Keywords: traffic simulation; freight traffic; operator company; railway station; oligopolistic market; Cartesian ovals; Pascal's limaçon; software package.

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ECONOMIC–GEOGRAPHICAL METHOD DELIMITING WAGON FLOWS IN THE REGION CONSIDERED: MODEL AND ALGORITHM

Summary. The problem of effective management of the railway freight flows in the conditions of the multiplicity of operators requires the rationalization of the transportation process. The further development of the authors' research on creating the mathematical model of the railway freight flows in the region transportation and technological system is presented. For the first time, the theory of algebraic curves of higher orders is used to create a territorial model of the oligopolistic market of freight traffic. The algorithm for creating a model of freight transportation is based on the analysis of the qualitative and quantitative indicators of the operator company in the considered region with the use of analytical, heuristic, and graphic capabilities of math software. The theoretical substantiation of the territorial picture, the freight transportation market in the region is obtained. The carried-out research allows to specify possible ways of optimization of freight traffic distribution.

1. INTRODUCTION

The modern development of railway transport and technological systems (TTS) in a single transport space, as well as the development and implementation of control systems for the multimodal transportation process requires to create new methods of distribution and to correct the existing ones of railway freight flows. Studies in this area, but by other methods were carried out in refs. [1-5].

Due to the technical features of logistic connection among various types of transport, there are a number of problems that are manifested in «abandoned» trains, an increase in the turnover of the railway wagon, excess idling of the ships in ports, inefficient loading of storage areas, and so on, which require an urgent and comprehensive solution.

The improvement of the indicators of operation for the carload fleet of the operator companies, which transport freights along the international corridors in the portside TTS is a strategic goal for the sustainable development of the rail transport in accordance with the needs of the country's economy on the basis of growing competitiveness of the industry, expansion of the investment mechanisms, and development of the railway transport services market.

The North-Caucasian Railway (NCR) is a branch of JSC "Russian Railways". It is a transit railway in the international transport system. There are international routes connecting the countries of Western Europe with the countries of Eastern Asia, as well as the countries of Northern Europe with the countries of South-Western and Southern Asia along its sections. International transport corridors (ITC) «North–South» and «Transsib» are important directions for providing of transit traffic through the territory of Southern Russia.

The North-Caucasian Railways (NCR) serve 11 regions of the Russian Federation, ensuring the freight traffic to the ports of the Azov–Black Sea basin (Table 1). According to the nature of the work, the NCR is a sideport and loading–unloading railway, and the share of unloading is twice the share of loading processes. All the ports of the Azov–Black Sea and the Caspian Sea basins are serviced by the port railway stations. Therefore, one of the most important tasks is the effective organization and management of loaded and empty trains [6].

Table 1

Indicators of annual cargo turnover (million tons) of ports of the Azov–Black Sea basin

Port	Years						
	2010	2011	2012	2013	2014	2015	2016
Novorossiysk	117,1	116,1	117,4	119,1	125,6	127,06	131,4
Tuapse	18,6	19,4	17,8	16,9	18,9	25,19	25,19
Rostov-on-Don	7,7	10,4	11,1	11,6	12	13,62	15,3
Taganrog	2,9	3,5	3,4	3,9	5,1	5,92	4,9
Azov	4,3	4,8	5,1	7,7	7,9	8,05	7,2
Kavkaz	10,1	8,3	9,4	10,1	12,3	13,7	15,4
Temryuk	1,9	2,4	2,3	3,7	4,5	4,7	5,1
Yeysk	3,6	4	3,6	3,3	4,1	3,92	4,3

2. ECONOMIC AND GEOGRAPHICAL APPROACH TO THE RAILWAY TRAFFIC FLOWS

We turn to the theory of algebraic curves of higher orders to create a territorial model of the oligopolistic market of freight traffic. The geometric idea that was used for the approach [7] was developed in ref. [8] in an analytical form by means of the computer mathematics system to a common transport–logistic situation. In the paper [9], a new approach to the distribution of port cargo traffic (in the case of limiting of the capacity of railway lines) is presented under which an economic and geographical model of the railway range under consideration is made. As a result, we obtain a territorial picture of the transport services market to solve the corresponding issues of the optimal distribution of railway traffic volume. We consider it appropriate to draw attention to the work [10] in which a geometric model is built for the probabilistic port hinterland based on intermodal network flows jointly using discrete choice analysis and geographical information of shippers.

In this paper, this approach reached an essential development in several directions. The territorial model of the transport market is more complex and diverse in the mathematical and logistical sense. The number of wagon distribution stations, as well as options for choosing the type of freight and the type of rolling stock increase significantly.

We shall consider the general method developed by the authors for the optimal distribution of wagon flows on the example of the southern part of the North Caucasian economic region. The research carries out the framework of the operator company, on the example of JSC «First Freight Company» (Freight One) [11]. Timber was selected as the cargo that is delivered in the company’s own open wagons—gondola cars—from six stations of loading: Krasnodar-Sortirovochny (1), Rostov-Zapadnyy (2), Nesvetay (3), Dzheguta (4), Sosyka-Yeyskaya (5), and Bataysk (6) to 12 destinations (stations or ports): Novorossiysk (1), the Kavkaz (2), Tuapse (3), Taganrog (4), Azov (5), Temryuk (6), Vyshestebliеvskaya (7), Makhachkala (8), Ust-Donetskaya (9), Zarechnaya (10), Kiziterinka (11), and Grushevaya (12).

In accordance with the tariff manuals, the cost of transportation of a gondola car with timber from the loading stations to unloading stations (ports) is calculated taking into account the distance of travel

(Table 2). The analytical expression for values has the form $c = a + b \cdot l$, where a is the cost of initial–final operations per loaded railway wagon, b is the cost of movement operations per 1 km of transportation, and l is the distance of transportation, in kilometers.

Table 2

The cost of gondola cars transporting from loading stations to unloading stations (ports)

Operator company	Loading stations		Novorossiysk		Kavkaz		Tuapse-Sortirovochnaya		Taganrog		Azov		Temryuk		Vyshesteblievskaya		Makhachkala		Ust-Donetskaya		Zarechnaya		Kiziterinka		Grushevaya	
			L, km	C, thousand roubles	L, km	C, thousand roubles	L, km	C, thousand roubles	L, km	C, thousand roubles	L, km	C, thousand roubles	L, km	C, thousand roubles	L, km	C, thousand roubles	L, km	C, thousand roubles	L, km	C, thousand roubles	L, km	C, thousand roubles	L, km	C, thousand roubles	L, km	C, thousand roubles
JSC Freight One	1	Krasnodar	140	15,2	255	17,2	152	36,41	366	20,7	311	25,50	189	36,41	196	16,2	786	28,3	445	21,8	289	24,72	294	17,8	113	14,8
	2	Rostov-Zapadnyy	394	21,3	493	24,2	444	21,8	61	12,3	52	12,1	427	21,8	434	21,7	908	30,1	183	16,2	14	11,2	32	11,6	367	20,8
	3	Nesvetay	498	24,3	597	25,6	548	25,1	201	16,5	156	15,6	531	24,7	538	24,7	1012	31,4	96	12,8	134	15,2	113	14,8	471	22,3
	4	Dzheguta	481	24,2	596	25,6	378	20,8	522	24,7	471	22,2	530	24,7	537	24,7	579	25,6	605	24,5	449	21,7	454	22,2	454	22,2
	5	Sosyka-Yeyskaya	313	18,2	428	21,8	324	19,8	216	16,6	165	15,9	362	20,8	369	20,7	759	27,8	299	17,8	143	15,6	148	15,6	286	17,9
	6	Bataysk	372	20,7	471	22,2	423	21,7	85	12,7	30	11,5	405	21,2	412	21,2	886	30	164	15,9	8	11,1	13	11,2	345	20,3

The graphs presented in Table 2 show that for each of the loading stations under consideration, the dependence of the cost c (thousand rubles) of transportation of one gondola car with timber from the length l (km) of the passed route is linear. The corresponding data for two large stations are shown in Fig. 1. In order to find the type of this dependence for each loading station, the static data from Table 2 is placed in Table 3.

Analytical expressions of the dependence of the gondola transportation cost c (thousand rubles) on the length of the route l (km) are given in Table 4 for each of the loading stations. They were obtained by means of processing of numerical data in Table 3 by the method of the least squares. After rounding, the values of all the coefficients b turned out to be 0,02.

Table 3

Ranking of transportation costs for loading stations

Krasnodar			Rostov-Zapadnyy			Nesvetay			Dzheguta			Sosyka-Yeyskaya			Bataysk		
n	*l*	*c*	*n*	*l*	*c*	*n*	*l*	*c*	*n*	*l*	*c*	*n*	*l*	*c*	*n*	*l*	*c*
12	113	14,8	10	14	11,2	9	96	12,8	3	378	20,8	10	143	15,6	10	8	11,1
1	140	15,2	11	32	11,6	11	113	14,8	10	449	21,7	11	148	15,6	11	13	11,2
3	152	15,5	5	52	12,1	10	134	15,2	11	454	22,2	5	165	15,9	5	30	11,5
6	189	16,2	4	61	12,3	5	156	15,6	12	454	22,2	4	216	16,6	4	85	12,7
7	196	16,2	9	183	16,2	4	201	16,5	5	471	22,2	12	286	17,9	9	164	15,9
2	255	17,2	12	367	20,8	12	471	22,3	1	481	24,2	9	299	17,8	12	345	20,3
10	289	17,8	1	394	21,3	1	498	24,3	4	522	24,7	1	313	18,2	1	372	20,7
11	294	17,8	6	427	21,8	6	531	24,7	6	530	24,7	3	324	19,8	6	405	21,2
5	311	18,2	7	434	21,7	7	538	24,7	7	537	24,7	6	362	20,8	7	412	21,2
4	366	20,7	3	444	21,8	3	548	25,1	8	579	25,6	7	369	20,7	3	423	21,7
9	445	21,8	2	493	24,2	2	597	25,6	2	596	25,6	2	428	21,8	2	471	22,2
8	786	28,3	8	908	30,1	8	1012	31,4	9	605	24,5	8	759	27,8	8	886	30

In all the expressions obtained in Table 4, the values of the coefficient b coincide. One of the explanations of this situation is the infrastructure factor, that is, the normalized fee of the network carrier of JSC «RZD». There are also internal organizational reasons related to the company itself. That is the regularly executed plan for the trains supply that is uniformly compiled for all the stations where the railway wagons are located [12]. It should also be noted that the cost-uniformity of transportation in the expressions given above is manifested precisely in the components related to the movement operations. This circumstance is a direct economic indicator of the fact that the uniform regulators of transport costs and the mechanism of the transportation process (at least, within the framework of the functioning of JSC «Freight One») is to some extent debugged.

Table 4

Expressions of the cost freight transportation for loading stations

Krasnodar $c = 12,24 + 0,02l$	Rostov-Zapadnyy $c = 11,58 + 0,02l$	Nesvetay $c = 12,57 + 0,02l$
Dzheguta $c = 12,51 + 0,02l$	Sosyka-Yeyskaya $c = 12,48 + 0,02l$	Bataysk $c = 11,5 + 0,02l$

Further, we give examples of transport and logistics recommendations within the framework of the constructed territorial model of the freight transport market.

3. GEOMETRIC EUCLIDEAN MODEL OF THE FREIGHT TRANSPORT MARKET

At the first stage, a *geometric Euclidean model (GEM)* of the freight transport market is formed, in which all the routes of the railway wagons are assumed to be conditionally rectilinear. Therefore, the lengths of the routes are the Euclidean distances between the stations where the wagons are located and the stations (ports) of unloading. The analytical expressions of transportation costs presented in Table 4 allow creating the appropriate model of the oligo(duo)political market in the region under consideration that is serviced by an operator company (e.g., JSC «Freight One»). Stations where the wagons are located can be considered as the participants of the oligopoly, among which one of the types of intrafirm competition is realized. It can be seen as a non-antagonistic rivalry between the stations where the wagons are located in order to make the most efficient use of the company's resources.

To formulate the task on the flat geographic map of the railroad transport region under consideration, we will adopt a Cartesian coordinate system, the origin of which is located at the point of a large junction (marshaling) station, for example, Krasnodar. The choice of such an initial point is made for conditional «binding» of the geometric model to the real territory and it is of no fundamental importance. In this case, we are guided by the fact that this station is located on the most important railway routes of the transportation process and dominates among other considered loading stations according to the features of the road development.

The axis of abscissas is located in the direction from the west to the east, and the axis of ordinates is from the south to the north. In the proposed model, the criterion for delineating of the «influence area» of the loading stations is the cost of goods transporting from these stations to the destinations (ports). In ref. [8], it was shown that the «influence area» of the subjects of the freight transportation for the case of a market duopoly is separated by the part of some algebraic line. The implicit equation of this line of the fourth order has the form:

$$\begin{aligned}
&\left(q_1^2 - q_2^2\right)^2 x^4 + 2\left(q_1^2 L + q_2^2 L\right)\left(q_1^2 - q_2^2\right)x^3 + 2\left(q_1^2 - q_2^2\right)^2 x^2 y^2 - \\
&-2\left(2q_2^2 p^2 - \left(\frac{q_1^2 L^2}{4} - \frac{q_2^2 L^2}{4} - p^2\right)\left(q_1^2 - q_2^2\right) - \left(q_1^2 L + q_2^2 L\right)^2\right)x^2 + 2\left(q_1^2 L + q_2^2 L\right)\left(q_1^2 - q_2^2\right)xy^2 + \\
&+2\left(2q_2^2 L p^2 + \left(\frac{q_1^2 L^2}{4} - \frac{q_2^2 L^2}{4} - p^2\right)\left(q_1^2 L + q_2^2 L\right)\right)x + \left(q_1^2 - q_2^2\right)^2 y^4 - \\
&-2\left(2q_2^2 p^2 - \left(\frac{q_1^2 L^2}{4} - \frac{q_2^2 L^2}{4} - p^2\right)\left(q_1^2 - q_2^2\right)\right)y^2 - q_2^2 p^2 L^2 + \left(\frac{q_1^2 L^2}{4} - \frac{q_2^2 L^2}{4} - p^2\right)^2 = 0 .
\end{aligned} \tag{1}$$

– where q_1 and q_2 are the average transport costs of the subjects under consideration, and L is the distance between the subjects under consideration.

It is shown in ref. [8] that line (1) is a Cartesian oval and, in particular, can turn out to be a Pascal's limaçon. Thus, it follows from the analytical and geometric nature of the problem that the lines that delimit the «influence-areas» of the railway stations can be very diverse.

In addition, a visualization of metamorphoses, which occur with the «influence area» of the subjects of the transportation process when the coefficients q_1, q_2 p change, is shown in the environment of the system of analytical calculations.

The coefficient p in equation (1) is equal to $\left|p_{k_1} - p_{k_2}\right|$. Here, $k_1 \neq k_2$ and p_k are taken from the expressions of the dependence of transportation costs (Table 4)

$$c_k(l) = p_k + ql \quad (k = 1,...6) \qquad (2)$$

for two considered loading stations.

Speaking about the transport situation under consideration in this paper, first, we will distract ourselves from the general formulation of the oligopolistic problem and outline the features of the freight operation carried out by any pair of loading stations independently of other entities. As can be seen from equation (1), for this kind of duopoly, when the equality $q_1 = q_2$ holds (which is the case in this paper), the order of the algebraic line under consideration decreases substantially. As noted in ref. [9], in this case, it turns out to be one of the branches of the hyperbola, in the foci of which the stations forming the duopoly are located. As a result, the whole plane is divided into two parts by the branch of the hyperbola, referring to the focus based at the station location, for which the coefficient p_k in expression (2) turns out to be the greatest.

Due to the coincidence of the coefficients for all the considered loading stations for length *l* of the traversed route (see formula (2)), it turns out that the boundary of the «influence area» of each of these stations is the union of some parts of the hyperbolas indicated above. In Fig. 2, two fragments of the image of the oligopolistic market, formed by six loading stations, related to the stations of Bataysk and Krasnodar, are shown. One of the cases of the different coefficients for length *l* is considered below. Descartes'ovals appear in this case.

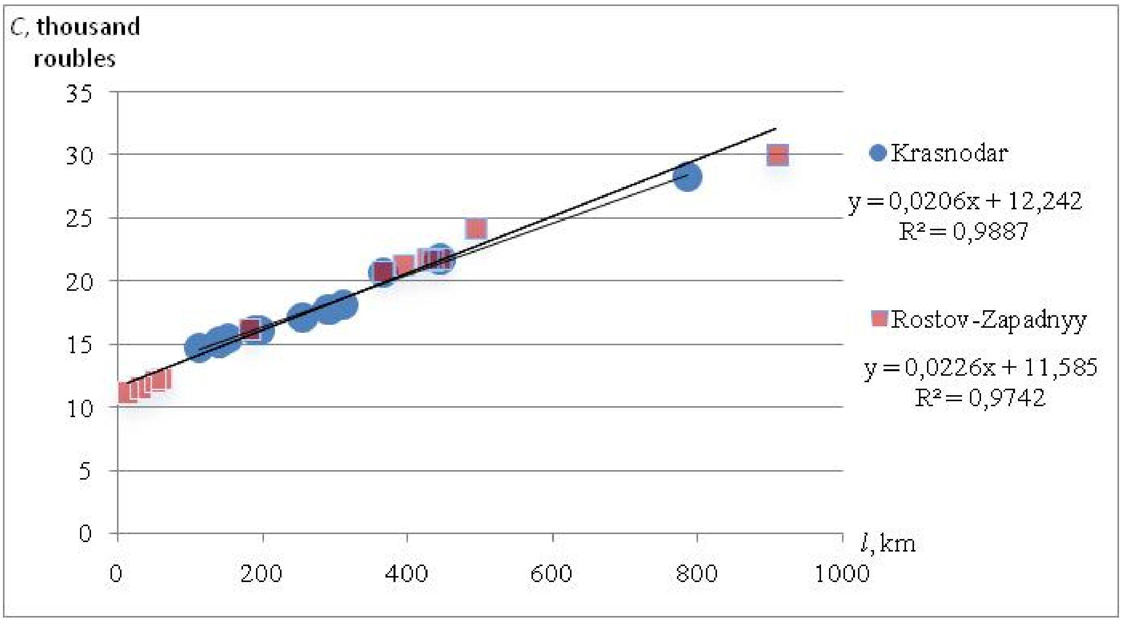

Fig. 1. Graphical depiction of the dependence of the transportation cost from the loading stations Krasnodar and Rostov-Zapadnyy

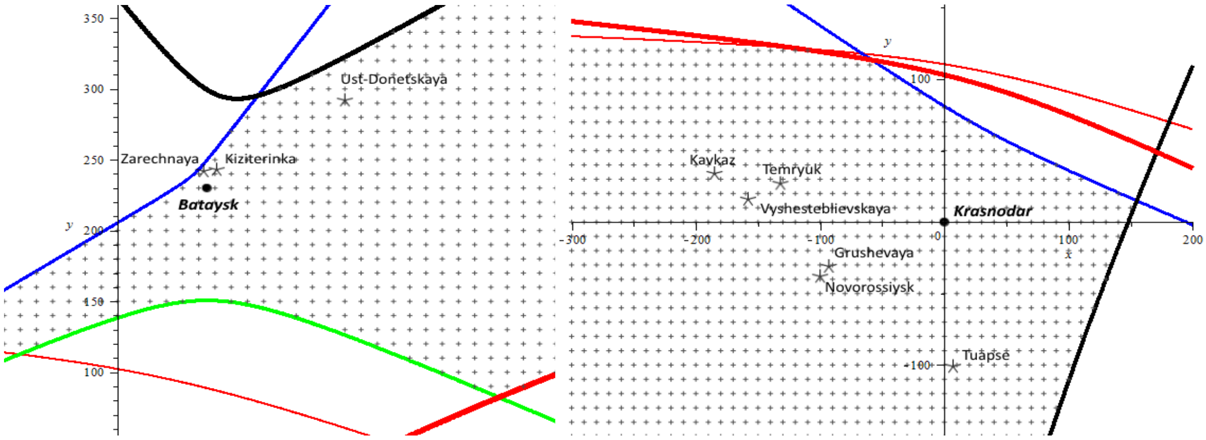

Fig. 2. «Influence area» of Bataysk and Krasnodar stations in *GEM*

A complete territorial picture of the freight market, comprised of six loading stations, is described, generally speaking, in $C_6^2 = 15$ curves. The image of all such curves on one drawing is difficult for visual perception. Therefore, in Fig. 3, we have shown the territorial picture of the oligopolistic market, which is a combination of fragments of the above-mentioned species, related to the considered loading stations.

In particular, it turns out that none of the port railway stations considered in this paper (indicated in Fig. 2, 3 by asterisks) can be found in the «influence area» of the stations Nesvetay, Sosyka-Yeyskaya, and Dzheguta. With such expenses for transportation of goods, these stations are not competitive in the considered market of transport services.

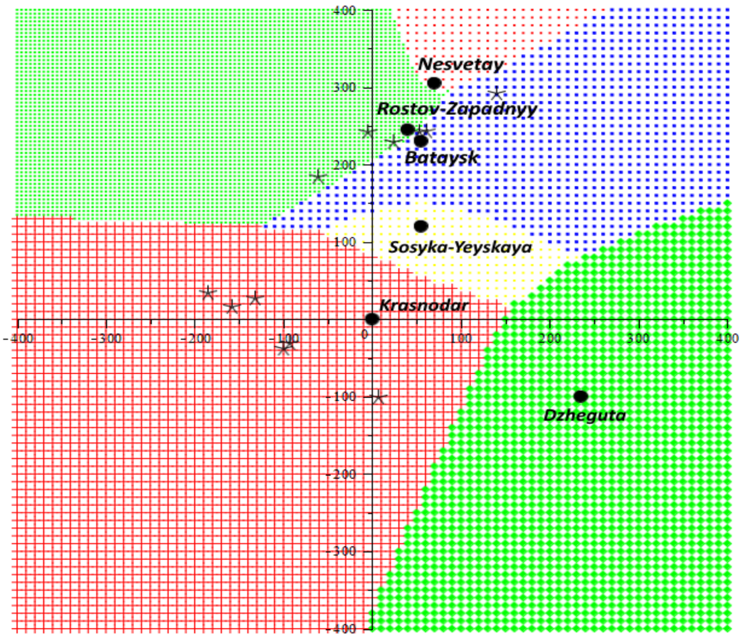

Fig. 3. Geometric Euclidean model of oligopolistic transport market on the example of freight transportation of JSC «Freight One»

4. POSSIBLE ADDITIONAL CONSTRUCTIONS AND DEVELOPMENT OF *GEM*

In the *GEM*, an «ideal» territorial picture of the transport services market is given. The circumstance, that the connection between the pairs of stations in the existing transport network can be not only along rectilinear segments, is not taken into account. Therefore, in real situations, a second stage of the construction may be needed that will result in the *routing* model of the freight market *GEMM*, obtained by some adjustments of the initial *GEM*.

First of all, it is necessary to pay attention to the destination stations (ports), which are close to the boundary of the «influence area» of the station where the wagons are located. As an example, we will consider the port station Ust-Donetskaya, located near the curve dividing the «influence area» of Nesvetay and Bataysk stations (Figs. 2 and 3). Taking into account the remarks made above, we will make additional calculations in accordance with the actual routes. The length of the shortest railway route from Nesvetay station to Ust-Donetskaya station is 96 km, and from Bataysk station—164 km. Using the obtained above expressions of cost dependence *c* (thousand rubles) on length *l* (km) of the passed route (Table 4) for every considered station, we get respectively

$$C_N = 12,57 + 0,02 \cdot 96 = 14,49 \text{ and } C_B = 11,05 + 0,02 \cdot 164 = 14,33$$

As a result, it turns out that $C_B = 14,33 < 14,49 = C_N$. That is, there is no need to adjust the *GEM* in this case. The location of the Ust-Donetskaya port station in the *GEMM* in relation to the Nesvetay and Bataysk loading stations from the point of view of their belonging to the «influence areas» remains the same as in the *GEM*.

Now, we will consider the ways to change the «influence area» of the station where the wagons are located in such a way that it's new «influence area» will cover the unloading stations (ports) that were previously located in the «influence areas» of the other stations. Let us give two variants of the solution of this problem different in a geometric and organizational–economic sense.

In the first case, this goal can be achieved by changing the coefficient p_k, by means of which the cost of initial–final freight operations is expressed in the expression of the cost of transportation from a given station. In the second case—changing the coefficient q, is an expression of the corresponding movement costs. For example, we will consider Nesvetay as a loading station, and Ust-Donetskaya—as the station of destination.

Fig. 4 shows the local image of the changed «influence area» of the Nesvetay loading station (compare with Fig. 3), which is obtained as a result of a decrease of the coefficient p_3 (see formula (2)) with the value 12,57 to the value 11,9.

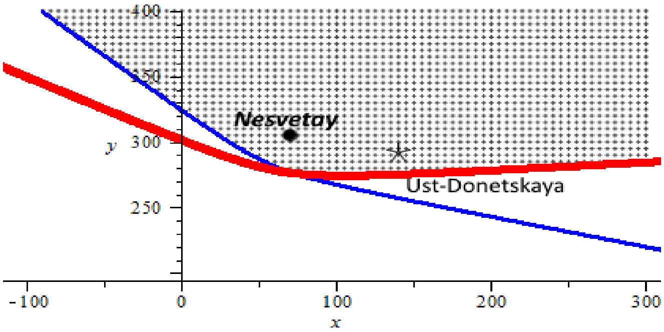

Fig. 4. Local image of the changed «influence area» of Nesvetay station

Fig. 5 shows a global image of the «influence area» of the Nesvetay loading station, which is obtained as a result of a decrease of the coefficient q in the expression of the cost of transportation from this station from a value of *0,02* (previously identical for all the loading stations) to a value of *0,01*. As a result, the port station Ust-Donetskaya finds itself in the new «influence area» of the station under consideration (compare with Fig. 3).

One should pay attention to the fundamental difference in the territorial configuration in Fig. 5 from the earlier «influence areas». The entire territorial picture of the oligopolistic transport market is being transformed with a decrease in the movement costs related to the Nesvetay station, compared with the remaining unchanged values for other loading stations. First, the «influence area» of this station becomes unlimited, while «influence areas» of all other stations are limited. Second, in this case, Pascal's limaçons, but not the hyperbole, act as the lines of demarcation with the «influence areas» of other loading stations.

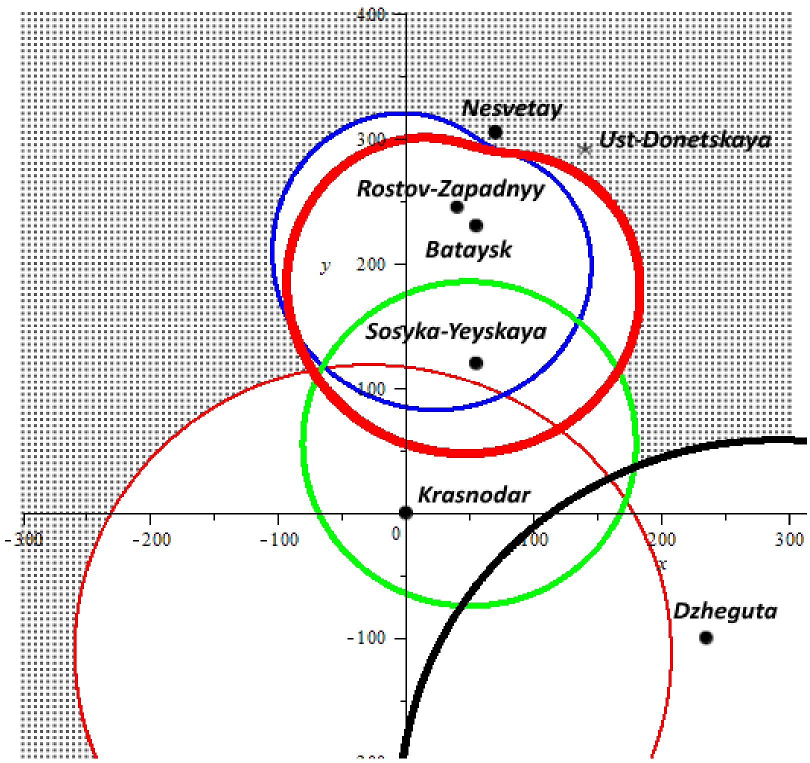

Fig. 5. Global image of the changed «influence area» of Nesvetay station

The result of making of the geometric Euclidean model *(GEM)* of the freight transport market of the portside TTS can serve as a theoretical basis for creating a real *GEMM* of the routing picture of freight transportation in the given region, which will ensure more rational distribution of the car traffic volume.

The above geometric constructions can be supplemented and extended by appropriate probability–theoretic and statistical research.

5. CONCLUSION

The method of economic–geographical demarcation is proposed, which allows to allocate «influence areas» of network-loading stations when using the rolling stock of the operator company and transporting goods to port unloading stations. The novelty of the method is the use of classical algebraic curves to create a territorial model, the oligopolistic market of freight transport. It is shown, along with hyperbola branches, that curves of the fourth order, namely, Cartesian oval and Pascal's limaçon are the lines that demarcate the "influence areas" of the loading stations. The geometric Euclidean model obtained by this way is the basis for constructing the routing model of the freight transport market. Analytical and graphical capabilities of mathematical software allow to build an algorithm for modeling freight transportation based on the analysis of the qualitative and quantitative indicators of the operator's company [13]. Based on a comprehensive assessment of the infrastructure and with the use of specialized software products, possible ways of optimizing the distribution of railway freight flows are indicated.

Acknowledgements

The research is conducted with support of the Russian Foundation for Basic Research (#17-20-04236 ofi m RJD).

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Received 05.10.2016; accepted in revised form 07.06.2018