Journal of Network Intelligence ©2024 ISSN 2414-8105
Taiwan Ubiquitous Information Volume **9**, Number **1**, February **2024**

Two-stage Heuristic Algorithm for Dynamic Train Operation Plan of High-speed Express Freight Train

Lingming Jiang

School of Transportation and Logistics
Southwest Jiaotong University, Chengdu 610500, China
Beijing National Signal and Communication Research & Design Institute Group Co., Ltd
Beijing 100070, China
wishjlm@126.com

Zexi Shen

School of Transportation and Logistics
Southwest Jiaotong University, Chengdu 610500, China
victor_shenzx@163.com

Rongyao Liu

Yibin City Cui Ping District Rural Road Construction Service Center
Yibin 644000, China
liurongyao_ll@my.swjtu.edu.cn

Xinyi Wang, Jinshan Pan*

School of Transportation and Logistics
Southwest Jiaotong University, Chengdu 610500, China
1369919160@qq.com, jshpan@swjtu.cn

Fangzhu Pu

New Corridor Logistics Group Co., Ltd. of Sichuan Port and Shipping Investment
Chengdu 610000, China
410607652@qq.com

*Corresponding author: Jinshan Pan
Received August 16, 2023, revised September 20, 2023, accepted December 30, 2023.

Abstract. *Based on the traditional railway freight transportation organization model, train schedules are compiled based on annual cargo transportation statistics and forecasts. This belongs to a static transport planning mode which has difficulty in adapting to market dynamics and often faces issues of mismatched flow lines. In this paper, a dynamic train schedule compilation model is proposed based on train operation plans. It focuses on the characteristics of high-speed express freight train transportation, such as high demand volatility and strict delivery time requirements. The model incorporates the ideas and processes of dynamic train scheduling for fast freight transportation on high-speed railways. The objective is to maximize the revenue of high-speed freight train transportation while minimizing the delivery time of freight. To achieve this, a dynamic space-time network-based model for high-speed express freight train planning is established. The paper designs a two-stage heuristic solution method based on an improved Dijkstra algorithm and a genetic algorithm. In the first stage, the preparation is made by finding a set of candidate paths. The improved Dijkstra algorithm is used to find the k shortest paths between each OD pair of freight flows, which are then filtered. In the second stage, the genetic algorithm is deployed, employing chromosome encoding methods, initial population generation methods, and selection and crossover methods that are in line with the characteristics of the model. This stage ultimately obtains the high-speed rail express freight train operation plan within a given period. Finally, the feasibility of the model and algorithms is validated through examples.*

Keywords: Rail transport; High-speed railway express; Train operation plan; Genetic Algorithm

---

1. **Introduction.** With the stable growth in demand for express delivery services in China, utilizing the surplus capacity of high-speed railways to operate dedicated high-speed freight trains and achieve economies of scale in high-speed express delivery has become an important trend in the development of high-speed rail freight. Traditional railway freight transportation relies on statically compiling freight train formation plans based on statistical and predictive freight demand, which can easily lead to situations where there are lines without flow or flow without lines. The railway freight transportation system is a dynamic system, and in particular, the operation plan for high-speed express freight trains should be market-oriented, starting from meeting the needs of freight owners and being able to respond actively to changes in the market environment. Therefore, it is urgent to further address and optimize the operation plan for high-speed express freight trains based on the dynamic market demand for freight flow.

Scholars both domestically and internationally have conducted a series of studies on the operation plan of express freight trains. Ceselli et al. [1] proposed various express freight organization models for railways, which include strict constraints such as time windows for freights and capacity limitations to optimize the overall operation of the railway system. Anghinolfi et al. [2] designed a method that includes the distribution of freight containers, researching the optimal scheduling of trains and the optimal allocation of freight containers. Kim et al. [3] constructed an optimization model for railway freight service network design, and Crainic [4] researched the influence between transportation nodes and paths. Boejko et al. [5], Samà et al. [6], Mu and Dessouky [7], and others designed algorithms to determine the fastest routes for freight trains in the railway network. In the construction of models for freight train operation plan, Martinelli and Teng [8], Claessens et al. [9], Fukasawa et al. [10], and others used integer programming models, while Ghoseiri et al. [11] employed multi-objective programming models. Wu et al. [12] proposed a lightweight vehicle social network security authentication protocol based on fog nodes, and Li et al. [13] proposed a new scheme using elliptic curve algorithms to improve the shortcomings of Wu's protocol, which utilized the idea of node storage and updating. Chen et al. [14] proposed an authentication scheme that can be deployed in digital-twin-enabled autonomous vehicle environments. In terms of algorithms, Shi et al. [15] and Ceselli et al. [1] utilized Lagrangian heuristic algorithm, while Claessens et al. [9] used branch and bound method. In the context of the Internet of Vehicles (IoV), there are similar constraints and challenges: there are strict requirements for real-time data transmission and computation. Therefore, the process of data processing is highly dynamic and needs to adjust based on real-time feedback and requirements. Scholars such as Hu [16] and Li [17] studied the planning-based transportation organization model for China's existing railway freight transportation system, focusing on freight transportation production organization technology and freight transportation planning. However, the studies mentioned above were conducted under the traditional freight transportation organization model, optimizing the operation plan based on statically predicted freight flow, without considering the dynamic nature of express freight transportation demands and their limited ability to adapt to the fluctuations in daily transportation operations. Addressing the shortcomings of the planning-based transportation organization model mentioned above, Ni [18] and Chen [19] proposed a groundbreaking dynamic planning-based railway freight transportation organization model to achieve dynamic, timely, and refined freight transportation. Wu [20] considering dynamically changing freight flow, studied the optimization problem of the operation plan. They proposed a mechanism to match market freight flow with the operation plan and designed an adjustment mechanism for the train's operation plan. They also developed a multi-objective optimization model for the compilation of freight train operation plans and designed a solving algorithm applicable to the model.

Currently, research on railway express freight transportation mainly focuses on carrying trains and confirmation trains. There is relatively less research on the transportation mode of dedicated freight trains. The existing planning-based transportation organization model has difficulty in responding dynamically to the transportation demands of freight owners and has limited adaptability to daily transportation operation fluctuations. This paper aims to study the dynamic compilation method for high-speed rail express freight train schedules, considering the dynamic changes in the fast freight market and the time requirements for delivery on specialized trains for high-speed rail freight transportation.

2. **Problem Analysis.** The operation of high-speed express freight trains involves the handling of freight during station stops, which requires manual loading and unloading operations. Sufficient time must be allocated for these operations, but long station stops can cause significant waste of track capacity. Additionally, excessive station stops can affect the timeliness of high-speed express delivery, making it difficult to achieve fast and timely delivery. Therefore, this paper imposes simplified restrictions on the number of station stops for high-speed express freight trains: the train is limited to a maximum of one station stop for loading and unloading operations at intermediate stations.

High-speed express freight trains have the following operations at intermediate stations:

(1) The train stops at intermediate stations for loading and unloading operations. Intermediate station is a broad concept that includes high-speed passenger stations borrowed for freight use, modified high-speed passenger stations, modified passenger depots or yards, high-speed freight stations, and freight depots, among others.

During the operation of freight train units, excluding double handling operations (unloading and then loading), if the freight train unit stops at an intermediate station for loading and unloading operations, it indicates that the train is carrying multiple flows of goods with different origins and destinations, and the transportation routes of these flows overlap spatially. When the limit for the number of station stops is set to a maximum of one, the situation of the goods carried by the train during the stop at an intermediate station can be illustrated using Figure 1. The freight train unit transports two flows of goods with different origins and destinations, both starting at station A. The train needs to stop at station B to unload flow 1, and then continue its journey to transport flow 2 to the final destination.

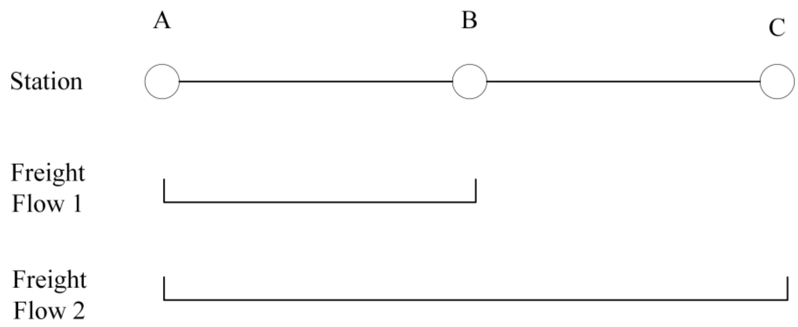

Figure 1. Schematic diagram of train stopping for express freight train

In this operation mode, although there is a condition to allow the train to stop at intermediate stations for partial loading and unloading operations to meet transportation time constraints, the transportation capacity of the B-C section cannot be fully utilized, and the loading and unloading operations of the freight train unit would consume a considerable amount of time. Therefore, when studying the operational plan for high-speed express freight, the discussion of train stops for loading and unloading operations at intermediate stations is not considered, and this situation will not be further discussed in the following text.

(2) Train stops at depot for combination or grouping operations

During the operation of high-speed passenger train units, train sets are generally not disassembled to ensure passenger safety. Similarly, freight train units are not disassembled during operation to ensure timely delivery of goods. When there is a shortage of capacity or train sets at the depot, combining or grouping operations of freight train units at these locations can effectively alleviate the transportation organization pressure on the high-speed freight department. Therefore, in order to fully utilize the line capacity and reduce the fixed operating costs of trains, the freight train units can be combined or grouped at depots or yards with operational capabilities during the journey.

The types of train set formations mainly include single-unit and multiple-unit formations. To efficiently utilize the network capacity and save train operating costs, single-unit trains can be combined at the depot to form multiple-unit trains, and multiple-unit trains can be separated at the depot to form single-unit trains to fully utilize railway resources. The formation types of high-speed freight train units are mainly influenced by factors such as the level of demand from freight owners in the origin and destination cities, the transit time of high-speed freight trains, fluctuations in freight volume during special events such as Double Eleven and Mid-year promotional event, and the equipment and facilities conditions at stations along the route.

Figure 2 represents two freight train units with the same destination station. Freight train unit D2 undergoes a train combination operation with train unit D1 along the way, and the two single-unit trains are combined into a multiple-unit train D3 at the depot A2.

Figures 3 and 4 respectively represent two different grouping operations of multiple-unit trains. In Figure 3, N1 and N2 represent two different freight flows with different

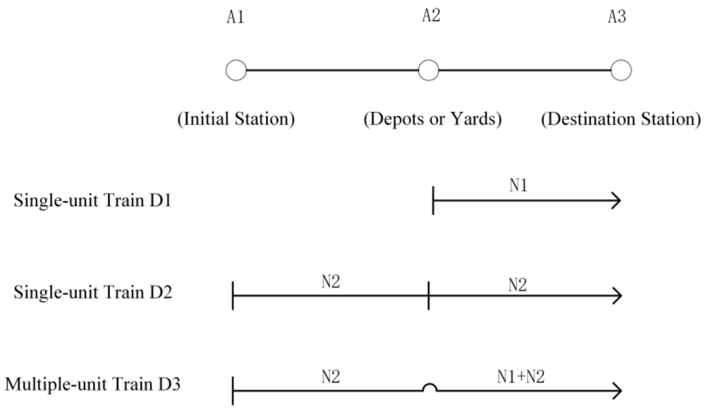

Figure 2. Combined operation mode for express freight train

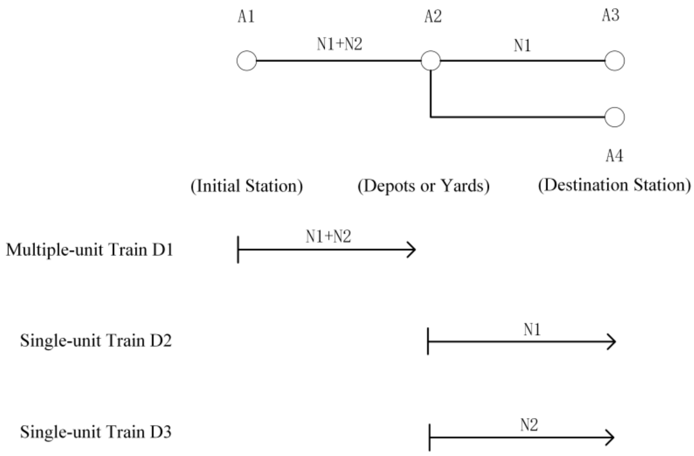

Figure 3. The first train grouping mode for express freight train

destinations. After the multiple-unit train completes its operation in the A1-A2 section, a grouping operation is performed to form two single-unit trains with different destinations. In Figure 4, after the multiple-unit train completes its operation in the A1-A2 section, a grouping operation is performed, and single-unit train D2 continues its journey to the destination in the A2-A3 section. After the multiple-unit train undergoes a grouping operation at the depot, a multiple-unit train D3 is operated in the A1-A2 section, while a single-unit train D2 is operated in the A2-A3 section.

The impact of market freight flow fluctuations on operational plans can be divided into two aspects: changes in freight volume and changes in the delivery time of express goods.

Firstly are changes in freight volume. Freight flow is described by factors such as flow capacity, direction, and timing, and it forms the basis for the development of operational plans for high-speed rail express freight trains. Changes in freight flow direction can be considered as a decrease of freight volume to 0 in a certain direction, accompanied by the addition of a certain quantity of freight in the opposite direction. Therefore, changes in freight flow direction are included in the category of changes in freight volume. Based on the impact of freight volume changes on train operation plans, changes in freight volume can be classified into two categories:

1. The freight volume between OD pairs for high-speed rail express freight transportation increases from 0 or decreases to 0.

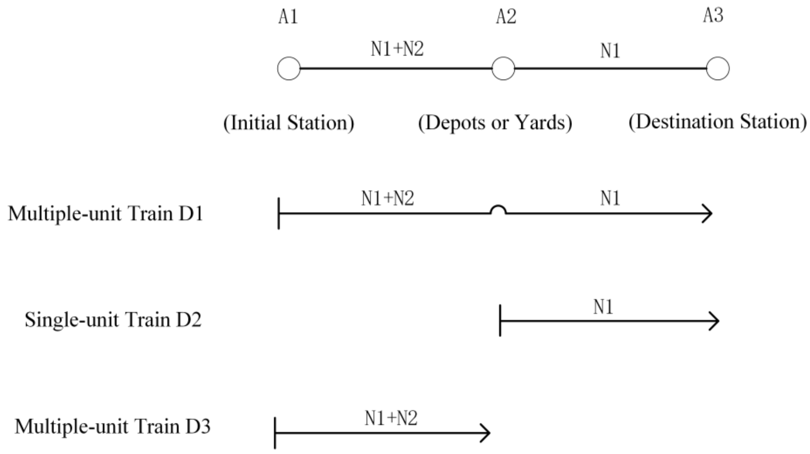

Figure 4. The second train grouping mode for express freight train

2. The freight volume between certain OD pairs changes to some extent. Secondly, changes in the delivery time of express goods. The majority of goods transported in the high-speed rail express market are positioned as "high-end" transportation products, and they mostly consist of high-value-added goods. These goods have a high requirement for timeliness. Failing to deliver goods safely within the requested delivery time not only results in economic losses for the businesses but also causes irreparable damage to their reputation.

The delivery time of express goods in high-speed rail can be represented by Formula (1):

$$T_{od} = \Sigma T_s + T_l + T_{un} + L/V \tag{1}$$

T_{od}—The actual delivery time of goods with OD as the origin and destination points;
$\sum T_s$—total station stoppage time along the train route;
T_l, T_{un}—loading and unloading time of goods;
L—train running distance between OD pairs
V—train running speed.

Traditional train operation planning and optimization methods generally use a static transportation network without considering the time dimension. Therefore, they cannot reflect the impact of changes in delivery time on train operation plans. Based on the characteristics of high-speed rail express freight transportation, the timeliness of transportation should be a key factor to consider. Therefore, it is necessary to introduce the time dimension for optimization when developing operational plans.

In this paper, when preparing a dynamic train operation plan for high-speed rail express freight, the market OD freight flow situation is considered to determine a set of alternative paths for freight flow between OD pairs. Based on the capacity of high-speed rail freight stations, the capacity of high-speed rail lines, and the loading and unloading situations of goods, the delivery time requirements between OD pairs are taken into account. Dynamic selection of train operating paths, determination of train operating time periods, and station stoppage arrangements are made from the set of alternative paths, in order to meet the dynamic changes in market freight flow.

Therefore, as shown in Figure 5, this paper proposes a process for developing a dynamic train operation plan for high-speed express freight based on freight flow demand:

Firstly, to reflect the dynamic market freight flow demand in the operation plan, it is necessary to determine a set of alternative paths for each OD freight flow based on the market freight flow situation;

Secondly, to ensure the delivery time of express goods, the time factor is introduced into the transportation network during the planning period. Reasonable time intervals are established, and a high-speed rail express freight space-time network is created. The set of alternative paths for each OD freight flow is expanded based on time intervals to obtain a set of alternative paths based on time periods;

Then, considering the capacity of high-speed rail freight stations, the capacity of high-speed rail lines, freight handling situation, and the constraints of goods transportation time, a high-speed rail express freight service network is established;

Finally, based on the high-speed rail express freight service network, dynamic selection of train operating paths and time periods is conducted, resulting in a dynamic train operation plan for high-speed rail express freight. This plan includes train running paths, train operating time periods, station arrangements, etc.

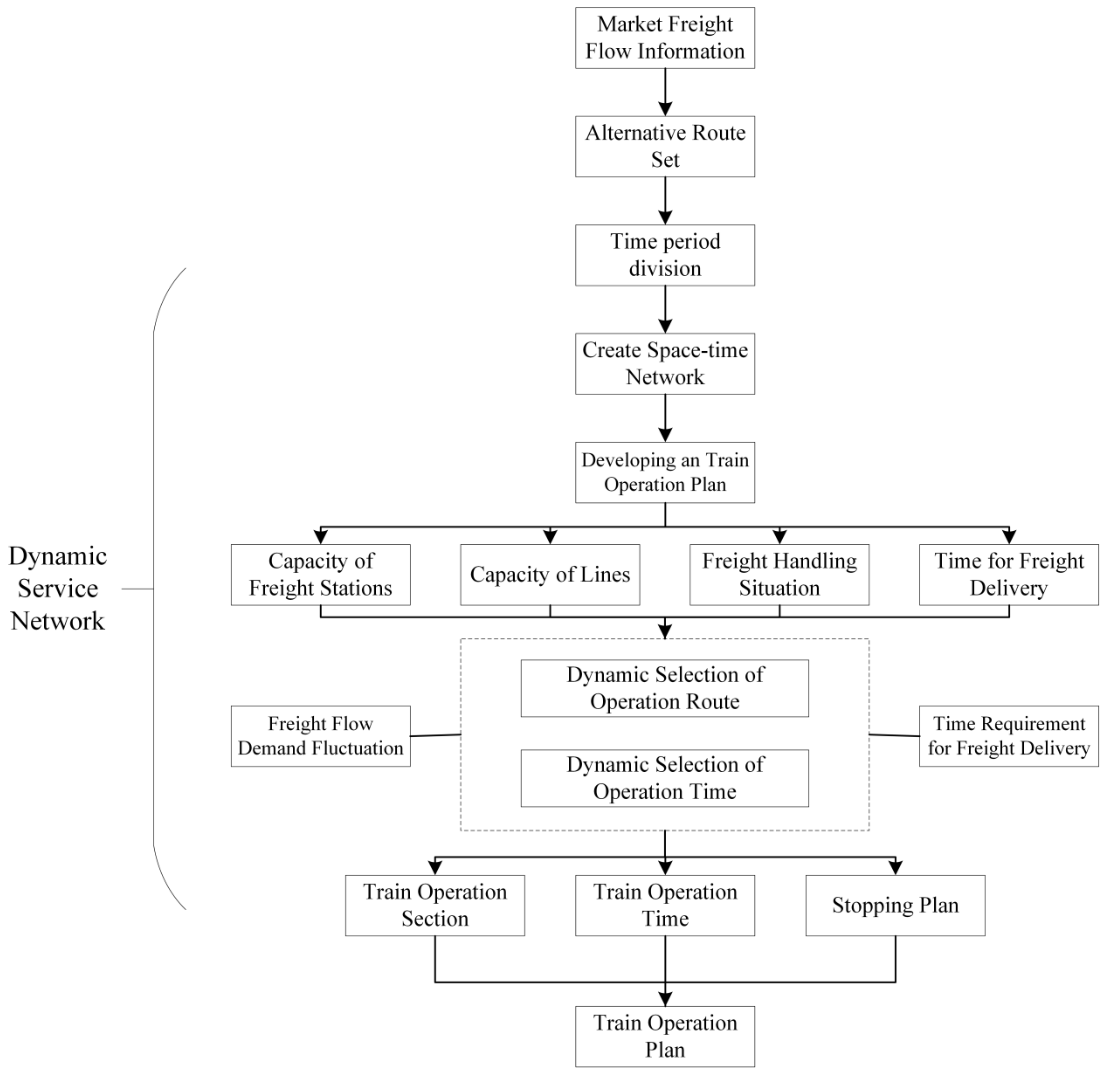

Figure 5. The process for developing an operation plan for high-speed express freight train based on freight flow demand

3. Dynamic High-Speed Express Freight Train Operation Planning Model.

3.1. Assumptions and Symbol Explanations.

3.1.1. *Condition Assumptions.* The condition assumptions of this model are as follows:

(1) Background Assumption: It is assumed that a significant number of high-speed rail freight trains are in operation, and the high-speed rail freight stations (including using passenger stations for freight purposes) are operational with equipment and facilities that meet the requirements for high-speed rail express freight train operations.

(2) Known Passenger Train Timetable: High-speed rail express freight services are conducted while ensuring that they do not interfere with high-speed passenger transportation. Therefore, it is assumed that detailed information about the passenger train timetable is known.

(3) Station Operation Capacity Assumption: It is assumed that the equipment and facilities at the stations meet the requirements for high-speed rail express freight services, and their capacities are sufficient.

(4) Railway Line Capacity Assumption: It is assumed that the capacity of the high-speed rail lines meets the requirements for high-speed rail express freight train operations, and the grades of the high-speed rail lines are the same.

(5) Unique Station Assumption: Each city is considered to have only one high-speed rail freight station, which is abstracted as a single node.

3.1.2. *Symbol Explanation.*

Set Definitions:

N: Set of space-time networks, $N = (V, E)$. V represents the set of high-speed rail freight stations, and all stations mentioned below are assumed to be high-speed rail freight stations.

E: Set of transport arcs e in the space-time network, the index of E includes i, j, d, f, p, c. An individual transport arc is represented as $e(i, j, d, f, p, c)$, where i and j are the identifiers of the preceding and succeeding nodes of the arc, $i \leq j$. To an arc e_{ij}, when $i \neq j$, it indicates that the arc is a running arc. When $i = j$, it indicates that the arc is a stopping arc. d represents the transportation distance of the arc e, f represents the freight volume of the arc e, p represents the transportation price of the arc e, and c represents the unit mileage cost of the arc e. This study adopts a dynamic service network. It extracts the demand nodes from the static service network and expands them in the time dimension to address the resource allocation issues in both time and space dimensions. Taking the space-time network in Figure 6 as an example, the red arcs represent: The train departs from station A at time T_0, passes through three operational periods, and arrives at station D. At station D, unloading operations and other necessary tasks are performed, followed by a wait of two periods before departing from D and returning to station A. This complete arc describes a complete train operation plan and train route.

V: The set of nodes v of arc a in a dynamic space-time network, where the set index includes $i, t^{\mathrm{arr}}, t^{\mathrm{dep}}$. The complete representation of a node for a particular transportation arc is $v(i, t^{\mathrm{arr}}, t^{\mathrm{dep}})$, where i represents the node's identifier, t^{arr} represents the arrival time of the transportation arc at this node, and t^{dep} represents the departure time. Since waiting arcs and parking arcs are set in the service network, for all nodes on arcs, $t^{\mathrm{arr}} = t^{\mathrm{dep}}$, simplifying the representation of nodes to $v(i, t)$.

Decision variables

a_e^g: Whether freight flow g choose service arc e to transport.

$$a_e^g = \begin{cases} 1, & \text{if freight flow } g \text{ chooses service arc } e \text{ to transport,} \\ 0, & \text{if freight flow } g \text{ does not choose service arc } e \text{ to transport.} \end{cases} \tag{2}$$

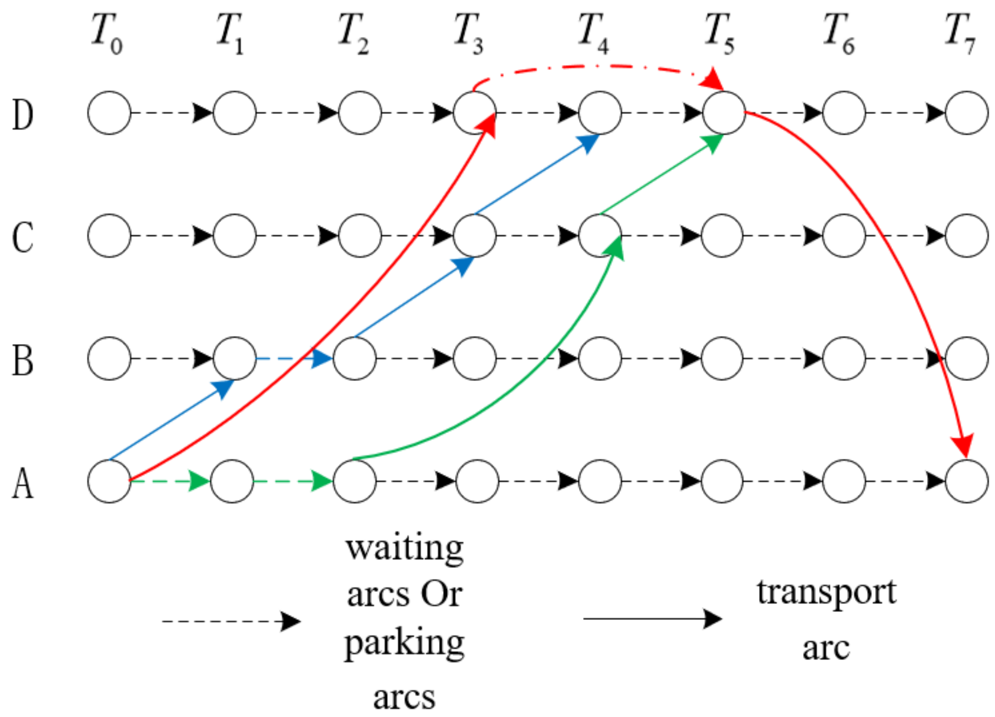

Figure 6. Schematic diagram of the spatial-temporal network

β_e^t: Whether service arc e provide transport service during period t.

$$\beta_e^t = \begin{cases} 1, & \text{if service arc } e \text{ provides transport service during period } t, \\ 0, & \text{if service arc } e \text{ does not provide transport service during period } t. \end{cases} \tag{3}$$

Other parameters are defined as follows:
$t_{\text{delay},i}$: Stopping time at station i;
c_{in}: Operation income of railway department;
p_e: Unit transportation price of arc;
f_e: Freight volume of arc;
dis: Transportation distance of arc;
c_{fix}: Fixed cost of running trains;
t_e: Transportation time of arc in service network;
c_e: Unit distance cost of arc;
ξ: Marshalling quantity of trains, $\xi = 8$ represents single marshalled trains, $\xi = 16$ represents multiple-unit train;
B_{ij}^t: Carrying capacity of section ij during t period, ij corresponds to station information of arc;
n_g^e: Quantity of freight flow g of selective service arc e;
P: Maximum number of stopping times during train operation.

3.2. **Model Construction.** The establishment of the freight train dedicated train deployment model is similar in general direction to the optimization of passenger train deployment schemes. Therefore, the model considers maximizing the economic benefits of the railway department and minimizing the transportation time of goods as the optimization objectives. At the same time, it takes into account factors such as time requirements for freight delivery, interval capacity constraints, service network transportation arc capacity constraints, minimum freight train load constraints, train stopping constraints, and uniqueness of freight flow paths. The model is established for the compilation of dynamic high-speed freight train deployment schemes.

3.2.1. *Model Objectives.* In this work, the model objectives are as follows:

(1) Economic benefits of the railway department:

Railway operating revenue: The operating income of high-speed freight train transportation is mainly related to the unit price of goods transportation, the volume of freight, and the transportation distance. It is represented by Formula (4):

$$c_{in} = \sum_{e \in E} p_e \cdot f_e \cdot dis_e \tag{4}$$

Railway operating costs: The operating costs of high-speed freight train transportation can be divided into fixed costs and variable costs. Fixed costs are only related to the number of train deployments. Variable costs are mainly related to the number of train deployments, freight quantity, train composition quantity, and transportation distance. The operating costs can be represented by Formula (5):

$$c_{cost} = \sum_{e \in E} \beta_e^t \cdot c_{fix} + \sum_{g \in G} \sum_{e \in E} \xi \cdot dis_e \cdot c_e \cdot \alpha_e^g \cdot n_g^e \tag{5}$$

To sum up, the economic benefits goal of the railway department can be represented as:

$$\max c = \sum_{e \in E} p_e \cdot f_e \cdot dis_e - \sum_{e \in E} \beta_e^t \cdot c_{fix} - \sum_{g \in G} \sum_{e \in E} \xi \cdot dis_e \cdot c_e \cdot \alpha_e^g \cdot n_g^e \tag{6}$$

(2) Minimum freight transportation time:

Freight transportation time mainly contains train operation time and stopping time, which can be represented as:

$$\min t = \sum_{e \in E} \alpha_e^g t_e + \sum_{e' \in E} \alpha_{e'}^g t_{e'} \tag{7}$$

3.2.2. *Restraint conditions.* The restraint conditions are as follows.

(1) Freight arriving time constraints

$$T'_d \leq T_o + \sum_{e \in E} \alpha_e^g t_e + \sum_{e' \in E} \alpha_{e'}^g t_{e'} \leq T_d, \forall g_{od} \in G \tag{8}$$

The paper assumes that each train can make at most one stop at an intermediate station. When a train stops at an intermediate station, the service arcs in the network are divided into two, denoted as e and e'. The departure time of the second arc must differ from the departure time of the first arc by one time interval. T_o represents the earliest time interval for transporting freight flow g_{od}. T'_d and T_d represent the earliest and latest time intervals for the freight flow requested by the shipper to be delivered. t_e represents the transportation time of the service arc e in the service network.

(2) Section carrying capacity constraints

$$\sum_{i,j \in e} \beta'_{e_{i,j}} \leq B'_{ij}, \forall e \in E \tag{9}$$

Section carrying capacity refers to the surplus capacity deducted from the high-speed rail passenger transportation capacity, only reserved for the operation of dedicated freight train units.

(3) Capacity of arc constraints in service networks

$$\sum_{g\in G}\sum_{i,j\in e}\alpha_{e_{ij}}^{g} n_{g}^{e} \le m_{\xi}, \forall e \in E \tag{10}$$

m_ξ represents the maximum capacity when the train composition quantity is ξ.

(4) Minimum train load constraints

$$\beta_e' m_\xi^{\min} \le \sum_{g\in G} \alpha_e^g n_g^e, \forall e \in E \tag{11}$$

$m_\xi^{\min}$ represents the minimum train load when the train composition quantity is ξ. Formula (11) represents train can operate only when the load of the train achieves certain standard.

(5)Unique constraint of freight flow path

$$\sum_{e\in E} \alpha_e^{g_{od}} \le 1, \forall g_{od} \in G \tag{12}$$

(6) Train stopping constraints

$$\beta_{e'}^{t} = \beta_e^{t-t_e}, \forall d_e = o_{e'} \tag{13}$$

Constraints above also indicate that the end of first arc have to be the start of the second arc. d_e represents the end of arc e, o_e represents the start of arc e'.

(7) Node freight flow balance constraints

$$\beta_e^t \sum_{\substack{e\in E \\ o_e = o_g}} \alpha_e^g = \beta_e^t, \forall g_{od} \in G \tag{14}$$

$$\beta_e^t \sum_{\substack{e\in E \\ d_e = d_g}} \alpha_e^g = \beta_e^t, \forall g_{od} \in G \tag{15}$$

$$\beta_e^t \sum_{\substack{e\in E \\ d_e = i}} \alpha_e^g = \beta_e^t \sum_{\substack{e'\in E \\ o_{e'} = i}} \alpha_{e'}^g, \forall g_{od} \in G, i \in V, i \ne o_g, i \ne d_g \tag{16}$$

g_{od} represents the flow whose start is o and the end is d. Constraints (14)-(16) not only represents node freight flow balance constraints, but also indirectly reflects the principle of undivided freight flow when transporting.

(8) Constraints on the number of train stops.

$$\sum_{i\in o\sim d}^{d} \alpha_{ii}^{g_{od}} \le P, \forall g_{od} \in G \tag{17}$$

In this paper the train only stop P times during the whole operation. A simplified way can be expressed: The train only stops at the intermediate station for one time or none.

(9) Logical relation constraints

$$\alpha_e^g \le M\beta_e^k, \forall e \in E, g \in G \tag{18}$$

$$\alpha_e^g \in \{0,1\}, \forall e \in E, g \in G \tag{19}$$

$$\beta_e^k \in \{0,1\}, \forall e \in E, g \in G \tag{20}$$

Formula (18) represents only when arc e is sure to transportation service, can freight flow g choose arc e to implement transportation work. M is a positive number large enough.

4. **Algorithm Design.**

4.1. Approach to Model Solution. The above model belongs to a multi-objective optimization problem, which can be transformed into a multi-objective linear programming problem after linearization. However, the introduction of time factors in the transportation network leads to an increase in problem size, and commercial linear programming solvers may take a long time or even fail to produce results. Therefore, this paper designs a two-stage heuristic method based on the Dijkstra algorithm and genetic algorithm to solve the model.

The first stage is the generation of alternative paths. Based on the existing physical network, the Dijkstra algorithm is used to find the k-shortest paths between all pairs of flow od points. Based on these paths, the paths that do not meet the delivery time limits are eliminated, and the transportation paths are replaced with the second shortest paths until satisfactory service paths that meet the delivery time limits for the flow are found. Normally, there are 2-3 alternative paths for each flow OD pair, with a minimum of one alternative path.

The second stage involves designing a genetic algorithm to determine the train operation and flow allocation plans based on the alternative path set.

4.2. Model Solution Algorithms. The first stage is the generation of alternative path sets. The main objective is to minimize the travel distance between freight stations for train operations. The shortest path algorithm is used as the basis to gradually search for the shortest and k-shortest paths between each OD pair. The paper mainly use the Dijkstra algorithm.

The steps to search for the shortest path from A to B using the improved Dijkstra algorithm are as follows:

Step 1: Designate A as the starting point. Set set P to accommodate the points and corresponding lengths of the shortest paths already obtained, and set set T to accommodate the points whose shortest paths have not been found yet and the distances from those points to the starting point A.

Step 2: Initially, set P only contains the starting point A, and set T contains all nodes except the starting point. The distances of nodes in T are set to the distances from the starting point to each respective point. If a node is not adjacent to the starting point, the distance is set to infinity.

Step 3: Select the node with the shortest distance from the starting point among the nodes in set T, add it to set P, and remove it from set T.

Step 4: Update the distances from each node in T to A.

Step 5: Return to Step 3 until all nodes have been traversed, and record the length of each segment of the searched shortest path.

Step 6: Set the length of the shortest edge in the obtained shortest path as infinity. Return to Step 1 and search for the k-1 shortest path.

Once the shortest path from A to B is computed, the method to calculate the k-shortest path from A to B only needs to remove one of the shortest edges obtained in the aforementioned steps and calculate the k-shortest path at that point.

The second stage involves using a genetic algorithm to determine the train operation plan and flow allocation plan. It primarily includes the following:

(1) Chromosome encoding method

As shown in Figure 7, a specific integer coding method is designed. Odd positions with a value of 1 indicate the selection of the corresponding service arc, otherwise it is 0. Even positions correspond to the grouping types of the odd position service arcs. Typically, the grouping types for multiple unit trains are either single unit or coupled, so the even positions take values of 0, 8, or 16. The chromosomes for individual time periods are concatenated to form a complete chromosome. For ease of representation, the figure shows a complete chromosome stacked by time periods.

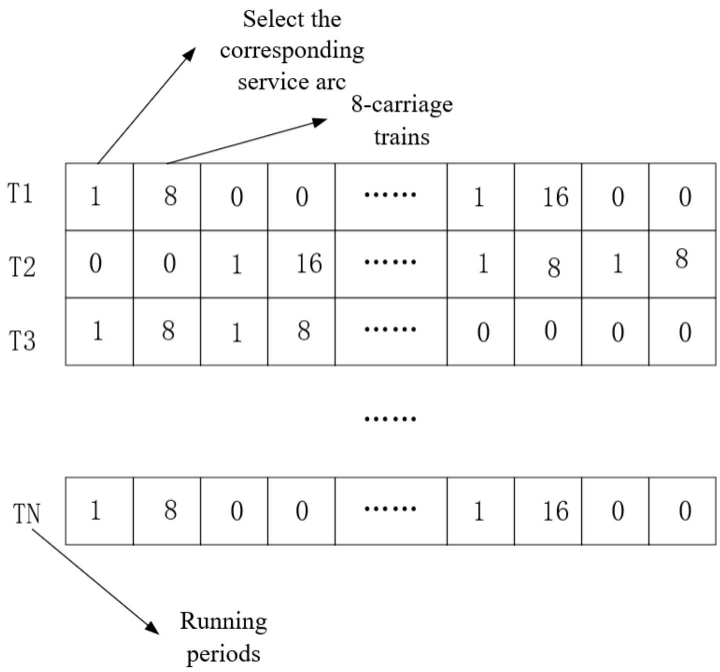

Figure 7. Schematic diagram of chromosome coding

(2) Population Generation

The initial population is generated based on the set of alternative paths.

Assuming there are n time periods and each time period has m freight flows od, the number of alternative paths for each od can be defined as $trip_n^m$. Based on known freight flow data, the freight flows are divided into time periods, and each od is assigned at least one alternative path, typically generating 2-3 alternative paths for each od.

When generating the initial population, each od in each time period selects at least one alternative path. The odd positions in the chromosome are set to 1, and the corresponding even positions are randomly set to 8 or 16. After generating the population, feasibility checking is performed based on the constraint conditions, and infeasible chromosomes are directly eliminated.

(3) Fitness Calculation

The model established in this paper is a constrained multi-objective optimization model. The dimensions of the two objectives need to be normalized using normalization methods. Then, the external penalty function method is used to transform the problem into an unconstrained optimization model. Max-min normalization is used to normalize the objective function, which can be represented as:

$$x_{0-1} = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{21}$$

After normalizing the objective functions (6) and (7), they can be represented as equation (22):

$$obj : \min T = \lambda_1 c_{0-1} + \lambda_2 t_{0-1} \tag{22}$$

λ_1 and λ_2 represent the weighting factors of the two objectives.

Once the fitness of each chromosome is calculated, the selection probability for each individual is calculated.

(4) Selection

Good individuals are selected from the population (parent generation). The selection probability of each individual is calculated based on its fitness value, and then the individuals are selected using the roulette wheel selection with replacement method to form a new population (offspring generation) from the parent population. The population size of the parent and offspring generations should remain the same.

(5) Crossover

Crossover operation simulates the exchange of chromosome segments between parent chromosomes. For each time period, there are m freight flows od. To avoid generating infeasible offspring chromosomes, a random freight flow od is selected, and the crossover operation is performed at the last node of that freight flow od, with the crossover position being an even position. After crossover, feasibility checking is still performed for the offspring chromosomes. Infeasible individuals are discarded, and new chromosomes are generated to make up for the population size.

(6) Mutation

Mutation operation randomly changes the value at a specific position in the chromosome. A mutation probability is set, and a uniform distribution random number between 0 and 1 is generated. If the random number is less than the mutation probability, the chromosome undergoes mutation. A random time period is selected, and the value at the odd position in that time period is randomly adjusted. If the value changes from 0 to 1, the value at the corresponding even position changes randomly to 8 or 16. If the odd position in the chromosome changes from 1 to 0, the value at the corresponding even position changes from the original value to 0.

(7) Evolution

Evolution is the iterative process of the algorithm, where the population is continuously updated, and the objective function gradually approaches the global optimum.

5. **Case Study.**

Using selected data from postal service operations, a partial high-speed rail network is chosen to validate the feasibility and practicality of the two-stage heuristic genetic algorithm for the dynamic train scheduling model for high-speed rail freight.

5.1. **Road Network and its Parameter Setting.**

The selected road network consists of 9 stations and 13 sections, as shown in Figure 8.

5.1.1. *Station and Interval Data.*

It is assumed that each station meets the requirements for operating dedicated freight trains. The distances between sections and the interval throughput capacities are given in Table 1. The interval throughput capacity represents the number of freight trains that can be operated on the railway section in a day. The station capacity and interval throughput capacity are surplus capacities deducted from meeting the requirements of high-speed passenger transportation, and they are only available for dedicated freight train operations.

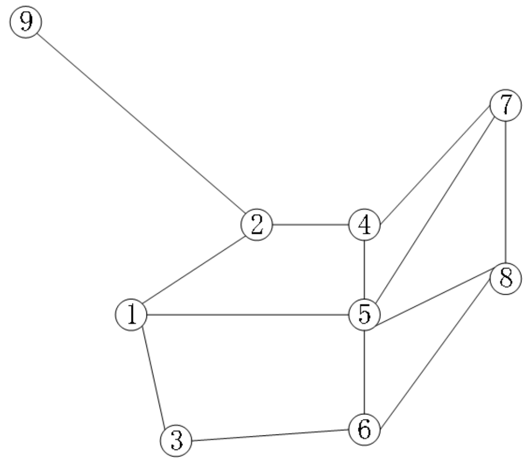

Figure 8. Physical network diagram

Table 1. Segment mileage and passing capacity

Section	Distance (km)	Passing Capacity (train set)	Section	Distance (km)	Passing Capacity (train set)
1-2	1000	6	5-6	1000	5
1-3	1000	3	4-7	500	5
1-5	1500	3	6-8	500	5
2-4	500	10	5-7	1000	3
2-9	2000	5	5-8	1000	2
3-6	1500	4	7-8	1000	5
4-5	500	6	-	-	-

5.1.2. *Freight Train Set Data.* This study refers to the relevant data on freight trains from Wu's research [23]. The unit variable cost of a dedicated freight train set is 0.0023 yuan/kg/km. The train operating speed is 250 km/h. The fixed operating cost per train is 8000 yuan. The cost of station operations during train stops is 500 yuan per train. The time required for a series of operations at intermediate stations is denoted as a time period. The reference article determines that an 8-carriage freight train set has a capacity of 120 tons. The objective in this case study is to minimize the total operating cost.

The data in this paper is presented in "carriages" as the unit. The variable cost per train is 34.5 yuan/car km. It is assumed that a single consist train must be loaded with at least 7 carriages of goods to meet the operating conditions, and a multiple-unit train must be loaded with at least 13 carriages of goods to meet the operating conditions.

5.1.3. *Freight Flow Data.* For simplicity in calculations, the dynamic train scheduling model requires that the train Operation time between any two stations is not less than the length of one time period in the space-time network. In this case study, one day is considered one cycle, and the length of one time period is 2 hours. Four hours of comprehensive maintenance window time are excluded, resulting in 10 time periods in a cycle. In the space-time network, all subsequent calculations and operations are conducted at the time period level. Therefore, the freight flow data is split into time periods accordingly. For the split data that cannot meet the minimum capacity for train operations, they are placed at the end of the priority queue for each OD pair. The results are shown in Table 2. The freight flow data (quantities) are presented in carriages as the unit.

Table 2. Freight flow information between nodes based on time period

Number	OD	Quantity	Transit Period	Number	OD	Quantity	Transit Period	Number	OD	Quantity	Transit Period
H1	1-2	8	1-5	H19	2-8	16	2-7	H33	7-8	15	2-5
H2		8	3-5	H20		7	5-9	H34		8	4-6
H3		7	4-6	H21	2-9	7	5-9	H35		8	7-10
H4	1-3	8	4-6	H22	3-6	8	4-7	H36	1-2	1	1-5
H5		8	7-9	H23		8	6-9	H37	1-5	1	4-7
H6	1-4	7	1-6	H24	3-8	8	3-9	H38	3-6	1	6-9
H7		8	4-7	H25		8	4-9	H39	4-7	2	2-3
H8	1-5	7	2-5	H26	4-7	8	2-3	H40	5-8	1	6-9
H9		8	6-10	H27		7	4-9	H41	7-8	2	7-10
H10		8	4-7	H28	4-8	7	5-8	-	-	-	-
H11	1-8	14	2-8	H29		7	6-9				
H12		7	4-10	H30	4-9	8	3-8				
H13	1-9	7	2-10	H31	5-8	16	6-8				
H14	2-4	7	3-5	H32		8	6-9				
H15		8	5-7								
H16		8	6-8								
H17	2-6	8	3-8								
H18		15	5-9								

5.2. **Generation of Alternative Sets.** Using the k-shortest path method based on the Dijkstra algorithm designed above, preliminary alternative paths between each freight flow OD pair are obtained. These paths are then combined with the delivery time limit of each freight flow for path selection. Path options that clearly do not meet the delivery time limit requirement are discarded, resulting in a set of alternative paths needed for the train scheduling model solving algorithm. Details are in Table 3.

Table 3. Alternative routes based on delivery time limit

OD	Alternative Route	OD	Alternative Route
1-2	1-2(1000)	2-9	2-9(2000)
1-3	1-3(1000)	3-6	3-6(1500)
1-4	1-2-4(1500)	3-8	3-6-8(2000)
1-5	1-5-4(2000)	4-7	4-7(500)
	1-5(1500)	4-8	4-7-8(1500)
	1-2-4-5(2000)		4-5-8(1500)
1-8	1-5-8(2500)		4-5-6-8(2000)
	1-2-4-5-8(3000)	4-9	4-2-9(2500)
	1-2-4-7-8(3000)	5-8	5-8(1000)
1-9	1-2-9(3000)		5-6-8(1500)
2-4	2-4(500)	7-8	7-8(1000)
2-6	2-4-5-6(2000)		
	2-4-7-8-6(2500)		
2-8	2-4-5-8(2000)		
	2-4-7-8(2000)		
	2-4-5-6-8(2500)		

5.3. **Simulation Calculation and Result Analysis.** Based on the above data, the Python programming language is used to implement the Geatpy algorithm library. Since the profitability of high-speed express freight transportation is not specifically calculated in this case study, the objective function (6) can be modified to minimize the total operating cost. Considering that the goods are delivered within the delivery time limit as ensured by the constraints, the minimization of transportation time, which is the primary objective in the total objective function (22), can be assigned a relatively lower weight. For example, the coefficients λ_1 and λ_2 can be set to 0.8 and 0.2 respectively.

Due to the high requirements for timeliness in high-speed express freight transportation and the relatively long operation time at intermediate stations, excessive stops would affect the timeliness of high-speed express freight transportation. Therefore, it is assumed in this paper that high-speed express freight trains have at most one stop for operation at intermediate stations. Some parameter values in the algorithm are set as shown in Table 4. After 75 iterations, the algorithm obtained the optimal result. Among them, the

Table 4. Genetic algorithm parameter values

Parameter	Definition	Value
`popsize`	Size of population	100
P_{cross}	Chromosome crossover probability	0.75
P_{mutation}	Chromosome variation probability	0.05
`Generation`	Maximum number of iterations	500

optimal value for the operating cost of the railway department is 14,781,750 yuan, and there are still 105 tons of freight remaining to be transported. The algorithm iteration process is shown in Figure 9, and the results of the operation plan calculation are shown in Table 5

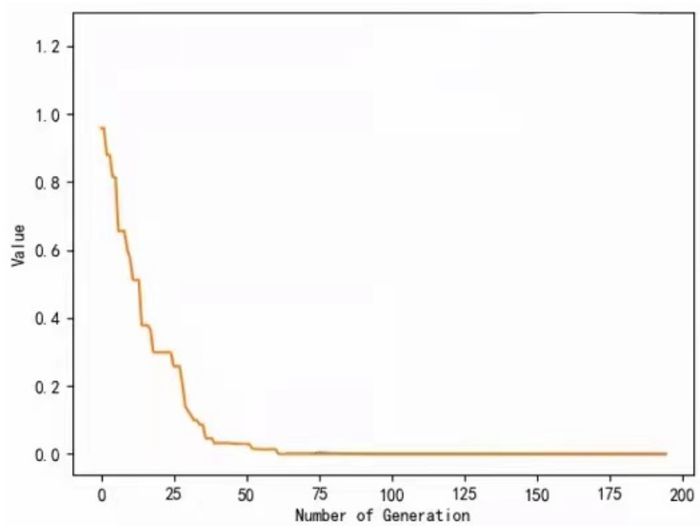

Figure 9. Algorithm iteration process diagram

Table 5. High-speed rail express train operation plan

Number of Train	Origin	Stop	Destination	Operating Period	Formation Type	Operating Routing	Freight Loaded
DH1	1	2	4	1	16-car formation	1-2-4	H1,H6,H36
DH2	1	2	9	3	16-car formation	1-2-9	H2,H13
DH3	1	-	2	4	8-car formation	1-2	H3

Continued on next page

Table 5 continued from previous page

Number of Train	Origin	Stop	Destination	Operating Period	Formation Type	Operating Routing	Freight Loaded
DH4	1	-	3	7	8-car formation	1-3	H5
DH5	1	-	4	4	8-car formation	1-2-4	H7
DH6	1	-	5	2	8-car formation	1-5	H8
DH7	1	-	5	6	8-car formation	1-2-4-5	H9
DH8	1	-	5	4	8-car formation	1-5	H10
DH9	1	-	8	2	16-car formation	1-5-8	H10
DH10	1	3	8	4	16-car formation	1-3-6-8	H4,H12
DH11	2	-	4	5	8-car formation	2-4	H15
DH12	2	-	4	6	8-car formation	2-4	H16
DH13	2	4	6	3	16-car formation	2-4-5-6	H14,H17
DH14	2	-	6	5	16-car formation	2-4-5-6	H18
DH15	2	-	8	2	16-car formation	2-4-5-6-8	H19
DH16	2	-	8	5	8-car formation	2-4-7-8	H20
DH17	2	-	9	5	8-car formation	2-9	H21
DH18	3	-	6	6	8-car formation	3-6	H23
DH20	3	-	8	5	8-car formation	3-6-8	H25
DH21	4	-	7	2	8-car formation	4-7	H26
DH22	4	-	7	4	8-car formation	4-7	H27
DH23	4	-	8	5	8-car formation	4-7-8	H28
DH24	4	-	8	6	8-car formation	4-5-8	H29
DH25	4	-	9	3	8-car formation	4-2-9	H30
DH26	5	-	8	6	16-car formation	5-8	H31
DH27	5	-	8	6	8-car formation	5-6-8	H32
DH28	7	-	8	2	16-car formation	7-8	H33
DH29	7	-	8	4	8-car formation	7-8	H34
DH30	7	-	8	7	8-car formation	7-8	H35

From the table, it can be seen that the main mode of transportation between nodes is direct freight trains. There are a total of 25 dedicated trains for direct freight operations and 5 dedicated trains for on-stop freight operations. Among them, the remaining freight after transportation by the 8-carriage trains include the freight flows H37 (15 tons remaining), H38 (15 tons remaining), H39 (30 tons remaining), H40 (15 tons remaining), H41 (30 tons remaining), etc. It is necessary to arrange confirmation trains and carrying trains to deliver these goods to their destination on time. This also indicates that even with the operation of high-speed rail express on a nationwide scale, there is still a need for localized confirmation and carrying trains.

To ensure the utilization efficiency of train sets and improve operational efficiency, the aforementioned non-stop trains mainly perform grouping operations for coupled trains during intermediate stops, such as DH2, DH10, DH13, and DH19. Other trains need to perform both grouping and loading/unloading operations during the journey, for example, the coupled train DH1, where 9 carriages are loaded with freight flows H1 and H36. Even after the grouping of coupled trains, there is still one carriage of freight that needs to be unloaded, and the remaining freight H6 is transported to station 6 by a single-carriage train after the unloading operation is completed.

6. **Conclusion.** To meet the timeliness requirements of high-speed express freight and shorten the compilation period and duration of operation plan formulation, reflecting the market fluctuations of freight flows, this paper constructs a dynamic train operation plan model and solving method for high-speed rail express. It designs a k-shortest path solving method based on the Dijkstra algorithm, uses a heuristic method to obtain a set of candidate paths, and uses a genetic algorithm to determine the train operation plan.

The effectiveness of the model and algorithm is verified through examples. The two-stage heuristic algorithm designed in this paper has high efficiency in solving the dynamic train operation plan model for high-speed rail express, and it can also generate good results for the problem of formulating operation plans for dynamic train operation of high-speed rail express under large-scale network conditions in China. It can provide good impetus for the future development of high-speed express freight transportation in China. At the same time, the results of the case also prove that even with the operation of high-speed rail express on a nationwide scale, there is still a need for localized confirmation and shuttle trains.

This paper assumes that there are enough trains when studying the operation plan for high-speed rail express. It does not consider issues related to the utilization of trains. However, in practical situations, the limitation of the number of trains often leads to mismatched line flows. Further research needs to be conducted on the relevant issues of freight train utilization.

Acknowledgements. This research was supported by the National Natural Science Foundation of China (Project No. 52072314; 52172321; 52102391), Sichuan Science and Technology Program (Project No. 2022YFH0016; 2022YFQ0101), China Shenhua Energy Co., Ltd., Science and Technology Program (Project No. CJNY-20-02), China Railway Chengdu Bureau Group Co., Ltd., Science and Technology Program (CX2202), Key R&D Program of Guangzhou (202206030007), Key science and technology projects in the transportation industry of the Ministry of Transport (2022-ZD7-131), the fundamental research funds for the central universities (2682022ZTPY068, 2682023ZTZ002), China State Railway Group Co., Ltd. Science and Technology Program (P2022X013; K2023X030).

REFERENCES

[1] A. Ceselli, M. Gatto, M. Lübbecke, M. Nunkesser, H. Schilling, "Optimizing the Cargo Express Service of Swiss Federal Railways," *Transportation Science*, vol. 42, no. 4, pp. 450-465, 2008.

[2] D. Anghinolfi, M. Paolucci, S. Sacone, S. Siri, "Freight transportation in railway networks with automated terminals: A mathematical model and MIP heuristic approaches," *European Journal of Operational Research*, vol. 214, no. 3, pp. 588-594, 2011.

[3] D. Kim, C. Barnhart, K. Ware, G. Reinhardt, "Multimodal Express Package Delivery: A Service Network Design Application," *Transportation Science*, vol. 33, no. 4, pp. 391-407, 1999.

[4] T. Crainic, "Service network design in freight transportation," *European Journal of Operational Research*, vol. 122, no. 2, pp. 272-288, 2000.

[5] W. Bożejko, R. Grymin, J. Pempera, "Scheduling and Routing Algorithms for Rail Freight Transportation," *Procedia Engineering*, vol. 178, pp. 206-212, 2017.

[6] M. Samà, P. Pellegrini, A. D'Ariano, J. Rodriguez, D. Pacciarelli, "Ant colony optimization for the real-time train routing selection problem," *Transportation Research Part B Methodological*, vol. 85, pp. 89-108, 2016.

[7] S. Mu, M. Dessouky, "Scheduling freight trains traveling on complex networks," *Transportation Research Part B*, vol. 45, no. 7, pp. 1103-1123, 2011.

[8] D. R. Martinelli, H. Teng, "Optimization of railway operations using neural networks," *Transportation Research Part C Emerging Technologies*, vol. 4, no. 1, pp. 33-49, 1996.

[9] M. T. Claessens, N. M. van Dijk, P. J. Zwaneveld, "Cost optimal allocation of rail passenger lines," *European Journal of Operational Research*, vol. 110, no. 3, pp. 474-489, 1998.

[10] R. Fukasawa, M. Aragão, O. Porto, E. Uchoa, "Solving the Freight Car Flow Problem to Optimality," *Electronic Notes in Theoretical Computer Science*, vol. 66, no. 6, pp. 42-52, 2002.

[11] K. Ghoseiri, F. Szidarovszky, M. J. Asgharpour, "A multi-objective train scheduling model and solution," *Transportation Research Part B Methodological*, vol. 38, no. 10, pp. 927-952, 2004.

[12] T.-Y. Wu, X. Guo, L.Yang, Q. Meng, C.-M. Chen, "A lightweight authenticated key agreement protocol using fog nodes in Social Internet of vehicles," *Mobile Information Systems*, vol. 2021, 3277113, 2021.

[13] Z. Li, Q. Miao, S. A. Chaudhry, C.-M. Chen, "A provably secure and lightweight mutual authentication protocol in fog-enabled social Internet of vehicles," *International Journal of Distributed Sensor Networks*, vol. 18, no. 6, 2022.

[14] C.-M. Chen, Q. Miao, S. Kumar, T.-Y. Wu, "Privacy-preserving authentication scheme for digital twin-enabled autonomous vehicle environments," *Transactions on Emerging Telecommunications Technologies*, 2023. [Online]. Available: https://doi.org/10.1002/ett.4751

[15] F. Shi, S. Zhao, Z. Zhou, "Optimizing train operational plan in an urban rail corridor based on the maximum headway function," *Transportation Research Part C: Emerging Technologies*, vol. 74, pp. 51-80, 2017.

[16] S. Hu, *Theory and Method of Planning Railway Train Operation Organization*, China Railway Press, 2017.

[17] H. Li, "The Reform of Railway Freight Transport Organization Mode and Related Technology Research, " M.S. dissertation, Beijing Jiaotong University, 2008.

[18] S. Ni, *Theory and System Design of Collaborative Compilation of Market-Oriented Dynamic Train Diagrams*, Science Press, 2019.

[19] W. Chen, "Research on the theory and technology of market-oriented dynamic freight train running diagram compilation," M.S. dissertation, Southwest Jiaotong University, 2020.

[20] X. Wu, "Research on the running plan of railway freight trains based on dynamic freight flow," M.S. dissertation, Southwest Jiaotong University, 2018.

[21] Y. Wu, "Research on the running mode of high-speed railway freight trains," M.S. dissertation, Southwest Jiaotong University, 2017.