Geometric routing model as a new approach in mathematical modeling of wagon flows rational distribution

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Abstract. In the ongoing transport and logistics researches, a coefficient of railway line non-straightness is introduced, by means of which, for the considered loading stations, the specifics of the location of the railway network in a given region are taken into account. The use of this coefficient makes it possible to increase the efficiency and practical expediency of applying the method of economic and geographical delimitation of the «influence areas» of the loading stations. As a result, it is possible to construct a mathematically substantiated geometric routing model of the territorial oligopolistic market for freight transportation formed by the considered loading stations. As an effective tool in the research process, a system of analytical calculations is used.

1 Introduction

1.1 Literature review

In the conditions of cardinal changes in the trend of globalization processes, including the geographical reorientation of cargo flows, there is an increasing need to develop new approaches to modeling the process of transport and logistics systems functioning. Let us give a brief review of papers that are, to one degree or another, devoted to the research of these issues.

The paper [2] is devoted to some problems related to the optimization of processes occurring in the transport and logistics system. In [3], researches are focused on the use of some methods of applied mathematics in relation to the functioning of railway transport. In [6], the methodology for predicting the future development of unregulated industries, especially in the transport sector, is considered. In particular, the development of competition in the field of freight rail transport in Finland is assessed. In [7], the questions of finding individual seaports in Europe are studied based on the proposed methodology using a professional route planner for road freight and distance catalogs.
In [8–9], in particular, it is noted that uncertainty conditions are increasingly considered in optimization problems that arise in real transport and logistics activities. Usually, various modeling methods are tried to be applied to the analysis of complex systems in these non-deterministic environments. In [10], an optimization model for multimodal transportation was developed, in which the total time of transportation and its cost are minimized. In [11], the aim of the research is to find the optimal transportation scheme under the assumption of the uncertainty of the possible multimodal transport network used.

1.2 Substantiation of the relevance of new approaches in freight transportation processes modeling

Economically justified distribution of wagon flows can reduce the time and reduce the cost of freight transportation, increasing the productivity of the entire transport and logistics system. It should also be noted that there is a demand for alternative transportation routes in situations where the existing transport routes do not allow us to qualitatively solve the set logistics problems. The reason for the difficulties that arise here, as a rule, is the congestion of the corresponding transport infrastructure and objective features of a geographical nature. In such cases, it is necessary to look for new routes that can provide equally efficient and cost-effective delivery options.

Along with the operator companies, Russian Railways faces another problem, namely, competition from road transport. Therefore, joint and well-coordinated efforts of all subjects of the rail freight transportation process are important in creating attractive conditions for clients.

The total number of players in the market of operator companies has been stable over the past few years. Most often, the freight wagon fleet is redistributed between existing operators (which is fully explained by the action of market mechanisms). The main reason for what is happening is the high cost of new wagon and the complexity of the technology implementation cycle in the field of rail freight transportation in general. In connection with the reorientation of cargo flows, in many cases there is a surplus of wagons and high-sides wagon that are idle in the network and thereby complicate the comprehensive and full-fledged functioning of the transport services market (Fig. 1). Thus, for operators, the importance of increasing the manufacturability of transportation, expanding the number of routes, as well as the ability to influence the carrier's operational decisions.

Fig. 1. Dynamics of the tariff rate for the provision of high-sided wagon in 2020-2022, RUB/t-km

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The foregoing confirms the presence of complex transport and logistics problems, the solution of which can be provided, including the development of new approaches in the mathematical modeling of freight transportation processes.

2 Materials and Methods

2.1 General principles for building a model in the duopoly case

In this paper, we will consider not the Euclidean, but the railway (tariff) distance between loading stations and unloading stations. One of the tools for constructing an appropriate transport and logistics model will be such a concept as the coefficient of railway line non-straightness for the loading station. The specified coefficient allows taking into account the specifics of the location of the network of transport routes relative to the station in question, that is, it has a direct practical meaning. (Note that such a concept is no less appropriate when research road transportation.)

The value of the specified coefficient calculated for each loading station makes it possible to build a geometric routing model (GRM) of the oligopolistic freight transportation market formed by these stations.

Let us describe the general principles of constructing a GRM for the case of a duopoly. (Note that in this paper, loading stations act as duopolists (or oligopolists), and unloading stations act as destinations for freight transportation). Let $e_{el}$ and $m_{ml}$ be the Euclidean distances and railway (tariff) distances from the given duopolist to the freight destinations. Let us introduce into consideration a random variable $\xi$ whose values are ratios $m_{el}/e_{el}$. For each duopolist, we define the coefficient of railway line non-straightness $k$ as the mathematical expectation of a random variable $\xi$. If we assume that the random variable under consideration has a uniform distribution law, then the indicated numerical characteristic is in the form of the arithmetic mean of this value calculated for all destinations of freight transportation.

As in the construction of the GEM, it is assumed that a certain (having a nominal character) Cartesian coordinate system is introduced on a flat geographical map of the region. Let $L$ be the distance between the 1st and 2nd duopolists. We will assume that they are at the points $0, 0$ and $A(L, 0)$. Note that the choice of the coordinates of the locations of the duopolists is also conditional and is necessary in order to apply the method of analytical geometry further, referring to the analytical calculations system. Let $i_{ip}$ and $i_{iq}$ be the cost of initial-end operations and the cost of traffic operations (per 1 km of route) spent on one wagon, $i_{ik}$ are the railway line non-straightness coefficients for duopolists ($i = 1, 2$). As in the GEM, the «influence areas» of the duopolists will be delimited by a line that is determined by the cost of transportation from the duopolists' locations to destinations. Thus, the equation of the specified line in GRM has the form:

$$p_{i} + q_{i}k\sqrt{x^{2} + y^{2}} = p_{i} + q_{i}k\sqrt{(x-L)^{2} + y^{2}}$$

For equation (1), we single out the most meaningful and interesting special cases, theoretical explanations for which are given in [14–16]. If $p_{i} \neq p_{j}$, then we get the Descartes' oval (in particular, Pascal's limaçon),
In our research, we actively use the computational, analytical and graphic capabilities provided by the Maxima (Free Ware) analytical calculations system. On Fig. 3 depicts (found by the specified system) Pascal's limacon, of the duopolists under the assumption that

\[ L = \ldots \quad p_1 = \ldots \quad p_2 = \ldots \quad q_1 = q_2 = \quad k_1 = \quad k_2 = \ldots \]

196,79 \( L = \ldots \quad p_1 = \ldots \quad p_2 = \ldots \quad q_1 = q_2 = \quad k_1 = \quad k_2 = \ldots \)

1,25 \( k_1 = \quad \quad k_2 = \ldots \)

We see that the 1st duopolist outperforms the 2nd duopolist in territorial competition if we consider destinations that are close enough to both duopolists. This is due to inequality

\[ p_1 < p_2 \quad q_1 < q_2 \quad k_1 > k_2 \]

However, since \( q_1 k_1 > q_2 k_2 \), then the 1st duopolist is less competitive in transportation over long distances.

2.2 Project characteristics

As an object of implementation of the GRM of the territorial cargo market developed in this paper, we consider the following specific project.

Let us research the issues of rational management of wagon flows directed to port stations located on the loop of the North Caucasus Railway. We will assume that the loading stations are the following: Bystrorechenskaya, Chapaevka - Rostovskaya, Nesvetaj, Konokovo and Labinskaya. The unloading stations are the port stations belonging to the Azov-Black Sea basin: Tuapse, Novorossijysk, Vyshesteblievskaya, Kavkaz, Ejsk, Taganrog, Azov and Zarechnaya. The rolling stock is formed by wagons of a universal type – high-sidewall wagon, in which the transportation of goods of a very wide range is allowed.

When constructing the GRM (as in the case of the GEM), it is assumed that for the loading stations there are appropriate numerical data for the unloading stations in question. As a result of the least squares processing of numerical data for each of the above loading stations, an analytical expression was found for the dependence of the cost of transportation \( c \), thousand rubles, on the distance, km (Table 1).

<table>
<thead>
<tr>
<th>Loading stations</th>
<th>Transportation cost dependence</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>( c = a + bl )</td>
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![Fig. 2 Delimitation of «influence areas» of duopolists](image-url)
Table 2 shows the values of the coefficient of railway line non-straightness calculated for the indicated loading stations.

<table>
<thead>
<tr>
<th>Loading stations</th>
<th>Coefficient of railway line non-straightness, $k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bystrorechenskaya</td>
<td>1.54</td>
</tr>
<tr>
<td>Chapaevka - Rostovskaya</td>
<td>1.52</td>
</tr>
<tr>
<td>Nesvetai</td>
<td>1.69</td>
</tr>
<tr>
<td>Konokovo</td>
<td>1.22</td>
</tr>
<tr>
<td>Labinskaya</td>
<td>1.48</td>
</tr>
</tbody>
</table>

### 3 Results and Discussion

The result of these research is presented based on the territorial picture of the oligopolistic freight transportation market, obtained on the basis of the GRM, formed by the loading stations considered in the paper (Fig. 4).

#### 3.1 GRM of duopolistic freight markets

Let's start with duopolistic situations. On Fig. 3a shows the division of the considered part of the polygon by the Descartes oval into the «influence areas» of the Nesvetai and Konokovo loading stations.

Since for the Konokovo station (see Tables 1 and 2) the product is less than the corresponding product calculated for the Nesvetai station, then the «influence areas» of the Nesvetai station is a bounded set on the plane.

Thus, the Konokovo station is more competitive in relation to those unloading stations that could be located far enough from both loading stations. In general, based on the table 1 and 2 numerical values, we can conclude that in all duopolistic situations, the «influence areas» of one of the loading stations is a limited set on the plane. This is especially pronounced for the Konokovo – Labinskaya duopoly (Fig. 3b). We also note that in this case, a non-trivial and very typical state of affairs for the GRM model appeared, when a number of unloading stations located closer to one of the loading stations from the point of view of the Euclidean distance turned out to be included in the «influence areas» of another station. The above applies to the unloading stations Vyshesteblievskaya, Kavkaz and Ejsk.
3.2 GRM of the oligopolistic freight transportation market

\[ C_5 = \text{...} \]
In particular, it turns out that the frontier of the «influence area» of the Labinskaya station consists of one component, which is a Descartes oval obtained in a duopolistic situation (compare with Fig. 3b).

It seems appropriate to continue research using the method of economic-geographical delimitation of the «influence areas» of loading stations in order to build the GRM of the corresponding territorial oligopolistic market.

4 Conclusions

The coefficient of railway line non-straightness introduced in the paper makes it possible to significantly increase the efficiency and practical expediency of applying the method of economic-geographical delimitation of the loading station «influence areas» in transport and logistics researches. The geometric routing model (GRM) developed using the specified coefficient makes it possible to find the «influence areas» of loading stations, taking into account the specifics of the railway network configuration. As a result, a mathematically substantiated picture of the territorial oligopolistic market of freight transportation is obtained, formed by the considered loading stations.

The proposed approach is common for land modes of transport and, taking into account the relevant specifics, can be applied in the research of freight transportation by road. We note the expediency of using analytical computing systems as a universal tool that performs, among other things, a heuristic function in solving the considered transport and logistics problems.

References

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