Determining Alternative Train ODs under Cyclic Train Operation Mode for a Large-scale Rail Network

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Abstract. Although the cyclic train operation mode has been widely applied in many small-scale rail networks, it is more practical for a part of trains to use this mode under large-scale rail networks with complex structure and diverse travel demand. For a large-scale rail network, this paper analyzes how to determine alternative train ODs (origins and destinations). Specifically, we discuss the main elements, principles and methods of determination of cyclic and acyclic train ODs of the rail network. The proposed method is applied to a high-speed rail network in China to obtain alternative train ODs. The resulted scheme of train ODs can provide an important basis for designing a cyclic line plan.

Introduction

Cyclic mode is a train operation mode that each train line is the same among each period [8]. The mode has characteristics of high frequency, balanced-distributed departure time, and convenient transfer, thus it can optimize passenger service quality. Compared with the railway network in Europe and Japan, the railway network in China is larger and the travel demand is more complex. In this type of railway network, some of train ODs are suitable to be operated using cyclic mode, while the others are suggested to be operated still under acyclic mode.

Cyclic line plan is a basic plan of passenger railway operation, and it includes an important task of determining train ODs. Nevertheless, existing researches have not paid much attention to the alternative cyclic train ODs under cyclic mode. Oltrogge(1994) promoted a framework of determining the train lines. Bussieck et al. [1,2], Claessens [3], Scholl [4], Schöbel [5] and Borndörfer [6] studied on the line pool generation based on the framework. Bussieck [2] and Claessens [3] have taken cost optimization as a goal. Bussieck has adapted an outer approximation algorithm of DICOPT, and Claessens has used the branch and bound algorithm. Scholl [4] considered enumeration mothed to deal with customer-oriented line planning problem. Schöbel [5] and Borndörfer [6] formulated a model with objective of minimizing transfers. Schöbel considered to use Dantzig-Wolfe decomposition, and Borndörfer adapt shortest path algorithms. Jin-mei Li [7] has studied cyclic mode application on Beijing-Shanghai railway in China, although in reality China uses acyclic train operation mode,

This paper puts emphasis on generating alternative train ODs under cyclic mode combined with acyclic mode. Based on the recent passenger demand data and existing high-speed line plan, cyclic and acyclic train ODs generation principle and mothed will be analyzed and an adjustment mothed for some existing train ODs will be promoted.

The Procedure of Determining the Train ODs

The train OD is an important element in a line plan. The generation step of a cyclic line plan is shown in Fig. 1, in which the problem of determining the alternative train ODs is lacated. The problem is described as judging whether train OD pairs among terminals can be operated as cyclic or acyclic mode though a series of principles. Different from the optimization of an element in a line plan, this problem is suitable to be solved using operation knowledge rather than optimization methods. A framework is proposed for the determination of the problem, and the procedure is shown in Fig. 2.
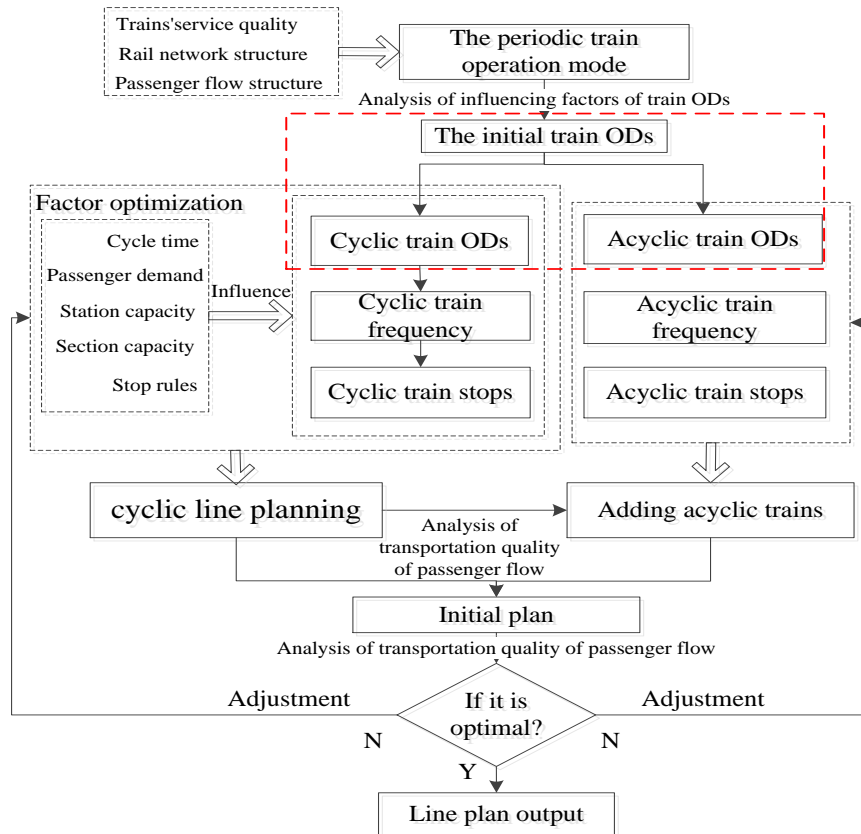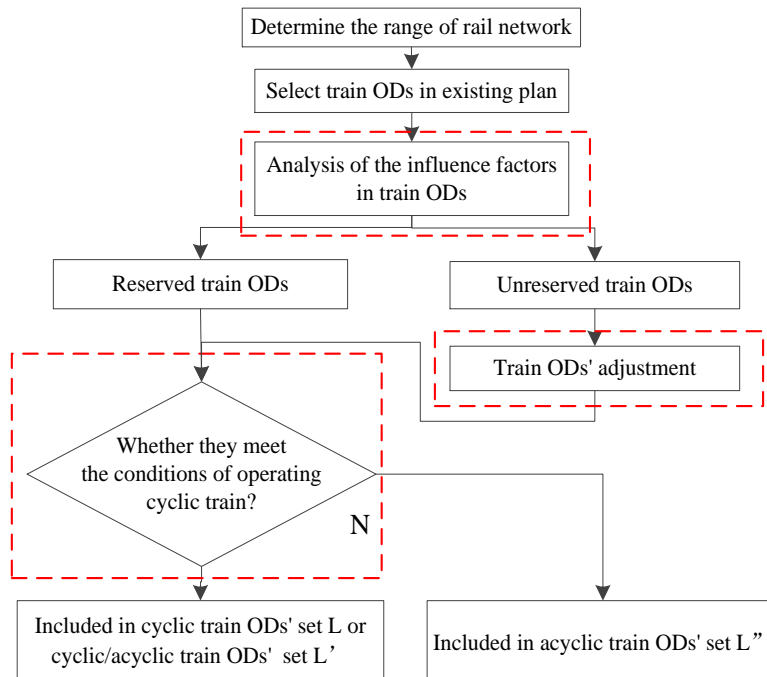
Fig. 1 Generation step of a cyclic line plan

Fig. 2 Determination process of the alternative train ODs

Based on the existing train line plan, the alternative train ODs are divided into three sets through analyzing the influence factors, including: cyclic, acyclic and cyclic or acyclic alternative ODs, which provides the basis for line planning stage. Next we will analyze three sub-problems in detail which are indicated in Fig. 2 using dotted boxed, including: the influence factors in train ODs, cyclic train ODs' determination method and train ODs' adjustment.

Principle of Alternative Train ODs Generation

Determining Conditions of Train ODs

When identifying alternative train ODs, the matching relation between trains and passenger flow in the existing plan should be fully considered. Taking the Chinese high-speed rail network as an example, there are particular characteristics of train ODs in the existing plan:

1. A large number of long-distance trains. The distance of the longest train has reached to 2,760 km, but the ratio between long-distance passengers and long-distance train is not high.

2. Great variety of train ODs. The total kind of train ODs is more than 740 and the organization of train operation is complicated.

3. Unbalanced service quality. The train service frequencies of some passenger ODs are too low and the train service times are concentrated on a certain period of time.

Keeping these characteristics in mind, the paper analyzes the factors influencing train ODs and determines the train ODs in the existing plan that can be reserved or adjusted. The ratio between origin-destination passengers of a train and seating capacity of that train is a key factor which influences whether a train OD is to be reserved or not. The higher the ratio is, the higher the passenger load factor is in the train, and the better revenue of the train is.

Fig. 3 shows the analysis steps. The calculation process of the OD section passengers of a train OD is to divide each rail line in the network into several passenger-flow sections in accordance with the hubs connecting two or more rail lines, and to add all the quantities of passenger ODs of which origins are in the train OD's departure section and destinations are in the train OD's terminal section.

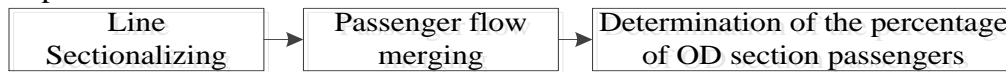| Line Sectionalizing	→	Passenger flow merging	→	Determination of the percentage of OD section passengers

Fig. 3 Steps to determine the train ODs

The formula for calculating the the ratio between origin-destination passengers of a train and seating capacity of that train is stated as follows:

$$\alpha = q_{OD} / \left(f_{OD} \times R \right). \tag{1}$$

Where, α represents the ratio-value, q_{OD} represents the OD section passengers, f_{OD} represents the train frequency, and R represents the train seating capacity. Under the condition that the frequency is one at least, and the ratio-value should not be less than α_0. Thus, the train OD of which origin-destination passengers are not less than $R\alpha_0$ can be reserved, or it should be adjusted. Because long-distance trains usually have to run through several sections and the OD section passengers are relatively fewer in long-distance OD, their α-values are often lower than the α-values of short-distance trains. Therefore, the value of α_0 is associated with the running distance of the train OD.

Determining Methods of Cyclic and Acyclic Train ODs

The determination of cyclic and acyclic train ODs should consider station function, train running distance and the amount of passenger flow.

1. Station function

The station which can be used as the departure or arrival terminal is usually an important hub station. In order to facilitate the passenger transfer and the work organization of the stations, the terminal stations of a cyclic train OD should be hub stations with an EMU depot allocated near them.

2. Train running distance

The running distance of the cyclic trains should be within the range of dominant distance when the railway competes with other transport modes. The range of dominant distance of high-speed trains is almost 500-1,000km in Japan and European countries, but in China the upper bound of the range could reach about 1,500km. As the range is relatively fuzzy, a concept of membership function is introduced in determining the distance range of cyclic trains. Let $H(l)$ be the membership function of the fuzzy set

"Dominant distance of high-speed trains", H represents the fuzzy set "Dominant distance of high-speed trains", l represents train running distance. The formula is shown in Eq. (2).

$$H(l) = \begin{cases} 1 - \left(\dfrac{l_1 - l}{l_1}\right)^2 & 0 < l < l_1 \\ 1 & l_1 \leq l < l_2 \\ 1 - \left(\dfrac{l - l_2}{l_3 - l_2}\right)^2 & l_2 \leq l < l_3 \\ 0 & l \geq l_3 \end{cases} \tag{2}$$

The values of l_1, l_2, l_3 depend on the distance distribution of the existing plan in 2017, which is shown in Table 1.

Table 1 The distance distribution of high-speed trains

Distance distribution	Number of trains	Ratio
0-500	823	38.32%
500-1,000	622	28.96%
1,000-1,500	466	21.69%
1,500-	237	11.03%
Total	2,148	100.00%

The values of l_1, l_2, l_3 were 500, 1,000 and 1,500 in this paper. The train OD of which distance membership is greater than H_0 could be operated as cyclic mode, otherwise it will be operated as acyclic mode.

3. The amount of passenger flow

In order to increase the number of train ODs in each period and extend the service range of cyclic train ODs, the cycle time of the plan is set to be 2 hours, and the number of cycles in a day is 5 at least. In order to improve the load factor of cyclic trains, the α-value should not be less than α' in general and should be larger than α''. Thus, the origin-destination passengers of a cyclic train OD should reach $5R\alpha'$. For a cyclic or acyclic alternative train OD, it should be within a range of $R\alpha''$ to $5R\alpha'$. And for an acyclic train, it should be between $R\alpha_0$ and $5R\alpha''$. The values of α' and α'' are associated with the running distance of the train OD. The value of α_0 is associated with the running distance of the train OD.

The determination procedure of the cyclic and acyclic train ODs is shown in Fig. 4.
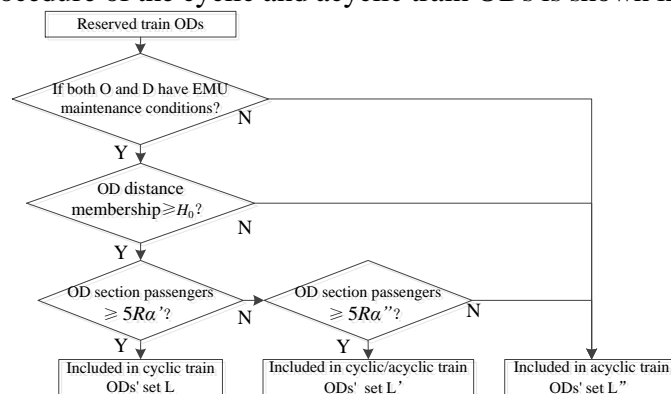

Fig. 4 Determination procedure of the cyclic and acyclic train ODs

Train OD Adjustment Strategies

For those train ODs which are long-distance and do not meet the operational requirements in section 3.1, they should be truncated to two train ODs of which running distances are in the distance range of cyclic trains. The following strategies should be taken into consideration in selecting a transfer station of the train OD:

1. Arrange in large cities with developed economy and dense population.
2. Ensure balanced utilization of different transfer stations.
3. Consider to transfer using cyclic trains as much as possible.

4. Train ODs with the same or a similar direction should be transferred at the same station.

The transfer stations of train ODs are usually chosen as those with the lowest percentage of transfer passengers. After the truncating treatment, the train ODs must be re-clustered according to the principles in section 3.2. The procedure for determining the transfer stations is shown in Fig. 5.
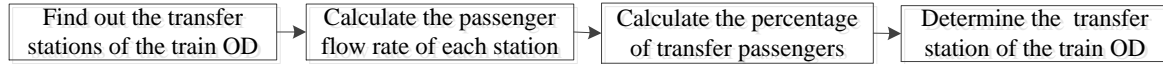
| Find out the transfer stations of the train OD | → | Calculate the passenger flow rate of each station | → | Calculate the percentage of transfer passengers | → | Determine the transfer station of the train OD |

Fig. 5 Procedure for determining the transfer stations

Case Analysis

Description of the Rail Network

A sub high-speed rail network in China is selected to conduct a case study, as shown in Fig. 6.

Fig. 6 A case study high-speed rail network

Based on the data of existing plan, all the stations and trains in the Beijing-Shanghai high-speed railway and connected lines are selected. The Beijing-Shanghai high-speed railway is divided into six passenger flow areas through Tianjin, Ji'nan, Xuzhou, Bengbu and Nanjing, while for other rail lines, each line is divided into one passenger flow area according to the connection and terminal station. In the rail network, Beijing, Shenyang, Tianjin, Ji'nan, Qingdao, Xuzhou, Hefei, Nanjing, Shanghai, Hangzhou and Hangzhou are hubs, and all of these stations have EMU depots nearby. They will be served as the terminal stations of cyclic trains.

Determination of Train ODs

A total of 38 train ODs in the network is selected from the ODs in the existing plan. According to the actual situation in China, the average train seating capacity(R) is 1,000, and the value of H_0 is set to be 0.3 in this case. The values of α_0, α' and α'' are shown in Table 2.

Table 2 Values of α_0, α' and α''

	0<l≤500km	500km<l≤1,000km	1,000km<l≤1,500km	l>1,500km
α_0	80%	60%	40%	20%
α'	80%	60%	40%	/
α''	40%	30%	20%	/

According to the principles in section 3, the train ODs and the merged passengers are obtained, as shown in Table 3.

Table 3 Alternative train ODs

No.	O	D	Distance[km]	OD passengers	Mode
1	Beijing South	Shanghai Hongqiao	1,318	13,807	Cyclic
2	Beijing South	Ji'nan West	406	13,309	Cyclic
3	Beijing South	Nanjing South	1,023	6,475	Cyclic
4	Beijing South	Xuzhou East	692	6,557	Cyclic
5	Xuzhou East	Shanghai Hongqiao	626	9,099	Cyclic
6	Ji'nan West	Shanghai Hongqiao	912	5,814	Cyclic
7	Tianjin (West)	Shanghai Hongqiao	1,213	3,977	Cyclic
8	Nanjing South	Shanghai Hongqiao	295	43,145	Cyclic
9	Tianjin (West)	Shenyang North	666	14,221	Cyclic
10	Ji'nan West	Qingdao	413	24,229	Cyclic
11	Zhengzhou East	Xuzhou East	360	8,538	Cyclic
12	Nanjing South	Hangzhou East	256	20,089	Cyclic
13	Beijing South	Hangzhou East	1,279	4,552	Cyclic
14	Beijing South	Qingdao	819	8,329	Cyclic
15	Zhengzhou East	Shanghai Hongqiao	986	4,341	Cyclic
16	Hefei South	Shanghai Hongqiao	459	7,543	Cyclic
1	Beijing South	Qinghuangdao	388	1,451	Acyclic
2	Beijing South	Tangshan	241	1,105	Acyclic
3	Huainan East	Shanghai Hongqiao	563	899	Acyclic
4	Ji'nan West	Zhengzhou East	646	1,060	Acyclic
5	Zhengzhou East	Hangzhou East	947	1,454	Acyclic
6	Qingdao	Zhengzhou East	1,027	458	Acyclic
7	Qingdao	Hangzhou East	1,269	560	Acyclic
8	Shenyang North	Shanghai Hongqiao	1,964	738	Acyclic
1	Qingdao	Shanghai Hongqiao	1,308	1,778	Cyclic or Acyclic
2	Beijing South	Hefei South	1,000	2,750	Cyclic or Acyclic
3	Shenyang North	Ji'nan West	972	2,088	Cyclic or Acyclic
4	Qingdao	Xuzhou East	682	2,923	Cyclic or Acyclic
5	Hefei South	Hangzhou East	413	2,759	Cyclic or Acyclic

As shown in table 3, 29 rain ODs meet the determining requirements in the existing plan. According to the above principles, the alternative train ODs are decreased compared with the existing plan. Some train ODs like Bengbu South-Nanjing South which is short-distance and does not meet the operational requirements of cyclic trains is merged into the long-distance train ODs. Besides, a direct or transfer service can be provided for each OD within the network range theoretically. For cyclic and acyclic alternative train ODs, it can further use an optimization model to determine that it runs under a cyclic mode or an acyclic mode.

Determination of Transfer Stations

According to section 2, Beijing, Tianjin, Ji'nan, Xuzhou, Nanjing and Shanghai are selected as transfer hubs. Table 4 shows the train ODs that needed to be truncated in this case.

Table 4 Train ODs needed to be truncated

No.	O	D	Distance[km]	OD passengers
1	Qingdao	Hefei	990	252
2	Shenyang North	Qingdao	1,370	383

By using principles in section 3.3, the transfer stations of each train OD in the rail network are shown in Table 5.

Table 5 The transfer stations of each train OD

O	D	Transfer stations	Transfer passengers	Conveyed passengers /Day	The percentage of transfer passengers'
Qingdao	Hefei South	Xuzhou	232	1,442	16.09%
Hefei South	Qingdao	Xuzhou	192	934	20.56%
Qingdao North	Shenyang North	Ji'nan	302	1,610	18.76%
Shenyang North	Qingdao North	Ji'nan	229	1,275	17.96%

In Table 5, the percentages of transfer passengers are within the acceptable range, and all of the transfer passengers among these train ODs can use transfer service by riding cyclic trains. No new train OD is added after the above train ODs are truncated.

Conclusion

Considering a train operation mode which combines the cyclic mode with acyclic mode, this paper proposes the principle of generating alternative train ODs for a large-scale rail network. Influencing factors of the station function, train running distance and the amount of passenger flow are analyzed. The paper also analyzes the existing train ODs in a sub high-speed railway network in China, determines the cyclic and acyclic train ODs according to the proposed strategies, and truncates some long-distance trains at selected transfer nodes. This study paves a way for the generation of a cyclic line plan and timetable. Future research can be devoted to determine the elements of train service frequency and stopping pattern of a line plan.

Acknowledgement

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