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Optimal Train Operation Adjustment under Service Disruptions

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Abstract. Train service disruptions can be caused by unexpected situation in operation, which lead to large-scale train delays and passenger stranded. In this paper, the service disruption that is caused by the down train having fault in the section is described. According to the section where the fault train stops and the operating processes of trains, rescue plan is determined. Meanwhile, in order to alleviate the train delays and stranded passengers, the short-turning strategy is used for adjustment. Based on the delay caused by fault and the turning-back stations in the line, turning-back strategies can be determined and the effects of reducing stranded passenger and delay time are compared to determine the optimal turning-back strategy. On the other hand, the strategy which just adjusts headway and stopping time after line reopen is also used. Compared with two strategies simulation results, the short-turning strategy is faster to reduce passenger retention and resume normal operation.

Keywords: train schedule, train rescue, operation adjustment, short-turning

1. Introduction

During the daily operation of urban rail transit, disruptions occur due to an increase of the capacity demand, infrastructure malfunctioning or emergencies in operation. Some disruptions may result in trains can't passing sections. Therefore, it is necessary to organize the short-turning operation by using parking lines, crossing line or turning-back lines to maintain operation of trains [1]. In [2], the frequencies of trains are analysed by short-turning strategy, meanwhile, timetable calculation is not taken into consideration. The strategy that a short-turning without stopping at intermediate stations is studied in [3], however, stranded passengers are not able to be absorbed quickly. In [4], short-turning is applied not as a means of dealing with usual demand conditions, but as a method to manage passenger overloads after an episode of demand increase. In [5], short-turning strategy is used in operation disruption, according to the location and range of the fault sections, there are usually three adjustment strategies, they are shown in the Fig.1, Fig.2 and Fig.3.

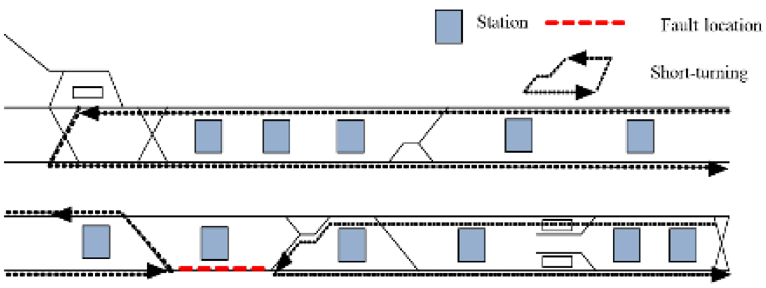

Fig.1: Short-turning in both sides

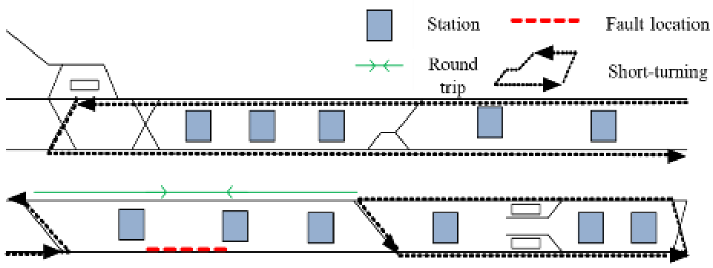

Fig.2: Short-turning and round trip

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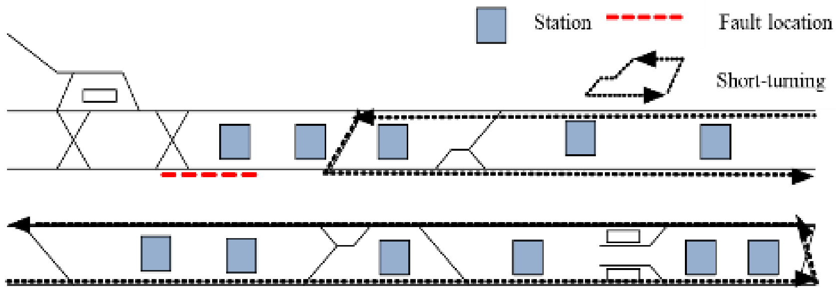

Fig.3: Short-turning in one side.

This paper takes a train fault in section as an example, in order to move the fault train and recover normal operation, another train is organized to rescue [6]. During rescue process for the fault train, short-turning strategy shown in Fig.1 is used to maintain operation. The regulation with short-turning strategy will be simulated, and departure and arrival time, dwell time will be obtained by means of an optimization model.

2. Problem Formulation

2.1. Model Parameters

To formulate the operation adjustment problem, the following notations in table 1 will be used before we get the mathematical model.

Table 1: Model parameters

S_t T_r	Stations and trains in the line
Ar_j^i ar_j^i	Scheduled and actual arrival time of $i \in T_r$train at station$j$
De_j^i de_j^i	Scheduled and actual departure time of train$i \in T_r$at station$j$
$R_{i,j}^0$ $R_{i,j}$	Scheduled and actual running time of train$i \in T_r$of section$j$
$t_{min\ j}$ $t_{max\ j}$	Minimum and maximum stopping time at station$j \in S_t$
T_{hwmin} T_{hwmax}	Minimum and maximum headway between two trains
a_u a_d	Train acceleration and deceleration
$R_{min\ j}$	Minimum running time of section$j$
P_m	Max passengers load of a train
Vf_i	Number of passengers entering station per second
$P_{i,j}$	Passengers of train $i \in T_r$ at station$j \in S_t$
Fo_j^i	The number of the passengers detained on the platform when the train i departs from station j
S_a	The distance from the station where passengers on rescue train off to the position where fault train stops
S_c	The distance from the station where passengers on fault train off to specific storage
T	Total time of the rescue
V_r V_h	Normal running speed and speed after fault train and rescue train coupling

2.2. Train Delay Time Model

The following trains are unable to operate normally and will be delay because of disposing the fault, the disposing time T, i.e., the delay time is determined by T_c,T_a,T_h,T_p,T_f[7].

$$T = T_c + T_a + T_h + T_p + 2 * T_f \tag{1}$$

T_c: The time from fault occurring to being confirmed;

T_a: The time from rescue train being informed to arriving at the fault spot;

T_h: The time of the rescue train coupling the fault train;

T_p: The time of fault train being pushed to the specific storage;

T_f: The time of all the passengers on rescue train and fault train alighting;

T_c, T_h, T_f are determined by the operator's proficiency, in this paper we assume the value of these variables is constant. In order to facilitate the establishment of the model, we assume the starting process of the train runs at a uniform acceleration speed, the running process runs at a constant speed, the stopping process runs at a uniform deceleration speed.

$$T_a=\begin{cases}\sqrt{2S_a(a_u+a_d)/a_ua_d} & S_a\leq V_r^2(a_u+a_d)/2a_ua_d\\ (S_a/V_r)+V_r(a_u+a_d)/2a_ua_d & S_a>V_r^2(a_u+a_d)/2a_ua_d\end{cases}\tag{2}$$

T_p is determined by the distance which is from the position where fault train stops to the temporary storage station, the pushing speed is regulated from 25km/h to 35km/h [8], and in this paper, we assume the speed is 30km/h. The pushing process is made of two parts: rescue train pushes fault train to the station where passengers on train get off; and the fault train is pushed to the temporary storage. As is mentioned above, in the first part, we suppose the distance is S_c and the spent time is t_c. And in the second part, we suppose the distance is S_s and the spent time is t_s. The spent time is calculated as follows:

$$t_c=\begin{cases}\sqrt{2S_c(a_u+a_d)/a_ua_d} & S_c\leq V_h^2(a_u+a_d)/2a_ua_d\\ (S_c/V_h)+V_h(a_u+a_d)/2a_ua_d & S_c>V_h^2(a_u+a_d)/2a_ua_d\end{cases}\tag{3}$$

$$t_s=\begin{cases}\sqrt{2S_s(a_u+a_d)/a_ua_d} & S_s\leq V_h^2(a_u+a_d)/2a_ua_d\\ (S_s/V_h)+V_h(a_u+a_d)/2a_ua_d & S_s>V_h^2(a_u+a_d)/2a_ua_d\end{cases}\tag{4}$$

Therefore, the total delay time T can be obtained.

3. Train Operation Adjustment Strategy

3.1. Adjustment Strategy after Removing Fault

The traditional adjustment method for delay is adjust the running time in sections, headways between trains and dwell time at stations. The equations below describe the running time in sections, constraints of headway and stopping time of the trains.

$$R_{i,j}=\begin{cases}ar_{j+1}^i-de_j^i & de_j^i<ar_{j+1}^i-R_{minj}\\ R_{min\,j} & de_j^i<ar_{j+1}^i-R_{minj}\end{cases}\tag{5}$$

The influence of passenger flow is taken into count. The literature describes the dwelling time has a linear relationship with the number of the passengers at stations. $t_{min\,j}$ is the minimum stopping time at station j, a_j is the extension rate of stopping time caused by delay. Therefore, the dwelling time is:

$$t_j=\{\begin{matrix}t_{max\,j} & t_{min\,j}+a_j(d_{i,j}-d_{i-1,j}-D_{i,j}-D_{i-1,j})>t_{max\,j}\\ t_{min\,j}+a_j(d_{i,j}-d_{i-1,j}-D_{i,j}-D_{i-1,j}) & \text{the other}\end{matrix}\tag{6}$$

The evacuation of passengers is also added to measures, and the objective function is established and optimized. Optimization objects considered in this paper contains delay time and stranded passengers:

$$\min J=a_1\sum_{i=1}^n\sum_{j=1}^m(|de_j^i-De_j^i|+|ar_j^i-Ar_j^i|)+a_2\sum_{i=1}^n\sum_{j=1}^m Fo_j^i\tag{7}$$

according to different demands of managers, the proportions a_1 and a_2 can be adjusted.

The constraints are as follows:

$$de_j^i-ar_j^i\geq t_{min\,j}\tag{8}$$

$$ar_{j+1}^i-de_j^i\geq R_{min\,j}\tag{9}$$

$$ar_j^{i+1}-ar_j^i\geq T_{hwmin}\tag{10}$$

$$de_j^{i+1}-de_j^i\geq T_{hwmin}\tag{11}$$

3.2. Short-turning Adjustment Strategy

In this paper, the trains are unable to pass the stations which is behind the fault train. If the trains can not pass following stations after a period of disposing, the trains in the opposite direction can be organized to turn back at certain station to make up the longer interval [8-10]. It is important to determine the turning-back station, the train of turning back and the number of turning-back trains. In order to minimize the effect of stranded passengers, turning-back station should be close to the point of the fault [11-12]. However, passengers on the turning-back train have to alight at turning-back station, resulting in a sudden increasing passengers at the turning-back station, it will lead to the following trains delay [13]. In this paper, we consider the delay in the opposite direction caused by the turning-back train and the number of stranded passengers as the adjustment target, and optimize short-turning regulation strategy.

3.3. Optimization Algorithm

This paper adopts particle swarm optimization algorithm of linear decreasing to optimize objects. Following Eberhart and Kennedy's naming conventions, D is the dimension of the search space. The i^{th} particle is represented by $X_i=(x_{i1}, x_{i2}, \ldots\ldots x_{iD})$ and its previous best is $P_i=(p_{i1}, p_{i2}, \ldots\ldots p_{iD})$. The index of the best in the whole group is g. Each particle in PSO flies in the search space with a velocity which is dynamically adjusted according to its own flying experience and its companions' flying experience [14-16]. w is redesigned according to the reference [17-19]

$$v_i^{k+1}=wv_i^k+c_1r_1(p_i^k-x_i^k)+c_2r_2(p_i^k-x_i^k) \tag{12}$$

$$x_i^{k+1}=x_i^k+v_i^{k+1} \tag{13}$$

$$w=w_{max}-\frac{(w_{max}-w_{min})}{t_{max}}*t \tag{14}$$

Where c_1 and c_2 are two positive constants, r_1 and r_2 are two random functions in the range [0, 1], w_{min} and w_{max} are the maximum and minimum value according to expert system, t_{max} is the maximum iteration, t is the current iteration.

4. Simulation and Solution

In this paper, the operating parameters of an urban rail transit are as follows in table 2. The third train has a fault and stops between station 6 and station 7, the fourth train receives the rescue mission, the subway line data is shown in Fig.4. 1th station, 3th station, 5th station, 6th station, 8th station and 10th station are turning-back stations, and the turning-back time is 120s.

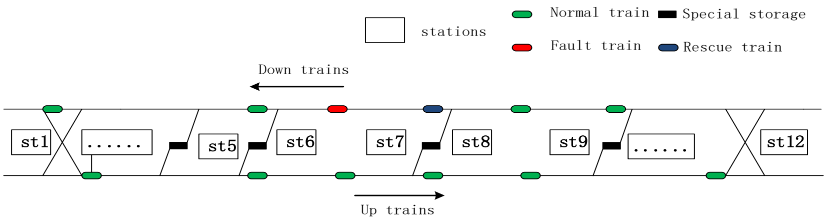

Fig.4: Subway line in the case of train fault

Table 2: Parameters in simulation

S_t	12			T_r				15				
T_{hw}^0 (s)	240			$T_{hw\min}$ (s)				90				
S_a (m)	1300			S_c (m)				400				
S_s (m)	2200			F_m				1800				
a_u (m/s^2)	0.8			a_d (m/s^2)				-0.6				
V_r (m/s)	40			V_h (m/s)				30				
Fault train	3th			Rescue train				4th				
S_t	1	2	3	4	5	6	7	8	9	10	11	12
$t_{\min j}$ (s)	30	25	25	25	30	25	25	25	25	25	25	30
$t_{\max j}$ (s)	40	35	35	35	40	35	35	35	35	35	35	40
Vf_j (s)	1.18	1.31	1.29	1.34	1.37	1.31	1.40	1.27	1.32	1.34	1.29	0
Section	1	2	3	4	5	6	7	8	9	10	11	-
$R_{i,j}^0$ (s)	172	116	226	106	114	161	114	118	241	163	115	-
$R_{\min j}$ (s)	166	110	220	100	106	155	109	110	235	155	110	-

4.1. Simulation after Removing Fault

The improved PSO algorithm takes the minimum delays and stranded passengers as the optimization objects. Here we set $a_1 = 0.4$, $a_2 = 0.6$, the population of the swarm is 100, the number of iteration is 100. Fig.5 shows the simulation results.

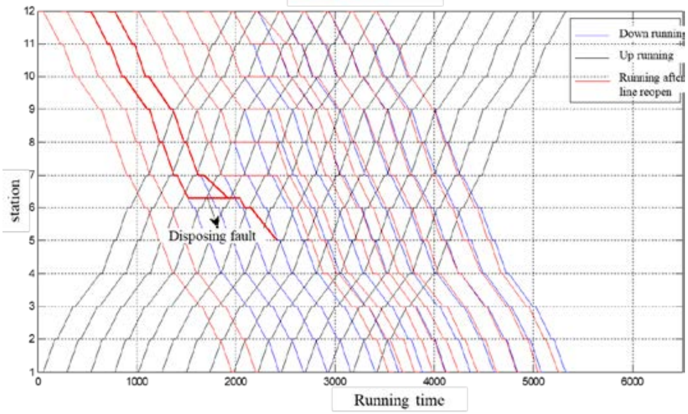

Fig.5: The operation after service restored

In Fig.5, the blue lines and black lines represent scheduled timetable of up trains and down trains, Because of disposing fault, the following trains are backlogged at the stations, and this leads many trains delay and passengers stranded. The following stations can’t pass trains during disposing fault and passengers at fault train and rescue train get off at station 6 and 7, that also causes large numbers of passengers stranded at following stations, as shown in Fig.6. After disposing the fault, trains pass the following stations densely. Stranded passengers at stations after each train passing the station are shown in Fig.7.

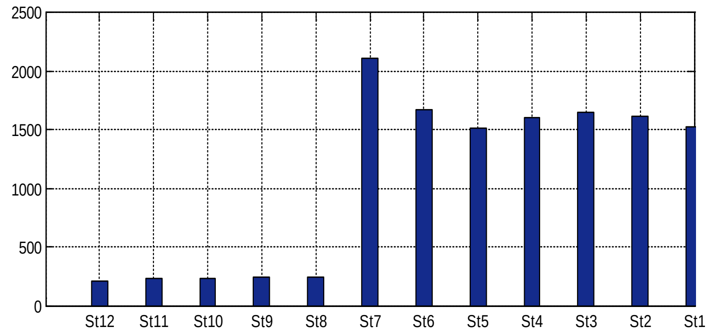

Fig.6: Stranded passengers when line reopened

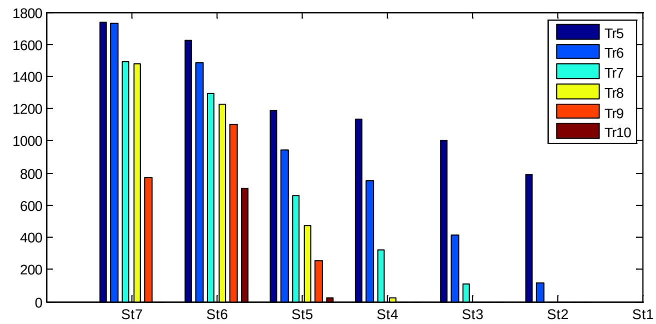

Fig.7: Stranded passengers after each train passing station

4.2. Simulation Using Short-turning Adjustment Strategy

In this paper, when down trains can’t pass the fault position more than five minutes, the up train is assigned to turn back at certain turning-back station. When the line is opened to traffic again, it is regarded as the end time of turning-back operation. According to the operation and line parameters, the location of fault and the time of dealing with emergencies, the turning-back cases can be determined. Case 1: up 5th train turns back at 6th station. Case2: up 5th and 6th trains turn back at 6th station. Case 3: up 5th train turns back at 5th station. Case 4: up 5th and 6th trains turn back at 5th station. Case 5: up 6th train turns back at 3th station, and case 6: up 6th and 7th trains turn back at 3th station. The percentage of the delay time and the stranded passengers which accounts for the total delay time and the total stranded passengers is shown in Fig.8. Based on the optimization objects, the optimal strategy is case 1. Fig.9 shows the operation under the best short-turning strategy. Stranded passengers at stations after each train passing the station are shown in Fig.10.

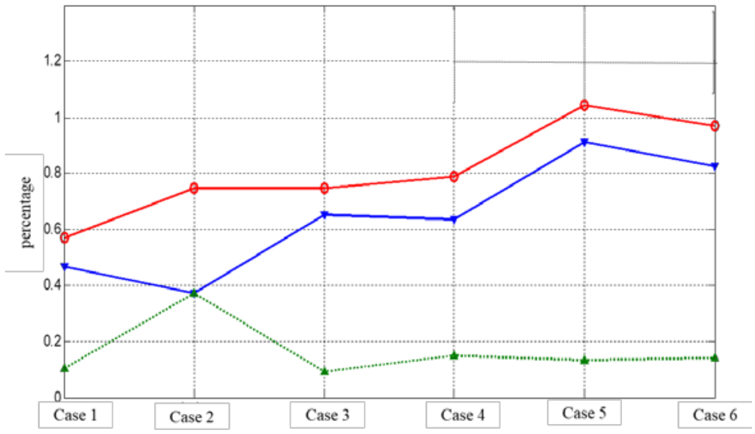

Fig.8: The comparison under each turning-back strategy

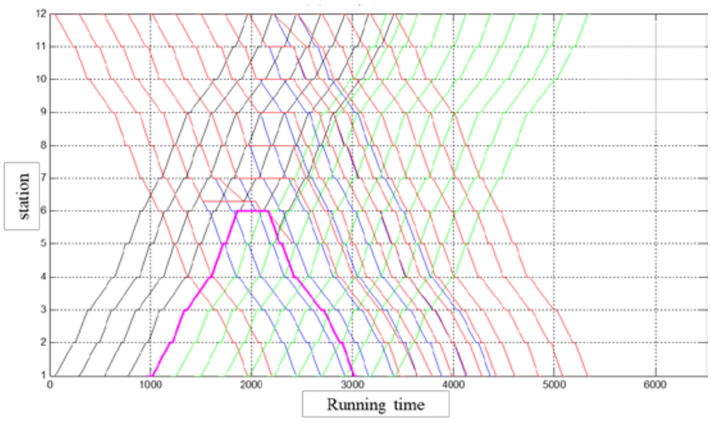

Fig.9: Operation with optimal short-turning strategy

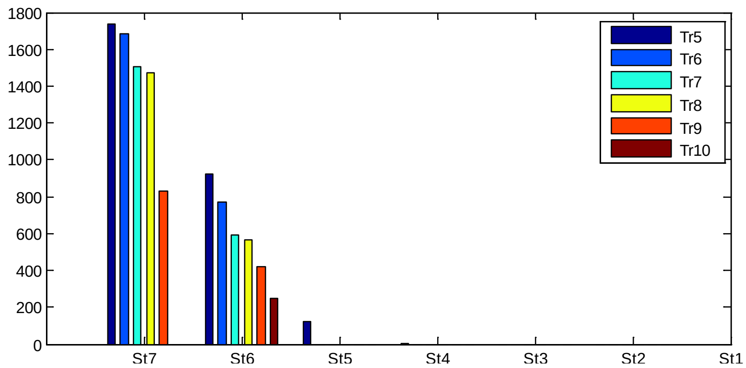

Fig.10 Stranded passengers at station with optimal short-turning strategy

In Fig.9, the up 5th train turns back at station 6, the purple line represents the turn-back of up train., this regulation greatly reduces the number of stranded passengers at the following stations. Meanwhile, as a part of the clear-off passengers are transported by the turn-back train, the number of stranded passengers at the station 6 significantly reduces. So it is available to choose short-turning to relieve congestion when the lines can't operate normally, and it is effective to turn back at large numbers of stranded passenger stations.

4.3. Two Adjustment Strategies Comparisons

By comparing these two different adjustment strategies, it can be seen that the short-turning adjustment can quickly restore the operation to the planned operation. The operation of the 9th train downstream in Fig.9 basically resumes the planned operation, but the operation of the 15th train in Fig.5 has not been restored to the planned operation. Turning-back operation of the up train makes up for the problem of excessive running interval at following stations caused by the faulty train, as a part of the clear-off passengers are transported by the turn-back train, the number of stranded passengers at the station 6 significantly reduces. Compared with Fig.7, short-turning adjustment strategy can quickly reduce the detention of platform passengers. Simulation results indicate the effectiveness of short-turning strategy when the service of traffic disrupts. So it is available to choose short-turning to relieve congestion when the lines can't operate normally, and it is effective to turn back at large numbers of stranded passenger stations.

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