China's railway train speed, density and weight in developing

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Abstract

Purpose – This study aims to analyze the development direction of train speed, density and weight in China.
Design/methodology/approach – The development of China's railway in the past 40 years can be divided into 3 stages. At the stage of potential tapping and capacity expansion, it is important to improve the train weight and density by upgrading the existing lines, and improving transportation capacity rapidly. At the stage of railway speed increase, the first priority is to increase train speed, reduce the travel time of passenger train, and synchronously take into account the increase of train density and weight. At the stage of developing high-speed railway, train speed, density and weight are co-developing on demand.
Findings – The train speed of high-speed railway will be 400 km h^{-1}, the interval time of train tracking will be 3 min, and the traffic density will be more than 190 pairs per day. The running speed of high-speed freight EMU will reach 200 km h^{-1} and above. The maximum speed of passenger train on mixed passenger and freight railway can reach 200 km h^{-1}. The minimum interval time of train tracking can be compressed to 5 min. The freight train weight of 850 m series arrival-departure track railway can be increased to 4,500–5,000 *t* and that of 1,050 m series to 5,500–6,400 *t*. EMU trains should gradually replace ordinary passenger trains to improve the quality of railway passenger service. Small formation trains will operate more in intercity railway, suburban railway and short-distance passenger transportation.
Originality/value – The research can provide new connotations and requirements of railway train speed, density and weight in the new railway stage.

Keywords Speed, Density, Weight, Potential tapping and capacity expansion, Railway speed increase, High-speed railway
Paper type Research paper

1. Introduction: matching relation of train speed, density and weight

Train speed, density and weight are the important technical indicators representing railway transport capacity, transport quality and technical level, and the core contents of *Main Technical Policies for Railways*. The three are closely related, mutually restricted and promoted, and have different development emphases in different development periods of Chinese railways. Especially in the high-speed railway era, many new characteristics appear

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among them. On the basis of summarizing the matching relation of train speed, density and weight, this paper divides railway development course of China in the past 40 years into 3 stages: potential tapping and capacity expansion, railway speed increase and developing high-speed railway, discusses the development and change process of the main technical indicators of train speed, density and weight as well as the requirements in the railway technical policies for their development in the three stages, and puts forward the development direction of China's railway train speed, density and weight in the future.

1.1 Train speed and density

Train speed, which is usually divided into maximum speed (design speed), operation speed, technical speed, traveling speed and cargo delivery speed, etc., is the main technical indicator reflecting railway equipment performance, transport organization level, transport service quality and overall technical level (Wang, 1990). The higher the maximum speed, the undoubtedly higher the operation speed will be; the higher the operation speed, the higher the technical speed will be; the higher the technical speed, the higher the traveling speed will accordingly be. The traveling speed of passenger train and the delivery speed of cargoes are the most direct technical indicators reflecting the speed of railway transportation of passengers and cargoes. Passengers are concerned about the traveling speed, while the owners of freight are concerned about the delivery speed of cargoes. Railways shall focus on improving such two indicators to attract passengers and owners of freight (Tian, 2001).

Train density, also known as traffic density, refers to the average number of trains per kilometer within a certain range (such as the whole railway or a certain line) and time, usually the actual traffic volume (the number of passenger and freight trains) passing through the line Section 1 day and night. Train density, which is related to such factors as passenger and freight transport demand, train weight (formation) and line carrying capacity, is an important technical indicator reflecting how busy the line transportation is. The higher the train density, the heavier the load of the line will be, and the busier the transportation will be (Tian, 2001).

Train speed is related to train density through the carrying capacity of the line. To a great extent, train speed determines the period in the train diagram (automatic block section is the interval time of train tracking) and the carrying capacity of a parallel train diagram; different parking schemes of passenger trains and mixed operation of trains with different speeds have different occupancy (coefficient of removal is generated) on the carrying capacity of parallel train diagram, which largely determines the carrying capacity of non-parallel train diagram, that is, the line carrying capacity. Train density is based on the line carrying capacity, which reflects the utilization of line carrying capacity. If the line carrying capacity is low, the traffic density cannot be high; however, the high line carrying capacity can create conditions for increasing the traffic density.

The tracking interval time of double-track automatic block district train is $I = \max\{I_{\text{tracking}}, I_{\text{departure}}, I_{\text{arrival}}, I_{\text{passing}}\}$, where I_{tracking} refers to the train section tracking interval time, $I_{\text{departure}}$ refers to the train departure tracking interval time, I_{arrival} refers to the train arrival tracking interval time and I_{passing} refers to the train passing tracking interval time, which are all related to train speed. When the passenger and freight trains of conventional railway are operated according to four-aspect automatic block tracking under LKJ control condition, the trains generally complete speed regulation braking in two block sections (the train drops to the specified speed before the home signal when stopped at the entrance). Under such conditions, appropriate increase of train operation speed is conducive to the compression of I_{tracking}, I_{arrival} and I_{passing} (Tian, Zhu, & Xu, 2002b).

Compared with the conventional railway, high-speed railway is equipped with CTCS-2/3 train control system, which greatly shortens the interval time of train tracking and significantly improves the line carrying capacity. The higher the operation speed of high speed train, the longer the braking distance monitored by onboard equipment for train control will be, and the speed of high speed train is in inverse relation with I_{tracking}, I_{arrival} and I_{passing}. The higher the train speed, the longer the interval time of train tracking will be. Train speed and density of high-speed railway are in negative correlation.

For $I_{\text{departure}}$, increasing train operation speed plays a positive role. Train departs at a limited speed within the range of the station, and is sped up when it leaves the station. High speed trains are more conducive to shortening $I_{\text{departure}}$ than ordinary speed trains (Tian, Zhang, & Zhang, 2015; Zhang, Tian, & Jiang, 2013).

Under the condition of CTCS-2 train control, when a high speed train encounters a long heavy downgrade, if the sum of the monitoring braking distance, safety protection distance and additional-time running distance required for operation at normal speed exceeds the distance of the maximum number of receivable idle block sections ahead, it is necessary to limit the speed (Zhang & Tian, 2017); for the avoidance of speed limit, the method of extending the block section length is often adopted, but this will extend the interval time of train tracking and results in a negative correlation between train speed and interval time of train tracking.

In double-track automatic block section, whether on high-speed railway or conventional railway, when trains with different speeds are operated on the same line, the greater the speed difference between the trains is, the greater the coefficient of train removal will be, and the lower the line carrying capacity will be (Zhang, Tian, & Yan, 2017). As for the high-speed railway taking regular passenger trains into account, the maximum speed of high speed trains does not exceed 250 km h^{-1}, and the maximum speed of regular passenger trains does not exceed 160 km h^{-1}. There is a large speed difference between regular passenger trains and high-speed trains, which has a great influence on carrying capacity. The traffic density of high-speed railway is lower (Jiang, Tian, & Zhang, 2012). In order to improve the carrying capacity of high-speed railway, it is an effective measure to operate trains with the same speed class; of course, the unbalanced stop of high-speed railway trains and the rigid constraint of arrival/departure time of cross-line trains are also important factors affecting the carrying capacity.

In semi-automatic block section, the period in the train diagram is composed of train operation time in the restricted section and time interval between two adjacent trains at station. Increasing the train operation speed will directly reduce the train operation time at section and compress the period in the train diagram, which is conducive to improving the line carrying capacity and increasing the traffic density.

1.2 Train weight and speed

Train weight refers to the traction weight of locomotive, that is, the sum of dead weight and loading capacity of train. The railway train load norm specified in the direction of line (section) is usually called tonnage rating of the train. Statistically, the average gross traction weight of train refers to the average gross ton-kilometers completed by each leading locomotive kilometers in a certain period and within a certain range (National Railway Administration of the PRC, 2014). The weight of passenger trains is mainly reflected in the number of train formation. The formation of EMU trains is relatively fixed, and most of them are 8-train formation and 16-train formation. Two EMUs with 8-train formation of the same model can be reconnected for operation. The weight level of freight trains, generally as a development symbol of freight trains, is related to the factors of transport demand, infrastructure conditions, traction and braking capacity of rolling stock, etc.

Train weight is closely related to speed. Generally, the determination of train weight shall meet the conditions that the train shall run at a speed not lower than the continuous speed on the ruling grade, and shall still have the specified acceleration after reaching the maximum operation speed on the flat and straight road (National Railway Administration of the PRC, 2018). The former relation is shown in Formula (1), and the latter relation is shown in Formula (2).

$$Q_{\text{ruling grade}} = \frac{F_c\lambda_y - P(\omega_0' + i_x)g \times 10^{-3}}{(\omega_0'' + i_x)g \times 10^{-3}} \quad (1)$$

$$Q_{\text{level grade}} = \frac{F_g - P\omega_0' g \times 10^{-3} - P(1+\gamma)\alpha}{\omega_0'' g \times 10^{-3} + (1+\gamma)\alpha} \quad (2)$$

where $Q_{\text{ruling grade}}$ and $Q_{\text{level grade}}$ are the train weight determined by the acceleration reserved on the ruling grade and the flat and straight road, respectively, t; F_c, F_g are the continuous tractive effort of locomotive and the locomotive tractive effort when the train runs at the specified maximum speed, kN; ω_0', ω_0'' are the basic resistance of locomotive and vehicle unit operation, $N \cdot kN^{-1}$; P is the calculated weight of locomotive, t; λ_y is the utilization coefficient of locomotive tractive effort; i_x is the ruling grade of line, ‰; γ is the rotational mass coefficient; g is the acceleration of gravity, m s^{-2}; α is the residual acceleration of trains running at the specified maximum speed, which is not less than 0.03 m s^{-2} for passenger trains, 0.01 m s^{-2} for freight trains and 0.05 m s^{-2} for EMU trains.

The residual acceleration α not only indicates that the train has corresponding acceleration when it reaches the specified maximum speed at the flat and straight road, but also indicates that the train can run at the specified maximum speed constantly on the up-gradient corresponding to the α value. For example, when the operation speed of high speed train $\nu_{ax} = 350$ km h^{-1} and $\alpha = 0.05$ m s^{-2} is required, it means that when the high speed train runs at a constant speed of 350 km h^{-1} on a flat and straight road, it also has an acceleration of 0.05 m s^{-2}; at the same time, it also means that the high speed train can keep running at a constant speed of 350 km h^{-1} on the 5‰ up-gradient.

It can be seen from Formulas (1) and (2) that the train weight is inversely proportional to the speed, and the higher the train speed, the smaller the train traction weight will be. For passenger trains, in order to increase the speed under the premise of constant train weight (number of cars for formation), rolling stock with better performance must be adopted. For freight trains, the most effective way to improve the traction weight is to use high-power locomotive, and to use double- or even multi-locomotive traction in long and heavy downgrade section.

The train weight calculated by Formula (1) is generally larger than that calculated by Formula (2), and the main function of Formula (1) is to determine the line section where double or supplementary locomotives are required. Generally, after the train weight is determined by Formula (2), corresponding ruling grade can be calculated by Formula (1) when the train weight matches the speed. The two formulas have different emphases. When the ruling grade of the track section is large, the train weight (mainly freight train weight) is mainly limited by the calculation result of Formula (1); when the horizontal and vertical sections of the line are in good condition, or when the ruling grade is large, but supplementary, double- or multi-locomotive traction is adopted, the weight of district train is mainly determined by Formula (2). The weight (formation) of ordinary passenger trains is mainly determined according to the calculation results of Formula (2) and passenger flow demand. Power decentralized technology is adopted for high-speed EMU trains, and both the traction and braking capacity are great. The traction and braking capacity of 16-car formation is twice of that of 8-train formation. The weight has little influence on speed, but the long and heavy up-gradient has great influence on speed. For example, the design speed of Xi'an–Chengdu high-speed railway is 250 km h^{-1}, while the operation speed of EMU trains with the highest speed of 200–250 km h^{-1} is even not up to 140 km h^{-1} when they cross the 25‰ up-gradient of Qinling Mountains.

1.3 Train density and weight

Train density and weight determine the traffic capacity of railway or the actually completed transport volume. The most direct and effective measure to improve the traffic capacity of railway is to increase train weight and traffic density.

The relation between freight train density and freight train weight is (Ministry of Railways of the PRC, 1984)

$$n_{\text{freight}} = \frac{\Gamma_{\text{freight}} \times 10000}{Q\varphi_{\text{load}}\gamma_{\text{full}} \times 365} \quad (3)$$

where n_{freight} refers to the freight train density, train; Γ_{freight} refers to the annual freight demand in one direction, 10,000 t/year^{-1}; Q refers to the freight train weight, t; φ_{load} refers to the loading capacity coefficient of freight train; γ_{full} refers to the full load coefficient of freight train.

It can be seen from Formula (3) that the traffic density of freight train is inversely proportional to the weight of freight train. In order to improve the traffic capacity or complete a certain freight volume, the first measure is often to increase freight train weight, and even to run heavy haul train, so as to release the tension of carrying capacity without increasing the traffic density; in case of sufficient carrying capacity or conditions to improve the carrying capacity, the measures to increase the freight train density are also taken frequently. To improve freight train weight, many factors such as locomotive traction capacity, line profile conditions, effective length of arrival and departure track, static load of car and technical station operation capacity shall be considered; to increase the freight train density, many factors such as line carrying capacity, technical station operation capacity, locomotive number and routing shall be considered. At present, in order to adapt to the competition in the freight market and meet the diversified transport needs of the owner of freight, various types of light freight trains such as container trains, freight trains, refrigerated trains and express trains have been launched in China, and freight train weight is in diversified development; meanwhile, for the purpose of ensuring the delivery time of cargoes, some freight trains may not reach full weight or full length before departure, but will be marshaled and departed quickly according to the arrival time (plan). All these need to be guaranteed by certain line carrying capacity (Wang, 2009).

For passenger transport, train weight is mainly reflected by train formation. Expanding passenger train formation and increasing passenger train number are important measures to improve the traffic capacity of passengers. The relation between passenger train density and passenger train weight (formation) is as follows:

$$n_{\text{passenger}} = \frac{P_{\text{passenger}} \times 10000}{A_{\eta} \times 365} \quad (4)$$

where $n_{\text{passenger}}$ refers to the passenger train density, train; $P_{\text{passenger}}$ refers to the annual passenger demand in one direction, 10,000 persons $\cdot$ a^{-1}; A refers to the average fixed number of passenger trains, person; η refers to the average seat occupancy rate of passenger trains.

When the passenger train density and weight (formation) are determined, more consideration shall be given to the scale of passenger flow volume, service frequency, convenience, comfort and the ability to compete with other modes of transportation. In order to solve the problem of tight transportation or line carrying capacity during peak passenger flow, long formation is often adopted to expand passenger capacity. However, the weight of passenger trains (formation) is not the higher the better, which is not only limited by the scale of passenger flow volume to other destinations, but also by factors such as passenger comfort, convenience degree and waiting time. Increasing the service frequency can not only meet the demand of passengers for quantity, but also meet the demand of passengers for quality. As for short-distance passenger transport on high-speed railway (especially intercity railway), suburban railway and conventional railway, small formation trains are generally operated intensively, so as to increase the service frequency, meet the requirements of passengers for comfortable travel at any time and improve the competitiveness of railway passenger transport. Under the situation that more and more attention is paid to passenger transport in Chinese railways, great efforts shall be made to increase the number of train pairs and improve service quality in terms of passenger transport.

2. Development characteristics of train speed, density and weight

According to the national conditions and road conditions, a technical system with Chinese characteristics must be established for Chinese railways, which will pay equal attention to passenger and freight transport, give consideration to both quantity and quality, carry out reasonably combined and coordinated development of train speed, density and weight, lay equal stress on high and new technology and applicable technology, and provide different levels of technical equipment. The so-called reasonable combination is mainly to adopt corresponding train speed, density and weight according to different line conditions and the passenger and freight transport tasks undertaken, so as to improve the transport efficiency and benefit. The so-called coordinated development is mainly to deal with the relation among train speed, density and weight, so that the combination of the three can effectively improve the transport quality and expand the transport capacity (Wang, 2009). In order to meet the needs of economic and social development, different emphases have been imposed on the development of train speed, density and weight in different periods of China's railway.

2.1 Potential tapping and capacity expansion (1978—1996)

In the late 1970s, China made a major strategic decision to implement reform and opening up by focusing on economic construction. Great changes took place in the national and social outlook. With rapid economic development, increasing transport demand and fully strained railway transport capacity, it was difficult to buy tickets or transport goods, which suffers great social censure. Therefore, it was urgent for the transportation industry with railway as the backbone to develop rapidly and improve the transport capacity enormously. During this period, limited by national financial resources, large-scale railway construction was not much, so potential tapping and capacity expansion became the focus of railway development in this period, that is, making full use of limited financial resources and renovating and upgrading the key bottlenecks of transport capacity. Such idea was reflected in the development sequence and different emphases of train speed, density and weight, which could be proved by several editions of *Main Technical Policies for Railways*. In May 1983, the former Ministry of Railways promulgated the *Main Technical Policies for Railways* (1st edition), which stipulated that "gradually increasing train weight as well as traffic density, and on such basis, appropriately improving traffic speed," and put "increasing weight and density" in the first place of railway development, so as to significantly improve the railway traffic capacity and obtain better economic benefit. In November 1988, the *Main Technical Policies for Railways* (2nd edition) further emphasized the aim to "vigorously increase train weight, actively increase traffic density and appropriately improve traffic speed. On the basis of optimizing the combination of the three, realizing heavy weight, high density and medium speed, so as to significantly improve the transport capacity and obtain better social and economic benefits," which highlighted the importance and urgency of "increasing weight and density" in promoting railway development and meeting transport demand. The *Main Technical Policies for Railways* (3rd edition) promulgated in June 1994 still maintained the formulation and sequence of weight, density and speed, which were expressed as "to vigorously increase train weight, actively increase traffic density and strive to improve traffic speed. With the goal of greatly improving transport capacity and obtaining better economic and social benefits, realize the optimal combination of weight, density and speed". However, changing "appropriately improve traffic speed" to "strive to improve traffic speed" indicates that during the period, railway transportation still put "increasing weight and density" in the first place, and began to pay attention to the improvement of traffic speed foreseeingly while developing in the sequence of "weight, density and speed" (Ministry of Railways of the PRC, 1983–2013).

"Increasing weight and density" was the theme of railway development in this period. In terms of increasing train weight, measures such as greatly increasing the proportion of diesel and electrified railways and extending the effective length of station arrival and departure track were taken to increase the weight of freight train of arrival and departure track with an effective length of 850 m from 3,500 *t* to 4,000 *t*; the effective length of arrival and departure track was extended to 1,050 m and the train weight was increased to 5,000 *t* in the track section with conditions and needs. The effective length of arrival and departure track of Datong–Qinhuangdao dedicated coal transport line was 1,700 m, and the maximum train weight was 10,000 *t*; as for passenger trains, the number of train formation was gradually increased from 13–14 to 16–17 in trunk lines, partially expanded to 18-19, and then gradually expand to other lines. At the same time, adjust the content of train formations and increase the train capacity (Department of Science and Technology of the Ministry of Railways, 1995). In terms of increasing traffic density, the proportion of double-track and automatic block railway was continuously increased, the tracking interval time of double-track automatic block district train was reduced from 10 min to 8 min, even to 7 min, and the maximum passenger and freight train traffic in the track section reached 110–120 pairs; by adding intermediate station or railway station and adopting semi-automatic block equipment, the carrying capacity of parallel train diagram on single track railway was increased to more than 40 pairs, and the maximum passenger and freight train traffic in the track section reached 30–35 pairs (Department of Science and Technology of the Ministry of Railways, 1995).

Through the potential tapping and upgrading of existing lines and the construction of a few new lines, the quality of railway transport equipment was improved, and the weight and traffic density of railway freight trains were greatly improved, as shown in Table 1 (for the convenience of comparison, the data of 2007 in the speed increase stage of railway and that of 2019 in the stage of high-speed railway development were also included in Table 1). It could be seen from Table 1 that in 1996, compared with 1980, the proportion of diesel and electrified railways increased from 18.1% to 69.3%, the mileage proportion of automatic block tracks increased from 12.1% to 26.9%, the proportion of wagons with a loading capacity of 60 *t* and above increased from 35.8% to 81.4%, and the average weight of freight trains increased by 30.2% from 1,994 *t* to 2,603 *t*. The passenger traffic density and the density of freight traffic increased by 112.3% and 99.5%, respectively. Although the railway transport capacity was greatly improved at this stage, it still could not meet the rapidly increasing passenger and freight transport demand and the increasing service quality requirements in China.

2.2 Railway speed increase (1997—2007)

Since 1990s, driven by further expansion of national opening-up policy, the highway, civil aviation and water transport in transportation industry have made full use of their respective favorable conditions to achieve rapid development, and the completed passenger and freight volume and passenger and freight turnover have increased year by year. However, due to various internal and external reasons, the development of railways has lagged behind and failed to give full play to its due role. Under the condition that the whole society passenger

Table 1.
Main technical indicators of China's railway train speed, density and weight

Year	Length in operation/km	Automatic block track/km	Proportion of diesel and electrified railways/%	Proportion of wagons with a loading capacity of 60 *t* and above/%	Technical speed of passenger train/(km h^{-1})	Traveling speed of passenger train/(km h^{-1})	Technical speed of freight train/(km h^{-1})	Traveling speed of freight train/(km h^{-1})	Passenger traffic density/(10,000 persons km km^{-1})	Density of freight traffic/(10,000 *t* km km^{-1})	Average weight of freight train/*t*
1980	53 321	6 044	18.1	35.8	54.2	43.4	43.5	28.7	276	1 143	1 994
1996	64 931	15 254	69.3	81.4	58.7	49.5	44.1	30.4	586	2 280	2 603
2007	77 966	26 526	100	87.7	78.8	68.9	47.6	33.2	1 084	3 475	3 193
2019	139 926	44 211	100	91.6	95.7	85.6	55.2	42.1	1 298	2 862	3 316

Note(s): Except the length in operation which is subject to nationwide railway statistical data, all others are subject to national railway statistical data volume is rising year by year, the railway passenger volume and its market shares, however, decreased year by year during 1995-1997, and the transport capacity and transport quality of railway were seriously unable to adapt to the social development. Under the situation, it was not only urgent to expand the transport capacity of railway, so as to meet the increasing demand of passenger and freight volume, but also to give priority to speeding up the delivery of passengers and cargoes, improving the quality of passenger and freight transport and realizing safe, fast, comfortable, economical and convenient passenger and freight transport. Therefore, speed increase was implemented to existing railway lines, that is, to carry out technological upgrading on existing lines, replace technical equipment such as rolling stock, organize major comprehensive test and technical research on speed increase of existing lines more than once, form the speed increase theory of existing lines and greatly increase the train speed of existing lines. At the same time, the structure of transport products was adjusted; express and fast passenger trains in various forms such as "evening-departure and morning-arrival," "morning-departure and evening-return" and "one-day arrival," as well as rapid freight trains in various forms such as luggage and parcel-dedicated trains and "five scheduled" trains, were operated. At the same time, the *Main Technical Policies for Railways* (4th edition) promulgated in October 2000 also adjusted the sequence of train weight, density and speed to train speed, density and weight, and put forward a new policy of "generally increasing the traffic speed, actively increasing the traffic density and reasonably determining the train weight."

The evolution of train speed, density, weight sequence and the change of wording intensity in the *Main Technical Policies for Railways* reflected that the general increase of train speed, especially the speed of passenger trains, was the key point of railway development during this period, and meanwhile, the capacity was expanded by speed increase, reflecting the transformation of China's railway from the focus on freight transport to both passenger and freight transport, from attaching importance to the growth of transport quantity to taking into account of both quantity and quality, from the emphasis on expanding transport capacity and improving economic benefits to meeting transport market demand and improving economic and social benefits (He, 2005).

Based on the reality and policy requirements, during the ten years from 1997 to 2007, six large-scale speed increases were implemented successively in China's railway. The main contents and effects are shown in Table 2. By upgrading small radius curve, replacing speed increase turnout, laying continuously welded rail, replacing new sleeper, rectifying line disease, changing level crossing to vertical crossing, closing fence, changing three-aspect automatic block to four-aspect automatic block, installing general locomotive signal, adopting speed increase locomotive and rolling stock, etc. (Tian, Xiao, & Xu, 2002a), the speed of line with an extended mileage of 22,000 km and a design speed of not more than 120 km h^{-1} were increased to 140,160 or 200 km h^{-1} and above. Compared with 1996, the technical speed and traveling speed of passenger trains in 2007 were increased by 34.2% and 39.2%, respectively (see Table 1). The speed increase of existing lines drove the increase of railway train density and weight correspondingly. Through the speed increase upgrading, the interval time of train tracking was further reduced; the minimum tracking interval time of EMU trains was shortened to 5 min; the minimum tracking interval time of ordinary passenger trains was shortened to 6 min; and the minimum tracking interval time of freight trains was shortened to 7 min. Transport organization measures, such as train dispatching in succession, was adopted, and the traffic density was improved. The number of passenger and freight trains on some lines exceeded 130 pairs. Compared with 1996 (see Table 1), the passenger traffic density and the density of freight traffic increased by 85.0% and 52.4%, respectively, in 2007. Through speed increase upgrading, double track railway, electrified railway and arrival and departure track with the effective length of 1,050 m were increased; the train weight was improved; and the average weight of freight trains was increased by

Table 2.
Main contents and effects of six speed increases for China's railway

Speed increase time	Main contents	Effect
The 1st speed increase April 10, 1997	Focusing on Beijing–Shanghai, Beijing–Guangzhou (Beijing–Wuhan) and Beijing–Harbin trunk lines, the speed increase was implemented with the highest operation speed of 140 km h^{-1}. For the first time, 78 trains of "evening-departure and morning-arrival" were launched	The extended mileage of lines above 120 km h^{-1} was 1,398 km, including 58 km of 130 km h^{-1}, 588 km of 140 km h^{-1} and 752 km of 160 km h^{-1}. The scheduled technical speed of passenger trains was 63.7 km h^{-1} and the traveling speed was 54.9 km h^{-1}, which were 5.3 and 6.8 km h^{-1} higher than those in 1993, respectively
The 2nd speed increase October 1, 1998	The 140 km h^{-1} speed increase lines were extended with the focus on Beijing–Shanghai, Beijing–Guangzhou and Beijing–Harbin trunk lines, and the number of speed increase passenger trains was increased. The number of "evening-departure and morning-arrival" trains was increased to 228, including 116 cross-administration "evening-departure and morning-arrival" trains	The extended mileage of 120 km h^{-1} line was 11,868 km, and that of line above 120 km h^{-1} was 6,449 km, including 456 km of 125 km h^{-1}, 1,367 km of 130 km h^{-1}, 3,522 km of 140 km h^{-1} and 1,104 km of 160 km h^{-1}. The technical speed of scheduled passenger trains was 63.95 km h^{-1}, and the traveling speed was 55.16 km h^{-1}. Tilting train X2000 was adopted on Guangzhou–Shenzhen Railway, and the maximum operation speed reached 200 km h^{-1}
The 3rd speed increase October 21, 2000	The speed increase lines extended to the southwest, and the key lines were Lanzhou–Lianyungang, Lanzhou–Urumchi, Beijing–Kowloon and Zhejiang–Jiangxi railways, etc. There were 266 "evening-departure and morning-arrival" trains, including 138 cross-administration "evening-departure and morning-arrival" trains	The extended mileage of lines above 120 km h^{-1} was 9,581 km, including 456 km of 125 km h^{-1}, 1,053 km of 130 km h^{-1}, 510 km of 135 km h^{-1}, 6,458 km of 140 km h^{-1} and 1,104 km of 160 km h^{-1}. The technical speed of scheduled passenger trains was 68.17 km h^{-1} and the traveling speed was 59.92 km h^{-1}
The 4th speed increase October 11, 2001	Speed increase was mainly implemented through electrification upgrading, single track upgrading and model replacement. Wuhan–Guangzhou section of Beijing–Guangzhou railway and Harbin–Dalian railway were sped up in combination with electrification upgrading; Zhejiang–Jiangxi railway was sped up by changing the model; Wuhan–Chongqing and Chengdu Passage (Hankou–Danjiangkou railway, Xiangyang–Chongqing railway, Dazhou–Chengdu Railway) and Beijing–Kowloon railway were sped up through technological upgrading. There were 237 "evening-departure and morning-arrival" trains, including 118 cross-administration "evening-departure and morning-arrival" trains	The extended mileage of lines above 120 km h^{-1} was 13,838 km. The technical speed of scheduled passenger trains was 70.32 km h^{-1} and the traveling speed was 61.92 km h^{-1}

(*continued*)

Speed increase time	Main contents	Effect
The 5th speed increase April 18, 2004	Qinhuangdao–Shenyang Passenger Dedicated Line was put into operation; the speed increase upgrading of Beijing–Shanghai railway, Beijing–Guangzhou railway (north of Wuchang), Beijing–Kowloon railway and Beijing–Qinhuangdao railway was completed; speed increase upgrading of road and bridge corridors was completed; double track of Baoji–Lanzhou section was completed and opened to traffic; double track of Zhuzhou–Liupanshui Railway was put into operation and sped up. The maximum operation speed was 160 km h^{-1}. For the first time, 19 pairs of non-stop express passenger trains (non-stop train number starting with Z) were operated, and locomotives directly supplied power to passenger cars. There were 305 "evening-departure and morning-arrival" passenger trains, including 169 cross-administration "evening-departure and morning-arrival" trains	The extended mileage of lines above 120 km h^{-1} was 16,500 km, including more than 7,700 km of lines above 160 km h^{-1}. The traveling speed of scheduled passenger trains was 65.7 km h^{-1}, that of non-stop express trains was 119.2 km h^{-1} (non-stop train number starting with Z), and that of express passenger trains was 92.8 km h^{-1}. 11 non-stop express trains departed successively on Beijing-Shanghai Railway at the interval of 7 min during prime time
The 6th speed increase April 18, 2007	High-speed EMU trains were introduced, the maximum operation speed was increased to 200 km h^{-1}. There were 18 speed increase lines, including Beijing–Shanghai, Beijing–Harbin, Beijing–Guangzhou, Beijing–Kowloon, East Lanzhou–Lianyungang, Zhejiang–Jiangxi, Qingdao–Ji'nan, Guangzhou–Shenzhen and Lanzhou–Urumchi railways, etc. There were 337 "evening-departure and morning-arrival" trains, 26 pairs of non-stop express passenger trains (non-stop train number starting with Z), and 257 pairs of 200 km h^{-1} and above EMU trains	The extended mileage of lines above 120 km h^{-1} was 22,000 km, that of lines above 160 km h^{-1} was 14,000 km, that of lines above 200 km h^{-1} was 6,003 km, and that of lines above 250 km h^{-1} was 846 km. The traveling speed of passenger trains was 70.18 km h^{-1}

Table 2.

22.7%. Generally, 5,000 and 5,500 t freight trains were operated on the busy trunk lines such as Beijing–Shanghai, Beijing–Guangzhou and Beijing–Harbin railways (China Railway Society, 2008).

Through speed increase, 200 km h^{-1} EMU trains, 160 km h^{-1} ordinary passenger trains and 5,000 t freight trains were operated on the same line, which created a new record of potential tapping and capacity expansion of existing railway lines in China, realized the purpose of speed increase and capacity expansion and initially released the "bottleneck" restriction of railway transportation. As a successful practice of promoting the coordinated development of train speed, density and weight of existing lines, it made important contribution to national economic and social development, and gained wide high appreciation of society. The phrase "speed increase" became the synonym for changing the existing backward concept and practice at that time and implementing accelerated development and rapid progress. The speed increase of railway made the speed increase technology of existing lines in China reach the world advanced level and laid a good foundation for the development of high-speed railways later.

2.3 Developing high-speed railway (2008—Now)

After 10 years' railway speed increase, especially in the late stage of speed increase, railway people generally realized that speed increase on existing lines was far from meeting the demand of people for convenient and fast travel, and it was even more difficult to greatly improve the transport capacity and solve the difficulty of freight transport. To implement the development mode of passenger and freight separation and high-speed passenger transport, the development of high-speed railway became an inevitable trend. Therefore, in August 2004, the *Main Technical Policies for Railways* (5th edition) continued to emphasize "generally increasing train speed, actively increasing train density and appropriately increasing train weight," and meanwhile, put forward "seriously implementing the Mid-and-Long-Term Railway Network Plan", "developing passenger dedicated lines between large and medium-sized cities and developing intercity railways in densely populated areas," "the speed of passenger dedicated lines is 200–350 km h^{-1}," "the interval time of train tracking is 3–4 min", "establishing the general development goal of coordinated development of high-speed passenger transport, heavy-load freight transport and high traffic density." It could be seen that the 5th edition of *Main Technical Policies for Railways* maintained the development sequence of train speed, density and weight, and meanwhile, it begun to shift the development focus to high-speed railway (Ministry of Railways of the PRC, 1983–2013).

In fact, the sixth large-scale speed increase of railway was not only a large-scale speed increase of existing lines, but also a preview of developing high-speed railway.

"AC-DC-AC" power decentralized high-speed EMU and CTCS-2 train control system were adopted for speed increase trains. The train control center and balise were adopted on the ground, and PD3 rail, heavy sleeper, I-class ballast, No. 18 turnout and 1.25 m high platform were adopted for speed increase lines in a large area, which were the technical equipment and standards adopted by the high-speed railway later.

On August 1, 2008, the first high-speed railway, Beijing–Tianjin intercity railway, was put into operation, marking the all-round entrance into the era of high-speed railway in China. Subsequently, thousands of kilometers of high-speed railways were put into operation every year. Therefore, the *Main Technical Policies for Railways* (6th edition) promulgated in January 2013 proposed to "accelerate the formation of a fast passenger transport network with "four north-south lines and four west-east lines" as the skeleton," "give priority to the construction of passenger dedicated lines with different speed classes in urban dense areas," "build and improve passenger transport with high speed and convenience, heavy load and rapidness, and reasonable match of speed, density and weight," indicating that the focus of railway development in this period was high-speed railway; at the same time, *Main Technical Policies* *for Railways* (6th edition) defined high-speed railway, heavy haul railway and passenger-freight railway respectively, and put forward requirements for the technical indicators of speed, density and weight of the three types of railway.

During this period, China's national strength increased obviously; the investment in railways increased significantly; and the length of railways in operation increased rapidly. On average, more than 6,600 km of new lines were put into operation every year, of which nearly 3,000 km of high-speed railways were put into operation (see Table 1). By the end of 2021, the length of railways in operation in China has reached 150,000 km, of which the length of high-speed railways was 40,000 km, forming high-speed railways with various speed classes such as 300–350 km h^{-1} and 200–250 km h^{-1}, and the length of 350 km h^{-1} high-speed railways has reached 14,600 km; the interval time of train tracking was 4 min, and the daily traffic volume was up to 160 pairs; there were 8-car, 16-car and a small number of 17-car EMU train formations (16-car and 17-car EMU train formations were put into operation on Beijing–Shanghai high-speed railway in 2019).

At present, high-speed railways have been put into network operation. The railway network structure is more optimized, and the transport capacity is greatly improved. The railway capacity to meet the passenger and freight transport needs is increasing day by day, and the situation of tight transport capacity has been basically eliminated. The "limiting section" has been basically eliminated, and the transportation "bottleneck" and weakness have been significantly reduced. The sequence of train speed, density and weight development is not as obvious as before. It is no longer necessary to emphasize what is to be developed "vigorously," what is to be developed "generally" and what is to be developed "appropriately." Therefore, the development direction of train speed, density and weight has become different from that of the first two stages, and the three are in a new stage of on-demand development and co-development.

3. Development direction of train speed, density and weight

In the past 40 years, with the development of China's railway, train speed has experienced several stages such as "appropriate improvement," "vigorous improvement," "general improvement" and "high speed development"; train density experienced several stages such as "increasing," "actively increasing" and "actively enlarging"; train weight experienced several stages such as "gradually increasing," "vigorously improving," "reasonably determining" and "appropriately increasing." The development emphases of the three were different at different stages. At the stage of potential tapping and capacity expansion, connotative development was emphasized, while the speed increase stage was the extension and upgrading of the stage of potential tapping and capacity expansion, making the potential tapping and capacity expansion of railway rise to a new stage and a higher level. Nowadays, China's railway is in the period of high-speed railway development, and the development scale far exceeds the planned one. As for whether the lines that are put into operation every year, or the lines that are under construction or planned, their scale is great. China's railway is in a new stage of expanding reproduction, and the pattern of railway transport has undergone a fundamental change. Railway transport is changing from capacity restriction and adaptability to high-quality service. Such development trend promotes the development of railway train speed, density and weight to a higher level.

3.1 Train speed

After six large-scale speed increases, China's conventional railway has formed a pattern of passenger trains with the maximum operation speed of 160 km h^{-1}, ordinary freight trains with the maximum operation speed of 80 and 90 km h^{-1}, and express freight trains with the maximum operation speed of 120 and 160 km h^{-1}. In the future, passenger trains driven by locomotives shall be gradually replaced by 160 and 200 km h^{-1} power decentralized EMUs and new power centralized EMUs. The maximum operation speed can still be maintained at 160 km h^{-1}, but the quality of passenger service will be greatly improved. The spacing of mixed passenger and freight railways with the designed speed of 200 km h^{-1} is 4.4 m. Based on several studies and tests, after certain safety measures were taken for freight trains, high-speed trains and freight trains could be operated normally on the same line, without requiring passenger and freight trains not to meet each other. High-speed railway greatly improves the operation speed, technical speed, traveling speed and service quality of passenger trains. The designed operation speed of high-speed railway shall be gradually resumed; a complete set of technology shall be further studied and developed for 400 km h^{-1} high-speed railway; and 400 km h^{-1} high-speed trains shall be operated to promote railway technology to a new level. High-speed freight trains can be operated after the technical operation conditions at the departure and arrival terminals of high-speed railway are met. At present, the problems such as the departure and arrival operations, station loading and unloading operations, the running tracks of hub and technical economy shall be solved emphatically.

3.2 Train density

LKJ, the train operation monitoring device of conventional railway, shall be subject to the speed continuous control mode. The CTC central station centralized control mode, centralized traffic control, moving block and locomotive automatic driving technology shall be gradually popularized and applied, which will be beneficial to improving the organization of train operation, reducing the interval time of train tracking, increasing the traffic density and ensuring the traffic safety. In the double-track automatic block section, the tracking interval time of EMU trains can be reduced to 5 min, ordinary passenger trains can be reduced to 6 min and that of freight trains can be reduced to 7 min. The carrying capacity of parallel train diagram can be improved by 10–20%, and the train density can reach 110–120 pairs $\cdot$ d^{-1}. When the passenger trains are at 50 pairs $\cdot$ d^{-1}, the annual freight volume of the track section can reach more than 70 million tons. Automatic inter-station block is widely used in single track railway. The carrying capacity of parallel train diagram can reach more than 50 pairs, and the maximum traffic density can be increased to more than 35 pairs $\cdot$ d^{-1}.

At present, the maximum traffic density of high-speed railway reaches 160 pairs. In order to further improve the traffic density of busy lines, it is still an important way to shorten the interval time of train tracking and achieve the design goal of 3 min. At present, the main factors affecting the 3 min tracking interval time of high-speed trains refer to the complex throat structure of large passenger station, the long train route, and the limitation on the utilization of braking capacity of EMUs and the configuration of train control system parameters. To reduce the interval time of train tracking, it is necessary to optimize the line design, design the station with many connecting directions and arrival and departure tracks by yard as far as possible, and shorten the throat length of the station; it is necessary to improve the utilization rate of braking capacity of EMUs, reduce the route processing time, completely cancel the successive route of high-speed railway, adopt moving block and automatic train operation system (ATO), optimize the operation method of train reception and departure and the use method of arrival and departure track, and adopt the same operation speed in the same track section to avoid speed difference between trains (China Railway Corporation, 2015). After the above measures are taken, it is possible that the interval time of train tracking can be reduced to 3 min and the maximum traffic density can reach more than 190 pairs $\cdot$ d^{-1}. The station yard structure of urban railways is relatively simple, and the design speed is lower than that of high-speed railway. With the adoption of the optimized train operation control system, the interval time of train tracking can be up to 2.5 min, and the maximum number of operating train pairs in peak hours can be up to 24 (China Railway Society, 2017).

3.3 Train weight

In terms of passenger trains, EMU train formations mainly include 8-car, 16-car and a small number of 17-car formations. In the future, 16-car formation can be adopted in the direction and time period (holidays and weekends) with large passenger flow volume and in busy sections, while short 8-car train formation can be adopted for intercity railway and urban railway. The ordinary passenger train formation is determined according to the demand, and the maximum number is not more than 20 cars; power centralized EMUs will gradually replace the existing passenger trains driven by locomotives, and the long formation can be up to 19 cars to improve the quality of railway passenger service. 160 and 200km/h decentralized EMU will also be widely promoted and applied in conventional railway. It is predictable that small formation and high-density traffic will become the inevitable requirement of passenger transport market with increased intercity railway and suburban railway. In the same time, there will be more small formation train operated in short-distance high-speed railway and other short-distance passenger transport. The railway passenger train number will increase sharply in our country, but the average number of cars for formation will reduced.

In terms of freight trains, freight transport will continue to develop in the direction of heavy load, express and high efficiency in the future. The axle load of 160 km h^{-1} express freight trains does not exceed 17 *t*, while that of 120 km h^{-1} express freight trains does not exceed 18 *t*, and the train weight is about 1,500 *t*; the weight of high-speed express freight trains does not exceed 1,000 *t*. At present, the axle load of ordinary freight cars is mainly 23 *t*, while that of special-purpose freight cars is 25 *t*. In the future, the general-purpose freight car with axle load of 27 *t* shall be popularized, and freight car with axle load of 30 *t* shall be researched and developed, so the number of freight car with heavy axle load will increase to a certain extent. Since 2006, except for particular-kind freight cars and special-purpose freight cars, the national railway has no longer purchased freight cars with a load below 70 *t*, which creates conditions for further improving the static load of freight cars. In 2017, freight cars with marked loading capacity of 70 *t* and above accounted for 49.8% of the total, and the static load of coal cars reached 69.8 *t* on average. In practice, the vehicle load per meter of track can reach 6.54 $t\,m^{-1}$ ($= 93.6 \div 14.3$). Based on these conditions, the freight train weight of arrival and departure track with the effective length of 850 m series can be increased to 5,000 *t* ($\approx(850-40-30) \times 6.54$), and the converted length is 70; the freight train weight of arrival and departure track with the effective length of 1,050 m series can be increased to 6,400 *t* ($\approx(1{,}050-40-30) \times 6.54$), and the converted length can be increased to 89. Therefore, it is appropriate to determine the freight train weight of arrival and departure track with effective length of 850 m series and 1,050 m series as 4,500–5,000 *t* and 5,500–6,400 *t* respectively.

4. Conclusion

Train speed, density and weight are the most representative indicators of railway transport capacity and quality, which are closely related. China's economic and social development pattern and its demand for transportation determine that China's railway train speed, density and weight must be given consideration correspondingly. The development practice of railway over the past 40 years has also been promoting the three to be taken into account correspondingly, and they have distinct characteristics in different periods. Promoting the coordinated forward development of the three and making them reach the world advanced technology level improve the transport capacity and quality of China's railway. At present, China's railway has been in a new stage of development, and the tasks of strengthening foundation, ensuring safety, improving quality and increasing benefits are arduous. It is necessary to continue to expand the scale of railway network, vigorously develop high-speed railway, and pay more attention to improving the efficiency and benefits of railway operation, which gives new connotations and requirements to the railway train speed, density and weight. With the development of railway and the constant adjustment of transport demand, as well as the popularization and application of new railway technologies, China's railway train speed, density and weight will be developed towards a higher level to provide stronger transport capacity and better transport services for the society.

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