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Research on high-speed railway operation adjustment model based on priority

Liao Zhiwen, Yong Qin and Mingming Wang
Beijing Jiaotong University, Beijing, China

Received 3 April 2021
Revised 19 October 2021
Accepted 19 October 2021

Abstract

Purpose – This paper aim at providing decision support for operational adjustment. In order to effectively reduce the external interference impact on train operation.

Design/methodology/approach – According to the reality that there are two kinds of high-speed trains running in China, considering the reality that there are two speed level train running in Chinese high-speed railway, this paper proposed the high-speed railway operation adjustment model based on priority, and the objective function is to minimize interference impact on train operation.

Findings – Adjustment strategy based on priority than based on sequence can effectively reduce the interference influence on train operation, which makes the train resume the planned operation back on schedule more quickly.

Research limitations/implications – The solution of large-scale cases is too slow, and the practical application is limited.

Originality/value – The model was verified by a case, and the case results proved that adjustment strategy based on priority than based on sequence can effectively reduce the interference influence on train operation, which makes the train resume the planned operation back on schedule more quickly.

Keywords High-speed railway, Train operation adjustment, The priority

Paper type Research paper

1. Introduction

In the train running process, all kinds of interference are inevitable, such as the equipment failure and bad weather, these external interference usually cause the section passing capacity to fail, when these section passing capacity is restored, under the premise of ensuring operation safety, how to reasonably arrange the train departure sequence and departure time so that the deviation between the actual train operation and the planned operation diagram after interference is as small as possible is the key to train operation adjustment.

In essence, train operation adjustment is an optimization problem of train resource redistribution. There are two main ideas for establishing mathematical models: one is to

The authors gratefully acknowledge the support provided by Major Program of National Natural Science Foundation of China (No. 61833002) and High-level Talents Training Program of Ministry of Transportation of China (No. I18I0001).

Smart and Resilient Transportation
Vol. 4 No. 1, 2022
pp. 12-21
Emerald Publishing Limited
e-ISSN: 2632-0495
p-ISSN: 2632-0487
DOI 10.1108/SRT-04-2021-0005

abstract train operation as the occupation of train resources from the micro level (Hirai *et al.*, 2009; Meng *et al.*,2012; Wang *et al.*, 2019; Liao *et al.*, 2021); the other is to abstract train operation as event activity network for modeling from the macro level (Shimizu *et al.*, 2008; Nakamura *et al.*,2011; Zhan *et al.*, 2015; Peng *et al.*, 2018). Hirai *et al.* (2009) proposed his train operation adjustment model that focused on the parking scheme of trains under severe interference, and he designed the Petri net algorithm to solve the problem. Meng *et al.* (2012) proposed a two-stage stochastic expectation model with compensation and an incomplete continuous multistage decision model designed a branch and bound algorithm to solve the problem. Both models could improve the train punctuality level to a certain extent. However, this study was based on the modeling of single-track railways, which was not practical for the actual situation in China. Wang *et al.* (2019) further considered the train running path and established the train operation adjustment model to minimize the total train delay time. However, when the scale of the problem was large, the model could not quickly obtain a feasible solution. Liao *et al.* (2021) established an optimization model of train operation diagram based on cumulative flow variables. In view of the difficulty of solving large-scale problems with traditional algorithms, the author designed a Lagrange algorithm to solve the problem.

Shimizu *et al.* (2008) established a constraint model to manage the train stop scheme and the train departure sequence under severe delay. This constraint programming technology can effectively reduce the train delay in earthquake scenarios. The model established by Nakamura *et al.* (2011) can adjust train operation and optimize rolling stocks at the same time. Zhan *et al.* (2015) abstracted the high-speed railway network into an event activity network established a train adjustment model with the objective function of minimizing the impact of interference on train operation. The author designed a two-stage algorithm to solve the problem. However, all the test examples are single lines, so the applicability of the model needs to be further verified. Peng *et al.* (2018) further considered the problem of train section and station parking in case of section failure, and his model described the process of train operation adjustment more detailed.

The research results of train operation adjustment are rich, but there are few researches for the real situation of Chinese high-speed railways, and their applicability is insufficient. Therefore, this paper establishes a priority-based train operation adjustment model based on Chinese high-speed railway real situation and researched train operation adjustment under the failure of the passing capacity of the high-speed railway section of the line.

2. Train operation adjustment

The train will inevitably be disturbed by external interference during operation. When the interference occurs, it will usually lead to the loss of the passing capacity of the section, resulting in the two-way trains of the section being unable to pass, and subsequent trains must wait at the previous station or section until the passing capacity is restored; Figure 1 shows this train adjustment process.

The train adjustment measures include changing the departure sequence and time as well as the stop scheme. On the Chinese high-speed railway network, there are two speed levels of train running, 250 km/h and 300 km/h. If two trains were stop at the same station due to a fault, when the passing capacity is restored, the higher-level 300 km/h train is arranged to depart first. This departure adjustment strategy that prioritizes the train speed level is a priority-based adjustment strategy, as shown in Figure 1(a). If the train departure is carried out in the order of arrival at the station, it is a common order-based adjustment strategy, as shown in Figure 1(b).

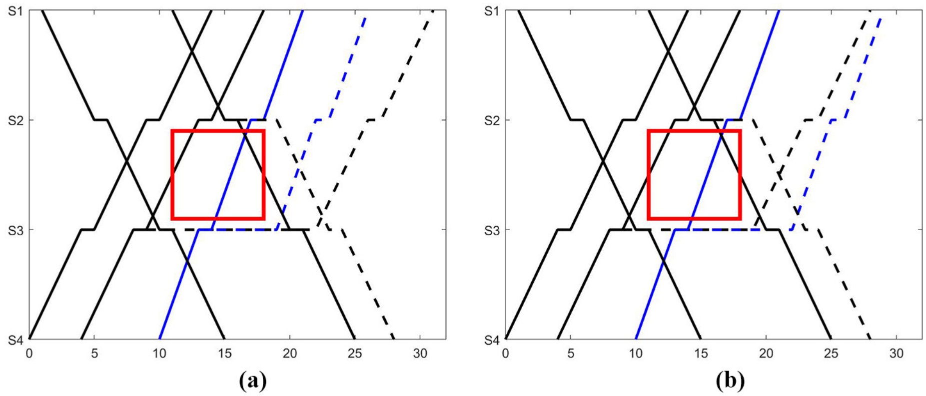


Figure 1.
Two different train departure adjustment strategies

Note: The dotted line is the adjusted train running line

3. Model establishment

Aiming at the reality of mixed running of high-speed trains of 250 km/h and 300 km/h in Chinese high-speed railway network, to describe the process of train operation adjustment more scientifically, this paper establishes a priority-based train operation adjustment model.

3.1 Model assumptions

- The time when the pass capacity is lost and recovered is known.
- The arrival and departure lines of the station are available for the trains going up and down without restriction.
- The trains run as planned before the section passing capacity fails.

3.2 Symbols of parameters and variables

The process of a train traveling from one station to the next station is called a train running activity, and those parameters and variables related to train operation activity are shown in Table 1.

3.3 Objective function

The main purpose of train operation adjustment is to restore operation as graph + as soon as possible and reduce the deviation between actual operation and planned operation. This model takes the minimum deviation between the actual operation of all trains and the planned operation as the objective function, and the degree of deviation is weighted and added by the difference between the actual departure time and the planned departure time of each train operation activity, and the difference between the actual arrival time and the planned arrival time.

$$min = f_a \sum_{a \in A} Tdr_a - Tdp_a + f_a \sum_{a \in A} Tar_a - Tap_a \tag{1}$$

Symbols	Meaning
a	Running activity
A	Set of all running activities
Tdp_a	Running activity a planned departure time
Tap_a	Running activity a planned arrival time
Tdr_a	Running activity a actual departure time
Tar_a	Running activity a actual arrival time
fa	Running activity a priority parameter
$N(a)$	Running activity a next running activity
$Sd(a)$	Running activity a departure station
$Sa(a)$	Running activity a arrival station
Tra	Running activity a section minimum running time
Tsa	Running activity a station minimum stop time
s_a	Line started station
s_e	Line terminal station
Id	Minimum departure interval
Ia	Minimum arrival interval
Iad	Minimum departure and arrival interval
Te1	Start time of section passing capacity failure
Te_2	Recover time of section passing capacity
Se_1	Station 1 corresponding to the section where the passing capacity is invalid
Se_2	Station 2 corresponding to the section where the passing capacity is invalid
$\theta_{a,a'}$	Running activity a and a' whether overtaking 0–1variable
$\omega_{a,a'}$	Running activity a and a' whether meet the arrival and departure interval 0-1variable
x_a, y_a, z_a	0-1 variable

Table 1. Meaning of symbols

3.4 Constraints

In this model, it is assumed that the start time of all running activities is greater than or equal to the planned start times.

$$Tdr_a \geq Tdp_a, a \in A \tag{2}$$

Section running time constraint: When the train is running in the section, the running time must be greater than or equal to the minimum running time of section.

$$Tdr_{N(a)} - Tar_a \geq Tr_a, a \in A : Sa(a) \neq s_a \wedge Sa(a) \neq s_e \tag{3}$$

Station stop time constraint: When the train stops at each station, the stop time must meet the minimum stop time requirement.

$$Tar_a - Tdr_a \geq Ts_a, a \in A \tag{4}$$

Departure interval constraint: When two trains leave continuously at the same station, the departure time interval must be greater than or equal to the minimum departure interval.

$$Tdr_a - Tdr_{a'} + M^*\theta_{a,a'} \geq Id, a, a' \in A : a \neq a' \wedge Sd(a) = Sd(a') \tag{5}$$

$$\theta_{a,a'} + \theta_{a',a} = 1, a, a' \in A\text{: } a \neq a' \wedge Sd(a) = Sd(a') \tag{6}$$

Arrival interval constraint: When two trains continuously arrive at the same station, the arrival time interval must be greater than or equal to the minimum arrival interval.

$$Tar_a - Tar_{a'} + M^*\theta_{a,a'} \geq Ia, a, a' \in A\text{: } a \neq a' \wedge Sa(a) = Sa(a') \tag{7}$$

$$\theta_{a,a'} + \theta_{a',a} = 1, a, a' \in A\text{: } a \neq a' \wedge Sa(a) = Sa(a') \tag{8}$$

Departure and arrival interval constraint: When two trains arrive and depart at the same station, the time interval between them must meet a certain interval.

$$Tar_a - Tdr_{a'} + M^*\omega_{a,a'} \geq Iad, a, a' \in A\text{: } a \neq a' \wedge Sa(a) = Sd(a') \tag{9}$$

$$Tdr_a - Tar_{a'} + M^*(1-\omega_{a,a'}) \geq Iad, a, a' \in A\text{: } a \neq a' \wedge Sa(a) = Sd(a') \tag{10}$$

This model assumes that the train runs as planned before the failure occurs.

$$Tar_a = Tap_a, a \in A : Tap_a < Te_1 \tag{11}$$

Whether depart or arrive at the end of failure.

$$(Te_2+1)(1 - x_a) \leq Tdr_a \leq Te_2 + M(1 - x_a), a \in A \tag{12}$$

$$(Te_2+1)(1 - y_a) \leq Tar_a \leq Te_2 + M(1 - y_a), a \in A \tag{13}$$

$$Te_1 \cdot z_a \leq Tar_a \leq Te_1 - 1 + M(1 - z_a), a \in A\text{: } Sd(a) = Se_1||Sd(a) = Se_2 \tag{14}$$

$$x_a + z_a \leq 1, a \in A\text{: } Sd(a) = Se_1||Sd(a) = Se_2 \tag{15}$$

Station capacity constraint: At the same time, the number of trains at the station must be smaller than or equal to its number of arrival and departure lines.

$$\sum_{a \in A:Sa(t)=s} y_a - \sum_{a \in A:Sd(t)=s} x_a \leq Cap_s, s \in S \tag{16}$$

3.5 Model solution

The model is a mixed integer programming model, which can be solved by ILOG CPLEX, a mathematical business solution software. The model is solved by ILOG CELEX 12.6 on a 64-bit computer with An Inter(R) Core(TM) I5-10210U 2.11ghz, 16GB memory and Windows 10 system.

4. Case study

4.1 Value of parameters

Design a double track high-speed railway as a model test example. There are 11 stations on the line, and a total of 32 trains are arranged. Among them, there are 17 train trips for the upside and 15 trains for the downside. There are two speed level 250 km/h and 300 km/h running on the line, including seven trains of 300 km/h and 25 trains of 250 km/h. The priority of 300 km/h train is higher than that of 250 km/h. The priority f of each 300 km/h operation activity is 2, and the priority of 250 km/h train is 1. In addition, the departure and arrival intervals are 3 min, the arrival and departure intervals are 2 min. The running time of the two classes of high-speed trains in each section and the stopping time at each station are shown in the following Tables 2 and 3.

4.2 Scenarios design

Three interference scenarios are designed for numerical experiments. Scenario 1, the section between stations C and D, breaks down at 13:40; Scenario 2, the section between stations E and F, breaks down at 11:00; Scene 3, the section between stations H and I, breaks down at 11:00. Assuming that the break down causes the passing capacity of the section to be lost, the duration takes 20, 40, 60, 80, 100 and 120 min, respectively, to be calculated. The priority-based model calculation results of the are shown in Table 4 below (Tables 5 and 6).

For the above three scenarios, most of the train adjustment schemes can be solved in a short time (20 s), indicating that the model can solve the operation adjustment scheme in a short time for the majority of failure scenarios, but the in third scenario when the duration is 120 min, the calculation time reaches 178.54 s. It is presumed that there is a high frequency

Section	Slow train/min	Fast train/min
A-B	40	35
B-C	13	12
C-D	22	20
D-E	45	40
E-F	35	30
F-G	28	25
G-H	15	13
H-I	25	22
I-J	30	25
J-K	26	22

Table 2.
Trains running time

Station	Slow train/min	Fast train/min	The No. of arrival and departure lines
A	–	–	4
B	2	2	3
C	2	2	3
D	7	5	4
E	2	2	3
F	3	2	3
G	2	2	3
H	3	2	3
I	5	3	4
J	2	2	2
K	–	–	4

Note: The slow train is 250 km/h train, and the fast train is 300 km/h train

Table 3.
Trains stop time

of departures during this period, so more trains need to be adjusted, and the calculation amount is relatively large (Figure 2).

4.3 Comparison with sequence-based adjustment strategy

For the six failure durations in Scenario 2, sequence-based adjustment strategy was applied respectively to adjust the train operation after the interval was recovered through capacity. The deviation degree between the actual train and the planned operation was used to measure the influence degree of interference on the train operation. The calculation results are as shown in Table 7 (Figure 3).

Compared with the order-based adjustment strategy, the priority-based adjustment model solution established in this paper has a certain degree of reduction in train operation deviation (ranging from 20.84% to 9.26%), indicating that priority-based model can effectively reduce the impact of interference on train operation compared with the sequence-based adjustment strategy.

Sensitivity analysis: To explore the influence of section passing capability failure time on the deviation degree caused by the train, sensitivity analysis was conducted, and the start time of the failure was set to be the same. The last time of section passing capability was set

Start time	Restore time	Last time/min	Deviation (objective function)	Calculation time/s
13 : 40	14 : 00	20	544	7.27
13 : 40	14 : 20	40	1008	7.69
13 : 40	14 : 40	60	1460	7.53
13 : 40	15 : 00	80	2630	7.73
13 : 40	15 : 20	100	4163	10.33
13 : 40	15 : 40	120	5835	11.02

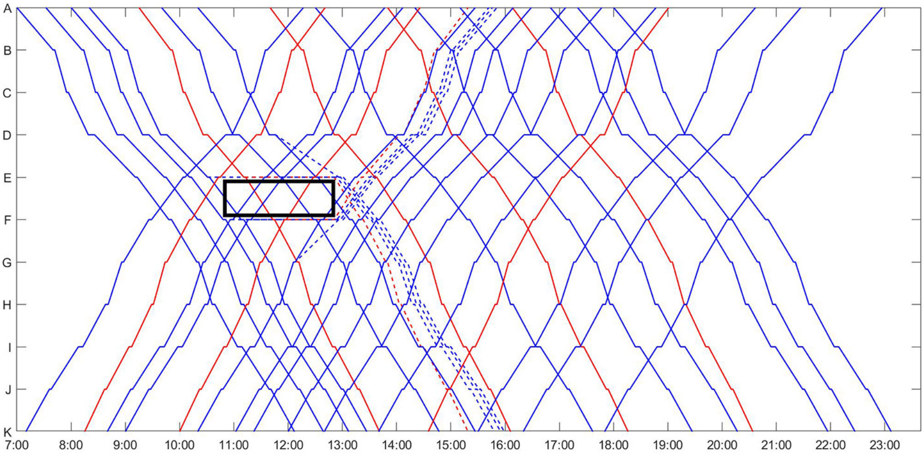
Table 4.
Scenario 1 results

Start time	Restore time	Last time/min	Deviation (objective function)	Calculation time/s
10 : 50	11 : 10	20	643	7.84
10 : 50	11 : 30	40	1643	8.99
10 : 50	11 : 50	60	2976	11.68
10 : 50	12 : 10	80	4523	8.98
10 : 50	12 : 30	100	6458	15.66
10 : 50	12 : 50	120	8698	23.17

Table 5.
Scenario 2 results

Start time	Restore time	Last time/min	Deviation (objective function)	Calculation time/s
12 : 45	13 : 05	20	1250	7.75
12 : 45	13 : 25	40	2190	8.41
12 : 45	13 : 45	60	3384	8.72
12 : 45	14 : 05	80	4795	12.46
12 : 45	14 : 25	100	6247	10.05
12 : 45	14 : 45	120	8075	178.54

Table 6.
Scenario 3 results



Note: The dotted line is the adjusted train running line

Figure 2. Adjustment train graph (Scenario 2 with 120 last time)

Last time	Sequence based	Priority based	Reduction percentage (%)
20	777	643	20.84
40	1948	1643	18.56
60	3320	2976	11.56
80	5090	4523	12.54
100	7236	6458	12.05
120	9503	8698	9.26

Table 7. Different adjustment strategy comparison

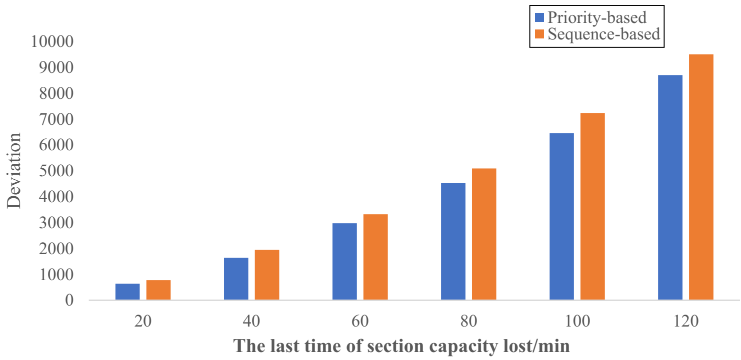


Figure 3. Different adjustment strategy comparison

to be 20, 40, 60, 80, 100 and 120 min, respectively, for experiments. The calculation of the three failure scenarios was carried out, and the following figure was obtained (Figure 4).

As can be seen from the above figure, in the three scenarios, when the failure starts at the same time, the longer the failure time of interval passing ability is, the greater the deviation between the train and the planned operation is. This conclusion is consistent with the

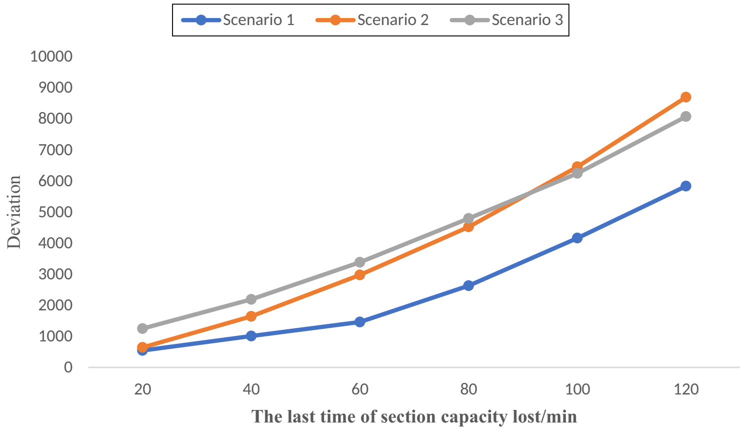


Figure 4.
Sensitivity analysis of the last time of section capacity lost

reality. To restore the planned operation as soon as possible, the fault must be solved as soon as possible, and the passing ability must be restored.

5. Conclusion

Based on the practical characteristics of Chinese high-speed railways, this paper establishes a double track operation adjustment model based on train priority under the losing of section passing capacity. Taking a double track high-speed railway as a case background, three failure scenarios under six durations time are designed to carry out to verify the model; the solution results show that the model can solve the train operation adjustment plan in a short time (20 s). Compared with the sequence-based adjustment strategy, the model can effectively reduce the deviation of the actual operation between the planned graph further reduce the impacts of interference on train operation, which can provide decision support for dispatchers to adjust train operation in the event of a sudden failure in the section.

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Corresponding author
Liao Zhiwen can be contacted at: 19120832@bjtu.edu.cn