The Train Paths Selection Model of Express Freight Train Based on the Entire Transportation Time

Wang Kai-kaí¹, a, He Shi-wei², b*

¹School of Traffic and Transportation, Beijing Jiaotong University, Beijing, China
²School of Traffic and Transportation, Beijing Jiaotong University, Beijing, China
a-e-mail: 18120895@bjtu.edu.cn
b-e-mail: shwhe@bjtu.edu.cn

Abstract—Express freight train occupies an important position in the railway freight transportation market due to its stable transportation process and good timeliness. In order to ensure the transportation stability and timeliness of express freight trains, the selection of train paths is an extremely important procedure. A scientific and reasonable selection method of train paths is a necessary guarantee for express freight trains to exert their unique advantages as freight products, and influences the quality of freight services and economic benefits. The train timetable was transformed into a space-time network. With the minimum entire transportation time as the optimization objective, and the influence factors of train trip time, transit time in the stations and freight transit period as constraints, a train paths selection model of express freight trains was constructed. The model can realize the reasonable selection of train paths. Finally, an example was given to demonstrate the feasibility and effectiveness of the model and provide a theoretical basis for the railway operation department.

1. INTRODUCTION
Train timetable is an important technical document in the daily operations of railway transportation. It stipulates the specific time when the train runs in sections and when it arrives or passes through each station. It is the basis for the railway operation department to organize the train operation. As a railway freight product with timeliness as an important competitiveness, railway express freight trains have higher requirements in terms of transit time and freight transit period than general railway freight trains. Therefore, in order to shorten the entire transportation time, ensure the completion of the cargo handover work within the freight transit period, and meet the possible individual needs of cargo owners for freight services, the selection of train paths of the express freight train is particularly critical.

Many scholars have done a variety of research on the train timetable. Li Jian¹ considered different levels of trains, and took the minimum of the weighted value of each train’s stay on the way as the optimization objective, designed a 0-1 integer programming model for the selection of the train paths, and adopted a particle swarm algorithm to search the solution of the model. Xu Han² constructed an event activity diagram to study the structure of the train timetable, considering the constraints such as periodic structure and flexible connection, and constructed the train paths adding model based on flexible connection to realize the optimization for period and non-period train timetable. Zhang Xiaobing³ took the minimum transit time of the cargo flow as the optimization objective, and constructed a 0-1 integer programming model based on the freight transit period of the freight train, which was solved by the
simulated annealing algorithm. Yu Houlun\textsuperscript{[4]} took the shortest total time of the direct freight trains at the technical stations along the way as the objective function, and established the optimization model of the direct freight train path in the straight section. Jiang Feng \textsuperscript{[5]} constructed a space-time network to convert the train timetable drawing into a route searching problem, and designed a heuristic algorithm to solve it.

Based on the above research status, in the current research on the train timetable of railway express freight trains, the research on the freight transit period is relatively rich, but there are relatively few studies that take into account the entire transportation time of the freight train. The compact entire transportation process and short entire transportation time are of great practical significance for the railway operation department to determine the operation plan, draw the train timetable and respond to emergencies in the transportation process. Therefore, it is necessary to construct an express freight train paths selection model based on the entire transportation time under the premise of ensuring the freight transit period of the goods, and design examples to verify the validity of the model, and provide decision support for the daily freight work of the railway operation department.

2. THE CONSTRUCTION OF THE TRAIN PATHS SELECTION MODEL OF EXPRESS FREIGHT TRAIN

2.1 Problem description
Train timetable is a technical document that shows the time of train operation, arrival and passage in sections and stations, and contains information in two dimensions of time and space. In order to express the relationship between the train paths in the train timetable, the train timetable is transformed into a time-space network composed of nodes and arcs.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Spatiotemporal network of train timetable}
\end{figure}

The train trip arc is used to represent the train path, and the event node is used to represent the event node of train arrival and departure in the train timetable, including the departure node representing the train departure and the arrival node representing the train arrival. Two adjacent event nodes in the same station are connected by a dwell arc, which represents the relationship between different event nodes. The spatiotemporal network is shown in Fig.1.

Thus, the train timetable can be transformed into a spatiotemporal network \( G = (N, A) \), \( N = \{N_p, N_q\} \), \( N_p \) is the departure node set, and \( N_q \) is the arrival node set. \( A = \{A_r, A_d\} \), \( A_r \) is the train trip arc set, and \( A_d \) is the train dwell arc set.

Therefore, the problem can be transformed into finding a feasible route from the train's originating station to the train's destination in the time-space network, and making the route the shortest, that is, the shortest entire transportation time, thus turning the original problem into a route searching problem.

In order to keep the simplicity of the model, the following three basic assumptions are proposed:

1. The basic information of infrastructure such as stations and railway lines is known.
2. The basic train timetable and train schedule have been obtained.
3. The train can stop at any station, and all stations have basic equipment for operation.

2.2 The model construction

Equation (1) is the objective function of the model, and it is based on the shortest entire transportation time of the train, which mainly includes the actual trip time of the train in the section and the operating time at the station. The equation is as follows:

$$\min T = \sum_{l \in L} x_l t_l + \sum_{l \in L_1} x_l p_l + \sum_{l \in L_2} x_l q_l$$  \hspace{1cm} (1)$$

In the equation, $L$ is the train path set and $l \in L$, $L_1$ represents all the train paths in $L$ except the direct train paths between the cargo originating station and the final station and all the train paths starting from the originating station, $L_2$ represents all the train paths in $L$ except the direct train paths between the cargo originating station and the final station and all train paths arriving at the final station, $t_l$ is the trip time of the train path $l$ at the section, $p_l$ is the departure time of the train path $l$ at the originating station, and $q_l$ is the arrival time of the train path $l$ at the destination. $p_0$ is the earliest time when the train meets the operating conditions at the originating station, and $q_0$ is the latest time when the train meets the freight transit period at the destination. $x_l$ is a 0-1 decision variable, and the value is 1 when the train path $l$ is selected, otherwise it is 0.

Equation (2) is the flow balance constraint, which ensures that the selected train path plan can represent the operation process of the train from the originating station to the destination. The equation is as follows:

$$\sum_{l \in L_{+s}} x_l - \sum_{l \in L_{-s}} x_l = \begin{cases} -1 & s = 1 \\ 0 & s \in S_{md} \\ 1 & s = n \end{cases}$$ \hspace{1cm} (2)$$

In the above equation, $S$ is the stations set and $s = \{1, 2, 3, \ldots, n\} \subseteq S$, and $S_{md}$ represents all stations except the originating station and the final destination. $L_{+s}$ means all train paths arriving at station $s$, and $L_{-s}$ means all train paths starting from station $s$.

Equation (3) is the logical sequence constraint of train paths, which means that at any intermediate station along the route, the arrival time of the arrival train path connected by this station must be less than the departure time of the departure train path, so as to ensure that any two train paths connecting the same station have reasonable time connection relationship. The equation is as follows:

$$\sum_{l \in L_{+s}} x_l p_l - \sum_{l \in L_{-s}} x_l q_l \geq 0 \forall s \in S_{md}$$ \hspace{1cm} (3)$$

In the formula, $p_l$ is the departure time of the train path $l$, and $q_l$ is the arrival time of the train path $l$.

In the process of model solving, considering the possibility of loops, the model should be controlled by adding constraints, which are expressed as:

$$\sum_{l \in L_{+s}} x_l \leq 1 \forall s \in S_{md} \cup s = 1$$ \hspace{1cm} (4)$$

$$\sum_{l \in L_{-s}} x_l \leq 1 \forall s \in S_{md} \cup s = n$$ \hspace{1cm} (5)$$
Both equation (4) and equation (5) are constraints on the number of train paths. Equation (4) indicates that there is at most one departure train path connected to stations other than the destination, and equation (5) indicates that the number of arrival train paths connected to stations other than the originating station should not more than one, and the above two equations are to avoid loops in the network.

Equation (6) indicates that the train must meet the operating conditions before it can depart from the departure station. The equation is as follows:

$$\sum_{i \in \mathcal{L}} x_i p_i \geq p_0$$

Equation (7) indicates that in the selected operation plan, the train must complete the cargo handover at the destination within the specified time limit, that is, meet the necessary requirement for the freight transit period. The equation is as follows:

$$\sum_{i \in \mathcal{L}} x_i q_i \leq q_0$$

As the train timetable shown in the Fig. 2, if it is stipulated by the train transit period that the train can arrive at station C later than $t_2$, obviously according to the objective function of the model, the train path 8005 with shorter transportation time can be given priority. But if the train must arrive at station C between $t_1$ and $t_2$, 8001-8005 can only be selected as a feasible solution.

Equation (8) is a 0-1 constraint on the decision variable. When the train path $l$ is selected, the value is 1, otherwise it is 0.

$$x_i \in \{0, 1\}$$

The above is the objective function and constraints of the model. The model is a 0-1 integer programming model, which can be solved by the branch and bound method.

3. APPLICATION

In order to verify the validity of the train paths selection model of express freight train, the following example was designed for research. A railway line consisting of 6 stations and 5 sections was designed. Station A is the departure station of the train and Station F is the final destination of the train. All stations have sufficient transportation capacity and have infrastructure to meet the needs of train operations at station. The circuit structure is shown in Fig. 3.
Define 0 minute to represent the origin of the time axis, and all time nodes are calibrated in minutes, representing the time from the origin of the time.

Assuming that an express freight train completes all train preparation work at 83 minutes and meets the starting conditions, it is necessary to select a set of reasonable train paths in the basic train timetable, and travels from station A to station F according to the operation plan provided by the train paths. The delivery of the cargo shall be completed within the specified delivery time as required by the cargo owner.

Taking into account that different cargo owners or goods of different types have different requirements for freight transit period, in order to study the adaptability of the model to different situations, three different standard freight transit periods were given, and the optimized train operation schemes were studied respectively. The freight transit periods and corresponding delivery time are shown in Tab.1.

Tab.2 shows the basic train timetable information, which specifically indicates the departure station and arrival station, as well as the departure time and final arrival time of each train paths. The train path number contains the originating station information, for example, A1 represents the train path starting from station A, C1 represents the train path starting from station C, and so on.

| Table 1 Freight transit period |
|-------------------------------|
| Number | Freight transit period | Delivery time |
|-------|------------------------|---------------|
| 1     | 2760                   | 2843          |
| 2     | 2880                   | 2963          |
| 3     | 3120                   | 3203          |

| Table 2 Basic train timetable |
|--------------------------------|
| Train path number | Destination | Departure time | Arrival time |
|-------------------|-------------|----------------|--------------|
| A1 | C | 0 | 1130 |
| A2 | C | 243 | 1373 |
| A3 | C | 374 | 1504 |
| A4 | C | 503 | 1532 |
| A5 | C | 726 | 1856 |
| A6 | C | 857 | 1947 |
| A7 | C | 897 | 2027 |
| A8 | C | 981 | 2111 |
| C1 | F | 1211 | 2451 |
| C2 | E | 1439 | 2409 |
| C3 | E | 1521 | 2491 |
| C4 | E | 1553 | 2523 |
| C5 | E | 1597 | 2567 |
| C6 | E | 1901 | 2871 |
| C7 | F | 1997 | 3193 |
| C8 | E | 2212 | 3182 |
| E1 | F | 2454 | 2724 |
| E2 | F | 2509 | 2779 |
| E3 | F | 2587 | 2857 |
| E4 | F | 3242 | 3512 |
Table 3 Train paths selection plans of different freight transit period

| Plan number | Plan       | Transportation time | Delivery time |
|-------------|------------|---------------------|---------------|
| 1           | A3-C3-E2   | 2405                | 2779          |
| 2           | A4-C4-E3   | 2354                | 2857          |
| 3           | A4-C5-E3   | 2354                | 2857          |
| 4           | A6-C7      | 2336                | 3193          |

According to the above examples and parameters, the express freight train path selection model based on the entire transportation time was used to solve the problem, and the results of the train paths selection plans under different freight transit period were obtained. The results are shown in Tab.3.

When the freight transit period is 2760 minutes, the optimal plan is A3-C3-E2, and the whole transportation time is 2405 minutes. When the freight transit period is relaxed to 2880 minutes, 2 operation plans can be searched within the feasible range, namely A4-C4-E3 and A4-C5-E3, and the whole transportation time is 2354 minutes, which is shorter than that of plan 1. When the freight transit period is further relaxed to 3120 minutes, the optimal solution can be searched for A6-C7, and the entire transportation time is 2336 minutes, which is also the optimal solution within the scope of the operation chart. According to the results of the above train path selection, the railway transportation department can select the appropriate train path plan according to the cargo owner’s requirements for transportation time, receiving time, etc., as well as the train’s operation requirements and other related factors to adapt to the transportation needs under different conditions.

4. CONCLUSION

At present, railways are facing competition from multiple modes of cargo transportation such as air and water transportation. In this environment, improving the quality of freight services based on timeliness and improving the technology of transportation organization based on freight transit period become critical. This paper researched the transportation requirements of the freight plan, the freight transit period and other key factors, and constructed a 0-1 planning model with the minimum entire transportation time as the objective function to realize the selection of the express freight train paths. The model can be quickly obtained by the branch and bound method to obtain accurate solutions, and the rationality and effectiveness of the model was verified through the analysis of the example. So as to provide reference for the railway operation department to choose the express freight train paths.

ACKNOWLEDGMENT

Supported By National Key R&D Program of China of Ministry of Science and Technology of the People’s Republic of China (No.2018YFB1201402).

REFERENCES

[1] Li Jian, Lin Boliang, Tian Yaming, et al. Model and algorithm for optimizing train paths assignment of freight through train[J]. Journal of Beijing Jiaotong University, 2015, 39(6): 15-20.
[2] Xu Han, Nie Lei, Tan Yuyan. The adding train paths model on cyclic timetable based on flexible connection[J]. Journal of Railway Science and Engineer, 2018, 15(9): 2439-2447.
[3] Zhang Xiaobing, Li Shengdong, Lu Hongxia, et al. Study on Optimization of Train Path Section Base on Freight due Date[J]. Journal of the China Railway Socity, 2019, 41(5): 10-15.
[4] Yu Houlun, Da Xiang. Study on network graph of optimal selection of operation lines for direct freight train[J]. Journal of Shangdong Jiaotong University, 2019, 37(1): 37-41.
[5] Jiang Feng, Ni Shaoquan. A Large-scale Freight Train Diagram Optimization Heuristic Algorithm Based on Lagrangian Relaxation[J]. Journal of the China Railway Socity, 2020, 42(3): 21-31.
[6] Yang Yifan. Study on the Operation Plan of Railway Express Freight Train[D]. Chengdu: Southwest Jiaotong University, 2015.

[7] Sun Min. Study on Optimization of Railway Express Freight Trains Operation Plan[D]. Beijing: Beijing Jiaotong University, 2018.