Optimal Design of Urban Rail Train Operation Plan Based on Virtual Coupling

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***Abstract*—In recent years, virtual coupling trains have attracted extensive attention, which use reliable train to train (T2T) communication technology to realize train short-range tracking. When the headway between trains is small enough, it can be considered that a virtual coupling fleet is formed. Based on this concept, trains no longer rely on mechanical couplers to realize coupling. In this paper, several operation modes suitable for virtual coupling trains are proposed, and the operation scheme design methods are studied. Then taking Beijing Metro Batong line as an example, the genetic algorithm is used to solve the train operation scheme. Comparing the virtual coupling operation scheme with the current scheme, the results show that the virtual coupling scheme can effectively shorten the passenger travel time while ensuring the passenger traffic volume.**

Keywords-virtual coupling; train operation scheme; genetic algorithm

I. INTRODUCTION

In recent years, the widespread popularization of rail transit has greatly promoted people's travel. People can even commute across cities through rail transit every day, which has driven the development of social economy. However, the rapid growth of passenger flow leads to the increasing pressure of rail transit operation year by year. Recently, Shanghai line 16 has realized flexible group by means of online coupling and uncoupling. It can adapt to the imbalance distribution of passenger flow in time and space, which is of great significance to energy saving and efficiency improvement. However, due to the existence of mechanical couplers between trains, the train must be in the stop state to realize coupling or uncoupling operation, which takes a long time.

Virtual coupling (VC) trains refer to a way that trains do not rely on mechanical coupling, but instead use train to train (T2T) wireless communication technology to achieve coordinated operation of multiple trains at the same speed and very small intervals, as shown in Fig.1. In 2000, an initial idea of "Virtual coupling" was proposed to improve cargo transportation capabilities [1]. However, due to the limitation of technology at that time, there was no great progress in the next decade. In 2015, Shift2Rail launched in Europe proposed that virtual coupling is an important research direction of European railway, which officially raised a research boom of virtual coupling technology [2-3]. The research content is mainly focused on the scenarios of VC operation and the control method of the train formation [4]. Recent years, the Spanish CAF used the T2T communication technology to realize the 20km/h low-speed tramway experiment, and demonstrated the concept of virtual coupling trains running synchronously. In September 2021, a new type of urban express train developed by CRRC Tangshan rolled off the assembly line. Through the application of 5G technology, the train realized virtual coupling and flexible mixed running between trains. In addition, Traffic Control Technology (TCT) try to apply autonomous virtual coupling on Beijing Metro Line 11. The train can reduce the headway from the current 90s to 65s. Although the line will be put into operation at the end of 2021, the virtual coupling technology will be implemented until next year.

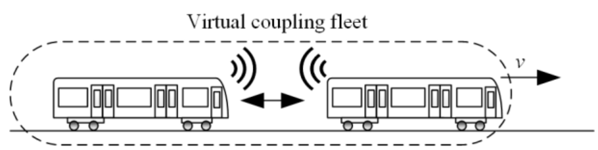

Figure 1. Virtual coupling fleet with T2T technology.

Virtual coupling has been highly valued by many vehicle manufacturers, railway related units and scientific research institutions, and has become the standard configuration of the "next generation smart train". It is necessary to study how to use the advantages of virtual coupling trains to improve the quality of rail transit. In this paper, the future virtual coupling train operation scenario is proposed, and the optimization model of train operation scheme is designed. Then, taking Beijing Metro Batong line as an example, the optimized train operation scheme is solved by genetic algorithm.

II. OPERATION SCHEME OF VIRTUAL COUPLING TRAINS

A. *Train operation mode of VC*

Since there are no mechanical couplers between virtual coupling trains, it can be realized that the train automatically leaves the formation or joins the formation when it approaches the intersection [1]. Through the transformation of the line network, such as adding an avoidance line, a more flexible and efficient operation plan can be realized, such as dynamic driving, overtaking and point-to-point operation.

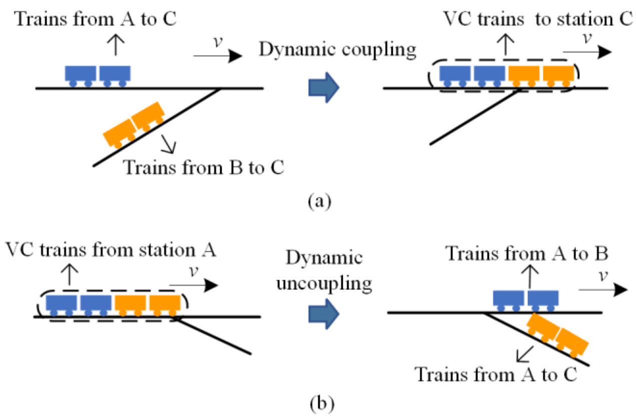

Figure 2. Train dynamic (a) coupling and (b) uncoupling diagram.

1) Dynamic driving

As shown in Fig.2 (a), it is the schematic diagram of dynamic coupling of train at the turnout, where two trains from different directions form a fleet through virtual coupling. This scenario mostly occurs when trains in different directions enter the central trunk line. Similarly, as shown in Fig.2 (b), a virtual coupling fleet can also be ungrouped at the turnout, so that the train can go to different destinations. When the train runs from the urban trunk railway to the suburbs, it has significant advantages.

2) Overtaking

As shown in Fig.3, it is the schematic diagram of platform line structure proposed in this paper. In addition to an up line and a down line, the station also has a "tidal line". The tidal line is connected to two main lines through turnouts. When the number of vehicles traveling in the up direction increases due to the increase in passenger flow, the express trains in the up train can temporarily quickly pass through the tidal line to realize overtaking, while the slow trains in the same direction will stop at the platform, as shown in Fig.3 (a). In the same way, as shown in Fig.3 (b), when the number of vehicles in the down direction increases, it is also possible to overtake the station by occupying the tidal line. The direction of the trains on the tidal

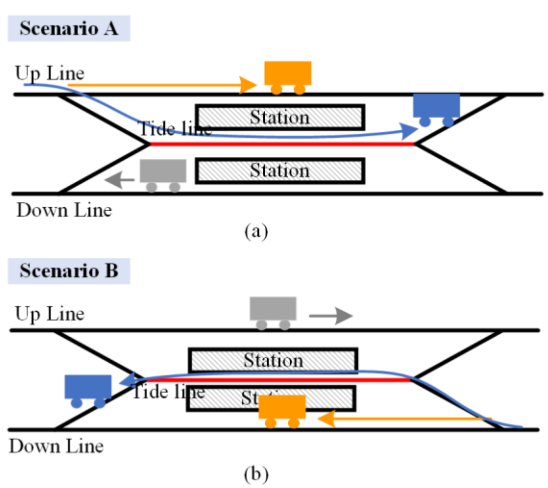

Figure 3. Schematic diagram of overtaking in (a) scenario A and (b) scenario B.

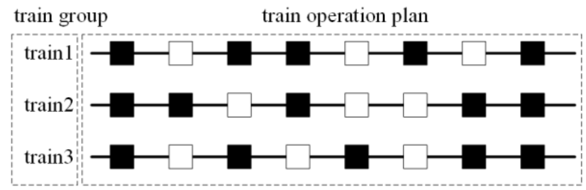

Figure 4. Schematic diagram of train operation scheme.

line can be different, which is related to the distribution of passenger flow, usually different in the morning and evening peaks.

In this way, for express trains, it will only stop at main stations to get on and off passengers and ignore the small stations on the way, which can greatly save the journey time of long-distance passengers. Meanwhile, slow trains stop at each station to cooperate with express trains, which can satisfy passenger demand for short-distance travel.

3) Point-to-point operation

Based on the perfect railway network and flexible operation scheme, virtual coupling can realize the "point-to-point" operation of trains. Passengers choose the corresponding vehicle to get on at the platform according to the destination. Then trains drive out of the platform in sequence and carry out virtual coupling on the main line. The trains run in a formation until the train reaches the turnout. Then, the fleet unravels at the turnout and drives to different destinations. It will bring great challenges to the formulation of train operation plan. A good operation plan will effectively shorten the passengers travel time and improve transportation efficiency, which will be a key content of the application research of virtual coupling technology.

B. Optimization design of operation scheme for virtual coupling trains

B. Lee proposed a train operation scheme by using VC in [5], where each train stops according to the specified dwell period and the trains staying at each station are the same. However it not considered the influence of passenger flow difference at different stations in the train stopping law. This paper puts forward a comprehensive design scheme of stopping in the whole line based on a train group. The trains in the train group have different stop schemes, and the stop schemes of all trains constitute a train operation scheme, as shown in Fig.4. Taking Beijing Metro Batong line as an example, this paper gives the operation scheme design process of trains from Tuqiao to Sihui during the morning rush hour.

1) Model assumptions

For trains adopting virtual coupling technology, only the tidal line shown in Fig.3 needs to be set in the station area, without the transformation of the line section. In the line section, each train runs at the same speed. The virtual coupling operation scheme proposed in this paper is to adopt overtaking mode on the basis of the current parallel operation diagram, so as to shorten the passenger travel time.

Table 1 shows three comparative train operation schemes. Since the virtual coupling technology can effectively shorten the headway between trains, it is designed to be 1 min. With the gradual maturity of virtual coupling technology, the headway is expected to be further shortened.

TABLE I. DESIGN INDEX OF THREE TRAIN OPERATION SCHEMES

	Operation schemes	Headway(s)	Stopping time(s)
Scheme A	Parallel operation diagram, stop by stop	120	30
Scheme B	Parallel operation diagram, stop by stop	60	30
Scheme C	Parallel operation diagram, across stations stop based on virtual coupled train	60	30

Different ways of train stopping will greatly affect passengers' travel experience. For example, if there are fewer trains at a certain station, passengers at that station or passengers who going to the station will spend more time waiting for the train. Therefore, it is necessary to comprehensively consider the stopping plan of each train to meet the needs of different passengers. In the scheme proposed in this paper, it is assumed that the longest waiting time for passengers is 10 min, so the train operation cycle T = 10 min. It corresponds to the extreme situation where only one train meets the passenger's demand in each departure cycle.

2) Design Principles

In order to meet the actual operation requirements, the train operation scheme design needs to meet the following basic principles:

- All trains stop at the departure station and terminal station;
- All trains stop at key stations, which refer to stations that have significantly increased passenger flow such as transfer stations;
- The operation plan can meet the travel of all passengers in this direction on the whole line;
- The number of trains stops on the whole line is as small as possible;
- The average passenger load factor of each train shall not be less than 90% and not higher than 120%;
- The time interval between train arrivals at each station is as even as possible.

III. MODEL ESTABLISHMENT AND SOLUTION OF OPTIMAL OPERATION SCHEME OF VIRTUALCOUPLING TRAINS

A. Train operation plan optimization model

1) Passenger lost time model

Under the new operation plan, due to the reduction in the number of trains stops, the passenger travel time will be significantly shortened. Therefore, a passenger loss time model is established to reflect the advantages of the design scheme, which expressed by (1).

$$t_{loss} = \sum_{i=1, i\neq j}^{n} \sum_{j=1}^{n} (t_{w_{i,j}} + t_{stop} \cdot k_{i,j} + t_c + t_d) * m_{i,j} . \tag{1}$$

The meaning of each parameter is as follows: i and j are the departure station and destination station of the passengers respectively; n is the number of stations on the whole line; t_{loss} is the total lost time of all passengers in a cycle; $m_{\text{i,j}}$ is the number of passengers from station i to station j in a cycle; t_{stop} is the stopping time at station i; $k_{\text{i,j}}$ is the number of trains stopping between station i and station j; $t_{\text{wi,j}}$ is the average waiting time of passengers going to station j at station i; t_{c} is passenger transfer time; t_{d} is the time difference caused by differences in train performance. Among them, $k_{\text{i,j}}$, $t_{\text{wi,j}}$ and t_{c} are closely related to the train operation plan.

2) Average train load factor

Reducing the number of train stops can effectively reduce the passenger travel time, but at the same time, it may not be able to load more passengers because the number of train stops is too small, which will reduce the transportation efficiency of the train. Therefore, this paper restricts the average load factor of trains to ensure the efficiency of train transportation. The passenger capacity of a train when it departs at the station can be calculated by (2).

$$C_i = C_{i-1} + m_{i,\infty} - m_{\infty,i} . \tag{2}$$

C_{i} is the number of passengers when the train leaves station i, $C_{\text{i-1}}$ is 0 when the train is at the departure station. $m_{\text{i},\infty}$ means the number of people boarding at station i, and $m_{\infty,\text{i}}$ means the number of people getting off at station i. Then, the average load factor of the train on the whole line can be expressed in (3), where C_{N} is the rated passenger capacity of train.

$$\varepsilon_c = \sum_{i=1}^{n} C_i / (nC_N) . \tag{3}$$

3) Optimization model of train operation plan

In order to make the train operation plan comprehensively consider the passenger's loss time and the train's transportation efficiency, the optimization model is established in (4)-(7).

$$\textbf{min} \quad \alpha t^{*}_{loss} - \beta \varepsilon_c \tag{4}$$

$$s.t. \quad 0.9 < \varepsilon_c < 1.2 , \tag{5}$$

$$0 < \alpha < 1 , \tag{6}$$

$$0 < \beta < 1 . \tag{7}$$

Among them, α and β are the weight coefficients of passenger loss time and train load factor respectively, and t^{*}_{loss} is the ratio of the passenger loss time between the virtual coupling optimization scheme (Scheme C) and the stop scheme at the same departure interval (Scheme B). The train load factor rate ε_{c} is limited to the range of 0.9-1.2.

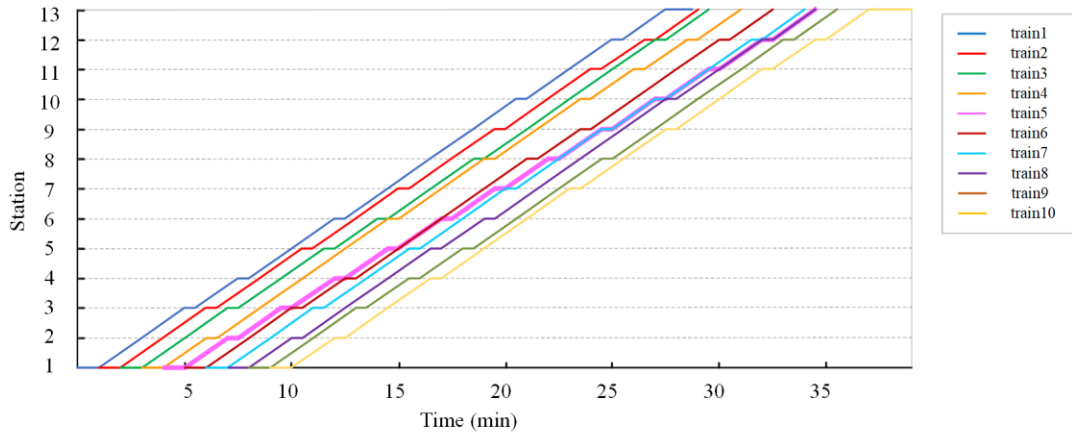

Figure 6. Optimized train operation diagram.

B. Train operation optimization plan

As the train stop plan in the operation plan shows an obvious combinatorial explosion trend with the increase in the number of trains and stations, the genetic algorithm is a satisfactory plan to solve such problems. For Batong Line, according to the design principle, all trains stop at Tuqiao, Sihui East and Sihui station. In order to ensure the demand of passengers at any station on the whole line, at least one train adopts the stop-by-stop method in each operating cycle.

The optimization model is established in MATLAB, and the genetic algorithm is used to solve the problem. The iteration curve is shown in the Fig.5, and algorithm converges to the optimal value after 160 generations. At this time, t^{*}_{loss} is 0.577 and ε_{c} is 0.9079. It shows that the designed train operation plan can reduce the passengers lost time to 57.7% compared with Scheme B, and the minimum load factor of the train can reach 90.79%. Table 2 compared the passenger lost time of the three scenarios proposed in the previous section. The results show that shortening the train departure interval can reduce the time lost by passengers, but adjusting the train operation mode is the most powerful means.

The optimized train operation diagram is shown in Fig.6. It can be seen from the operation diagram that each train will stop at different stations, and since the train 5 adopts the stop-by-stop mode, it will realize virtual coupling with the train 6, 7, and 8 successively during operation.

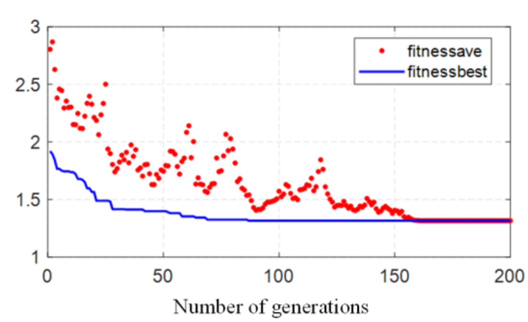

Figure 5. Iteration curve of genetic algorithm.

TABLE II. DESIGN OF MAIN PARAMETERS OF GENETIC ALGORITHM

	Scheme A	Scheme B	Scheme C
t^{*}_{loss}	1.151	1	0.577

IV. CONCLUSION

On account of flexible grouping of virtual coupling trains, it can realize interoperability, overtaking and other transportation modes, which brings more possibilities for intelligent transportation of rail transit. In order to quantitatively describe the potential advantages of virtual coupling technology, its operation scheme is discussed in detail. This paper takes the Batong Line of Beijing Metro as the object to study the train operation plan based on virtual coupling technology. For trains of the same speed class, only the stations along the line need to be renovated and a "tidal line" is added to realize overtaking. An optimization model of train operation plan is established, and the genetic algorithm is used to solve the problem. Comparing the virtual coupling operation scheme with the current scheme, the results show that the virtual coupling scheme can effectively shorten the passenger time while ensuring passenger traffic.

In the future, the design model of train operation scheme will be further optimized with the goal of trains point-to-point operation and considering complex scenarios such as cross line running.

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