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Freight Traffic Distribution Under Conditions of Limited Capacity of Railway Sections

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Abstract: The research aims to enhance methods for distributing freight flows across a railway network to ensure unhindered access to public railway transportation services for shippers. The study was conducted using the methodological framework of railway operation theory in conjunction with operations research methods. During the research, a method for distributing freight flows across a railway network, taking into account capacity constraints of specific sections, as well as a method for allocating additional transportation costs among shippers, is proposed. The originality of the research lies in improving the methodology for distributing freight flows across railway networks under capacity constraints. The proposed method makes it possible to consider the interests of individual shippers when using public railway transport by identifying sections with capacity constraints and adjusting tariff distances accordingly. The applied relevance is confirmed by the fact that implementing the results can improve methods of organizing wagon flows and determining freight tariffs, taking into account the interests of both railways and their customers.

Keywords: Railway transport, freight transportation, capacity, wagon flow, optimization

1. Introduction

Railway transport plays a significant role in the economies of Kazakhstan and Ukraine, accounting for 68% and 61% of total freight turnover, respectively. This high share reflects the raw-material orientation of both economies, which requires transporting large volumes of cargo over long distances. Under these conditions, railway transport remains the most efficient mode due to its high carrying capacity and relatively low transportation costs [1]. Railway networks of both countries, as well as the principles of railway transportation organization, were largely formed during the Soviet period. At that time, the railway system operated within a planned economy and was characterized by state ownership of both infrastructure and most consignors and consignees. Accordingly, transportation management methods were designed to ensure freight movement at the lowest possible cost. Today, both countries operate within market economies, where railway customers include enterprises with different ownership structures and competing interests. As a result, the organization of freight transportation on public railways under market conditions has become a key research issue.

The distribution of wagon flows across a railway network is a key stage in developing a train formation plan. This task involves identifying cost-effective routes to minimize transportation costs while ensuring efficient train formation and disbandment. For each route option, parameters such as section and station travel time, shunting fuel consumption, line capacity, and station handling capacity are evaluated. In practice, route selection is based on a comparative assessment of technical performance and economic efficiency [2]. Formal methods for solving this problem have been widely studied [3-5], with the objective of minimizing railway transportation costs. Various operations research approaches have been applied to the problem of organizing wagon flows into trains, including the transportation problem [3], the knapsack problem [4], and the simulated annealing algorithm [5]. However, the practical application of these solutions differs in Kazakhstan and Ukraine. In Kazakhstan, tariff distances are calculated using the shortest routes adopted during the Soviet period. The average cost per tonne-kilometre is determined by dividing the total costs of transportation under the optimal train formation plan by the total freight turnover calculated on the basis of these shortest distances. As noted in [6], this approach may lead to discrepancies between tariff values and the actual cost of transportation, since real routes may differ significantly from those used for tariff calculations. This problem became particularly acute for Ukrainian railways at the end of the 20th century. Following the economic crisis after the collapse of the USSR, freight traffic across the railway network decreased by about 70%. Wagon flows were concentrated on electrified lines, while sections operated by diesel traction remained largely underutilized. To ensure consistency between transportation costs and tariffs, Ukraine has calculated tariff distances according to the train formation plan since 1996. However, with increasing traffic volumes and capacity constraints on certain sections of the railway network, some freight flows are redirected to longer routes with higher transportation costs. Although the train formation plan minimizes the average transportation cost, it does not fully take into account the interests of individual shippers.

The reforms carried out in the European Union's railway transport have led to the separation of the infrastructure and transportation services market. The fundamental principle of the European Union's (EU) transport policy, established in Directive 2012/34/EU [7], is equal and unhindered access for carriers to railway infrastructure services. The effects of introducing competition were analyzed in [8] using game theory methods, showing that competition improves service quality and reduces transportation costs. However, the deregulation of the railway transport market has shifted attention to the assessment and allocation of railway infrastructure capacity and the pricing of infrastructure services [9,10]. An overview of infrastructure capacity assessment methods is provided in [11], while the structure of railway markets in different EU countries after the reforms is described in [12]. Capacity is allocated according to the order in which it is published by the infrastructure manager in Network Statements. As several carriers operate on the same infrastructure, conflicts and congestion may arise [13]. Similar challenges are observed in the US and Australia [14,15]. Some of these issues are addressed by creating reserve capacity [16]. When reserves are unavailable, access conflicts are resolved through coordination of requests, rejection of some applications, or redirection of traffic to alternative routes. Another approach to allocating railway capacity is the use of auctions, for which formal coordination methods are presented in [17,18]. However, these approaches cannot be directly applied in Kazakhstan and Ukraine due to differences in both market organization and transportation technology. In Ukraine, railway freight transport is provided by the state monopoly Ukrzaliznytsia JSC, while in Kazakhstan it is performed by the national carrier "KTZh-Cargo Transportation LLP", which holds a dominant market position. Under these conditions, the distribution of wagon flows across the railway network is determined mainly by interactions between the carrier and shippers rather than between the infrastructure manager and carriers. In addition, freight transport in Kazakhstan and Ukraine is performed by unscheduled freight trains, whereas in the EU it is organized according to fixed schedules.

Structural integrity of track components – such as thermite rail welds and ballasted track under dynamic loading – directly affects railway reliability and capacity. Defects or track settlement may impose speed restrictions or require traffic rerouting, reducing the efficiency and flexibility of freight operations [19,20]. These factors highlight the need for data-driven approaches to optimize freight traffic distribution and improve the use of existing infrastructure capacity.

The analysis of the literature reveals that, although the problem of wagon traffic distribution in branched railway networks has a long history, it requires further research to consider the peculiarities of railway operations in different countries. The relevance of the research for Kazakhstan and Ukraine is conditioned by the fact that their railway transportation networks were primarily developed during the USSR era to ensure domestic transportation. After these countries gained independence, the share of export and transit cargoes in their railway traffic increased sharply, leading to a significant shift in the direction of freight flows across the existing railway networks.

2. Research Data and Methods

The problem of freight traffic distribution across a railway network under capacity constraints in a monopolistic or dominant market comprises two sub-problems: determining the optimal distribution of freight traffic in the railway network, minimizing transportation costs, and distribution of railway transportation costs among shippers.

Operations research methods are employed to address the issue of freight traffic distribution across a railway network. Cargo transported between origin and destination stations is considered a separate type of product. A parametric orgraph $G(V, E)$ is used as a model of the transportation network. The vertices of the orgraph are divided into three subsets: departure vertices $v_{s,i} \in V_s$ and cargo destination vertices $v_{d,i} \in V_d$, $i = \overline{1..n}$ (where n is the number of product types), $v_{t,j} \in V_t$, $j = \overline{1..m}$ (where m is the number of transit vertices). It is assumed that vertices can be the origin or destination of only one cargo. In the event that several types of cargo depart from and/or arrive at a station, the vertices are duplicated. For example, Figure 1 shows a conventional representation of a station shipping 1 and 2 types of cargo with a volume of 10 and 20 units, respectively, and also receives cargo of type 3.

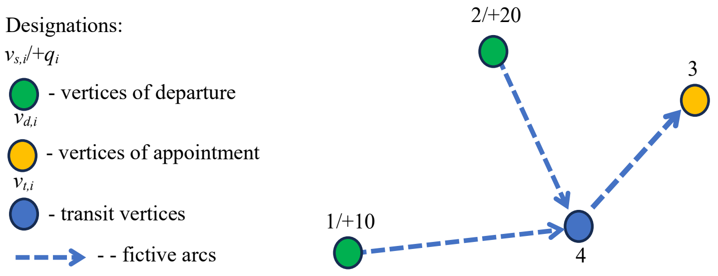

Fig. 1 Conventional representation of a station on the orgraph. Source: authors

The station in Fig. 1 is represented by four vertices (two origin vertices, one destination vertex, and one transit vertex), as well as three fictitious 0-length arcs.

The arcs of the orgraph $e_{uv} \in E$ correspond to the railway sections between stations (where u, v are indices of the vertices bounding the arc of the orgraph). The arc direction corresponds to the direction of transportation. Sections between stations, where transportation is carried out in two directions, are represented by two arcs $u \rightarrow v$ and $v \rightarrow u$ on the orgraph. The distances or the cost of transporting a unit of cargo c_{uv}, as well as constraint of throughput capacity d_{uv}, are specified for individual sections. The cargo flows to be carried across the network are given by the volumes q_i.

If $d_{uv}=\infty$ is true for all arcs, then the problem of freight traffic distribution across the network is reduced to finding the shortest distance for each freight traffic. The obtained solution determines the minimum freight flow that can be realized across a given transportation network$\sum CF_{\min}$. An example of a railway network with the shortest transportation routes is shown in Fig. 2.

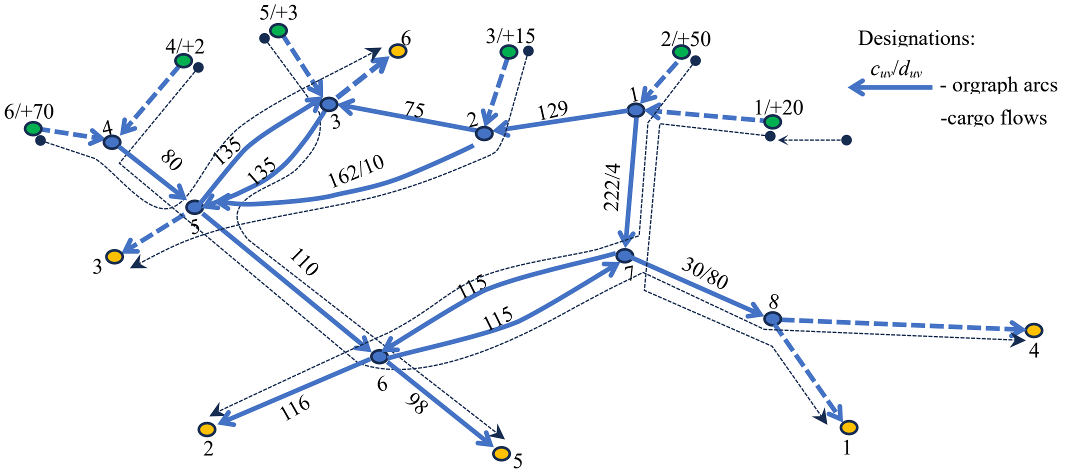

Fig. 2 Railway network with indication of the shortest transportation routes. Source: authors

If there are no capacity constraints across the network sections, which is shown in Fig. 1, the freight turnover will be$\sum CF_{\min}$= 46.869 million tonne-km. If there are capacity constraints on certain sections, it is necessary to coordinate the volumes of freight transported by different consignors on individual sections, which is done as part of the train formation plan development.

Denote the cargo volume of type *i* travelling along the arc e_{uv} as f_{uv}^{i}. As a result, the optimisation problem of cargo flow distribution can be represented as:

$$\sum CF = \sum_{e_{uv}\in E} \sum_{i} c_{uv} f_{uv}^{i} \to \min, i = \overline{1..n}\,, \quad [\text{mln tkm}] \tag{1}$$

$$\begin{cases} \sum_{i} c_{uv} f_{uv}^{i} \leq d_{uv} \\ \sum_{e_{iv}\in E} f_{iv}^{i} = q_i \\ \sum_{e_{ui}\in E} f_{ui}^{i} = -q_i \\ \sum_{e_{kv}\in E} f_{kv}^{i} - \sum_{e_{uk}\in E} f_{uk}^{i} = 0, \\ f_{uv}^{ij} \geq 0 \end{cases}, \quad [\text{mln t}] \tag{2}$$

where: u, v is the indices of the origin and destination vertices of the arc [-], respectively; c_{uv} is distance (cost) of transporting cargo along arc uv [km]; d_{uv} is throughput capacity constraint of the arc uv [mln t]; f_{iv}^{i} is the volume of the i-th type of cargo transported along an arc from the vertex corresponding to its departure station to the vertex *v* [mln t]; f_{ui}^{i} is the volume of the *i*-th type of cargo transported along an arc from the vertex *u* to the vertex corresponding to its destination station [mln t]; f_{uk}^{i}, f_{kv}^{i} is the volume of the *i*-th type cargo transportation, from vertex *u* to transit vertex *k* and from transit vertex *k* to vertex *v*, respectively [mln t]; *i* is type of cargo, indices of vertices corresponding to the departure and destination stations of the *i*-th type of cargo [-]; *k* is transit vertex index [-]; q_i is the volume of the *i*-th type of cargo transported across the network [mln t].

The problem of minimising the target function (1) under constraints (2) is a degenerate case of a multiproduct linear programming transportation problem for the case where each product has only one initial and one final vertex. Given the peculiarities of the problem, an algorithm based on sequential improvement of the transportation plan can be used to find its solution. The proposed algorithm consists of performing the following steps:

Step 1. Develop an initial transportation plan in which each cargo follows the shortest route.

Step 2. If the transportation plan satisfies the system of constraints (2), then the solution is complete. Superimpose the routes of wagon flows on the initial orgraph and determine the cargo turnover $\sum CF$.

Step 3. Determine the transportation distance l_i for each cargo.

Step 4. For cargo flows on arcs, such as:

$$\sum_i c_{uv} f_{uv}^i > d_{uv}, \quad \text{[mln t]} \tag{3}$$

Find alternative routes of cargo flows. For this purpose, it is necessary to remove the arcs for which $\sum_i c_{uv} f_{uv}^i \geq d_{uv}$ from the orgraph G and re-determine the shortest transportation distances a_{uv}^i for those cargoes that caused the arc overflow in accordance with condition (3).

Step 5. If there is no alternative route for any type of cargo transported along an arc with overflow of throughput capacity, the solution is complete. The transportation network does not allow the required volume of cargo to be transported.

Step 6. Assess the lengthening of the transportation route as:

$$\Delta_{uv} = \min_i \left(a_{uv}^i - l_i\right), \quad \text{[km]} \tag{4}$$

where: l_i is length of the shortest route for transporting the i-th type of cargo [km]; a_{uv}^i *is* the shortest length of an alternative route for transporting i-th type of cargo, passing through arcs with reserve of throughput capacity [km].

Step 7. Select the arc with the minimum value of Δ_{uv}; if several arcs have the same minimum value of Δ_{uv}, select the arc with the highest congestion of throughput capacity. Increase the transportation distance on the arc with the minimum value of Δ_{uv}, so as $c_{uv}^* = c_{uv} + \Delta_{uv}$.

Step 8. Redistribute freight flows across the network considering revised distances.

Step 9. Go to step 2.

The proposed iterative algorithm is a sequential improvement method aimed at finding a feasible transportation plan that minimizes the target function (1).

The convergence of the algorithm is guaranteed by the monotonic increase in the length of the arcs at each iteration. Since arc lengths never decrease and the number of arcs and cargoes is finite, the flow will gradually be redistributed to alternative routes until all throughput capacity constraints (2) are satisfied. The final feasible plan is globally optimal and is achieved through the principle of minimum necessary cost increment. In this case, the algorithm starts with a theoretical global minimum cost and, at each iteration, to eliminate inadmissibility an arc with the minimum route elongation is selected. Thus, the final feasible transportation plan is closest to the theoretical lower limit of costs, which satisfies the criterion of global optimality.

3. Results

The optimal transportation plan for the conditions described in Fig. 2 is shown in Fig. 3.

Considering the throughput capacity constraints of the railway network, its freight turnover will be $\sum CF$= 50.469 million tonnes-km. Arcs 1-7 and 2-5 with exhausted throughput capacity are shown in red colour in Fig. 2. It should be noted that the presented solution reflects only the task of minimizing the total costs of railway freight transportation and does not provide equal conditions of access to public infrastructure for shippers.

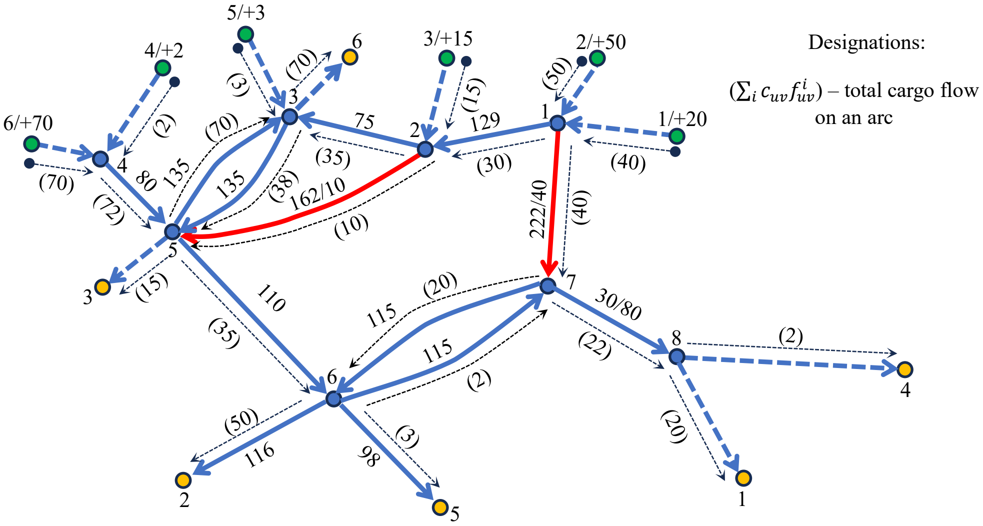

Fig. 3 Distribution of freight flows across a network with throughput capacity constraints on sections. Source: authors

The methodology applied in Kazakhstan provides for the tariffing of transportation services based on the minimum distance. The presence of congested sections across the railway network leads to an increase in freight turnover across the railway network compared to the tariff freight turnover determined by the shortest distance by the amount of Δ_{CF}, so that

$$\sum\text{CF}=\sum\text{CFmin}+\Delta\text{CF}\ , \quad [\text{mln tkm}] \qquad (5)$$

To compensate for the railway's expenses for additional freight turnover Δ_{CF}, when calculating the tariff, the cost of transportation is increased by a coefficient

$$k_t = \frac{\sum CF}{\sum CF_{\min}}, \quad [\text{-}] \qquad (6)$$

For example, in Figures 1 and 2, the coefficient is k_t=1.08. The disadvantage of this method is that the additional charge is distributed to all shippers. In particular, for the presented example, the increase in transportation costs will affect shippers 4, 5 and 6, although these shippers use a section of the network that does not have a throughput capacity shortage. It is worth noting that congested sections frequently occur on high-margin freight routes. The tariff system thus results in lower-income shippers subsidizing higher-income shippers.

In Ukraine, the freight tariff method is applied, which provides for the actual distribution of cargo flows. The disadvantage of this approach is that cargo flows that are redirected to longer routes have specific shippers whose competitiveness is reduced compared to shippers using the shortest routes. In particular, in Figure 2, to achieve minimum freight turnover under conditions of limited railway throughput capacity, the cargo of shipper 1 travelled along the shortest route, and that of shipper two along routes lengthened by an average of 67 km. This order, in particular, led to a conflict situation after the restoration of the railway bridge in the town of Voznesensk, which was destroyed during the hostilities. At the same time, cargo transportation from central Ukraine to the port of Yuzhny was redirected to a new, shorter route. At once, cargo routes to the port of Chernomorsk remained unchanged due to the limited throughput capacity of the restored section. As a consequence, the actions of Ukrzaliznytsia led to a change in the competitive conditions between stevedoring companies in the ports of Yuzhny and Chernomorsk.

To address the issue of redistributing the costs of additional cargo turnover among shippers in the presence of capacity constraints, it is proposed to enhance the method of estimating tariff distances between tariff points. For this purpose, a reference transportation plan is developed. Arcs with unfilled throughput capacity are included in the reference plan. For arcs with filled throughput capacity, an equivalent length is set to ensure that operational (actual) traffic is equal to the traffic across the network without throughput capacity constraints. In particular, in the example shown in Figures 1 and 2, due to the throughput capacity constraint on Arc 1-7, the freight turnover of shippers 1 and 2 increased from 15.540 million tonne-km to 18.900 million tonne-km. This increase in cargo turnover corresponds to an increase in tariff distance on arc 1-7 by the value δ_{1-7}=48 km from 222 km to 270 km. Due to throughput capacity constraints on arc 2-5, the shipper's three freight turnovers increased from 2.430 million tonne-km to 2.670 million tonne-km. This increase in freight turnover corresponds to an increase in the tariff distance on arc 2-5 by the value δ_{2-5}=16 km from 162 km to 178 km. The transportation network with adjusted tariff distances is shown in Fig. 3. The arcs for which adjustments were made in Fig. 4 are highlighted in red.

Further calculations of freight transportation tariffs can be carried out using the existing methodology based on the shortest tariff distances.

The proposed method provides such an alignment of operational and tariff cargo turnover, in which additional costs associated with using areas with exhausted throughput capacity are transferred directly to shippers interested in utilizing these routes.

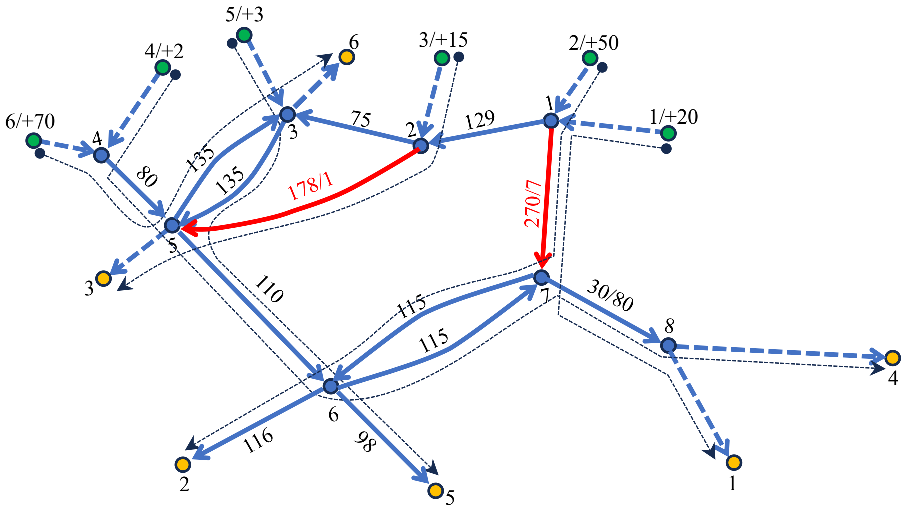

Fig. 4 Railway network with adjusted tariff distances. Source: authors

4. Discussion

Railway transport systems in Kazakhstan and Ukraine are primarily oriented toward freight transportation, most of which consists of raw materials. The main requirement for transporting such commodities is low service cost, ensured by centralized management of transportation processes and the high freight intensity of railway lines. This structural characteristic limits the effective division of the freight transport market among multiple carriers. In Kazakhstan, despite the demonopolization of the railway freight market initiated in 2001, most freight operations are still performed by the national carrier “KTZh-Cargo Transportation LLP”. In Ukraine, the freight transport market remains monopolistic, and the company established on the basis of Ukrzaliznytsia JSC is expected to retain a dominant position. Under these conditions, access to public railway transportation services and their pricing require regulatory oversight.

The tariff-setting approach used in Kazakhstan – based on calculating freight tariffs according to the shortest routes across the railway network – offers simplicity and predictability for shippers. However, it may lead to cross-subsidization, where the transportation costs of some shippers are effectively covered by others. In contrast, Ukraine’s transition to tariff-setting based on the actual distribution of wagon flows has created the problem of ensuring equal access to public railway transportation under limited capacity on certain network sections. In addition, within this system a monopolistic railway carrier may have incentives to overstate transportation distances in order to increase its profit.

The problem of fair access to railway transportation services is also relevant in deregulated markets. In the European Union, it is addressed through request coordination, refusal of some applications, traffic redirection, or auctions. Similar approaches are used in North America and Australia. However, these methods cannot be directly applied in Kazakhstan, Ukraine, and other countries where regulation concerns relations between a monopoly or dominant carrier and shippers rather than between infrastructure managers and carriers.

This study proposes a method to address this issue by adjusting tariff distances for sections with exhausted throughput capacity. The proposed approach retains the clarity and predictability of the shortest-route tariffing system while reallocating additional costs associated with congested routes directly to the shippers using them. In this way, cross-subsidization is reduced and a fairer distribution of transportation costs is achieved.

Despite differences in transport market organization, this approach is broadly consistent with Article 31(4) of Directive 2012/34/EU, which allows infrastructure charges to reflect capacity shortages. While the Directive proposes increasing infrastructure charges and this study suggests adjusting tariff distances, both mechanisms pursue the same objective: signalling resource scarcity and encouraging the development of capacity on congested sections.

The scientific novelty of the research lies in improving the methodology for distributing freight flows across railway networks under throughput capacity constraints. The proposed method explicitly considers the interests of individual shippers by identifying congested sections of the network and adjusting tariff distances accordingly. This approach refines the theoretical framework for freight flow distribution and provides practical tools for balancing the efficiency of railway operations with the principle of non-discriminatory access. The practical significance of the study lies in its potential to improve methods for organizing wagon flows and setting freight tariffs while balancing the interests of railway operators and service users.

The main limitation of the model is that it is static and deterministic in nature, whereas transportation volumes across the network change dynamically over time and differ from predicted volumes due to the influence of random factors. Future research should therefore focus on extending the method to ensure long-term stability of tariff distances while accounting for probabilistic changes in network load.

5. Conclusion

1. Market reforms in the economies of Kazakhstan and Ukraine necessitate a revision of the conditions governing the interaction between railways and shippers. Under current conditions, methods for organizing freight flows under throughput and capacity constraints should ensure not only cost minimization but also fair access to railway transportation services for all shippers.

2. The problem of freight traffic distribution across a railway network under throughput capacity constraints can be formulated as a multiproduct linear programming problem. Due to its degenerate

structure, an algorithm is proposed to improve the initial transportation plan. The resulting solution ensures the minimum average transportation cost, which is particularly important for railways mainly engaged in transporting raw materials. Due to the exhaustion of the throughput capacity of certain sections across the network, a portion of the wagon flows is redirected along longer routes, resulting in higher transportation costs.

3. To reconcile tariff-based and operational freight turnover, a method is proposed that adjusts tariff distances for sections with exhausted throughput capacity. This approach not only aligns the tariff freight turnover with operational flows, but also enables the identification of shippers using such sections and the distribution of additional transportation costs among them.

4. The developed method can be applied in monopolistic railway markets or where the carrier holds a dominant position. It retains the clarity and predictability of tariff distance calculation based on the shortest routes across the railway network while ensuring equitable access to public railway transportation services for different shippers.

Acknowledgments

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