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Tactical Capacity Assessment of a High-speed Railway Corridor with High Heterogeneity

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Abstract
Capacity assessment of high-speed railway corridor is critical in tactical planning process because it is beneficial to unearth the potential capacity and improve the capacity utilization without new investment in construction. China's high-speed railway corridor serves trains with high heterogeneity in different route, speed, and stopping plans. This paper first illustrates the necessity of assessing the corridor's capacity as a whole without decomposition. Based on the concept of base train equivalent (BTE), two methods named "capacity occupancy equivalent (COE)" method and "demand adaptation equivalent (DAE)" method are developed to standardize different types of trains into an equivalent unit. The case study of Jing-Hu high-speed railway corridor demonstrates that the methodology is concise in capacity assessment, and the impact of the long-distance direct service on corridor capacity utilization is also calculated.

Keywords
High-speed railway corridor, Capacity assessment, Base train equivalent, Heterogeneity, Demand adaptation

1 Introduction

The operation mileage of China's high-speed railway (CRH) is expected to be 30,000 km by 2020, forming a huge high-speed railway network. The high-speed railway corridor is the backbone of the network, providing local service by intra-line trains and long-distance direct service by cross-line trains (Figure 1). The origin and destination of the intra-line trains belong to the same corridor, while cross-line trains' origin and/or destination belong to the branch lines. The travel demands for different origins and destinations (OD) are extremely different over time and space dimensions along a long corridor. To meet with varieties of demand, trains run in different routes, different speed, and different stopping plans. Multiple types of trains running on the same corridor can cause different capacity impact and serious operational conflicts. Jing-Hu high-speed railway corridor, the busiest corridor in China's high-speed railway network, is facing the challenge of the increasing traveling demand. It is necessary to assess the corridor capacity and improve the capacity utilization.

Typically, the capacity of a rail corridor is defined as the number of trains that can safely pass within a period of time (Pouryousef, 2015). Considering the heterogeneity, Lai et al. (2012, 2015) use equivalent train unit to define capacity on lines. A few studies attempt to use "removal coefficient" to represent the impact of heterogeneous trains (Abramović B et al, 2004; Yang Z et al, 1995; Zhao, L.Z, 2001). However, most of the researchers divide the line or a corridor into sections as the first step of capacity assessment. The paradoxes of decomposition exist (Landex, A., 2008). When assessing the capacity of the corridor with high heterogeneity, the shortcoming of the decomposition is more obvious. The number of the capacity by adding up the number of trains in different types directly makes the result incomparable. In the latest version of the UIC 406 method (2013), it recommends to look at entire routes without decomposition when assessing long-distance services. However, there is not an explicit method.

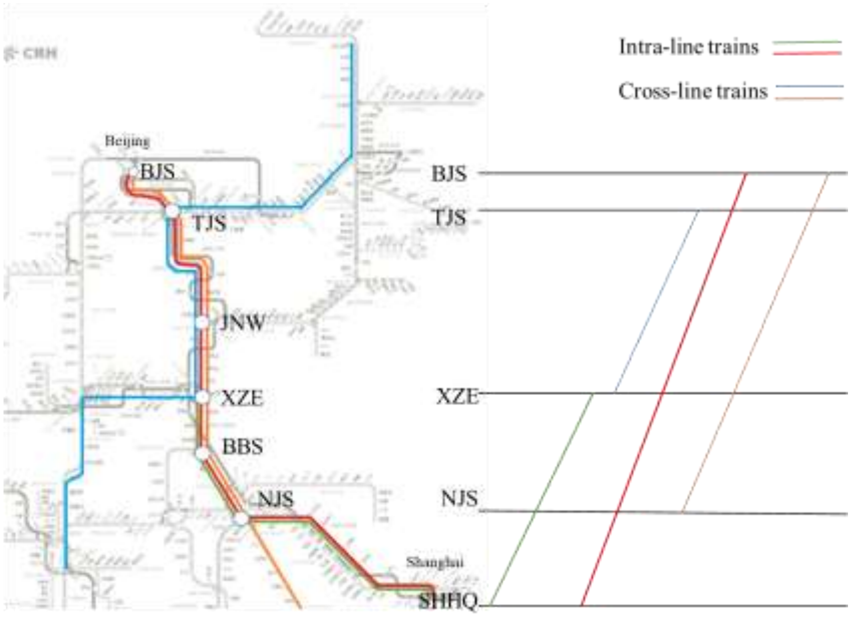

Figure 1 Intra-line trains and cross-line trains

This paper proposes a methodology for capacity assessment of high-speed railway corridor in the tactical level. We first illustrate that high-speed railway corridor with high heterogeneity should be regarded as a whole. Based on the concept of base train equivalent (BTE), "capacity occupancy equivalent (COE)" method and "demand adaptation equivalent (DAE)" method are developed to assess the corridor capacity by standardizing different types of trains into an equivalent unit. The case study of Jing-Hu high-speed railway corridor demonstrates that the methodology is concise in capacity assessment, and the cross-line trains' impact on corridor capacity utilization is calculated at the same time. In China, capacity assessment runs through strategic level (building of infrastructure), tactical level (timetabling), and operational level (short-term rescheduling and dispatching). Here we talk about the tactical capacity, which aims to unearth the potential capacity of the corridor under the current timetable. Therefore, this paper does not consider strategic level with little information of schedule (Jensen L W, 2017) or consider dynamic infrastructure occupancy under disturbances (Corman, 2010; C. Schmitz, 2017).

The remainder of the paper is organized as follows. In Section 2, we review relevant literature on capacity assessment methods. Section 3 explains the necessity of regarding the corridor as a whole in tactical capacity assessment. The methodology is then introduced in detail, and corresponding algorithm is developed and applied on Jing-Hu high-speed railway corridor as a case study in Section 4 and 5; and in the final section, conclusions and research extensions are also discussed.

2 Literature review

There exist various types of approaches for capacity assessment. Abril et al. (2008) classified the capacity methodologies as analytical methods, optimization methods, and simulation methods.

Analytical approach typically uses several steps of data processing through mathematical equations or algebraic expressions to determine theoretical capacity of the section/corridor at a planning level, as well as for the identification of bottlenecks in the infrastructure (Pouryousef, 2015; Riejos, 2016).

A widely used analytical method to assess capacity is defined by UIC (International Union of Railways) in their leaflet 406 (2013, 2004). The UIC406 leaflet describes how to assess the capacity consumed on a piece of infrastructure based on a given timetable using timetable compression. The definition of corridor in this leaflet is that corridors form the main structure of a railway network and are also considered to be a railway network's main source of revenue. In the UIC 406 method, the network is decomposed into sections for easier manageability. However, one of the shortcomings of this is that different network decompositions will lead to different results. Especially shorter line sections are a problem in the method (Landex, A., 2008). In the latest version of the UIC 406 method from 2013, it is recommended to look at entire routes without decomposition when assessing long-distance services. However, the latest version did not give a clear calculation method. In Germany, queueing based approach is common, focusing on knock-on delays (Wendler E, 2007; Weik N, 2016). In China, "removal coefficients of elimination" method (Abramović B et al, 2004; Yang Z et al, 1995; Zhao, L.Z, 2001; Xu, 2005) is used to represent the different impact of trains in different types. Base train equivalent (BTE) are proposed by Lai (2012) to identify the impact of heterogeneity on capacity. BTE models for headway-based analytical capacity analysis enables the standardization of rail capacity unit, facilitates assessment of the impact from heterogeneous trains, and allows comparison and evaluation of the capacity measurements from different lines and systems. The concept of equivalent is well known in many fields to deal with heterogeneity. Numerous of studies have been applied to use passenger car equivalent (PCE) for road capacity analysis (Elefteriadou L, 1997), pedestrian traffic (Galiza R J, 2012), etc.

Optimization methods are based on the design of saturated schedules and use mathematical programming models that achieve a high degree of saturation and simultaneously ensure certain level of quality of service (Abril et al, 2007). Majority of optimization methods are related to train timetabling problem (TTP).

Simulation methods attempt to replicate the actual operation of trains. Simulation tools are commonly used for detailed timetable analyses (Ralf Borndörfer, 2018). Several commercial software applications used as tools in the railway sector, including MultiRail, OpenTrack, Simone, RailSys, etc.

In conclusion, few researches concentrate on capacity assessment of high-speed railway corridor as a whole, and few papers pay attention to the demand adaptation when calculating the capacity utilization.

3 Corridor capacity assessment without decomposition

This section illustrates the necessity of regarding the corridor capacity as a whole. The weakness of corridor decomposition is explained from two aspects: the impact of cross-line trains and speed difference. To make a clear explanation, the necessary parameters are listed as follows. The corresponding values are requested by signal system and safety technic norms from China Railway Corporation.

- I Minimum interval between two trains in general, I=4min;
- I_1 Minimum interval when the train arrives and the following train passes through the same station, I_1=3min;
- I_2 Minimum interval when the train passes through and the following train departures from the same station,I_2=2min;
- t_b Additional time when braking, t_b=3min (if the train runs at 350km/h) or t_b=2min (if the train runs at 300km/h)
- t_s Additional time when starting, t_s=3min (either the train runs at 350km/h or 300km/h)
- t_d Deviation time between the best position for capacity utilization and the actual position in the train diagram

3.1 Cross-line trains

With the expansion of China's high-speed railway network, the traveling demand is stimulated as CRH has greatly reduced travel time and it is more punctual, comfortable, convenient, and safe. Cross-line trains are operated, aiming to provide long-distance direct service.

The cross-line trains are almost fixed in the timetable for the corridor line. Once it is adjusted, the timetables of the branch lines must be adjusted at the same time. When cross-line trains run into the corridor or run away from the corridor, the deviation time (t_d) happens because of the cross-line trains' inflexibility. It is hard to make seamless connection for all the cross-line trains. If a corridor is decomposed when assessing the corridor capacity, the deviation time will be easily ignored as each decomposed cross-line train will be regarded as an independent intra-line train. According to the Jing-Hu corridor timetable in the tactical planning process (2018), the total deviation time of five important Jing-Hu nodes (NJS, BBS, XZE, JNW, TJS in Figure 1) is 109min in up-direction during one day's operation period. Take NJS station for example (cross-line trains run into corridor via NJS station), the total deviation time of cross-line trains is 34min from 6:00-23:00. If the corridor is decomposed into sections, this part of time will be regarded as unused capacity after compression. The capacity will be $\lfloor 34/I \rfloor$=8 trains more than the actual value according to the current method. Therefore, the idle time caused by the cross-trains' inflexibility should be considered.

3.2 Speed

Train speed is an important factor in capacity assessment. In Jing-Hu corridor, trains travel in 350km/h or 300km/h. The time difference in two kinds of trains for each section (Δt_i) is listed in Table 1. The high speed and the long distance increase the impact of the speed difference.

A fast train (350km/h) can at least overtake $\lfloor 27/I \rfloor$=6 slower trains (300km/h) according to the travel time differences (Table 1). The overlap leads to additional stops. Here, we define the slower train (300km/h) as standard train, denoted as $\varepsilon_{300km/h} = 1$, because the proportion of slower trains is more than 90% in China. Therefore, the capacity occupancy coefficient of a fast train $\varepsilon_{350km/h}$ consists of two parts: the basic capacity occupancy coefficient ε_b (Formula 1) caused by the additional stops, and the additional capacity occupancy coefficient ε_d (Formula 2) caused by time deviation.

$$\varepsilon_b = \frac{(I_1 + t_b) + (I_2 + t_s)}{I}. \tag{1}$$

$$\varepsilon_d = \frac{t_d}{I} \tag{2}$$

The deviation time is between [0, I). In this paper, the granularity is 1min, and the initial feasible value of t_d is 0min, 1min, 2min or 3min. The algorithm of calculating t_d is as follows. The calculation results are listed in the right part of Table1, and the Figure 2 is the result when the initial t_d is 2min. Figure 2 and Table 1 are related, and the distance between the horizontal lines in Figure 2 reflects the distance between the two station.

Algorithm 1. Calculation of t_d

```
Data: t_d=[0,1,2,3], Δt_i (i=1, 2, ….n) (n: the number of sections)

for     t_d=0 …3 do
        for     i= n to 1  do   t_d^i = t_d^i + Δt_i
                If t_d^i − I > 0
                   t_d^i = t_d^i − I
                Else
                   t_d^i = t_d^i
        end
        t_d=max{t_d^i}
end
return          Average t_d
```

Therefore, $\varepsilon_{350km/h} = \frac{(3+2)+(2+3)}{4} + \frac{1.25}{4}$ =2.815, which means the capacity occupancy of a fast train equals to 2.815 slower trains. If the object is a section but not the corridor, the result must be smaller. The longer the distance is, the bigger the difference of the speed. For example, the capacity occupancy coefficient of the fast train is 2.625 for BBS-XZE by the same method. Therefore, considering the speed heterogeneity impact, the corridor should not be decomposed into sections when train runs along the whole corridor.

4 Methodology

In this section, "capacity occupancy equivalent (COE)" method is first developed to standardize different types of trains into an equivalent unit, aiming to assess the capacity of high-speed railway corridor as a whole. Then, "demand adaptation equivalent (DAE)" method is proposed. Traveling demand adaptation is taken into consideration, aiming to make the capacity utilization more efficient and profitable.

4.1 Capacity occupancy equivalent methods (COE)

There are multiple types of trains running along the corridor. As the capacity of high-speed railway corridor should be assessed as a whole, the key is to standardize different types of trains into an equivalent unit. The base train unit (BTU) in this problem is defined as the whole journey intra-line train, traveling from the end of the corridor to the other end of the corridor. According to the capacity occupancy of different type of trains in time-space dimension, equivalent coefficient of non-standard intra-line trains and cross-line trains can be calculated. For a train running through the corridor, the more capacity occupancy, the less efficient capacity utilization. In other words, the equivalent coefficient calculated by COE method is less than 1, and the equivalent coefficient value is less if the non-standard trains take up more capacity but make less profit.

(1) Non-standard Intra-line trains

The traveling span (S) of non-standard intra-line trains is shorter than the length of corridor (L) (see the green train in Figure 1). Compared with the base train unit, non-standard intra-line trains occupy the corridor but only make profit in S distance if no other trains can occupy the rest of the corridor efficiently. The reasons that there are no "connecting" trains in the timetable are: 1) The space and time resources has been occupied by the neighbour trains, because of the speed difference, stopping plans, priorities, etc. (Figure 3a); 2) The demand of the unoccupied capacity is low, and there is no need to arrange more trains.

If no other trains can occupy the rest of the corridor resources, it means the capacity of the whole corridor is not fully used. The equivalent coefficient of non-standard intra-line train is denoted as θ_1. Therefore, the equivalent coefficient for the train *i* is $\theta_1^i = \mathrm{S}_i/L$ for non-standard intra-line trains with different traveling distances. Otherwise, the connection train and this non-standard intra-line train can be equivalent to a base train unit if the "connecting" time is less than the maximum of the dwelling time domain. The "connecting" time can be regarded as the station dwelling time of the base train unit although these two trains are not connected actually (Figure 3b).

(2) Cross-line trains

The equivalent of cross-line train is more complex than intra-line train because of its inflexibility explained in Section 3. The deviation time of cross-line trains is an inefficient capacity occupancy. It happens not only when cross-line trains running into the corridor (denoted as t_d^{in}), but also when cross-line trains running away from the corridor and no other trains can use the rest part of the corridor resources, denoted as $t_d^{connection}$.

As the deviation time may happen when the cross-line trains run into the corridor or run away from the corridor, cross-line trains can be divided into A type cross-line train (either origin or destination belongs to the other lines in Figure 1 orange train) and B type cross-line train (both of them belong to the other lines in Figure 1 blue train).

a）A-type

The equivalent coefficient of A-type cross-line train is denoted as θ_2. If the A type cross-line trains have connected trains, the equivalent coefficient $\theta_2' = 1 - (t_d^{in} + t_d^{connection}) * \frac{v}{60}/L$. If the A type cross-line trains don't have connected trains, $\theta_2'' = (S - t_d^{in} * \frac{v}{60})/L$ (Figure 3c). Therefore, if the proportion of connected A type trains is α and unconnected ones is (1-α), the final equivalent coefficient of A type is:

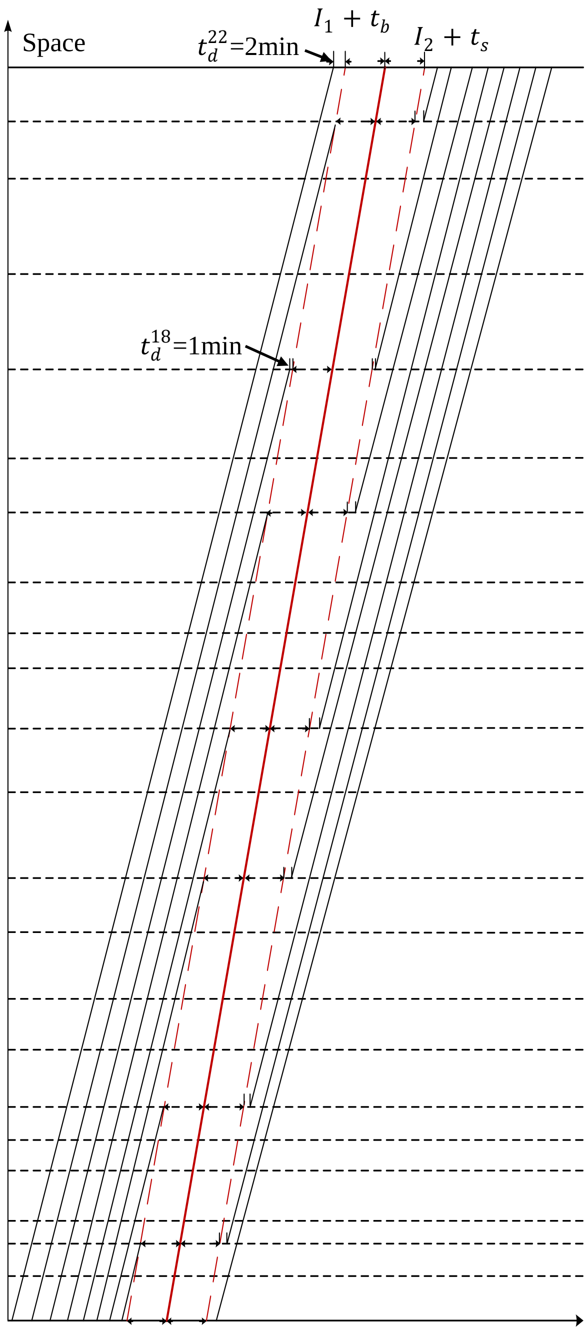

Figure 2 Example of Algorithm1

Name	i	Δt_i	t_d			
BJS			0	1	2	3
	22	2				
LF					0	1
	21	1				
TJS				0		
	20	2				
CZW			1			0
	19	2				
DZE				0	1	
	18	2				
JNW			1			0
	17	1				
TA					0	
	16	1				
QFE				0		
	15	1				
TZE			0			
	14	1				
ZZW						0
	13	1				
XZW					0	
	12	2				
SZE			0	1		
	11	2				
BBS					0	1
	10	1				
DY				0		
	9	1				
CZ			0			
	8	1				
NJS						0
	7	1				
ZJS					0	
	6	1				
DYN				0		
	5	1				
CZN			0			
	4	1				
WXE						0
	3	1				
SZN					0	
	2	1				
KSN				0		
	1	3				
SHHQ			2		0	1
maxt_d			2	1	1	1
average (max t_d)			1.25			

Table 1 Calculation of t_d

$$\theta_2 = \alpha \cdot \theta_2' + (1-\alpha)\sum_{k=1}^{k} \beta_k \cdot \theta_2^{''} \tag{3}$$

where β_k refers to the proportion of each kind of unconnected A type cross-line trains.

b）A-type

As there are two interfaces of B type cross-line trains, the equivalent coefficient should be divided into three parts. If it has two connected trains, $\theta_3' = 1 - 2 * (t_d^{in} + t_d^{connection}) * \frac{v}{60}/L$. If it has one connected trains, $\theta_3'' = S_{con}/L - (t_d^{in} + t_d^{connection}) * \frac{v}{60}/L$. S_{con} refers to the travel span of this kind of combination (Figure 3d). If B type train don't have connected trains, $\theta_2''' = (S - t_d^{in} * \frac{v}{60})/L$

Therefore, if the proportion of the above three kinds of B type trains is γ_1, γ_2 and γ_3, the final equivalent coefficient of B type is:

$$\begin{aligned}\theta_3 = \gamma_1 \cdot \theta_3' + \gamma_2 \cdot \sum_{m=1}^{m} \frac{\beta_m}{L}[S_{con}^m - (t_d^{in} + t_d^{connection}) * \frac{v}{60}] + \gamma_3 \\ \cdot \sum_{n=1}^{n} \beta_n \cdot (S_n - t_d^{in} * \frac{v}{60})/L\end{aligned} \tag{4}$$

where β_m, β_n refer to the proportion of corresponding trains.

Here, we define the proportion of intra-line trains and cross-line trains is φ and (1-φ), the proportion of A type cross-line trains and B type cross-line trains is ω and $(1-\omega)$. The equivalent coefficient based on "capacity occupancy equivalent" is:

$$\theta = \varphi \cdot \theta_1 + (1-\varphi) \cdot [\omega \cdot \theta_2 + (1-\omega) \cdot \theta_3] \tag{5}$$

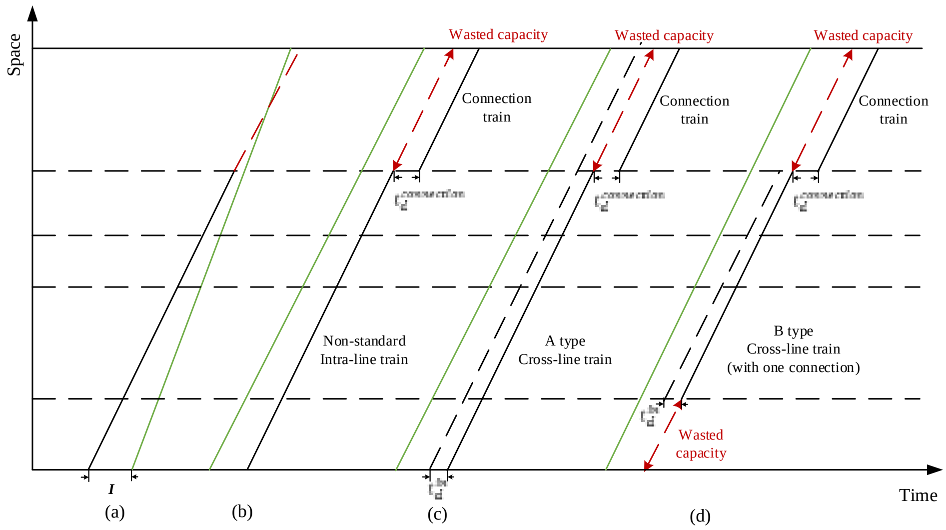

Figure 3 Illustration of parameters

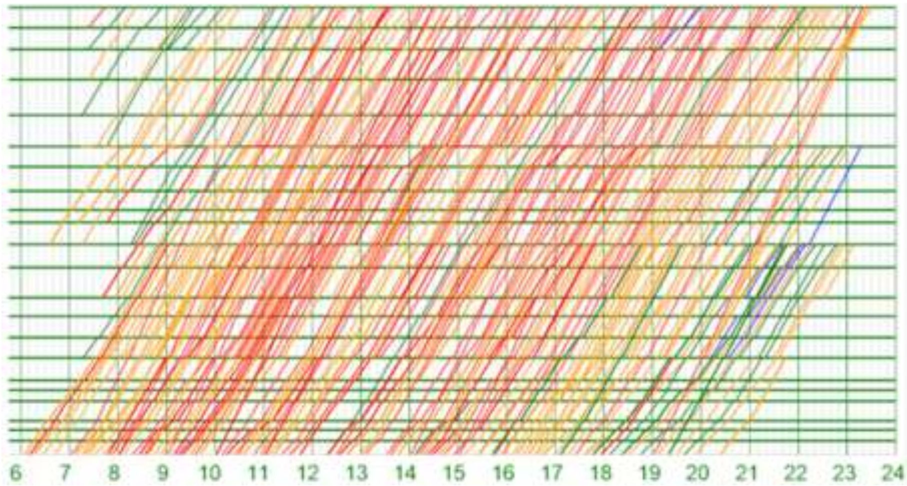

Figure 4 Capacity occupancy of speed difference

4.2 Demand adaptation equivalent method

The demand adaptation is directly related to the income. More trains don't equal to more passengers. The key of "demand adaptation equivalent (DAE)" method is adding the passenger load factor (σ) to the equivalent coefficient.

Figure 4 shows the average passenger load factor of each train running along the Jing-Hu corridor (in up direction) in 2017. The basic equivalent coefficient of a train is θ calculated in Section 4.1, then the demand adaptation equivalent coefficient can be $\theta' = \sigma \cdot \theta$.

5 Case study

Jing-Hu corridor is a typical high-speed railway corridor, connecting with metropolitan area and branch lines in the high-speed railway network. According to the train diagram (2018) in tactical planning process, there are 231 trains operating on Jing-Hu corridor in the up-direction (SHHQ-BJS) in one day.

The values of relative parameters can be statistically computed from the timetable as follows: $\varphi = 74\%, \omega = 70\%, \alpha = 22\%, \gamma_1 = 7.7\%,\ \ \gamma_2 = 38..5\%,\ \ \gamma_3 = 53.8\%$. $t_d^{in} \in (0,\ I)$, $t_d^{connection} \in (0, t_b + I_1 + I_2 + t_s\ )$. According to the central limit theory of great numeral, $t_d^{in} = 2$min and $t_d^{connection}$=5min as a simplification. The passenger load factor is clustered into four k partitions to simplify the demand analysis. The cluster centers and corresponding rates are 0.77 (40.6%), 0.90(25.0%), 0.65(24.6%), and 0.47(9.8%). Therefore, $\sigma = 0.77 * 40.6\% + 0.90 * 25.0\% + 0.65 * 24.6\% + 0.47 * 9.8\% = 0.744$. In this paper, we propose "DAE" method as a research direction, and give a simplified method for calculating the demand adaptation. The value of σ can be more specific according to each type of trains. The rest of the input data are listed in Table 2 and Table 3.

Table 2 Input data for A type cross-line trains

Section	Number of trains with connection	Number of trains without connection	β_k(%)	S_k (km)
SHH-NJS	9	6	6.5%	285.6
SHH-XZE	8	17	24.7%	616.1
SHH-JNW	1	6	6.5%	901.7
SHH-TJW	0	9	7.5%	1185.6
NJS-BJS	3	11	10.8%	1022.1
BBS-BJS	1	13	14.0%	846.8
ZXE-BJN	0	4	4.3%	691.6
JNW-BJS	10	24	25.8%	406

Table 3 Input data for B type cross-line trains

Connected Section	Train number	β_m	S_{con}^m	Section no connection	Train number	β_n	S_n
SHHQ-XZE	4	19.0%	616.1	NJS-XZE	7	25.0%	330.5
SHHQ-JNW	5	23.8%	901.7	NJN-JNW	2	7.1%	616.1
SHHQ-TJW	1	4.8%	1185.6	NJN-TJW	1	3.6%	900
NJS-BJS	7	33.3%	1022.1	BBS-XZE	6	21.4%	155.2
XZE-BJS	4	19.0%	691.6	BBS-JNW	1	3.6%	440.8
				BBN-TJW	1	3.6%	724.7
				XZE-JNW	7	25.0%	285.6
				XZE-TJW	1	3.6%	569.5
				JNW-TJW	2	7.1%	283.9

Based on "capacity occupancy equivalent (COE)" method, $\theta_2 = 0.521 + 0.433\alpha = 0.62$, $\theta_3 = 0.908\gamma_1 + 0.612\gamma_2 + 0.261\gamma_3 = 0.45$. In other words, an A type cross-line train is equivalent to 0.62 base train unit, and a B type cross-line train is equivalent to 0.45 base train unit. It is clear that is impact of B type is serious than A type cross-line trains because of $\theta_2 > \theta_3$. Among the 231 trains, there are 41 trains running from SHH to BJS, and non-standard intra-line trains are equivalent to 8.5. Therefore, the final equivalent capacity of Jing-Hu corridor is:

$$N = 231 \cdot [0.62\omega + 0.45(1-\omega)] \cdot \varphi + 41 + 8.5 = 147 \tag{6}$$

In other words, the capacity of the whole corridor is 147 base train units by "COE" method. In addition, the proportion of cross-line train(φ), the proportion of A and B (ω), and the connecting proportion of cross-line train (α, γ_i) are the key to the equivalents. To optimize the capacity utility of the main corridor, it is necessary control the proportion of cross-line trains and improve the level of coordination.

6 Conclusion

Most previous studies on railway capacity assessment is based on sections, and paid little attention to long-distance direct service by cross-line trains. This paper contributes a methodology for high-speed railway corridor's capacity assessment in tactical level. Based on the concept of base train equivalent (BTE), "capacity occupancy equivalent (COE)" method and “demand adaptation equivalent (DAE)” method are developed to standardize different types of trains into an equivalent unit. The equivalent method makes the different timetable comparable, especially the corridor with high heterogeneity. This paper also proposes the demand oriented capacity assessment method, which will be more instructive in capacity utilization. Considering the serious impact of cross-line trains, the proportion should be controlled, and more efforts are necessary to achieve a compromise between accessibility of long-distance direct services and efficiency of the whole network.

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References

Abril M, Barber F, Ingolotti L, et al. “An assessment of railway capacity”, *Transportation Research Part E Logistics & Transportation Review*, Vol. 44(5), 2008, pp. 774-806.

Abramović B, Čičak M, Mlinarić T J. “Methods for determining throughput capacity of railway lines using coefficients of elimination”, *Promet - Traffic - Traffico*, Vol. 16(2), 2004, pp. 63-69.

Corman, Francesco, et al, 2010. "A tabu search algorithm for rerouting trains during rail operations." *Transportation Research Part B: Methodological*, Vol. 44.1, pp: 175-192

Christoph Schmitz, Norman Weik, Stephan Zieger, Nils Nießen, Anke Schmeink, 2017. “Markov Models for the Performance Analysis of Railway Networks”, In: *Proceedings of The 7th International Conference on Railway Operations Modelling and Analysis (RailLille2017)*, Lille, France.

Elefteriadou L, Torbic D, Webster N. “Development of Passenger Car Equivalent for Freeways, Two-Lane Highways, and Arterials”, *Transportation Research Record Journal of the Transportation Research Board*, Vol. 1572(1), 1997, pp. 51-58.

Galiza R J, Ferreira L. “Developing Standard Pedestrian-Equivalent Factors Passenger Car–Equivalent Approach for Dealing with Pedestrian Diversity”, *Transportation Research Record Journal of the Transportation Research Board*, Vol. 2299(2299), 2012, pp. 166–173.

Jensen L W, Landex A, Nielsen O A, et al., 2017. “Strategic assessment of capacity consumption in railway networks: Framework and model”, *Transportation Research Part C*, vol. 74, pp. 126-149.

Lai Y C, Liu Y H, Lin T Y. “Development of Base Train Equivalent to Standardize Trains for Capacity Analysis”, *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2289(2289), 2012, pp.119-125.

Lai Y C, Liu Y H, Lin Y J., 2015. “Standardization of capacity unit for headway-based rail capacity analysis”, *Transportation Research Part C*, Vol. 57, pp. 68-84.

Landex, A., 2008. Methods to Estimate Railway Capacity and Passenger Delays (Ph.D. thesis). Lyngby, Denmark.

Pouryousef, Hamed, P. Lautala, T. White. “Railroad capacity tools and methodologies in the U.S. and Europe”, *Journal of Modern Transportation*, Vol.23.1, 2015, pp.30-42.

Ralf Borndörfer, Torsten Klug, Leonardo Lamorgese, Carlo Mannino et al.. "Handbook of Optimization in the Railway Industry", *International Series in Operations Research & Management Science*, Vol. 268, 2018, Springer, pp. 32.

Riejos F A O, Barrena E, Ortiz J D C, et al. "Analyzing the theoretical capacity of railway networks with a radial-backbone topology", *Transportation Research Part A*, Vol. 84, 2016, pp. 83-92.

Ruihua Xu. Operational Organization of Railway Transportation System. China Railway Publishing House, 2005.

UIC, 2004. Capacity (UIC Code 406). first ed. pp. 1-21.

UIC, 2013. Capacity (UIC Code 406). second ed. pp. 1-51.

Weik N, Niebel N, Nießen N. "Capacity analysis of railway lines in Germany – A rigorous discussion of the queueing based approach", *Journal of Rail Transport Planning & Management*, Vol. 6(2), 2016, pp. 99-115.

Wendler E. "The scheduled waiting time on railway lines", *Transportation Research Part B*, Vol. 41(2), 2007, pp. 148-158.

Yang Z, Yang Y, SunQuanxin, et al. "A Study on Parameters for Calculation Block Section Carrying Capacity and Trains' Coefficient of Removal on Beijing-Shanghai High Speed Railway", *Journal of Northern Jiaotong University*, Vol. S1, 1995, pp.1-8.

Zhao, L.Z.. "Calculation and analysis of carrying capacity of high-speed railway section", *China Railway Science*, Vol. 22(6), 2001, pp. 54-58.