorganization is: 1) significant development of computing facilities used in railway transport, an increase in their number to automate the transportation process; 2) significant growth of automated control systems, which allows to accelerate implementation of transport services; 3) enlargement of the management polygon, thereby unifying a large number of objects under a unified control.

By and large, it is necessary to set a goal in this plan to find the optimal number from the existing composition. As a criterion, it is possible to take, for example, the minimum exchange of trains between railways or the minimum cost of transporting a unit of cargo weight under various restrictions, including a restriction on the amount of freight work. But it is very difficult to implement such a plan. Therefore, we shall confine ourselves to a search for a rational method for finding enlarged railways (ER).

The matrix of correspondence $A = ((a_{ij}))$ (from the i-th railway to the j-th, including the transit train flows from the departure railway to the destination railway per day), corresponds to the initial data for the solution of ER problem. First of all, three requirements must be observed:

1. That is, a train passing through ER cannot even temporarily go beyond its borders to other similar ER.

2. The enlargement of railways should not be too small, so that the effect from it is not very noticeable, and it cannot be too large to threaten the loss of controllability. In other words, the enlargement is intended to correspond to the progress of computing facilities and automated systems that control the transportation processes, that is, to meet the modern growing level of management.

3. All ER by their scale value should not differ sharply from each other.

Information for design

We introduce the indicator «total exchange of train flows within one ER». Proceeding from its meaning, the enlarged railways should not be too different from each other: the maximum of the indicator for all ER cannot exceed its minimum by 1,5–1,9 times. It is necessary that conditional partners and competitors work under more or less similar modes, because it is impossible to achieve the equality of the indicator, because the original railways cannot be cut into parts.

Using the railway atlas for each of the existing fifteen railways (in the research we don't consider the Kaliningrad railway which is not directly interconnected with the network of other branches of the JSC Russian Railways) we determine those adjacent to it (having common boundaries) and write these data in Table 1.

Table 1

Data on contiguity of railways

1	October – Moscow – North
2	Moscow – October – North – Kuibyshev – Gorky
3	Gorky – Moscow – North – Kuibyshev – Sverdlovsk
4	North – October – Gorky – Moscow
5	North-Caucasian – South-East – Privolzhskaya
6	South-East – Moscow – Privolzhskaya – Kuibyshev
7	Privolzhskaya – Kuibyshev – North-Caucasian – South-East
8	Kuibyshev – Moscow – South-East – Privolzhskaya – South Ural – Gorky
9	Sverdlovsk – Gorky – South Ural – West Siberian
10	South Ural – Privolzhskaya – Kuibyshev – Sverdlovsk – West Siberian
11	West Siberian – South Ural – Sverdlovsk – Krasnoyarsk
12	Krasnoyarsk – West Siberian – Zabaikalskaya
13	Zabaikalskaya – Krasnoyarsk – East Siberian
14	East Siberian – Zabaikalskaya – Far East
15	Far East – East Siberian

Table 2

Table of total loading by railways

Number	Name of railway	Total loading on the railway (number of trains per day)
1	West-Siberian (Zsb)	117,1
2	Sverdlovsk (Svr)	68,4
3	South Urals (Yuur)	55,8
4	October (Oct)	52,4
5	Kuibyshev (Kbsh)	50,7
6	South-East (Yuvs)	34,2
7	Moscow (Msc)	34,1
8	North (Sev)	33,1
9	Krasnoyarsk (Krs)	31,9
10	East Siberian (Vsb)	28,93
11	Privolzhskaya (Prv)	28,9
12	Gorky (Grk)	20
13	North-Caucasian (Skv)	16,9
14	Far East (Dvs)	10,1
15	Zabaikalskaya (Zab)	5,6
	Total loading on the network	588,13

Table 3

Total unloading by railways

Number	Name of railway	Total unloading on the railway (number of trains per day)
1	October (Oct)	113,9
2	Moscow (Msc)	70,2
3	North-Caucasian (Skv)	61,3
4	Far East (Dvs)	60,0
5	Sverdlovsk (Svr)	36,2
6	South-East (Yuvs)	32,3
7	South Urals (Yuur)	31,6
8	North (Sev)	25,4
9	West-Siberian (Zsb)	23,7
10	Gorky (Grk)	21,4
11	Privolzhskaya (Prv)	16,8
12	Kuibyshev (Kbsh)	15,6
13	Zabaikalskaya (Zab)	12,0
14	East Siberian (Vsb)	10,7
15	Krasnoyarsk (Krs)	8,3

The source data used are inter-railway cross reference chart of train traffic (trains/day) for 2014. Then we first place all the railways in order of decreasing the total loading – Table 2, and then regarding unloading – Table 3.

Algorithm for allocation of polygons for inter-railway correspondence

1. We will name the number of trains per day according to the data of the inter-railway cross reference chart of train traffic. Train flow is a vector consisting of three components: the number of trains per day, the name of the departure railway, the name of the destination railway.

2. We arrange all the elements of inter-railway cross reference chart of train traffic in descending numbers of trains per day. We call the resulting series a sequence of decreasing train flows.

3. The first step is to take the maximum element of this sequence. On the line that contains it, we determine the railway that sends it (the point of departure), and by the column in which it is located, we name the railway where it goes (destination).

4. From Table 1 of contiguity of railways and the atlas, we find the shortest route (in km) from the departure railway to the destination railway. For brevity, let's call it the polygon of inter-railway correspondence of train traffic, and the flow of trains following this route, the initial train flow from the departure railway to the destination railway.

5. From inter-railway cross reference chart, we find trains that follow the route of the initial train flow (possibly by parts along intermediate roads). We call them intermediate train flows.

6. There are possible train flows that follow the shortest path to the destination railway through the departure railway. Let's call them passing train flows.

7. Taking the initial train traffic flow with all its intermediate and passing variants, we get the total train flow from the departure railway to the destination railway, which can be considered the capacity of the polygon of inter-railway correspondence.

8. We declare that a polygon of inter-railway correspondence of train traffic on the direction «departure railway – destination railway» is allocated and its capacity is determined for the maximum element of inter-railway cross reference chart of train traffic.

9. The second step is to take the next largest element of the sequence of decreasing train traffic, provided that it does not enter the polygon determined by the maximum element of the inter-railway cross reference chart of train traffic. The same condition must be observed for all subsequent selectable elements of the inter-railway cross reference chart. In addition, the next largest element of the sequence of decreasing traffic is taken, provided that its destination railway is not adjacent to it.

10. Repeating points 3–6 of the algorithm for the indicated element, we find the next polygon of inter-railway correspondence of train traffic on the direction «departure railway–destination railway» and its capacity, etc.

11. We place capacities of polygons of inter-railway correspondence of train traffic on the direction «departure railway–destination railway» in descending order.

12. Setting the capacity threshold below which it is not appropriate to take into account the capacities of the polygons, we single out the significant polygons of inter-railway correspondence, which will be further taken into account when forming enlarged railways.

Algorithm for ER formation

1. Let's first consider the case of a network of railways, in which there is a branch, which is a single line along which the railways are located sequentially. On this line, each railway has only two adjacent railways, namely, the railway ahead of it, and the railway located after it. If this line approaches the boundary of the network, then the last railway has only the railway that precedes it. Let's call this arrangement of railways linear. Then the polygon of inter-railways correspondence of train traffic for linear location of railways can be identified in one or several enlarged railways. It depends on the capacity of such a polygon. If the capacity corresponds to modern automated systems, controlling transportation, and the quality of potential managers meets the requirements imposed on the managers of ER, it is advisable to single out this polygon in one enlarged railway. If the capacity is several times greater than the possibility of quality management, then the polygon should be divided into several ER.

2. Let's pass to consideration of branches of a network of railways which contain several lines. In this case, we analyze the destination railways. If one such large railway is loaded with a significant part of the train traffic from different sufficiently large railways, and each of them is adjacent to each other, they can be included in one enlarged railway if it satisfies the requirements imposed on it and its future manager.

3. An enlarged railway can have train flows directed not to a single but to several destination railways.

4. The railway cannot be part of two or more enlarged railways.

5. Point 4 requires careful consideration, since there are different ways in which the railroad can enter the structure of a particular enlarged railway.

6. The most suitable option for the railroad to enter the enlarged one is the option in which the total number of domestic train flows entering each enlarged railway is maximized.

Application of the polygon algorithm

1. We will compile a list of elements in the inter-railway cross reference chart of train traffic in descending order of its value: Zsb $\to$ Dvs = 30, Zsb $\to$ Oct = 27, Svr $\to$ Oct = 21,7, Sev $\to$ Oct = 18,6, Zsb $\to$ Msc =18,3, Yuur $\to$ Svr = 17,8, Prv $\to$ Skv =14,2, Oct $\to$ Sev = 13,2, Zsb $\to$ Yuvs = 12,6, Kbsh $\to$ Skv=11,4, Yuvs $\to$ Msc = 11,4, Yuur $\to$ Kbsh = 10,6, Kbsh $\to$ Oct = 10,4, Msc $\to$ Oct = 9,6, Yuvs $\to$ Skv = 9,1, Zsb$\to$Yuur = 8,9, Grk$\to$Oct = 8,4. Here the figure indicates how many trains depart daily on average in this direction.

2. We will find the maximum element in the inter-railway cross chart of train traffic. In accordance with point 3 of the algorithm, it is the train flow Zsb $\to$ Dvs. The initial train traffic on the direction is 30 trains per day. Intermediate train traffic is 26,6 + 10,9 = 37,5 trains. Passing train flow from all the railways except for Zsb, Krs, Vsb, Zab, follow to Dvs through Zsb, and they comprise 13,9 trains per day. Then the capacity of the train flow Zsb $\to$ Dvs: 30 + 37,5 + 13,9 = 81,4 trains per day.

3. The next descending element in the inter-railway cross chart of train traffic is 27 trains per day. In accordance with point 3 of the algorithm – this is Zsb $\to$ Oct. Intermediate train traffic flows: Yuur $\to$ Oct – 4,7; Svr $\to$ Oct – 21,7; Grk $\to$ Oct – 8,4; Sev $\to$ Oct – 18,6; Zsb $\to$ Grk – 1,5; Zsb $\to$ Sev – 2,3; Yuur $\to$ Grk – 4,1; Yuur $\to$ Sev – 1,2; Svr $\to$ Grk – 5; Svr $\to$ Sev – 2,3. The total intermediate train traffic is 70 trains per day. Passing train traffic – 2,6. And then the capacity of the train flow Krs, Zsb, Yuur, Svr $\to$ Grk, Sev, Oct is 27 + 70 + 2.6 = 99,6 trains per day.

4. In accordance with point 9 of the algorithm for allocating polygons for inter-railway correspondence, the train flows Svr $\to$ Oct (21,7), Grk $\to$ Oct (8,4), Sev $\to$ Oct (18,6) can no longer be used. The next descending element is 18,3 trains per day. In accordance with point 3 of the algorithm – this is Zsb $\to$ Msc. Intermediate train flows: Yuur $\to$ Msc = 3,6, Svr $\to$ Msc = 6,0, Yuur $\to$ Kbsh = 10,6, Kbsh $\to$ Msc = 3,5. In total we have 23,7. Passing train flows: Krs, Vsb, Zab, Dvs $\to$ Msc = 5,3. Then the capacity of the train flow Zsb $\to$ Msc: 18,3 + 23,7 + 5,3 = 47,3 trains per day.

5. The following elements in descending order Yuur $\to$ Svr = 17,8, Prv $\to$ Skv = 14,2, Oct $\to$ Sev = 13,2 cannot be used by virtue of point 9 of the polygon allocation algorithm. It remains to take the element Zsb $\to$ Yuvs. The initial train flow is 12,6. Intermediate total train flow: 1,8 + 1,3 + 2,3 = 5,4. Passing total train flow: 0,3. The capacity of the train flow Zsb $\to$ Yuvs is 18,3. Further, since Yuvs, Prv, Skv are adjacent to each other, it is advisable to consider the total flow from Zsb to the polygon of Yuvs, Prv and Skv. Then it remains to find the capacity of train

flows Zsb → Skv and Zsb → Prv and add them to the capacity of the train flow Zsb → Yuvs. As a result, we get: 18,3 + 30,7 + 6,9 = 55,9.

6. The following elements in descending order: Kbsh → Skv = 11,4 have already been used in point 5; Yuvs → Msc = 11,4 enters the flow South → Msc, which is equal to 18,5, i.e. is too small compared to other train flows; Yuur → Kbsh = 10,6 in the polygon of point 4. Then Kbsh → Oct is included in the polygon (South–North-West): Skv, Prv, Yuvs, Msc, Kbsh → Oct, Sev. First, let's consider the total train flow Svk, Prv, Yuvs, Msc, Kbsh → Oct: 9,6 + 10,4 + 0,7 + 2,8 + 5,4 = 28,9. Then Skv, Prv, Yuvs, Msc, Kbsh → Sev: 1,6 + 0,4 + 1,8 + 0,7 + 1,3 = 5,8. The total train flow is 34,7.

7. Inter-railway train traffic between three adjacent roads Skv, Prv, Yuvs (polygon South) is 36,8 trains/day. A part of the inter-railway train flow of South–Center polygon (Skv, Prv→Sev, Oct) and East–South-West polygon (Krs, Zsb, Yuur → Skv, Yuvs) passes through the polygon. Total inter-railway correspondence is 72,6 trains/day.

8. Average inter-railway train traffic between three adjacent roads Zsb, Yuur, Svr is 43 trains/day. The polygon also accumulates correspondences of the directions: East–North-West (Krs, Zsb → Oct, Zsb → Grk, Zsb → Sev, Yuur → Grk, Yuur → Sev) = 38,7; East–Center (Krs, Zsb → Msc, Kbsh) = 51,2, East–South-West (Krs, Zsb → Prv, Skv, Yuvs) = 39,5. Total inter-railway correspondence is 129,4 trains/day.

Application of ER algorithm

1. We combine two train flows: 1) east to the north-west of the European part of Russia – Krs, Zsb, Yuur, Svr → Grk, Sev, Oct; 2) east to the center of the European part of Russia – Krs, Zsb, Yuur, Svr, Kbsh → Msc. This is advisable because the original railways are almost the same, only to the second train flow a Kbsh flow is added. Another change: final ER should include Msc from the second train flow. Both options are quite natural. Moreover, the flow from Zsb to Oct passes to some extent through Msc. In this regard, Msc is still connected with Grk, Sev, Oct, including the border with all three railways.

The combined train traffic from the original railways Krs, Zsb, Yuur, Svr, Kbsh to the final railways will have a capacity of 97,8 for the first train flow and 36,7 for the second one (the total capacity is 134,5 + 62,2 (internal train flow between Zsb, Yuur, Svr, Kbsh) = 196,7). The advantage of this approach is that, as a result, two strong, enlarged railways can be formed: the first consists of the original railways Zsb, Yuur, Svr, Kbsh, and the second – from the final railways Msc, Grk, Sev, Oct. Together they will serve the largest train flow on the territory of the Russian Federation. The internal exchange of train flows for the first is 66,4 for the second – 44,0.

2. The next polygon by its capacity is Zsb → Dvs: 31,4 + 35,5 + 3,9 = 70,8 trains per day (Zsb, Krs, Vsb, Zab, Dvs). Since Zsb has already entered the first enlarged one, it is removed, and the third enlarged railway gets for itself Krs, Vsb, Zab, Dvs. Its internal exchange of train flows is 40,8 trains per day, and the total – 111,6.

3. Another polygon – Zsb, Svr, Yuur, Kbsh → Prv, Skv, Yuvs – has a train traffic capacity of 18,3 + 30,7 + 6,9 = 55,9. The fourth enlarged railway is formed in the composition of Prv, Skv, Yuvs. Inter-railway correspondences inside it are 36,8 trains per day.

Conclusion. A rational method is proposed for solving the important problem which is the enlargement of the operation range of railways, which must be carried out in connection with: a) the significant development of both the computing facilities used in railway transport and the increase in their number; b) the significant increase in the share of automated systems that manage the transportation processes; c) the enlargement of the management polygons, the improvement of the resource base of production.

The method of finding rational forms of organization of transport structures is based on the use of the matrix of inter-railway train flows, algorithms for allocation of correspondence polygons, which make it possible to choose the variants of configuration of enlarged railways reasonably.

REFERENCES

1. Rachek, S. V. Foreign experience of railroad reforming [*Zarubezhnyj opyt reformirovanija zheleznyh dorog*]. *Izvestija Ural'skogo gosudarstvennogo ekonomicheskogo universiteta*, 2013, Iss. 6, pp. 62–66.

2. Wenzel, B. Digitale Planungsprozesse fur die Bahnausrüstungtechnik – Barrieren und Ansatze. *Signal + Draht*, 2016, 108, № 7–8, pp. 6–10.

3. Smith, K., Vosman, Q. SŽDC delivers big improvements to Czech network. *International Railway Journal*, published September 07, 2015 [Electronic source]: https://www.railjournal.com/index.php/europe/szdcdelivers-big-improvements-to-czech-network.html. Last accessed 04.08.2017.

4. Jiao Jingjuan, Wang Jiaoe, Jin Fengjun, Dunford, M. Impacts on accessibility of China's present and future HSR network. *Journal of Transport Geography*, Vol. 40, October 2014, pp. 123–132. https://doi.org/10.1016/j.jtrangeo.2014.07.004.

5. Qi Yuanjing, Jin Fengjun, Liu Tao, Jiao Jingjuan. Implementation methods and economic impacts of national node strategies. *Journal of Geographical Sciences* [Acta Geographica Sinica], 2016, Vol. 71 (12), pp. 2103–2118. DOI: 10.11821/dlxb201612003.

6. Jin Fengjun, Jiao Jingjuan, Qi Yuanjing, Yang Yu. Evolution and geographic effects of high-speed rail in East Asia: An accessibility approach. *Journal of Geographical Sciences*, 2017, Vol. 27, Issue 5, pp. 515–532. https://doi.org/10.1007/s11442–017–1390–8.

7. Rotoli, F., Malavasi, G., Ricci, S. Complex railway systems: capacity and utilization of interconnected networks. *European Transport Research Review*, 2016, Vol. 8, 8: 29. DOI 10.1007/s12544–016–0216–6.

8. Rotoli, F., Ricci, S., Navajas Cawood, E., Malavasi, G. Capacity versus punctuality assessment procedures and accessibility measures for rail networks. *Ingegneria Ferroviaria*, 2015, Iss. 12, pp.1011–1040.

9. Ricci, S., Luptak, V., Chovancová, M. Baseline Model to Increase Railway Infrastructure Capacity on a Single-Track Section: a Case Study. *Scientific Journal on Transport and Logistics*, Vol. 8, Iss. 2, pp. 69–80, ISSN (Online) 2336–3037, DOI: https://doi.org/10.1515/logi-2017–0018.

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