Study on the pattern of train arrival headway time in high-speed railway

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Abstract

Purpose – The design goal for the tracking interval of high-speed railway trains in China is 3 min, but it is difficult to achieve, and it is widely believed that it is mainly limited by the tracking interval of train arrivals. If the train arrival tracking interval can be compressed, it will be beneficial for China's high-speed railway to achieve a 3-min train tracking interval. The goal of this article is to study how to compress the train arrival tracking interval.

Design/methodology/approach – By simulating the process of dense train groups arriving at the station and stopping, the headway between train arrivals at the station was calculated, and the pattern of train arrival headway was obtained, changing the traditional understanding that the train arrival headway is considered the main factor limiting the headway of trains.

Findings – When the running speed of trains is high, the headway between trains is short, the length of the station approach throat area is considerable and frequent train arrivals at the station, the arrival headway for the first group or several groups of trains will exceed the headway, but the subsequent sets of trains will have a headway equal to the arrival headway. This convergence characteristic is obtained by appropriately increasing the running time.

Originality/value – According to this pattern, there is no need to overly emphasize the impact of train arrival headway on the headway. This plays an important role in compressing train headway and improving high-speed railway capacity.

Keywords High speed railway, Train headway, Train arrival headway, Regular pattern

Paper type Research paper

By the end of 2023, the mileage of China's high-speed railway operation reached 45,000 kilometres, with more than 9,600 trains in motion, and the passing capacity of important corridors continues to be strained, with the busiest section of Beijing-Shanghai high-speed railway running 188 pairs of high-speed trains per day between Jinan West and Tai'an station, 166 pairs of high-speed trains per day between Xuzhou East and Bengbu South station, and the Shanghai-Hangzhou high-speed railway reaching 167 pairs per day. Train headway is the key factor to determine the railway passing capacity. Japan's Tokaido

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Shinkansen uses 3 min as headway, and it is quite common for four consecutive trains to arrive and depart at 3 min intervals in the Tokaido direction (6 lanes) at Tokyo Station; the Tohoku Shinkansen uses 4 min as headway, and there are often more than 10 consecutive trains arriving and departing at 4 min intervals in the Tohoku direction (4 lanes) at Tokyo Station. At present, the train headway of China's high-speed railway mostly adopts 5 min, individual lines adopt 4 min and some trains of Shanghai-Hangzhou high-speed railway adopt 3 min. If the train headway of busy high-speed railways can achieve the design goal of 3 min, the line capacity can be greatly improved, more trains can be operated and better economic and social benefits can be generated.

China's high-speed railway has taken many measures to shorten the train headway such as optimizing the braking mode curve of the train control system, setting the speed limit for trains entering and leaving the station in sections, and shortening the polling time of the Centralized Traffic Control (CTC), etc. However, the vast majority of high-speed railways have not yet reached the design goal of 3 min, which is generally regarded as the limitation of the train arrival headway (Zhang, Tian, Jiang, & Wang, 2013; Tian, Zhang, Zhang, & Jiang, 2015). At present, the research on train headway (I) is mainly based on the fact that the two trains running in front and behind tracking do not affect each other, and the headway in train sections ($I_{\sec}$), headway between train departures (I_{dep}), headway between train arrivals (I_{arr}), headway between train passages (I_{pas}) are calculated in isolation and compared with each other in terms of their sizes ($I = \max\{I_{\sec}, I_{dep}, I_{arr}, I_{pas}\}$), so as to reach the conclusion that I is mainly restricted by I_{arr} (Zhang, Tian, & Yan, 2017). However, in the actual train operation work, especially during peak train operating hours, it is often arranged for trains to depart every 3 minutes closely, with trains running in close pursuit in the sections and dense station stops often lead to the deceleration of following trains, which is then continuously passed on, gradually causing subsequent trains to be able to achieve a 3 min arrival headway and achieving the purpose of compressing I_{arr} by sacrificing a small amount of running time in the sections. This paper will employ the method of train cluster operation simulation, allowing multiple trains to arrive at the station in continuous dense succession, to explore the patterns of high-speed trains arriving in close sequence and dense clusters, and study the feasibility of compression of I_{arr}, so as to provide technical support for compressing the train headway and improving the passing capacity of the line.

1. Simulation conditions and parameter values

The simulation process is to use OpenTrack software to let multiple trains (generally 6 trains) run continuously and intensively towards the station with normal running speed (e.g.350 km/h) at a certain headway (e.g. $I_{\sec}$ for 3 min), reduce the running speed to the specified speed before the home signal, and continue to run at this speed until stopping at the stopping mark on the departure and arrival track. During the train operation process, the train traction and braking performance and the train route handling standards of CTC are strictly followed. The train running speed is controlled strictly in accordance with the signal display and the requirements of the Chinese Train Control System (CTCS)-2/3 level train control system. By tracking and statistically analysing the variations in the train running trajectories and train headway, the study seeks to identify the patterns of changes in train arrival headway.

The specific simulation parameters are as follows: The stations and intermediate sections of the line are configured with straight alignments. The length of the intermediate block sections is set at 2 000 m, and the effective length of the station's departure and arrival tracks is designated as 650 m. In accordance with the requirements of the revised contents of the "High-Speed Railway Design Specifications" and the "Intercity Railway Design Specifications", the departure and arrival tracks set up not less than 60 m protection section, and the train stopping position marking 40 m from the protection section (as shown in

Figure 1). In order to check and calculate the arrival patterns of high-speed trains, the length of the station throat area (X in Figure 1) (The length can also be regarded as the common approach length for trains travelling in both forward and reverse directions) from 200 m to 1600 m to take different values (The majority of station throat lengths fall within this range), the distance for a train to enter the station is calculated as + 540m, the speed limit within the throat area is set at 80 km/h (The actual operational speed is maintained at 75 km/h), the safety protection distance before the home signal is set to 110 m. In simulation, the length of throat area is 200 m, 500 m, 600 m, 1000 m, 1200 m, 1500 m and 1600 m; the multi-unit electric train (EMU) has been configured with the China Railway Highspeed (CRH)380AL model equipped with a 300T train control system; the running speed of the train before entering the station is 350 km/h, 300 km/h, 250 km/h, 200 km/h and I_{sec} is taken 3 min, I_{sec} takes 4 min or 2.5 min under certain speed conditions, resulting in a total of 42 scenarios being simulated. The following is only a list of some simulation results analysing the train arrival headway pattern of high-speed trains running at 350 km/h and 200 km/h before entering the station, when the length of the throat area is taken as 200 m, 1000 m and 1600 m, respectively.

2. Train running speed before entering station: 350 km/h

When the train's running speed is 350 km/h, two simulation schemes with train headway of 3 min and 4 min are conducted, respectively.

2.1 Train headway in section: 3 min

The impact of train arrival headway is influenced not only by the train's running speed and the train headway, but also by the length of the throat area. Table 1–Table 3 respectively present the simulation results of six consecutive trains inbound stopping at the station with a speed of 350 km/h and a headway of 3 min, at throat section lengths of 200 m, 1000 m and 1600 m (the length of the common approach for both outgoing and incoming trains). Figures 2–4 respectively depict the distance-speed diagrams of train inbound stopping at the station for different throat area lengths. In the chart, Train 1, Train 2, Train 3, Train 4, Train 5 and Train 6 run at speed of 350 km/h in the headway of 3 min and reduces their speed to 75 km/h at a distance of 110 m before the home signal. The train then comes to a stop at the stopping mark of the station's departure and arrival line. Two adjacent trains constitute a set of train headway. From the chart, when the length of the throat area is long, the delay in clearing the approach of the preceding train may cause the following trains to slow down earlier.

In the table, the train's departure time and headway, refers to the starting time of the 6 trains running continuously at 350 km/h and the headway of the adjacent trains, the starting departure time of the 6 trains in Table 1 are the 0th, 180 s, 360 s, 540 s, 720 s, 900 s and the train departure headway are all at 180 s; the first model kilometre marker, start-up time and headway, refer to the train's first start braking location, time and headway with the preceding train. In Table 1, the first starting model mileage is 8.57 km, followed by five starting model

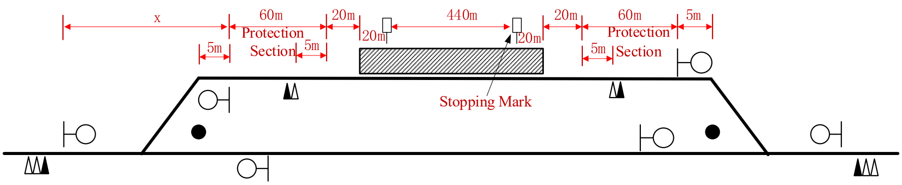

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Figure 1.
Schematic plan of the simulated station and layout of facilities

Table 1.
Simulation results of 6 trains stopping continuously at 350 km/h with 3 min headway when the length of the throat area is 200 m

Train track statistics points	Time and kilometre markers for continuous train tracking runs						Train headway				
	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 2-Train 1	Train 3-Train 2	Train 4-Train 3	Train 5-Train 4	Train 6-Train 5
Departure time and headway/s	0	180	360	540	720	900	180	180	180	180	180
First model kilometre marker/km	8.570	6.316	6.316	6.316	6.316	6.316	–	–	–	–	–
First model start-up time and headway/s	89	245	425	605	785	965	156	180	180	180	180
Kilometre marker (speed limit 75 km/h) before home signal/km	18.665	18.665	18.665	18.665	18.665	18.665	–	–	–	–	–
Time and headway before home signal (speed limit 75 km/h)/s	252	437	617	797	977	1157	185	180	180	180	180
Inbound stopping kilometre marker/km	19.515	19.515	19.515	19.515	19.515	19.515	–	–	–	–	–
Inbound stopping time and headway/s	312	497	677	857	1037	1217	185	180	180	180	180
Overall running time/s	312	317	317	317	317	317	–	–	–	–	–

Table 2. Simulation results of 6 trains stopping continuously at 350 km/h with 3 min headway when the length of the throat area is 1000 m

Train track statistics points	Time and kilometre markers for continuous train tracking runs						Train headway				
	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 2-Train 1	Train 3-Train 2	Train 4-Train 3	Train 5-Train 4	Train 6-Train 5
Departure time and headway/s	0	180	360	540	720	900	180	180	180	180	180
First model kilometre marker/km	8.57	6.316	6.316	6.316	6.316	6.316	–	–	–	–	–
First model start-up time and headway/s	89	245	425	605	785	965	156	180	180	180	180
Kilometre marker (speed limit 75 km/h) before home signal/km	18.665	18.665	18.665	18.665	18.665	18.665	–	–	–	–	–
Time and headway before home signal (speed limit 75 km/h)/s	252	437	617	797	977	1157	185	180	180	180	180
Inbound stopping kilometre marker/km	20.315	20.315	20.315	20.315	20.315	20.315	–	–	–	–	–
Inbound stopping time and headway/s	350	535	715	895	1075	1255	185	180	180	180	180
Overall running time/s	350	355	355	355	355	355	–	–	–	–	–

Table 3.
Simulation results of 6 trains stopping continuously at 350 km/h with 3 min headway when the length of the throat area is 1600 m

Train track statistics points	Time and kilometre markers for continuous train tracking runs						Train headway				
	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 2-Train 1	Train 3-Train 2	Train 4-Train 3	Train 5-Train 4	Train 6-Train 5
Departure time and headway/s	0	180	360	540	720	900	180	180	180	180	180
First model kilometre marker/km	7.57	5.316	5.316	5.316	5.316	5.316	–	–	–	–	–
First model start-up time and headway/s	78	235	415	595	775	955	157	180	180	180	180
Kilometre marker (speed limit 75 km/h) before home signal/km	17.665	17.665	17.665	17.665	17.665	17.665	–	–	–	–	–
Time and headway before home signal (speed limit 75 km/h)/s	241	428	608	788	968	1148	187	180	180	180	180
Inbound stopping kilometre marker/km	19.915	19.915	19.915	19.915	19.915	19.915	–	–	–	–	–
Inbound stopping time and headway/s	368	555	735	915	1095	1275	187	180	180	180	180
Overall running time/s	368	375	375	375	375	375	–	–	–	–	–

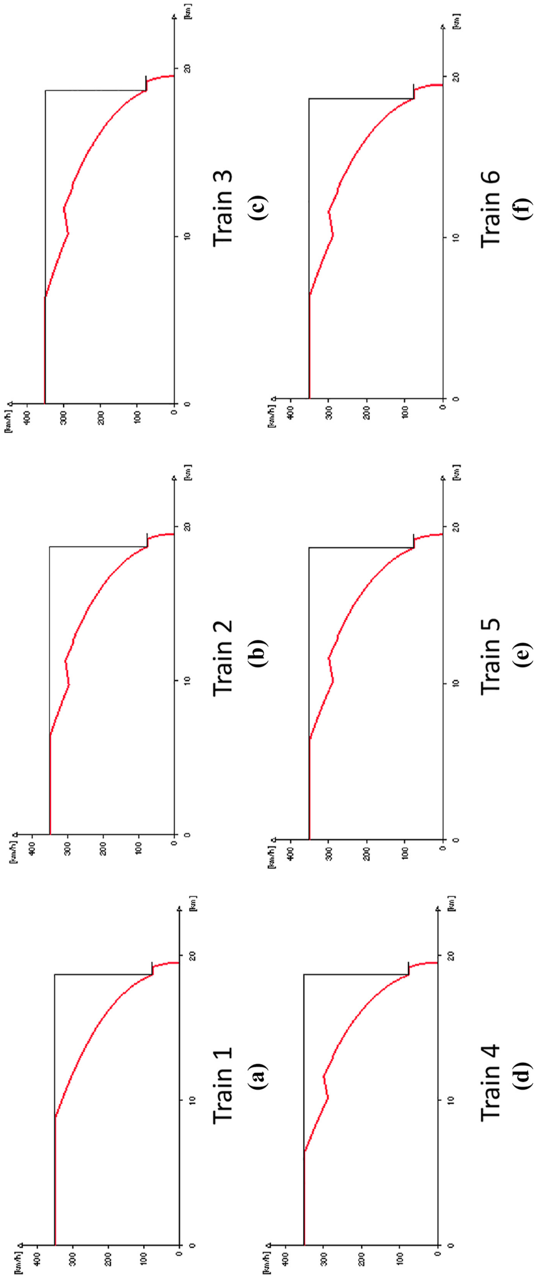

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Figure 2.
Operational distance-speed diagram for 6 trains at 350 km/h with 3 min headway between consecutive inbound stops for a 200 m length of throat area

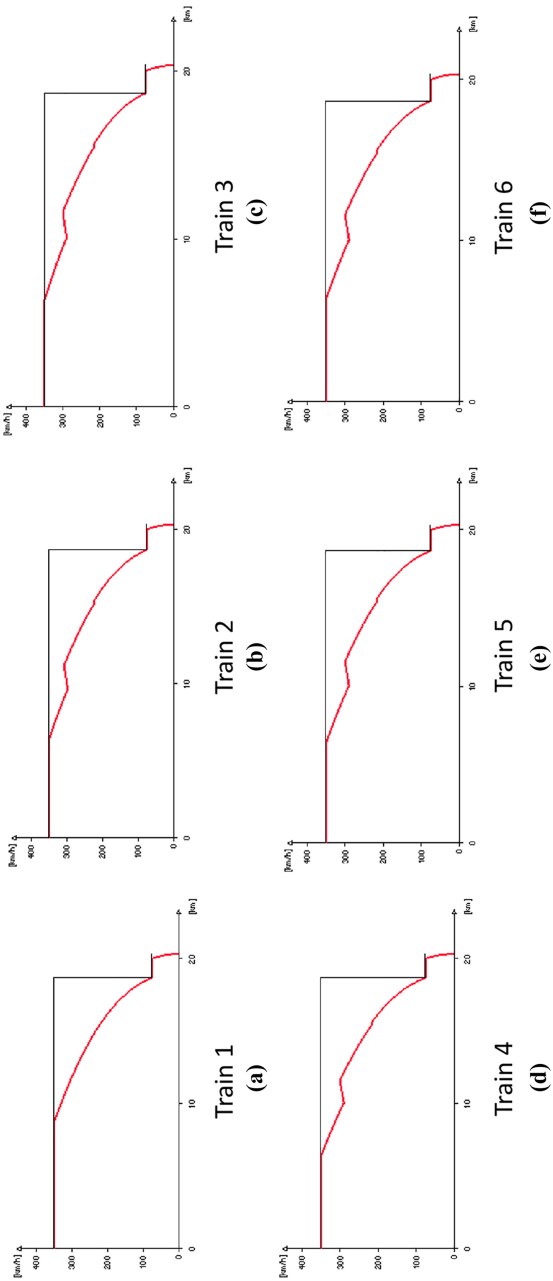

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Figure 3.
Operational distance-speed diagram for 6 trains at 350 km/h with 3 min headway between consecutive inbound stops for a 1600 m length of throat area

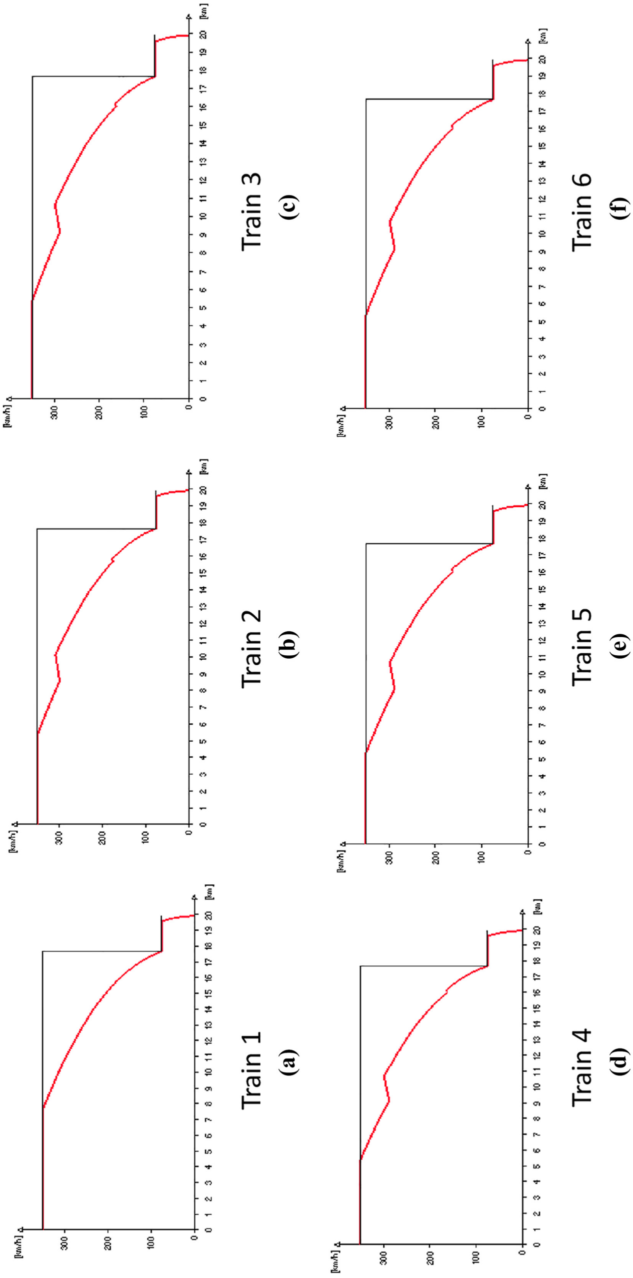

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Figure 4.
Operational distance-speed diagram for 6 trains at 350 km/h with 3 min headway between consecutive inbound stops for a 1600 m length of throat area

mileage are in 6.316 km; the kilometre marker, time and headway before home signal, refer to the train running to the kilometre marker, time and headway with the preceding train at 110 m before home signal; the station inbound stopping kilometre marker, time and headway, refer to the kilometre marker, time and headway with the preceding train for the train to stop at the position mark before the departure signal of the arrival-departure track. In Table 1, the first group of train's arrival headway is 185 s, followed by four groups of trains' arrival headway are 180 s; the overall running time, refers to the running time calculated as the difference between the train's inbound stopping time and its departure time.

From Table 1 it can be seen that when 6 trains run with 3 min headway, the headway of the first group of trains' inbound stopping becomes 185 s, while the headway of the following 4 groups of trains can still be maintained at 180 s; the overall running time is increased by 5 s for all the following trains except for Train 1, this is due to the fact that from Train 2 onwards, all trains start at 6.316 km in advance and by starting the model in advance, the running time is increased by 5 s, which is exchanged for the subsequent four groups of trains' arrival headway converging to 3 min.

When the length of the throat area was extended to 1000 m (from Table 2 and Figure 3), the simulation results were the same as throat area of 200 m in length.

When the length of throat area is extended to 1600 m (from Table 3 and Figure 4), the headway of the first group of trains' inbound stopping time is extended to 187 s, while the headway of the following four groups of trains can still be maintained at 180 s, the running time is increased by 7 s through the early start of the model from Train 2 to Train 6 in exchange for the arrival headway of the following four groups of trains are all converged to 3 min, and the simulation results are the same. At the same time, it shows that it is impossible for the first group of high-speed railway trains entering the station at 350 km/h to achieve 3 min arrival headway.

2.2 Train headway in section: 4 min

When the train headway in the section is extended to 4 min, and the same simulation methodology is employed. The simulation results are presented in Tables 4–6 (for simplicity, distance-speed diagrams are not included, as in the previous examples).

Table 4 demonstrates that under the condition of train headway in the section is 4 min, when the throat section length is 200 m, and 6 consecutive trains are running into the station at a speed of 350 km/h, there is no interference among them. And the train groups' arrival headway can also be maintained at a 4 min, without an increase in the running time within the section. When the length of the throat area reaches 1000 m (from Table 5), the first group of trains' headway is 241 s, followed by 4 groups of trains' headway are converged to 240 s, and the train running time are increased by 1 s. When the length of the throat area reaches 1600 m (from Table 6), the first group of trains' headway is 242 s, followed by 4 groups of trains' headway are converged to 240 s, and the train running time are increased by 2 s. The simulation results demonstrate that the arrival headway of trains converges to a duration of 4 min.

3. Train running speed before entering station: 200 km/h

The continued investigation into the train arrival patterns at a running speed of 200 km/h within the train section is conducted via simulation methods. Only the simulation results for throat section lengths of 200 m, 1000 m and 1600 m are presented. In comparison to the high-speed train operations at 350 km/h, train operations at a speed of 200 km/h are more conducive to achieving short headway. Therefore, the simulation results for adding trains that operate with a 2.5 min headway at a speed of 200 km/h are presented.

Table 4. Simulation results of 6 trains stopping continuously at 350 km/h with 4 min headway when the length of the throat area is 200 m

Train track statistics points	Time and kilometre markers for continuous train tracking runs						Train headway				
	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 2-Train 1	Train 3-Train 2	Train 4-Train 3	Train 5-Train 4	Train 6-Train 5
Departure time and headway/s	0	240	480	720	960	1 200	240	240	240	240	240
First model kilometre marker/km	7.57	7.57	7.57	7.57	7.57	7.57	–	–	–	–	–
First model start-up time and headway/s	78	318	558	798	1 038	1 278	240	240	240	240	240
Kilometre marker (speed limit 75 km/h) before home signal/km	17.665	17.665	17.665	17.665	17.665	17.665	–	–	–	–	–
Time and headway before home signal (speed limit 75 km/h)/s	241	481	721	961	1201	1441	240	240	240	240	240
Inbound stopping kilometre marker/km	18.515	18.515	18.515	18.515	18.515	18.515	–	–	–	–	–
Inbound stopping time and headway/s	301	541	781	1021	1261	1501	240	240	240	240	240
Overall running time/s	301	301	301	301	301	301	–	–	–	–	–

Table 5. Simulation results of 6 trains stopping continuously at 350 km/h with 4 min headway when the length of the throat area is 1000 m

Train track statistics points	Time and kilometre markers for continuous train tracking runs						Train headway				
	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 2-Train 1	Train 3-Train 2	Train 4-Train 3	Train 5-Train 4	Train 6-Train 5
Departure time and headway/s	0	240	480	720	960	1 200	240	240	240	240	240
First model kilometre marker/km	7.57	7.426	7.426	7.426	7.426	7.426	–	–	–	–	–
First model start-up time and headway/s	78	317	557	797	1 037	1 277	239	240	240	240	240
Kilometre marker (speed limit 75 km/h) before home signal/km	17.665	17.665	17.665	17.665	17.665	17.665	–	–	–	–	–
Time and headway before home signal (speed limit 75 km/h)/s	241	482	722	962	1 202	1 442	241	240	240	240	240
Inbound stopping kilometre marker/km	19.315	19.315	19.315	19.315	19.315	19.315	–	–	–	–	–
Inbound stopping time and headway/s	339	580	820	1 060	1 300	1 540	241	240	240	240	240
Overall running time/s	339	340	340	340	340	340	–	–	–	–	–

Table 6.
Simulation results of 6 trains stopping continuously at 350 km/h with 4 min headway when the length of the throat area is 1600 m

Train track statistics points	Time and kilometre markers for continuous train tracking runs						Train headway				
	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 2-Train 1	Train 3-Train 2	Train 4-Train 3	Train 5-Train 4	Train 6-Train 5
Departure time and headway/s	0	240	480	720	960	1 200	240	240	240	240	240
First model kilometre marker/km	7.57	7.426	7.426	7.426	7.426	7.426	–	–	–	–	–
First model start-up time and headway/s	78	317	557	797	1 037	1 277	239	240	240	240	240
Kilometre marker (speed limit 75 km/h) before home signal/km	17.665	17.665	17.665	17.665	17.665	17.665	–	–	–	–	–
Time and headway before home signal (speed limit 75 km/h)/s	241	483	723	963	1 203	1 443	242	240	240	240	240
Inbound stopping kilometre marker/km	19.915	19.915	19.915	19.915	19.915	19.915	–	–	–	–	–
Inbound stopping time and headway/s	368	610	850	1 090	1 330	1 570	242	240	240	240	240
Overall running time/s	368	370	370	370	370	370	–	–	–	–	–

3.1 Train headway in section: 3 min

The simulation results of the station throat length of 200 m, 1000 m and 1600 m are listed in Table 7–Table 9 respectively. When the length of throat area is 200 m and 1000 m, respectively, 6 consecutive trains run at 200 km/h speed into the station without interfering with each other, and the headway of train groups can be achieved in 3 min. When the length of throat area reaches 1600 m, the first group of trains' headway is 181 s, then the next 4 groups of trains' headway are converged to 180 s, and the train running time are increased by 1 s. At the same time, it shows that the high-speed railways which enter the station at the speed of 200 km/h can reach the arrival headway of 3 min as long as the throat area is not more than 1000 m.

3.2 Train headway in section: 2.5 min

The simulation results of the station throat length 200 m, 1000 m and 1600 m are listed in Table 10–Table 12 respectively. When the throat length is 200 m, 6 consecutive trains run at 200 km/h speed into the station without interfering with each other, and the headway between train groups can all be achieved in 2.5 min. When the length of the throat area reaches 1000 m, the first group and the second group of trains' headway are 151 s, then the three groups of trains' headway are converged to 150 s, and the train running time are increased by 2 s. When the length of the throat area reaches 1600 m, the headway of the first group of trains is 154 s, then the four groups of trains' headway are converged to 150 s, and the train running time are increased by 4 s.

The simulation also encompasses the operational performance of trains at speeds of 300 km/h and 250 km/h prior to their entry into the station, which exhibit a consistent pattern. Further checking shows that 2.5 min arrival headway can be achieved for the high-speed train entering the station at 200 km/h as long as the throat area is not more than 500 m.

4. Conclusions and recommendations

The simulation results with running speeds of 350 km/h and 200 km/h, headway of 3 min, 4 min and 2.5 min, and throat lengths of 200 m, 1000 m and 1600 m are summarized in Table 13. The fourth column in the table is the increase value of the whole running time of the 6 consecutive trains, the first value is the basis of the comparison, which refers to the increase value of the running time of Train 1, which is definitely 0, and the rest of the values are the difference between the running time of Train 1 and Train 6, which is subtracted from the running time of Train 1. The rest of the value is the difference between the running time of Train 2 to Train 6 and the running time of Train 1. Taking the first section of the throat area with a length of 200 m as an example, the comparison between Train 2 and Train 1 shows an increase of 5 s in the running time. Consequently, the headway for the first group of trains is 185 s. When comparing Train 3 with Train 1, the additional time is also 5 s, which is identical to the increase in Train 2's running time. Therefore, the headway for the second group of trains is 180 s. This pattern continues for subsequent comparisons.

Combining the above simulation results and the statistical data in Table 13, the following conclusions can be obtained:

(1) The headway between the intensive arrival of high-speed trains at stations is regular. When trains arrive intensively, the arrival headway between the first group or groups may be greater than the headway in section, but the subsequent arrival trains' arrival headway are converged to the headway in section, the specific patterns are: under the conditions of low running speed, long headway in the section and short length of the throat area (e.g., rows 4, 7, 8 and 10 of Table 13), the value of arrival headway is the same as the headway in section; under the conditions of high running speed, short

Table 7. Simulation results of 6 trains stopping continuously at 200 km/h with 3 min headway when the length of the throat area is 200 m

Train track statistics points	Time and kilometre markers for continuous train tracking runs						Train headway				
	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 2-Train 1	Train 3-Train 2	Train 4-Train 3	Train 5-Train 4	Train 6-Train 5
Departure time and headway/s	0	180	360	540	720	900	180	180	180	180	180
First model kilometre marker/km	15.146	15.146	15.146	15.146	15.146	15.146	–	–	–	–	–
First model start-up time and headway/s	273	453	633	813	993	1173	180	180	180	180	180
Kilometre marker (speed limit 75 km/h) before home signal/km	17.665	17.665	17.665	17.665	17.665	17.665	–	–	–	–	–
Time and headway before home signal (speed limit 75 km/h)/s	338	518	698	878	1058	1238	180	180	180	180	180
Inbound stopping kilometre marker/km	18.515	18.515	18.515	18.515	18.515	18.515	–	–	–	–	–
Inbound stopping time and headway/s	398	578	758	938	1118	1298	180	180	180	180	180
Overall running time/s	398	398	398	398	398	398	–	–	–	–	–

Table 8. Simulation results of 6 trains stopping continuously at 200 km/h with 3 min headway when the length of the throat area is 1000 m

Train track statistics points	Time and kilometre markers for continuous train tracking runs						Train headway				
	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 2-Train 1	Train 3-Train 2	Train 4-Train 3	Train 5-Train 4	Train 6-Train 5
Departure time and headway/s	0	180	360	540	720	900	180	180	180	180	180
First model kilometre marker/km	15.146	15.146	15.146	15.146	15.146	15.146	–	–	–	–	–
First model start-up time and headway/s	273	453	633	813	993	1173	180	180	180	180	180
Kilometre marker (speed limit 75 km/h) before home signal/km	17.665	17.665	17.665	17.665	17.665	17.665	–	–	–	–	–
Time and headway before home signal (speed limit 75 km/h)/s	338	518	698	878	1058	1238	180	180	180	180	180
Inbound stopping kilometre marker/km	19.315	19.315	19.315	19.315	19.315	19.315	–	–	–	–	–
Inbound stopping time and headway/s	436	616	796	976	1156	1336	180	180	180	180	180
Overall running time/s	436	436	436	436	436	436	–	–	–	–	–

Table 9. Simulation results of 6 trains stopping continuously at 200 km/h with 3 min headway when the length of the throat area is 1600 m

Train track statistics points	Time and kilometre markers for continuous train tracking runs						Train headway				
	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 2-Train 1	Train 3-Train 2	Train 4-Train 3	Train 5-Train 4	Train 6-Train 5
Departure time and headway/s	0	180	360	540	720	900	180	180	180	180	180
First model kilometre marker/km	15.146	14.916	14.916	14.916	14.916	14.916	–	–	–	–	–
First model start-up time and headway/s	273	449	629	809	989	1169	176	180	180	180	180
Kilometre marker (speed limit 75 km/h) before home signal/km	17.665	17.665	17.665	17.665	17.665	17.665	–	–	–	–	–
Time and headway before home signal (speed limit 75 km/h)/s	338	519	699	879	1059	1239	181	180	180	180	180
Inbound stopping kilometre marker/km	19.915	19.915	19.915	19.915	19.915	19.915	–	–	–	–	–
Inbound stopping time and headway/s	465	646	826	1 006	1 186	1 366	181	180	180	180	180
Overall running time/s	465	466	466	466	466	466	–	–	–	–	–

Table 10. Simulation results of 6 trains stopping continuously at 200 km/h with 2.5 min headway when the length of the throat area is 200 m

Train track statistics points	Time and kilometre markers for continuous train tracking runs						Train headway				
	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 2-Train 1	Train 3-Train 2	Train 4-Train 3	Train 5-Train 4	Train 6-Train 5
Departure time and headway/s	0	150	300	450	600	750	150	150	150	150	150
First model kilometre marker/km	15.146	15.146	15.146	15.146	15.146	15.146	–	–	–	–	–
First model start-up time and headway/s	273	423	573	723	873	1023	150	150	150	150	150
Kilometre marker (speed limit 75 km/h) before home signal/km	17.665	17.665	17.665	17.665	17.665	17.665	–	–	–	–	–
Time and headway before home signal (speed limit 75 km/h)/s	338	488	638	788	938	1088	150	150	150	150	150
Inbound stopping kilometre marker/km	18.515	18.515	18.515	18.515	18.515	18.515	–	–	–	–	–
Inbound stopping time and headway/s	398	548	698	848	998	1148	150	150	150	150	150
Overall running time/s	398	398	398	398	398	398	–	–	–	–	–

Table 11. Simulation results of 6 trains stopping continuously at 200 km/h with 2.5 min headway when the length of the throat area is 1000 m

Train track statistics points	Time and kilometre markers for continuous train tracking runs						Train headway				
	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 2-Train 1	Train 3-Train 2	Train 4-Train 3	Train 5-Train 4	Train 6-Train 5
Departure time and headway/s	0	150	300	450	600	750	150	150	150	150	150
First model kilometre marker/km	15.146	14.916	14.916	14.916	14.916	14.916	–	–	–	–	–
First model start-up time and headway/s	273	419	569	719	869	1019	146	150	150	150	150
Kilometre marker (speed limit 75 km/h) before home signal/km	17.665	17.665	17.665	17.665	17.665	17.665	–	–	–	–	–
Time and headway before home signal (speed limit 75 km/h)/s	338	489	640	790	940	1090	151	151	150	150	150
Inbound stopping kilometre marker/km	19.315	19.315	19.315	19.315	19.315	19.315	–	–	–	–	–
Inbound stopping time and headway/s	436	587	738	888	1038	1188	151	151	150	150	150
Overall running time/s	436	437	438	438	438	438	–	–	–	–	–

Table 12. Simulation results of 6 trains stopping continuously at 200 km/h with 2.5 min intervals in the throat area when the length of the throat area is 1600 m

Train track statistics points	Time and kilometre markers for continuous train tracking runs						Train headway				
	Train 1	Train 2	Train 3	Train 4	Train 5	Train 6	Train 2-Train 1	Train 3-Train 2	Train 4-Train 3	Train 5-Train 4	Train 6-Train 5
Departure time and headway/s	0	150	300	450	600	750	150	150	150	150	150
First model kilometre marker/km	15.146	14.916	14.916	14.916	14.916	14.916	–	–	–	–	–
First model start-up time and headway/s	273	419	569	719	869	1019	146	150	150	150	150
Kilometre marker (speed limit 75 km/h) before home signal/km	17.665	17.665	17.665	17.665	17.665	17.665	–	–	–	–	–
Time and headway before home signal (speed limit 75 km/h)/s	338	492	642	792	942	1092	154	150	150	150	150
Inbound stopping kilometre marker/km	19.915	19.915	19.915	19.915	19.915	19.915	–	–	–	–	–
Inbound stopping time and headway/s	465	619	769	919	1069	1219	154	150	150	150	150
Overall running time/s	465	469	469	469	469	469	–	–	–	–	–

Running speed /Km/h	Headway in section /min	Length of throat area /m	Added value in running time for continuous 6 trains/s	Arrival headway/s
350	3	200	0, 5, 5, 5, 5, 5, 5	185, 180, 180, 180, 180
		1 000	0, 5, 5, 5, 5, 5, 5	185, 180, 180, 180, 180
		1 600	0, 7, 7, 7, 7, 7, 7	187, 180, 180, 180, 180
	4	200	0, 0, 0, 0, 0, 0, 0	240, 240, 240, 240, 240, 240
		1 000	0, 1, 1, 1, 1, 1, 1	241, 240, 240, 240, 240, 240
		1 600	0, 2, 2, 2, 2, 2, 2	242, 240, 240, 240, 240, 240
200	3	200	0, 0, 0, 0, 0, 0, 0	180, 180, 180, 180, 180
		1 000	0, 0, 0, 0, 0, 0, 0	180, 180, 180, 180, 180
		1 600	0, 1, 1, 1, 1, 1, 1	181, 180, 180, 180, 180
	2.5	200	0, 0, 0, 0, 0, 0, 0	150, 150, 150, 150, 150, 150
		1 000	0, 1, 2, 2, 2, 2, 2	151, 151, 150, 150, 150
		1 600	0, 4, 4, 4, 4, 4, 4	154, 150, 150, 150, 150, 150

Table 13. Summary table of simulation results for continuous station arrivals of 6 trains with variable running speeds, headway, and throat lengths in different sections

headway and long throat length, the arrival headway of the first one or two groups of trains is greater than the headway in section, and the subsequent groups of trains' arrival headway could be converged to the headway in section (e.g., rows 1, 2, 3, 5, 6, 9, 11 and 12 in Table 13). The higher the running speed, the larger the headway in section, and the longer the throat area, the larger the arrival headway of the first group of trains (such as rows 1, 2 and 3 in Table 13), which exceeds the headway in section, only the exceeding value is not large and the maximum is not more than 7 s in Table 13.

(2) The convergence of the arrival headway to the headway in section comes at a certain cost, which is manifested as preemptive deceleration of trains starting from the second one and an extension of their section running times. Nonetheless, this cost is relatively small, with the extension in section running time being quite minimal, peaking at no more than 7 s, which is nearly negligible.

(3) When the running speed before the train enters the station is 350 km/h, the headway in section of 4 min compared with the headway of 3 min, the arrival headway is easier to approach or realize the train headway in section, such as the length of the throat area is 1600 m, the arrival headway for the first train group are 242 s and 187 s, respectively, differing by 2 s and 7 s from the 4 min and 3 min. When the running speed is 200 km/h before the train enters the station and the length of the throat area is 1600 m, the arrival headway for the first train group are 181 s and 154 s, respectively, differing by 1s and 4 s from the 3 min and 2.5 min.

The same pattern is obtained by simulating the situation of high-speed trains running at 250 km/h and 300 km/h with 3 min continuous arrival.

The above pattern is very useful for the study of determining the train headway (I). Train arrival headway (I_{arr}) was once considered to be the main factor limiting the train headway, but the simulation results proved that it is not completely so. As long as the high-speed train departs from the station, the headway in section can be realized 3 min, and after the intensive arrival at the station, the final headway of 3 min can still be realized, so as to achieve the compression of the train headway. Therefore, when determining the train headway (I), it is not necessary to over-emphasize the impact of the train arrival headway (I_{arr}) on I, and under general conditions, it can even be simply considered as $I = \max\{I_{\sec}, I_{dep}, I_{pas}\}$, which plays an important role in compression of I to improve the capacity of high-speed railway.

It should be noted that some large passenger stations have speed limits before entering the station, which provide natural conditions for shortening the arrival headway and it should be fully utilized. If in order to compress the train arrival headway, the concept and practice of artificially setting a speed limit before entering the station is inappropriate and undesirable.

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