Application of Dynamic Traffic Flow Modeling for Technical Routing in Freight Rail Transport

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**Abstract.** One of the key challenges in railway transportation management is the efficient distribution of transport loads and related operational activities among technical railway stations. To address this, a dynamic traffic flow model of the railway network has been developed to support the technical routing of freight transportation. This model facilitates the aggregation and analysis of traffic flow parameters within infrastructure nodes and enables the prediction of potential operational bottlenecks at railway stations. Implementation of the model significantly improves the precision of technical routing decisions—by up to 58%—while reducing organizational and operational costs associated with freight flow management by approximately 13%. Moreover, the model increases the applicability of analytical planning methods across railway networks of diverse structural configurations. The research outcomes have been practically applied on the Belarusian Railway through the introduction of regulatory guidelines and methodological recommendations for assembling freight trains of various categories. These outcomes have also been embedded into digital information systems to support algorithmic decision-making in real-time operational management.

**Keywords:** Railway transportation, traffic flow model, technical routing, freight transportation, infrastructure nodes, operational bottlenecks, organizational costs, analytical planning, digital information systems, real-time management

# INTRODUCTION

Throughout the development of railway transport, various strategies and methodologies have been applied to design effective systems for organizing freight flows across different train categories. A key goal of these systems is to establish a technical routing plan for freight transportation (TRFT), which ensures the efficient allocation of tasks related to processing and directing freight flows at technical railway stations within the network [1, 3].

An in-depth evaluation of current freight flow organization systems, alongside scientific and practical aspects of traffic management, shows that approximate methods are commonly used to determine optimal train formation plans. However, these approaches often suffer from inaccuracies in both input parameters and the outcomes they produce. Studies of existing analytical methods have highlighted significant limitations in their precision. Notably, as the number of railway stations involved in the calculation area increases, the chances of achieving an optimal solution diminish – falling below 1% when 15 or more stations are included. Moreover, the implementation costs for TRFT plans derived from these methods can exceed those of the true optimal solution by up to 13% [2, 4].

# FREIGHT FLOW ORGANIZATION SYSTEM IN TRAINS

At various stages of railway transport development, different approaches and methods have been employed to design an optimal freight flow organization system for trains of various categories. One of the primary objectives of the freight flow organization system is the development of the technical routing for freight transportation (TRFT). This plan ensures the rational distribution of work related to processing and passing freight flows among technical railway stations in the network [5, 9]. The TRFT is an integral part of the freight flow organization system and is one of the two methods of freight transportation routing (Figure 1).



**FIGURE 1.** System for organizing wagon flows into trains

A comprehensive analysis of the current state of freight flow organization systems and the scientific-practical aspects of traffic flow management reveals that, in practice, approximate methods are used to calculate the optimal train formation plan. Common issues across these methods include inaccuracies in the initial calculation parameters and the resulting solutions. Research on existing analytical methods has identified their accuracy limitations [3, 5]. The findings show that as the number of railway stations in the calculation zone increases, the likelihood of finding the optimal solution decreases, dropping to less than 1% for zones with 15 or more stations. Additionally, the costs associated with implementing TRFT based on these methods exceed those of the optimal solution, with deviations reaching 13%.

Further challenges arise during the validation of the TRFT organization against the available throughput capacity of railway infrastructure, particularly stations and junctions. Current practices for evaluating station capacity rely on analytical methods that fail to account for parallel operations in the transportation process, including TRFT. Calculations are performed for each technological line of the process, assuming all other variables remain constant. This leads to inaccurate management decisions when assessing the use of available station capacities.

An analysis of the problem's state in managing freight flow organization processes indicates unresolved issues in TRFT development within existing regulations, publications, and railway transportation management practices. Key technological challenges are rooted in the planning phase for an optimal organization system, specifically during the train formation plan calculation. The outcomes of these calculations—and the selection of a TRFT organization system—are significantly influenced by the accuracy of input parameters and the calculation method used. Input parameters are highly sensitive, and changes to even a single freight flow correspondence from the calculated value can drastically alter the entire TRFT organization system, impacting transportation process costs.

Enhancing the reliability and relevance of input parameters, as well as improving calculation methods, is essential. This necessitates research focused on developing more precise and adaptive calculation methods, increasing the accuracy of initial parameters, and creating models that consider the dynamic variability of traffic flow [6-8].

# DYNAMIC MODEL OF TRAFFIC FLOW

The TRFT organization technology is based on developing a rational system for consolidating multiple freight flow correspondences into a coordinated plan for train formation assignments across the railway network. This process includes an evaluation of the transportation capacity of railway stations. To achieve this, the topology of a railway station and its processes is represented as a formalized set of nodes and arcs in a Petri network, with the traffic flow modeled as tokens. Determining the magnitude of the traffic flow serves as a fundamental parameter in the TRFT organization system and is critical for modeling the operational work of railway stations, making it a significant research challenge.

To calculate traffic flow parameters at railway stations – the primary infrastructure where flow transformation occurs – modeling the formation and routing of freight flow and wagon flow correspondences across calculation zones is required. The model must allow for the determination of routes and parameters for individual correspondences while also aggregating the parameters of all correspondences within the traffic flow for the calculation zones.

Traffic flow is inherently vectorial, as its parameters include both magnitude and direction. The calculation zones of the railway network are represented as a symmetric graph, where the vertices correspond to technical and other required railway station categories, and the edges represent connecting sections and tracks. The graph structure is typically arbitrary, depending on the topology of the railway network being analyzed [10, 13, 15].

The mathematical representation of a railway transportation network can be formalized as a connected undirected graph *G=(S, E)*, where – is a finite unordered set of railway stations, and *E* – is a set of vertex pairs describing the topology of the railway network.

The set 𝐸 is defined by an adjacency matrix 𝐴 as follows:

(1)

(2)

where *aij*= 1 if stations *Si* and *Sj* are connected by a railway section with no intermediate designated stations; otherwise *aij*= 0; *n* is the number of railway stations in the network. For the defined graph *G*, a weight matrix *W* is established:

(3)

where *wij* is the weight (distance, time, cost) between stations *Si* and *Sj*, if ; otherwise, *wij* = 0.

Using the weight matrix 𝑊, a route vector *ri* is constructed for each station *Si* based on various optimization criteria (distance, time, cost):

(4)

where *Si*(*j*) is the station preceding station *Sj* on the route from *Si* to *Sj*.

The set of all route vectors for each station in the railway network forms the overall route model .

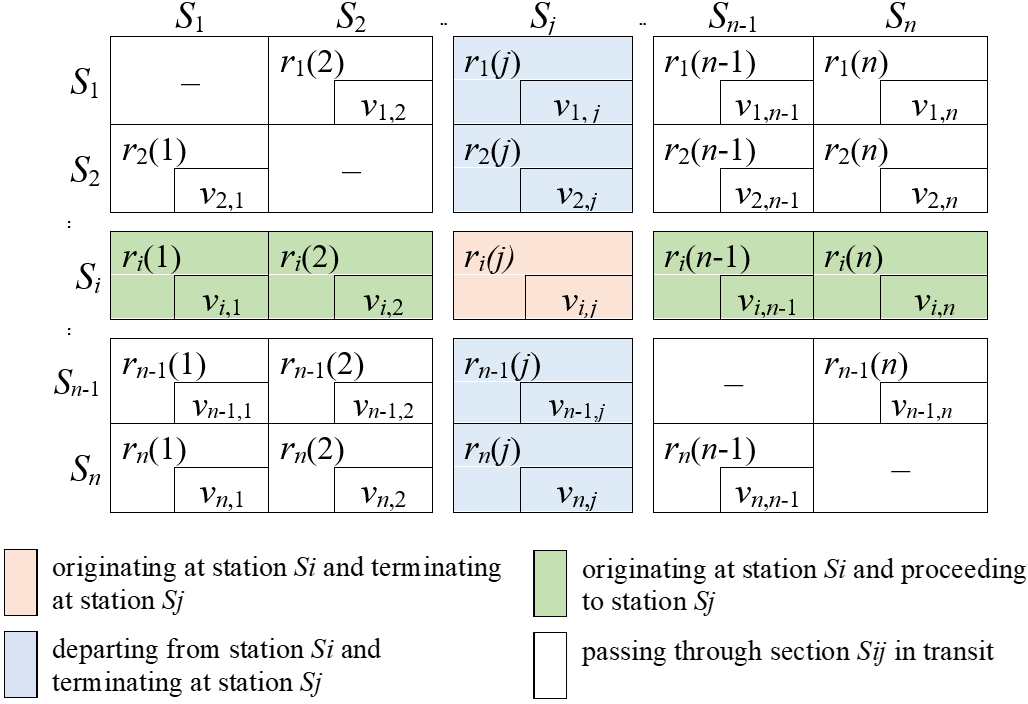
The above definitions provide a complete mathematical formalization of the railway network and form the foundation for describing the dynamic traffic flow model *T* within the railway network. This model can be generalized as:

*T = (V, R)*  (5)

(6)

where *V* represents the parameters (volume) of traffic flow correspondences from station *Si* to station *Sj*.

The network structure of the dynamic traffic flow model, as described by 𝑇, can be represented in tabular form. Each cell includes not only the parameters of traffic flow correspondences but also a vector characteristic of their route through all sections from the origin to the destination station (Figure 2).



**FIGURE 2.** Dynamic model of traffic flow

The proposed dynamic traffic flow model and the method for forming a station route tuple for traffic flow enable identification, aggregation, and calculation of traffic flow parameters at infrastructure facilities [8]. The algorithm for identifying and aggregating traffic flow within a specified railway section is shown in Figure 3.

The calculated parameters of the resulting traffic flow are used to solve various tasks of the TRFT, including the development of an optimal organizational system and subsequent analysis of the required capacity of railway stations.



*Traffic flow is categorized as follows: a) originating at station 𝑆𝑖 and terminating at station 𝑆𝑗; b) originating beyond station 𝑆𝑖 and terminating at station 𝑆𝑗; c) originating at station 𝑆𝑖 and continuing beyond station 𝑆𝑗; d) transiting through the railway section bounded by stations 𝑆𝑖 and 𝑆𝑗.*

**FIGURE 3.** Algorithm for identifying and aggregating traffic flow within a specified railway section

The development and real-time adjustment of the TRFT utilize a methodology for the relative evaluation of the feasibility of designating wagon flows as through train assignments [2, 11]. This methodology is based on the following principles:

1. Wagon flow correspondences can be designated as a separate through assignment only if the condition is met:

or (7)

where *npq* is the total size (calculated parameter) of the wagon flow between stations 𝑝 and 𝑞 (wagons); is the total savings in reduced costs due to the wagon flow *npq* avoiding intermediate technical station processing (wagon-hours); *Cpmp* is the cost of accumulating wagons at station 𝑝 for assignment to station 𝑞 (wagon-hours).

2. Wagon flow correspondences that do not meet this condition should not be designated as separate through assignments.

3. Analytical calculation methods, regardless of differences in mathematical formalization and task interpretation, should be based on the above principles. Each calculation iteration must include a procedure for the relative evaluation of the feasibility of designating wagon flow correspondences as separate through assignments.

The proposed methodology enhances the accuracy of the train formation plan calculations through a new relative evaluation criterion for the feasibility of designating wagon flows as through assignments. This criterion simultaneously considers numerical characteristics and operational properties of the traffic flow [12]. This approach reduces the costs of organizing and managing wagon flows through the railway network by up to 13% and expands the applicability of analytical methods across calculation zones with various configurations [3, 14].

# DYNAMIC MAP OF WAGON FLOWS

The proposed traffic flow model and associated methods for identifying and aggregating traffic flows at railway infrastructure facilities have been implemented in the development of software for monitoring and forecasting freight and wagon flows on the Belarusian Railway ("Dynamic map of wagon flows") [16-18].

The Dynamic map of wagon flows is an integral part of the informational support system for the transportation process on the Belarusian Railway. It provides the TRFT system with real-time data on freight and wagon flows, as well as their distribution across the railway network, considering various attributes such as wagon condition, type of rolling stock, ownership, etc.

The various output forms of the Dynamic map of wagon flows allow for the calculation and assessment of transportation loads on infrastructure facilities, considering planned transportation volumes. Traffic flow simulations can be performed using actual, shortest, or calculated routes. This capability enables the evaluation of the transportation potential of individual railway stations, sections, routes, and the entire network under different flow management scenarios [19-20].

To address TRFT tasks, output data on the completed wagon and train flows by railway stations are generated, forming the basis for analyzing the implementation of the TRFT.

# CONCLUSION

The Dynamic map of wagon flows automates the process of generating initial data on transportation loads at infrastructure facilities for the TRFT system. It also facilitates the modeling and evaluation of traffic flows under various route formation criteria and enables the prediction of potential operational challenges at railway stations.

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