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Research Article

The Analysis and Calculation Method of Urban Rail Transit Carrying Capacity Based on Express-Slow Mode

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Urban railway transport that connects suburbs and city areas is characterized by uneven temporal and spatial distribution in terms of passenger flow and underutilized carrying capacity. This paper aims to develop methodologies to measure the carrying capacity of the urban railway by introducing a concept of the express-slow mode. We first explore factors influencing the carrying capacity under the express-slow mode and the interactive relationships among these factors. Then we establish seven different scenarios to measure the carrying capacity by considering the ratio of the number of the express trains and the slow trains, the station where overtaking takes place, and the number of overtaking maneuvers. Taking Shanghai Metro Line 16 as an empirical study, the proposed methods to measure the carrying capacity under different express-slow mode are proved to be valid. This paper contributes to the literature by remodifying the traditional methods to measure the carrying capacity when different express-slow modes are applied to improve the carrying capacity of the suburban railway.

1. Introduction

Since the beginning of the 21st century, urban rail transit system in China has been rapidly developed, which accelerates the urbanization process of China. However, the traffic jam in megacities has become more and more severe alongside the urbanization. One of the solutions is to develop strong economy of suburban areas to attract people from city areas. The coverage of the urban railway transport, therefore, needs to be enlarged in order to facilitate the commuting between suburbs and city areas. As the suburb passenger flow increases rapidly, the regular rail transit system reveals its limitation in accommodating the increased flow and providing efficient services in terms of travel time. Comparing to the regular rail transit line, the length of suburb rail transit line (hereinafter referred to as "suburb line") is longer and the passenger flow shows uneven spatial and temporal distribution. Drawing upon these characteristics, a concept of the express-slow mode has been introduced to provide flexible and efficient services on suburb lines. The express-slow mode is a scheme in which express train(s) and slow train(s) are operated in an alternative and coordinate way within a time window.

Several researchers have investigated the methodologies and applications of the operation of heterogeneous trains in railway transport. Li and Mao [1] have investigated the differences of the tracking time interval between a heterogeneous train and a homogeneous train and found that the carrying capacity of the former was largely dampened. They also analyzed the dynamic relationships between the ratio of the number of the heterogeneous trains and their tracking time intervals. Bai et al. [2] developed an optimization model in order to find an equilibrium between the delay time and the number of departures and arrivals of trains. As the passenger flows accumulated on the delayed trains would cause severe safety issues, they also analyzed the carrying capacity in the context of a mixture of regular trains and trains delayed due to external factors. Chen et al. [3] established an optimization model in order to maximize the carrying capacity at peak hour of a high-speed railway passenger station. His model can not only explore factors influencing the carrying capacity of a train line, but also provide an efficient algorithm to find a better solution for the model. Wang et al. [4] have applied the fuzzy Markov chain theory to measure the carrying capacity on an intersectional line by considering the random factors influencing the carrying capacity.

However, to date few literatures have been dedicated to developing a systematic methodology to measure the carrying capacity of suburb lines when applying an express-slow mode [5, 6]. The objective of this paper, therefore, is to examine factors influencing the carrying capacity of suburb lines under the express-slow mode and develop a systematic methodology to calculate the carrying capacity in the same situation.

The remainder of this paper is organized as follows. Section 2 explores factors influencing the carrying capacity of suburb lines under the express-slow mode. In particular, we focus on the impacts of (i) the ratio of the number of express and slow trains, (ii) the number of overtaking maneuvers, and (iii) the overtaking location of express trains based on the demand of a certain urban rail station. In addition, the total en-route travel time is also considered as a significant factor. Applying the express-slow mode may reduce the travel time of express trains, but prolonging that of slow trains. Hence, the calculation of this indicator should consider the balance of travel time of different trains, which may have impacts on the service level of the urban railway system. Given these factors, this section also develops a systematic methodology to calculate the carrying capacity under the express-slow mode. Section 3 presents an empirical study to illustrate the application of the methodology established in Section 2. In Section 4, we summarize the main implications of our analysis and outline some avenues for further research.

2. Factors Influencing the Line Carrying Capacity

2.1. Line Carrying Capacity. The carrying capacity of an urban rail refers to the maximum frequency of a train [7] that passes through an urban rail line within a unit time (generally the peak hour) based on different types of trains, signal facilities, and traffic organization.

We first introduce a method to calculate the line carrying capacity of the regular rail traffic which is characterized by the parallel and periodic operation diagram. In addition, the intersections between urban rail traffic lines and stations along the lines are regarded as an integrated system. Therefore, the carrying capacity of the regular rail can be calculated as follows [8, 9]:

$$N_{\max} = \frac{3600}{I}, \tag{1}$$

where $N_{\max}$ is the maximum frequency of a train passing a line in one direction within a unit time (i.e., 1 hour in this paper) (expressed in "train/h") and I is the minimum time interval of two departure trains (expressed in "s").

I is generally calculated as follows:

$$I = \max\left\{I_{\text{tracking}}, I_{\text{turning back}}\right\}, \tag{2}$$

where I_{tracking} is the tracking duration of a train (expressed in "s"), $I_{\text{turning back}}$ is the minimum time interval between the arrival time of a train at the destination and the departure time of the same train starting from another direction of a line (expressed in "s").

In formula (1), the maximum time interval of train tracking and the maximum time interval of train turning back are considered.

In a combined mode with the coexistence of express and slow trains, overtaking should be taken in account when measuring the carrying capacity of an urban rail [10]. Overtaking occurs when a slow train is operated ahead of an express train and the interval of departure time between these two trains is less than the minimum time interval [11–14]. In other words, overtaking that allows an express train passing a station without stopping or departing ahead of a slow train in the same direction can maximize the carrying capacity under the express-slow mode. In addition, the stop frequency and waiting time of a slow train also influence the line carrying capacity. As the stop frequency and waiting time of the slow train increase, the interval of departure time between the express train and the slow one may decrease. Other factors influencing the line carrying capacity include the distance between two neighboring overtaking stations, the interval of a train's tracking time, the ratio of the number of express trains and slow trains, and the location of an overtaking station [15].

Based on the specific characteristics of the urban rail under the express-slow mode and factors influencing its operation, we remodify (1) and propose a methodology to measure the maximum carrying capacity of a suburb line applying the express-slow mode.

$$N_{\max} = K \times \frac{3600}{T_{\text{cycle}}}, \tag{3}$$

where $N_{\max}$ is the maximum carrying capacity of a line under an express-slow mode (train); T_{cycle} is the cycle time of a combined express-slow train ("s"); K is the total number of express and slow trains within a cycle time T_{cycle} (train).

As shown in (3), the carrying capacity of a suburb line under the express-slow mode increases as the cycle time is reduced.

2.2. The Impacts of the Express-Slow Train Mode on the Line Carrying Capacity. In this section, we explore a combined impact of the ratio of the number of express and slow trains and the total number of overtaking maneuvers on the line carrying capacity under the express-slow mode. We assume that the time intervals of two departing trains are the same and the ratio of the number of express and slow trains is equal to $k : m$ within a cycle [16–19].

As the situation that merely express trains are operated on a line does not allow the operated express trains to stop at any intermediate stations, which is unrealistic and would

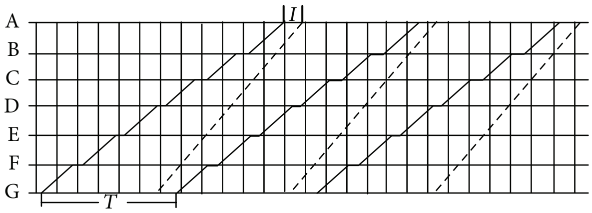

FIGURE 1: Scenario 2: $k : m = 1 : 1$ and no overtaking.

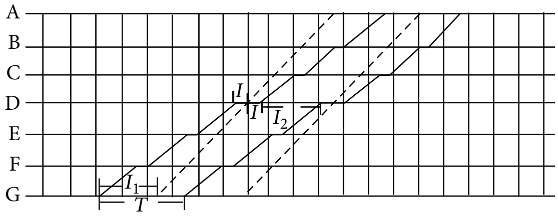

FIGURE 2: Scenario 3: $k : m = 1 : 1$ and overtaking occurring once.

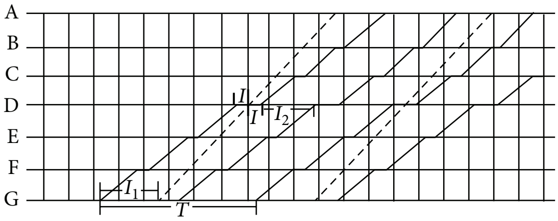

FIGURE 3: Scenario 4: $k : m = 1 : 2$ and overtaking occurring once.

lead to large demand loss [20], this paper does not consider this situation. Given the ratio of the number of express and slow trains, the total number of overtaking maneuvers is also considered. To simplify the calculation, we only consider three types of situation when overtaking occurs once, twice or no overtaking occurs. In this way, seven different scenarios are designed to develop different methods to measure the line carrying capacity.

Scenario 1 (only slow trains). In this scenario, as merely slow trains are operated and no overtaking occurs, the carrying capacity is measured based on the minimum time intervals between two slow trains. The equation is as (1).

This scenario is designed as the baseline of other proposed scenarios in order to figure out which scenario serves the best combination to maximize the line carrying capacity.

Scenario 2 ($k : m = 1 : 1$ and no overtaking). In this scenario, as no overtaking takes place, one express train is operated between two slow trains as shown in Figure 1.

Measuring the cycle time should consider the following two situations due to the higher speed of express trains [8, 21, 22]. First, if a slow train is operated before an express train, the time interval of the two trains arriving at the destination should not be larger than the minimum time interval of departures I. Second, if the situation is in the opposite, then the departure time difference of the two trains should be calculated. The cycle time of Scenario 2 is calculated as follows:

$$T_{\text{cycle}} = 2I + n \times t_{\text{stop}}, \tag{4}$$

where n is the stopping frequency of a slow train; t_{stop} is the sum of the time for acceleration and deceleration as well as the waiting time of a train at one station.

According to (3), the carrying capacity in Scenario 2, therefore, is calculated as follows:

$$N_{\max} = K \times \frac{3600}{T_{\text{cycle}}} = 2 \times \frac{3600}{\left(2I + n \times t_{\text{stop}}\right)}. \tag{5}$$

As can be seen from (5), the carrying capacity of Scenario 2 is determined by the stopping frequency n and the departure time interval I, which is constant when the operation scheme has been scheduled.

Scenario 3 ($k : m = 1 : 1$ and overtaking occurring once). In Scenario 2 when overtaking is ignored, the longer time interval between two departures can guarantee safety but may deteriorate the carrying capacity. Scenario 3 thus considers the overtaking occurring once.

As shown in Figure 2, A–G represent terminal stations; station D is available for overtaking. In order to guarantee the following express train to safely overtake station D, the departure time interval between the slow train and the express train should be extended to I_1. The time interval between the slow train and the express train at station D should not be less than I. Meanwhile, I_1 should be larger than I. The cycle time, therefore, is measured as follows:

$$T_{\text{cycle}} = 2I + n \times t_{\text{stop}}. \tag{6}$$

According to formula (3), the carrying capacity can be calculated by embedding (6) into (3). Comparing to Scenario 2, the carrying capacity of Scenario 3 increases due to the reduced number of stopping and waiting times at the intermediate station.

Scenario 4 ($k : m = 1 : 2$ and overtaking occurring once). Scenario 4 not only considers the condition of overtaking, but also doubles the number of slow trains. In this situation, an additional slow train is supplemented between every two cycles (Figure 3).

The operation period is detailed as follows:

$$T_{\text{cycle}} = 3I + n \times t_{\text{stop}}. \tag{7}$$

Although the number of slow trains increases, whether the carrying capacity also increases depends on the operation in practice. The carrying capacity of Scenario 4 is calculated as follows:

$$N_{\max} = K \times \frac{3600}{T_{\text{cycle}}} = 3 \times \frac{3600}{\left(3I + n \times t_{\text{stop}}\right)}. \tag{8}$$

Scenario 5 ($k : m = 1 : 2$ and overtaking occurring twice). Scenario 5 increases the number of overtaking maneuvers from 1 to 2, comparing to Scenario 4.

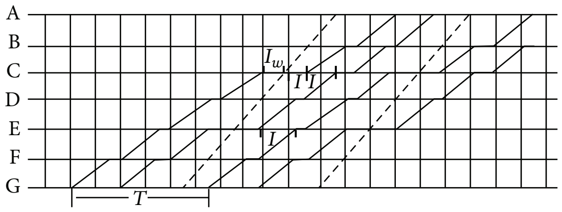

Figure 4: Scenario 5: $k : m = 1 : 2$ and overtaking occurring twice.

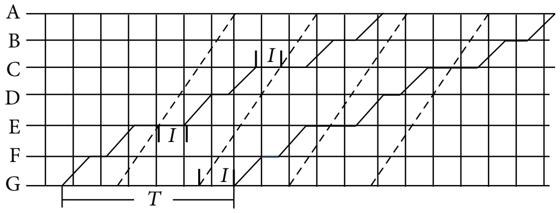

Figure 5: Scenario 6: $k : m = 2 : 1$ and overtaking occurring once.

As shown in Figure 4, an express train departs lagging behind two slow trains and overtakes the two slow trains at stations E and C, respectively. The cycle time of this scenario is measured as follows:

$$T_{\text{cycle}} = I_w + 3I + n \times t_{\text{stop}}, \tag{9}$$

where I_w is the waiting time of the first slow train until the overtaking express train departs the same station.

In such a condition, the carrying capacity is calculated as follows:

$$N_{\max} = K \times \frac{3600}{T_{\text{cycle}}} = 3 \times \frac{3600}{\left(I_w + 3I + n \times t_{\text{stop}}\right)}. \tag{10}$$

I_w is calculated separately given the entire section from station C to G. As an additional slow train is operated between a slow train and an express train at station E within a cycle, the time interval between the first departing slow train and the departing express train at station E depends on (i) the minimal time interval between the second departing train and the departing express train at station E and (ii) the departure time interval between the first slow train and the second slow train.

Scenario 6 (k:m = 2 : 1 and overtaking occurring once). Scenario 6 considers the situation when the overtaking occurs once and the number of express trains is doubled. The relationships between S_{AB} and S_{CD} should be taken into account.

As shown in Figure 5, overtaking can occur at either station E or station C. In the later condition, in order to ensure the safe operation conditions, it is required to select the longer operation time in the C~A section and G~E section as the integral part of the period [23], where the period expression is detailed as follows:

$$T_{\text{cycle}} = I_w + 3I + n \times t_{\text{stop}}. \tag{11}$$

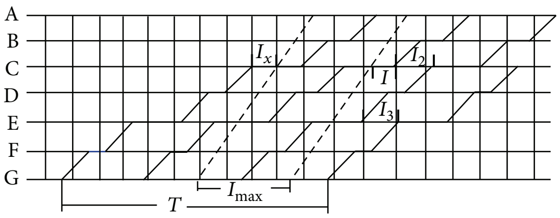

Figure 6: Scenario 7: $k : m = 2 : 3$ and overtaking occurring twice.

The calculation of the carrying capacity under the train service percentage and service condition is similar to that of Scheme (5); however, since the station stop time is shortened, so the carrying capacity can be calculated through (3).

Scenario 7 (k:m = 2 : 3 and overtaking occurring twice). In Scenario 7, the two preceding slow trains are overtaken by the following express train and a third slow train can be operated between two express trains in a cycle. Scenario 5 will be a simplified version of this scenario if the two express trains in a cycle are combined.

As shown in Figure 6, on the basis of Scheme (5), one $I_{\max}$ and two I are added, where $I_{\max}$ is the longest operation time between all sections, where the period expression is detailed as follows:

$$\begin{aligned} T_{\text{cycle}} &= I_w + I_{\max} + 3I + I_2 + I_3, \\ I_{\max} &= \frac{\max\left\{S_{\text{GF}}, S_{\text{FE}}, S_{\text{ED}}, S_{\text{DC}}, S_{\text{CB}}, S_{\text{BA}}\right\}}{v_m}, \end{aligned} \tag{12}$$

where $I_{\max}$ is the longest operation time of all sections (expressed in "s").

In this scenario, applying the express-slow mode can increase the carrying capacity of a suburb line, which further improves the serve quality for passengers. However, if the distance between two overtaking stations is too long, the longer waiting time for slow trains can also deteriorate the service level for passengers. Therefore, we suggest that the number of overtaking maneuvers should be reduced if a station cannot be restructured as an overtaking station in the short run.

2.3. Discussions of Seven Scenarios

2.3.1. The Impacts of Different Ratios of the Number of Express and Slow Trains on the Carrying Capacity. This subsection attempts to generalize the method to calculate the carrying capacity in a situation when overtaking merely occurs once, while the ratios of the number of express and slow trains can be random [24]. Taking Scenarios 3 and 4 as a comparison, the travel time of the latter increases by ΔT_{AG} as the number of slow trains doubled. Assuming that only one additional slow train is introduced within one cycle time, then we can generalize the method to the situation when the ratio of the number of express and slow trains is 1: m ($m \geq 2$). The

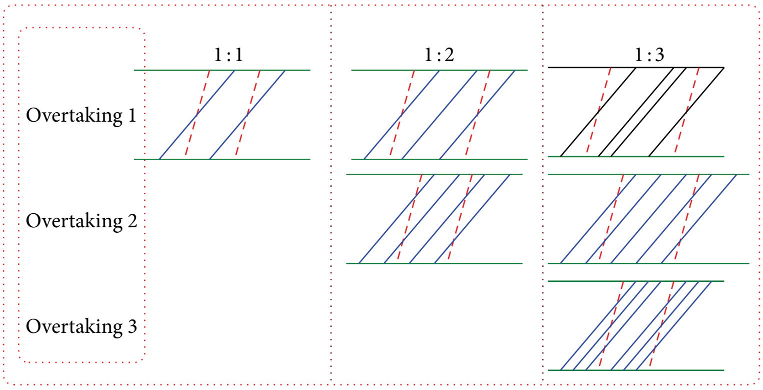

Figure 7: A comparison of different scenarios based on different overtaking frequencies.

average travel time of each train takes can be measured as follows:

$$I_{\text{aver}} = \frac{2I + \Delta t + m - 2}{m + 1}. \quad (13)$$

In formula (13), I and Δt are fixed; therefore, when m increases infinitely, I_{aver} will approach I; therefore, when m increases, the line carrying capacity will be improved. The similar conclusions can be deduced to the $n : m$ express-slow train service percentage.

In (13), I and Δt are fixed. An extra I is added to the equation in order to correspond to one addition of the slow train. When m increases infinitely, I_{aver} will approach to I. In other words, the line carrying capacity also increases, which may imply potential improvement.

2.3.2. The Impacts of Overtaking Frequencies on the Carrying Capacity.

$$\begin{aligned} T_{\text{cycle}} &= 3I + n \times t_{\text{stop}}, \\ T_{\text{cycle}} &= I_w + 3I + n \times t_{\text{stop}}. \end{aligned} \quad (14)$$

Recalling Scenarios 4 and 5, we summarize that overtaking twice can increase the carrying capacity given that the ratio of the number of express and slow trains is equal to 1 : 2. As the number of overtaking maneuvers increases, the reduced waiting time of the slow train means the decrease of the cycle time (Figure 7).

However, when the number of overtaking maneuvers increases to three or more, the passenger service level in practice can be dampened due to the increased number of stops of slow trains [25, 26]. This paper, therefore, does not consider the impact of overtaking maneuvers number over three on the carrying capacity.

2.3.3. Procedure to Calculate the Carrying Capacity Based on the Express-Slow Mode. This section introduces a procedure to calculate the carrying capacity based on the aforementioned seven scenarios under different ratios of the number of express and slow trains and the number of overtaking maneuvers. Three steps should be taken as follows.

Step 1. Given a predefined ratio of the number of express and slow trains, the cycle time and the time interval between two departing trains are calculated. Then the theoretical carrying capacity $N_{\max}$ is measured based on (5).

Step 2. This step determines whether an overtaking should be considered based on the following criterion: that is, $T_{\text{depart}} + t_{\text{express}} - t_{\text{slow}} < I_{\text{tracking}}$. If this criterion is satisfied, then the procedure goes to Step 3; otherwise, the line carrying capacity will be equal to $N_{\max}$ measured in Step 1.

Step 3. This step determines the number of overtaking maneuvers and the location of overtaking stations based on the ratio of the number of express and slow trains and the characteristics of passenger flow on a suburb line. The carrying capacity are then measured based on (6) to (12).

It is important to systematically examine the changes of the line carrying capacity drawing upon different ratios of the number of express and slow trains and different number of overtaking maneuvers. In this way, operators can figure out the combination scenario with the largest carrying capacity and establish a denser schedule upon which the time interval between two departure trains in the neighbor stations can be at its minimum.

3. Empirical Study

3.1. Line Introduction. The empirical study of this paper is Shanghai Metro Line 16 that applies the express-slow mode since 2013. In order to guarantee the safe overtaking of express trains, five stations of Line 16 are reconstructed. First, Luoshan Station has constructed one island and four tracks. Second, two islands and four tracks have been built at Hangtou East Station, Wild Zoo Station, and Huinan East Station, respectively. In addition, junction lines are set at every 1 or 2 railway section(s) [2]. The construction structure of Line 16 is shown in Figure 8.

Shanghai Metro Line 16 adopts the CBTC mode upon which the maximum speed can reach 110 km/h. In a recurrent situation, if a train stops at every station, then the total travel time is 51.4 mins; if a train stops merely at large stations

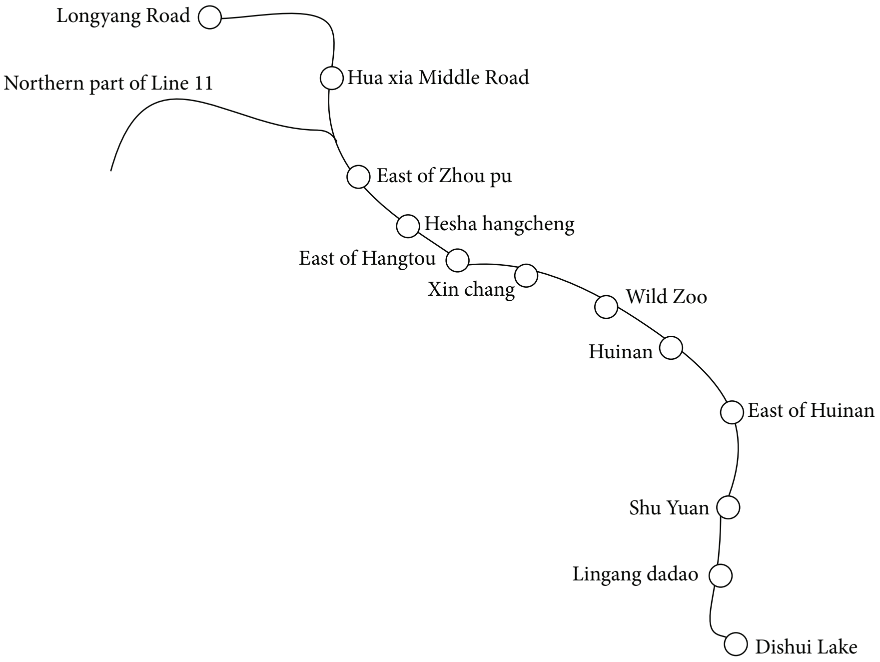

Figure 8: Schematic diagram of Shanghai Metro Line 16.

(give specific station names), then the total travel time is 35.4 mins [18, 27]. In general, Type A trains with three carriages are operated on Line 16 and can carry in total 648 passengers with seats. The passenger flow is strictly regulated in peak hours due to the severe crowding problem on Line 16 and the theoretical time interval of two departing trains in peak hours is 8 mins [28]. Based on the aforementioned parameters, the maximum number of passengers that Line 16 can accommodate can be estimated by the following equation:

$$\begin{aligned} P_{\max} &= \delta_{\text{train}} \times K \times \frac{60}{t_{\text{depart}}} = 648 \times 150\% \times \frac{60}{8} \\ &= 7290\,(\text{persons}). \end{aligned} \tag{15}$$

3.2. Changes of the Carrying Capacity of Line 16. Following the calculation procedure introduced in Section 2.3.3, this section examines the changing carrying capacity of Line 16 based on the scenarios proposed in Section 2.3.1. We first measure the carrying capacity of Line 16 given the three simplest scenarios, that is, $k:m = 1:1$, $k:m = 1:2$, and $k:m = 2:1$, respectively.

(1) When $k:m = 1:1$ and 2 express-slow trains run during the combined period,

$$\begin{aligned} N_{\max} &= s \times \frac{3600}{T_{\text{cycle}}} = 2 \times \frac{3600}{2I + n \times t_{\text{stop}}} \\ &= 2 \times \frac{3600}{2 \times 480 + 4 \times 50} = 6.2 \text{ trains}. \end{aligned} \tag{16}$$

(2) When $k:m = 1:2$ and 3 express-slow trains run during the combined period,

$$\begin{aligned} N_{\max} &= s \times \frac{3600}{T_{\text{cycle}}} = 3 \times \frac{3600}{I_w + 3I + n \times t_{\text{stop}}} \\ &= 3 \times \frac{3600}{90 + 3 \times 480 + 4 \times 30} = 6.5 \text{ trains}. \end{aligned} \tag{17}$$

(3) When $k:m = 2:1$ and 3 express-slow trains run during the combined period,

$$\begin{aligned} N_{\max} &= s \times \frac{3600}{T_{\text{cycle}}} = 3 \times \frac{3600}{I_w + 3I + n \times t_{\text{stop}}} \\ &= 3 \times \frac{3600}{60 + 3 \times 480 + 4 \times 30} = 6.7 \text{ trains}. \end{aligned} \tag{18}$$

In practice, the tracking duration of every express/slow train varies due to the differences of distance between stations, which will further influence the impacts of the ratio of the number of express and slow trains on the carrying capacity. Therefore, we also systematically examine the variation of the carrying capacity given different ratios of the number of express and slow trains (Table 1 and Figure 9), when the waiting time and the tracking duration of trains are predefined.

As can be seen from Figure 9, the changes of the carrying capacity present a V-shape curve. Only if the numbers of express and slow trains within a cycle are not equal can the carrying capacity be increased. Specifically, when the number of express trains is more than that of slow ones, the carrying capacity will increase as the ratio of the number of express and slow trains increase, and vice versa [29–31]. When the

Table 1: Carrying capacity of Line 16 under different ratios of the number of express and slow trains.

Express-slow train service percentage	∝ : 1	4 : 1	3 : 1	2 : 1	1 : 1	1 : 2	1 : 3	1 : 4	1 : ∝
Carrying capacity (train)	8.1	7.5	6.9	6.6	6.2	6.5	6.7	7.2	7.8

Table 2: Passenger flow of Metro Line 16 in the peak and off-peak period.

Station name	$\text{Peak}_{\text{total}}$ (passengers)	$\text{Peak}_{\text{average}}$ (passenger/h)	$\text{Off-peak}_{\text{total}}$ (passengers)	$\text{Off-peak}_{\text{average}}$ (passenger/h)
Longyanglu station	13,284	3,321	29,582	2,113
Huaxia Zhonglu station	4,536	1,134	13,748	982
Luoshanlu station	5,884	1,471	11,956	854
Zhoupudong station	4,136	1,034	11,214	801
Heshahangcheng station	1,648	412	4,536	324
Hangtoudong station	1,912	478	6,454	461
Xinchang station	6,512	1,628	19,614	1,401
Wild Animal Zoo station	2,364	591	8,470	605
Huinan station	5,608	1,402	16,814	1,201
Huinandong station	4,484	1,121	12,516	894
Shuyuan station	4,164	1,041	13,356	954
Lingangdadao	5,292	1,323	15,596	1,114
Dishuihu lake	9,376	2,344	26,698	1,907

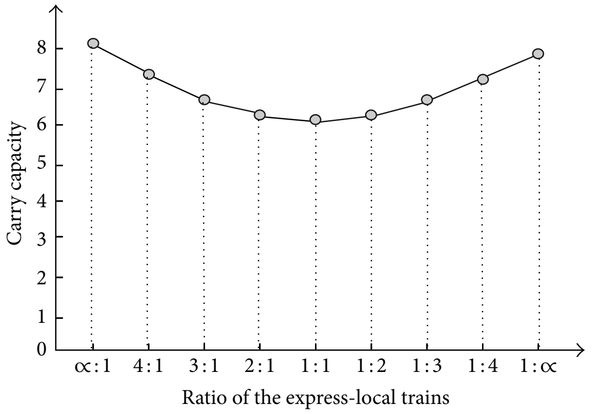

Figure 9: Diagram for relationship between express-slow train service ratio and carrying capacity.

number of express trains is equal to that of slow ones, the carrying capacity reaches its minimum. However, it should be noted that the determination of ratios is also affected by the actual demand at a certain time period of a day.

3.3. Better Rail Transit Management and Discussion. This section discusses how the proposed methodology can be applied in practice and provides suggestions for policy makers and metro operators. This is achieved by measuring the actual number of trains required to carry passengers at different period of a day. Then the ratio of the number of express and slow trains can be determined by comparing these numbers with the maximum carrying capacity under the express-slow mode as shown in Table 1.

We divide the time periods of a day into peak and off-peak hours due to their distinguished characteristics of demand. Two time periods, that is, 7:00~9:00 and 17:00~19:00, are considered as peak hours, while the left is defined as off-peak hours [6]. Table 2 presents the average number of passengers per hour during the two time periods.

The number of trains corresponding to the actual demand is measured as follows:

$$n_{\text{train}} = \frac{N_{\text{passenger}}}{n_{\text{rated}} \times \alpha \times n_{\text{marshalling}}}, \tag{19}$$

where n_{train} represents the number of trains required to carry passengers, $N_{\text{passenger}}$ represents the total number of passengers in a specific period, n_{rated} represents the designed capacity of a carriage, α represents the overloading coefficient, and $n_{\text{marshalling}}$ represents the number of marshaling tracks.

According to Table 2, the total number of passengers during the peak period is 16,259, so

$$\begin{aligned} n_{\text{train}} &= \frac{N_{\text{passenger}}}{n_{\text{rated}} \times \alpha \times n_{\text{marshalling}}} = \frac{16259}{310 \times 1.2 \times 6} \\ &= 7.28\,(\text{trains}). \end{aligned} \tag{20}$$

Comparing this number with the theoretical carrying capacity of Line 16 under the express-slow mode as shown in Table 1, the suggested ratio of the number of express and slow trains is 1 : 4.

The same calculation procedure also applies for the situation in the off-peak period, and the required number of trains is 6.10. The suggested ratio of the number of express and slow trains, therefor, is 1 : 1.

In their daily operation, the operator does not take into account the different characteristics of passenger flow during morning and evening peak hours on Shanghai Metro Line 16 [32]. As illustrated by this example, the proposed framework can not only determine the number of express and slow trains but also establish an equilibrium between demand and carrying capacity [33, 34]. This paper, therefore, provides guidance for both metro operators and policy makers.

4. Conclusions

This paper attempts to establish a systematic framework to measure the carrying capacity of a suburb line applying the express-slow mode by considering both the ratio of the number of express and slow trains and the number of overtaking maneuvers. We establish seven individual scenarios to develop different methods to measure the carrying capacity under this novel technique. We find that the proposed methods can be generalized into the situation when overtaking merely occurs once and the ratio of the number of express and slow trains is random. In addition, the number of overtaking maneuvers should be more than twice due to the deteriorated service level for passengers.

Taking Shanghai Metro Line 16 as a case study, we find that only if the numbers of express and slow trains within a cycle are not equal, the carrying capacity can be increased. Specifically, when the number of express trains is more than that of slow ones, the carrying capacity will increase as the ratio of the number of express and slow trains increases, and vice versa. When the number of express trains is equal to that of slow ones, the carrying capacity reaches its minimum. We further discuss how the proposed framework can help policy makers and metro operators make decisions by considering the balance between demand and carrying capacity.

In the future, the framework can be improved by establishing a comprehensive model to consider the ratio of the number of express and slow trains as a continuous variable instead of a discrete variable in this paper [35]. In addition, it is also a challenging task to measure and optimize the carrying capacity under the express-slow mode from a network perspective, upon which several different metro lines are crossed with each other.

Competing Interests

The authors declare that they have no competing interests.

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