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Vehicle Selection for Metropolitan Rail Service

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Abstract: The development of metropolitan rail service in China is lagging behind, which has become an obstacle for urban public transportation. There is no standardized system for vehicle selection. By analyzing the vehicle selection practice in the world, the technical criteria of existing vehicles, and vehicle technical indicators of major automobile manufacturers in China, this paper puts forward the selection principles that meet the requirements of matching functionalities, environmental protection, and economy. Through studying the vehicle selection for metropolitan (suburban) rail service, the paper establishes vehicle selection indicators in functionality and serviceability. Finally, the paper proposes the working procedures to guide the vehicle selection of metropolitan (suburban) rail service. **DOI:** 10.13813/j.cn11-5141/u.2020.0106-en

Keywords: metropolitan (suburban) railway; vehicle selection; functional indicators; service indicators; working procedures

0 Introduction

The metropolitan (suburban) railway is an important component of a city's comprehensive transportation system. It provides fast and large-capacity rail transit commuter service to connect the central urban area and surrounding town groups [1]. The requirements of the development of metropolitan (suburban) rail were clearly specified in the *Guiding Opinions on Promoting the Development of Metropolitan (suburban) Rail* (Development and Reform Foundation [2017] No.1 173) as follows: "By 2020, the major metropolitan (suburban) railway lines should mostly be built in megacities, megapolises, or certain large cities that meet the conditions in economically developed areas, such as the Beijing-Tianjin-Hebei urban agglomeration, the Yangtze River delta, the Pearl River delta, the middle reaches of the Yangtze River, and the Chengyu megapolis, to build the one-hour commute circle of the core area to the main surrounding areas. Moreover, the planning and construction of metropolitan (suburban) rail should begin for the remaining urban agglomerations and cities with necessary conditions in urbanized areas". Cities such as Beijing, Shanghai, Guangzhou, Chengdu, and Chongqing have clearly imposed requirements for the development of regional express lines and suburban railways in their urban plans and special transportation plans. Various major cities have ushered in a period of rapid development of metropolitan (suburban) rail, and several departments have also released relevant standards to clarify the design standards of metropolitan (suburban) rail, including *Code for Design of Metropolitan Rapid Rail Transit System* (T/CCES2-2017) and *Code for Design of City Railway* (T/CRSC0101-2017).

The choice of the rail transit system and the rail vehicle affects the transportation capacity and service level of the system, which is an important factor in the overall plan of the rail transit system. Therefore, how to choose a reasonable vehicle type is an important task for the development of metropolitan (suburban) rail. This paper summarizes the types and related specifications of the metropolitan (suburban) rail vehicles in the world and compares the existing technical standards in China with the vehicle technical specifications from vehicle manufacturers. It proposes vehicle selection principles for the metropolitan (suburban) rail based on the current development status and trend of the industry, establishes vehicle functionality and serviceability requirements, and presents the workflow for the comparison and selection of metropolitan (suburban) rail vehicles.

1 Characteristics of metropolitan rail vehicles

The metropolitan (suburban) rail vehicles that are in operation or under construction were analyzed to sort out vehicle characteristics such as the maximum speed, marshalling, passenger capacity, power supply, and seat arrangement (see Table 1).

Based on the comparison of the relevant attributes of metropolitan (suburban) rail vehicles, their characteristics are summarized below:

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Table 1 Characteristics of different types of metropolitan (suburban) rail service vehicles

Railway line	Vehicle type	Vehicle manufacturer	Maximum running speed/(km/h)	Number of cars	Passenger capacity/persons	Power supply system	Seat arrangement	Other special services
Tokyo Tsukuba Express	DC vehicle TX-1000 series	Kawasaki Heavy Industries	130	6	Rated capacity 926	DC 1 500 V	Longitudinal	Wheelchair space
	AC-DC vehicle TX-2000 series				Rated capacity 916	AC 20 kV	Longitudinal + Transverse	
London Crossrail	ELIZABETH LINE TRAINS	Bombardier	160	10	Maximum capacity of 1 500 passengers per train	AC 25 kV	Transverse + Longitudinal	Wheelchair space, real-time information, free Wi-Fi
Hong Kong Airport Express	Adtranz-CAF electric train	Co-manufactured by Spain CAF and German ADTRANZ (acquired by Bombardier)	140	8	Maximum capacity 350	DC 1 500 V	Transverse	Luggage rack, free Wi-Fi, charging outlet
Taiwan Taoyuan Airport MRT	Express train	Kawasaki Heavy Industries	100	5	320 seats	DC 1 500 V or 750 V	Transverse	Free Wi-Fi, charging outlet
	Commuter train	A vehicle manufacturer in Taiwan		4	256 seats		Longitudinal	
Shanghai Rail Transit Line 16	AC 19 electric train	CRRC Zhuzhou Locomotive Co., Ltd.	120	3 (some have 6)	A train with 3 rail cars can carry up to 1 218 passengers	DC 1 500 V	Transverse	Wheelchair space
Shanghai Jinshan Railway Line	CRH6A	CRRC Qingdao Sifang Co., Ltd.	200	8	Rated capacity 557, Maximum capacity 1 488	AC 25 kV	Transverse	Toilet, Wi-Fi, wheelchair space
Ningbo Yuci Intercity Line	CRH6F	CRRC Qingdao Sifang Co., Ltd.	160	8	510 seats with maximum capacity of 1 950	AC 25 kV	Transverse	Toilet, wheelchair space
Beijing Sub-center Line	CRH6A	CRRC Qingdao Sifang Co., Ltd.	200	8	771 seats with maximum capacity of 1 471	AC 25 kV	Transverse	Toilet, wheelchair space
Chengguan Railway Line	CRH6A-4002 EMU	CRRC Qingdao Sifang Co., Ltd.	200	8	484 seats with maximum capacity of 1 479	AC 25 kV	Transverse	Toilet, wheelchair space
Beijing Suburban Railway Line S2	NDJ3 “Harmony Great Wall” internal combustion EMU	CSR Qishuyan Locomotive and Rolling Stock Works (Locomotive), CSR Nanjing Puzhen Vehicle Factory (Passenger car)	200	9	Rated capacity 406	Diesel engine	Transverse	Toilet, wheelchair space
Wenzhou City Line S1	Wenzhou S1 EMU	CRRC Qingdao Sifang Co., Ltd.	140	4	192 seats with rated capacity of 902 and maximum capacity of 1 328	AC 25 kV	Longitudinal + transverse	Wheelchair space

Source: The sources for Tokyo Tsukuba Express, London Crossrail Line, Hong Kong Airport Express and Taiwan Taoyuan Airport MRT are References [2–5], and the sources for other railways are Baidu Encyclopedia and the product introduction on the official website of the corresponding vehicle manufacturer.

1) Overseas metropolitan (suburban) railways pay more attention to speed and comfort: The train’s maximum speed is generally 130–160 km/h with the travel speed of 50–80 km/h. Since the metropolitan (suburban) rail serves long distance trips, the transverse seat arrangement is adopted, and most of the space in a railroad car is used to place seats.

2) Overseas metropolitan (suburban) railways have realized flexible operation on multiple rail tracks. Moreover, some rail lines have adopted diversified vehicle models to adapt to power supply facilities in different sections.

3) The selection of vehicles is more flexible in China. For example, to fulfill the same purpose to provide rail transit service between the urban center and suburban towns, Shanghai Rail Transit Line 16 uses the vehicles for urban rail transit express lines with the speed of 120 km/h, while Shanghai Jinshan Railway Line and Beijing Sub-center Line use EMUs with the speed of 200 km/h.

4) The selection of vehicles for some metropolitan (suburban) railways in China is not reasonable. The vehicle selection did not fully match the railway specifications after existing railways were transformed to provide metropolitan (suburban) rail service. For example, the design speed of Beijing Sub-Center Line is 160 km/h, but a vehicle model of 200 km/h was selected. As a result, not only the performance of the vehicle is not fully realized, but also the line travel speed is reduced due to the relatively low acceleration and deceleration capabilities of high-speed vehicles. In addition, Beijing Suburban Railway Line S2 uses NDJ3 “Harmony

Great Wall" internal combustion EMUs driven by diesel engines, which is not in line with existing environmental protection concepts.

5) There is a certain gap in personalized equipment between trains in China and abroad. Personalized equipment for trains refers to other equipment that is provided beyond the basic level of train service to improve the comfortableness of passengers, such as free Wi-Fi and multimedia devices to broadcast real-time news. At present, Wi-Fi is not popular in metropolitan (suburban) trains in China, and the multimedia devices on the trains have not been used to play real-time information.

2 Analysis of technical specifications of rail vehicles in China

2.1 Industrial standards

This paper sorted out the published metropolitan (suburban) railway design standards, *Code for Design of City Railway* (T/CRS C0101-2016) and *Code for Design of Metropolitan Rapid Rail Transit* (T/CCES2-2017). From the perspective of functional planning, the main technical specifications of rail vehicles involved in these standards include the power receiving method, power supply system, horizontal and vertical curve radius, maximum slope, body width, interior height, door width, maximum operating speed, acceleration, braking speed, and number of standing passengers per square meter of floor area. Comparing these two standards shows that the values of the major specifications are basically the same. For example, both set the design speed of the metropolitan (suburban) railway to 100–160 km/h and the power supply to AC 25 kV [6–7].

2.2 Manufacturer's standards

To promote the technical resource sharing and the localization of vehicle technology, this paper studied the vehicles manufactured by CRRC Changchun Railway Vehicles Co., Ltd. (hereinafter referred to as "CRRC Changchun") and CRRC Qingdao Sifang Co., Ltd. (hereinafter referred to as "CRRC Sifang"). Moreover, it collected relevant vehicle data to be used as the basis for the selection of metropolitan (suburban) rail vehicles. Both companies have municipal (suburban) railway vehicles with a maximum operating speed of 120 to 200 $km \cdot h^{-1}$.

A summary of the vehicles manufactured by the two vehicle manufacturers shows that the existing metropolitan (suburban) rail vehicles have the following three characteristics: 1) The maximum running speed is basically 120–200 km/h. 2) The power supply system is mainly AC 25 kV, and some vehicles use DC 1 500 V. 3) The product portfolio is basically the same and includes four types of vehicles: ① intercity train with the maximum speed above 200 km/h; ② City Type A train; ③ train running at reduced speed on the national railway network with the maximum speed of 120–160 km/h; ④ City Type D train. However, as of 2017, only the CRH6A intercity EMUs and the CRH6F intercity EMUs manufactured by CRRC Sifang have obtained the qualification (including the model certificate and manufacturing license) from China State Railway Group Co., Ltd., which are allowed to enter the national railway network.

3 Principles of vehicle selection

Based on the experience in selection of urban rail transit vehicles and combined with China's relevant policies, development concepts and existing vehicle technology standards, the main principles of vehicle selection are proposed:

1) Adapt to the functional positioning requirements of metropolitan (suburban) rail: The *Guiding Opinions on Promoting the Development of Metropolitan (Suburban) Rail* (Development and Reform Foundation [2017] No. 1173) proposed that "the functional positioning of metropolitan (suburban) rail should be reasonably determined according to its demand characteristics, passengers, and service scope". At present, many major cities have prepared relevant plans for metropolitan (suburban) rail. Therefore, vehicle selection should comprehensively consider vehicle models that meet the standards, so that the selected vehicle model can conform to the technical positioning of metropolitan (suburban) rail.

2) Adapt to urban environmental conditions and environmental protection requirements: Xi Jinping stated in the report of the 19th National Congress of the Communist Party of China that "we must establish and implement the concept that clear waters and green mountains are as valuable as mountains of gold and silver and adhere to the basic national policy of saving resources and protecting the environment." When choosing a vehicle model, we should take into account the characteristics of the project line and the climatic environmental conditions on the one hand, and on the other hand, reduce the impact on the environment and landscape along the line.

3) Comply with resource sharing of maintenance technology: All factors should be considered and coordinated. Moreover, the selection of vehicle types should be controlled to realize the resource sharing of vehicles, maintenance equipment, and human resources in the urban rail transit network.

4) Consider the cost characteristics and comprehensively compare economy, safety, and adaptability factors: Considering functional requirements, construction investment, and operating cost, the vehicles with low life cycle cost (all costs associated with the product during its effective use period, including product design, manufacturing, procurement, use, maintenance, and waste disposal) should be selected. At the same time, the characteristics of various models are different.

Hence, different influencing factors must be analyzed based on engineering practice, and they should be assigned with different weights to compare and select vehicle models comprehensively.

5) Encourage new technologies and take into account China's national conditions and needs: Both technical maturity and technical renovation should be considered. New technologies should be encouraged, and vehicles that are economical, practical, safe, reliable, and easy to maintain should be selected in accordance with national conditions.

6) Encourage localization of vehicle technology: The national policy on the localization of urban rail transit vehicles should be conformed to. Vehicles that are conducive to localization and can meet the localization rate requirement should be selected. China-made vehicles should be encouraged in operation.

4 Comparison of vehicle functionality

Since the metropolitan (suburban) rail provides public transportation service between the central urban area and surrounding towns and cities, its vehicles must meet the fast and large-capacity requirements for commuter public transportation. Some metropolitan (suburban) rail service can use existing railways, and the need to connect to national railways should be considered. In addition, the selection of vehicles should also consider the corresponding economic cost. Therefore, a comparison and selection system is established from the perspective of the functionality of the metropolitan (suburban) rail, and it includes five aspects: safety, speed, capacity, interoperability, and cost.

4.1 Safety

Safety is the bottom line of transportation operations and service. The metropolitan (suburban) rail uses the same operation mode as that for buses. After purchasing tickets, passengers get on the train and choose their own seats, which may cause extreme congestion during peak hours, so the load level of vehicles must meet certain requirements. The overload level refers to the number of passengers on the train in the extreme load conditions, in which all seats are occupied and all floor areas are taken by standing passengers at the maximum rate. Based on the investigation of vehicle manufacturers, the overload levels of different models are obtained (see Table 2). For existing models, different vehicle models have various load levels. Among them, City Type A and City Type D have a greater advantage than intercity vehicles in terms of load levels. The vehicle selection in practice should consider the safety of the railway according to the scale of its passenger flow and actual operating conditions.

4.2 Speed

Metropolitan (suburban) rail must meet the demand for speedy travel, so it imposes a higher requirement for travel speed (also known as average speed, which refers to the average speed of the train traveling through a certain section).

Table 2 Overload levels of different types of vehicles

Train manufacturer	Vehicle model	Speed level/(km/h)	Vehicle overload level/(person/m^{-2})
	City Type A	120–160	8
	City Type D	120–160	8
CRRC Changchun	Hybrid Intercity 160	160	
	Intercity 160	160	6
	Intercity 200	200	
	140 City Type A	140	8
	140 City Type D	140	8
CRRC Sifang	140 Dual System Intercity	140	7
	CRH6F	160	6
	CRH6A	200	4

Source: Vehicle technical specifications provided by CRRC Changchun and CRRC Sifang.

Vehicle travel speed is related to factors such as station spacing, design speed, acceleration, deceleration, and slope. Generally, railway lines that serve larger spatial areas have longer line length and larger station spacing, and therefore higher design speed. The matching vehicles then have higher design speed and smaller acceleration and deceleration capacity. At present, the design speed of metropolitan (suburban) rail has four levels: 120 km/h, 140 km/h, 160 km/h, and 200 km/h, and they have different acceleration and deceleration performance.

A reasonable vehicle model should be selected to meet the operating requirement for the maximum speed ratio (refers to the ratio of the distance traveled at the highest speed to the distance between the two stations when the vehicle is traveling between the two stations). For a specific station spacing and vehicle design speed, the longer acceleration and deceleration distance can lead to the higher travel speed, but the energy consumption during acceleration and deceleration is far greater than that when vehicles are running at an even speed. Therefore, the speed and energy consumption factors should be comprehensively weighted to select a reasonable range for the maximum speed ratio [8]. A higher maximum speed ratio indicates a lower level of vehicle speed, so a vehicle model with a higher speed could be used to reduce running time. A lower maximum speed ratio means that the vehicle has a longer distance to accelerate and decelerate and a shorter distance to run at an even speed. Therefore, a vehicle with a lower speed could be selected to save the investment cost on vehicles. The acceleration and deceleration performance of vehicles with different speed levels can be obtained from the industrial standards, and they can be used to estimate the maximum speed ratios of vehicles with different speed levels given the same station spacing (see Figure 1).

The station spacing for China's national railways is generally large, and the maximum speed ratio is generally above 50% according to the experience in the construction and operation of existing lines. Metropolitan (suburban) railways serve the metropolitan area, and their station spacing has greater flexibility, which is between the station spacing for

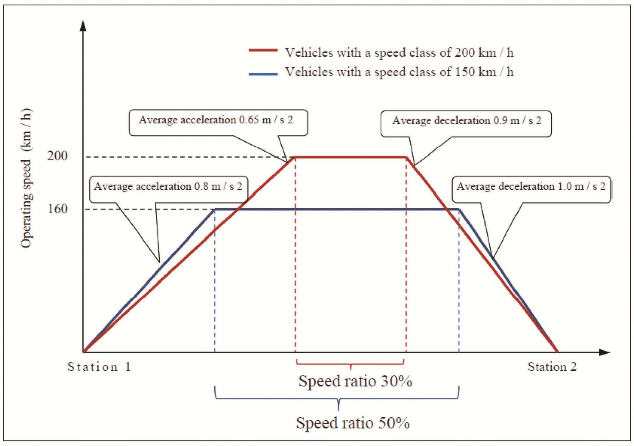

Figure 1 Relationship between station spacing and speed ratio for metropolitan(suburban)rail vehicles at different speed levels

Source: Reference [9].

national railways and urban subways and currently lacks clear engineering standards. After the factors such as vehicle speed and energy consumption are weighed, a reasonable maximum speed ratio is recommended to be around 50%. This paper uses the maximum speed ratio range of 40% to 60% to estimate the range of applicable station spacing for vehicles with different design speeds, which are used as the selection criteria for vehicles on different railway lines.

In this paper, the dwell time at the intermediate station is set to 1 min, and the maximum speed ratio is considered to be in the range of 40% and 60%. Based on the acceleration and deceleration capabilities of four vehicle models with the speed of 120 km/h, 140 km/h, 160 km/h, and 200 km/h, the station spacing and travel speed of each vehicle model are calculated (see Table 3). The results show that under the constraint of the optimal maximum speed ratio, the optimal station spacing for the four vehicle models is in general continuously distributed between 3–17 km, and the optimal travel speed is 53–125 km/h. The results also show that the higher speed level indicates the larger corresponding station spacing. Therefore, a vehicle with an appropriate speed level can be selected based on the station spacing of the railway line.

Table 3 Optimal distance between stations and travel speed under different design speeds and maximum speed ratios

Variable	Speed level/(km/h)			
	120	140	160	200
Minimum acceleration distance/km	1.2	1.9	2.8	5.1
Minimum deceleration distance/km	0.6	0.8	1.1	17.1
Station spacing with maximum speed ratio of 40% /km	3.0	4.5	6.5	11.4
Station spacing with maximum speed ratio of 60%/km	4.5	6.7	9.8	17.1
Travel speed with maximum speed ratio of 40%/ (km/h)	52.9	66	79.7	105.7
Travel speed with maximum speed ratio of 60%/ (km/h)	65	80.1	95.7	125.4

4.3 Capacity

As a large-capacity public transportation system, the metropolitan (suburban) rail should provide efficient transportation service to a large number of passengers along the railway line, so its transportation capacity should reach a certain scale. The capacity depends on departure interval, train formation, and train capacity.

1) Departure interval: Departure intervals are related to line conditions and operating conditions. Regarding line conditions, in order that passengers can be rescued in a timely manner when a rail accident occurs in a tunnel or on an overpass and engineering investment can be reduced, the maximum design capacity of the metropolitan (suburban) rail should not be greater than 24 pairs per hour, i.e., 2.5 min/train [7]. Regarding operating conditions, the time interval of locating the metropolitan (suburban) rail train and the operating time at the return-back station may exceed 2 min. Therefore, the minimum operating interval of the metropolitan (suburban) rail is suggested to be 2.5 min [7]. To meet the requirements for the departure interval and the operating conditions, this paper uses 3 min as the departure interval after taking into account the current technical conditions and on the premise of safety.

2) Train formation: Train formation is related to many factors such as the density of the passenger flow, the type of the train, the power of the locomotive, line conditions, station track, and the length of the platform. At present, subway trains in China usually consist of six or eight cars, and high-speed rail and intercity trains consist of eight or 16 cars. Metropolitan (suburban) railway platforms are generally controlled by eight cars.

3) Train capacity: The capacity of a train depends on the size of the vehicle, the number of doors, and the seat arrangement. It is also affected by the train's load safeness, crowdedness, and comfortableness. The train formation and the maximum train capacity (overload level) of various types of vehicles are provided by CRRC Changchun and CRRC Sifang.

Based on the parameters such as the maximum operating speed, the vehicle formation, and the maximum train capacity provided by CRRC Changchun and CRRC Sifang and assuming that the peak-hour departure interval is 3 min, the peak-hour peak-section capacities of various vehicle models are calculated. The results are listed in Table 4, which shows that City Type A and City Type D have a greater advantage than intercity vehicles in terms of the peak-hour peak-section capacity, while Hybrid Intercity 160 with six cars has a weak capacity.

4.4 Interoperability

For metropolitan (suburban) railways that are connected to national railways, their technical standards must be consistent with national railway standards. In other words, they must adopt the traction method, power supply system, signal

Table 4 Operating capacity analysis for different types of vehicles

Train manufacturer	Vehicle model	Maximum running speed/(km/h)	Number of trains in the peak/(train/h)	Train formation/(car/train)	Maximum train capacity/(person/train)	Peak-hour peak-section capacity/(10,000 persons/h)
CRRC Changchun	City Type A	120–160	20	8	2 600	5.2
	City Type D	120–160	20	8	2 812	5.6
	Hybrid Intercity 160	160	20	6	946	1.9
	Intercity 160	160	20	8	1 914	3.8
	Intercity 200	200	20	8	1 402	2.8
CRRC Sifang	140 City Type A	140	20	8	3 120	6.2
	140 City Type D	140	20	8	2 656	5.3
	140 Dual System Intercity	140	20	8	1 852	3.7
	CRH6F	160	20	8	1 998	4.0
	CRH6A	200	20	8	1 488	3.0

Table 5 Interoperability among different types of vehicles

Train manufacturer	Vehicle model	Maximum running speed/(km/h)	Power supply system	Vehicle clearance	Vehicle size	Interoperability	If qualified
CRRC Changchun	City Type A	120–160	AC25 kV, DC1 500 V	Subway	Narrow	×	No
	City Type D	120–160	AC25 kV	China National Railway	Short	×	No
	Hybrid Intercity 160	160	AC 25 kV, power battery or hybrid	China National Railway	Standard	√	No
	Intercity 160	160	AC25 kV	China National Railway	Standard	√	No
	Intercity 200	200	AC25 kV	China National Railway	Standard	√	No
CRRC Sifang	140 City Type A	140	DC1 500 V	Subway	Narrow	×	No
	140 City Type D	140	AC25 kV, DC1 500 V	China National Railway	Short	×	No
	140 Dual System Intercity	140	DC 1 500 V, AC 25 kV, dual power supply system	China National Railway	Standard	×	No
	CRH6F	160	AC25 kV	China National Railway	Standard	√	Yes
	CRH6A	200	AC25 kV	China National Railway	Standard	√	Yes

Source: Vehicle technical specifications provided by CRRC Changchun and CRRC Sifang

system, and clearance that are compatible with national railways [10]. In terms of model selection, the requirements of interoperability with national railways mainly include the requirements for the power supply system and vehicle technical standards.

1) Power supply system: Interoperability with national railways inevitably requires the power supply mode of AC 25 kV. From the perspective of the existing technologies and projects, the railways with a speed of 120–140 km/h can be powered with AC or DC power supply systems, with no obvious differences. However, when the speed reaches or exceeds 160 km/h, railways usually use the AC power supply system [6]. In addition, different power supply systems need to meet different engineering, management, and investment conditions.

2) Vehicle technical standards: Interoperability with national railways also needs to consider vehicle technical standards: ① The clearance requirements of the metropolitan (suburban) rail vehicle should be consistent with the national rail vehicle to meet the operating requirements of national railways and stations. ② The size of the vehicle should meet the vehicle technical standards of China State Railway Group Co., Ltd. ③ The metropolitan (suburban) rail vehicle should meet the requirements of the EMU Unified Project, including 33 sub-projects in six aspects: operation interface, application interface, passenger interface, maintenance interface, braking system, and detection and protection. Only if all three requirements described above are met, a vehicle model can obtain the qualification (including the model certificate and manufacturing license) issued by China State Railway Group Co., Ltd. to enter the national railway network.

Table 5 shows the interoperability analysis of the vehicle models from the two vehicle manufacturers. It shows that the vehicle models that are interoperable with the national railway are Hybrid Intercity 160, Intercity 160, and Intercity 200 manufactured by CRRC Changchun as well as CRH6F and CRH6A manufactured by CRRC Sifang.

4.5 Cost

The cost is related to vehicles and civil construction. Different vehicle models have varied cross-sectional areas and require underground passages or through tunnels with different sizes, resulting in differences in civil construction cost.

1) Vehicle cost includes procurement cost, maintenance cost and operating cost. ① Different types of vehicles have varied procurement cost. According to the price quotes provided by relevant vehicle manufacturers, the procurement cost of intercity vehicles is higher than that of metropolitan vehicles. ② Maintenance cost includes daily maintenance cost and periodic maintenance cost. The maintenance schedule and period are determined based on the vehicle model. Different levels of maintenance need different time and cost, which should refer to the maintenance price quotes from the manufacturer. ③ Operating cost includes track access fee, catenary service fee (including electricity consumption), station passenger service fee, and ticket service fee. When different types of vehicles operate on the same railway line, the track access fee is the same; however, the other three fees are different due to varied power and passenger capacities.

2) Two factors impact the civil construction cost. First, the requirements for clearance and the blockage ratio require various tunnel diameters, resulting in different civil construction cost. Second, different power supply systems require substations with varied scales along the railway line, resulting in changing construction cost.

There are three types of clearances: vehicle clearance, equipment clearance, and building clearance. The relationship of these three clearances in a tunnel is building clearance > equipment clearance > vehicle clearance. Different vehicle models require varied clearances, which affects the diameter and the cost of the tunnel. The blockage ratio is the ratio of the cross-sectional area of the train to the clearance area above the track surface in the tunnel. When a train enters the tunnel at a high speed and runs in the tunnel, compression waves and expansion waves appear alternately, which requires the vehicle to have a certain degree of tightness. The smaller blockage ratio indicates the higher requirement for the tightness of the vehicle. Therefore, the blockage ratio should be a relatively large value.

In terms of substations along the railway line, the AC25 kV power supply system provides high voltage power, and substations can be built every 30–80 km. It can save a lot of cost compared with the DC1 500 V power supply system, which requires a substation every 2.0–4.5 km. From the perspective of vehicle cost and civil construction cost, the vehicle clearance of the AC25 kV power supply system is greater than DC1 500 V, resulting in higher construction cost for underground sections.

According to China's experience, when the tunnel sections account for more than 1/3 of the entire railway line, it is more economical to choose DC1 500 V. If the metropolitan (suburban) railway is mainly located in the suburbs and most of the sections are on the ground, it is more economical to choose AC25 kV vehicles.

5 Comparison of vehicle serviceability

Once the metropolitan (suburban) railway meets the corresponding functionality requirements, vehicle serviceability standards should also be proposed based on its service characteristics (providing public transportation service), including standards on seats, toilets, doors, and handrails in the railway car.

5.1 Seat arrangement

There are three types of seat arrangements: transverse (passengers face towards or away from the direction of travel), longitudinal (passengers face a side of the railway car), and a combination of transverse and longitudinal seat arrangements. According to operational experience, seat arrangement has no direct impact on the safety of passengers for trains with a maximum speed of 160 km/h or below, but transverse seat arrangement is more comfortable than longitudinal seat arrangement although it takes more space.

Since the metropolitan (suburban) railway mainly serves passengers with longer travel distances, enough seats should be provided to meet the seating needs of all passengers at least during off-peak hours. Rail transit passenger flow generally has two peaks, one in the morning and the other in the evening. It is difficult to provide seats for all passengers in peak hours, but it should be ensured that passengers have seats in time periods other than the morning and evening peaks. The number of seats should be determined according to the highest passenger flow in the time intervals one hour before and one hour after the morning and evening peaks [9] (see Figure 2).

5.2 Toilet

There are no clear rules on whether to install toilets in a train. Subway trains usually do not have toilets, while trunk railway trains usually have toilets. It is widely accepted by Chinese vehicle designers that operation mode and user needs are the key factors to determine whether to install toilets and how many toilets to install in metropolitan trains. If the average on-board time is more than 1 h, toilets are needed on the train. If the travel time between two stations is short and there are toilets in the station, no toilets are needed on the train. Once a train has toilets, it is necessary to install water supply lines, drain pipes, and toilet waste retention tanks, which increase the operating cost of the train. Therefore, whether to install toilets on a train needs to comprehensively balance the relationship among the operation mode, user needs, and cost control.

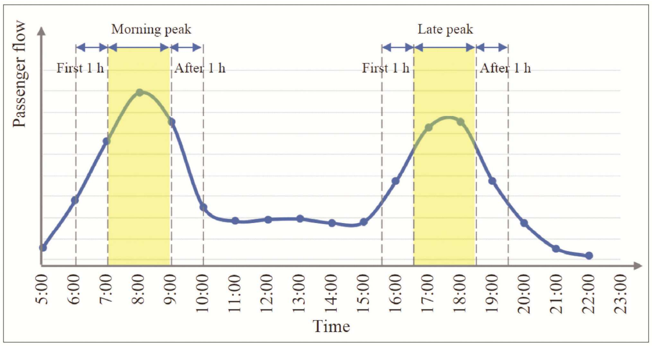

Figure 2 Time-varying characteristics of rail transit passenger flow

Source: Reference [9].

5.3 Door

The design of rail vehicle doors needs to balance passenger boarding and alighting efficiency and train carrying capacity. Adding more doors or increasing the door width will enlarge the passenger boarding and alighting efficiency, which leads to an increase in the standing space in the train. The peak passenger flow of metropolitan (suburban) rail is much higher than the off-peak passenger flow. When the bus operation mode is adopted in metropolitan (suburban) rail, a large number of passengers would rush onto the train during peak hours, and too many standing passengers may cause the passenger load to exceed the overload capacity and jeopardize the safe operation of the train. Installing less doors or reducing the door width will reduce the passenger boarding and alighting efficiency, namely that it takes a longer time for passengers to get on and off the train. As a result, the dwell time of the train at the station will increase, which leads to extended train departure intervals, less departures, and reduced operating capacity of the railway line.

At present, the *Code for Design of City Railway* (T/CRSC0101-2017) clearly defines the number of doors and the range of door width for city trains. The number of doors varies by vehicle types, and it should be determined by comprehensively considering the requirements for train operational safety as well as boarding and alighting efficiency.

5.4 Other service facilities

1) Handrail: When the future passenger flow is high, there will be more standing passengers. For their safety, it is recommended to add vertical handrails on the train. It is also recommended to add pull rings on the train to accommodate short passengers.

2) Luggage rack/area: For airport rail lines, it is recommended to designate luggage areas for large luggage bags on the train to facilitate airport passengers.

3) Internet communication and multimedia equipment: It is recommended to provide free Wi-Fi to passengers on the train. It is also recommended to install multimedia equipment at the connection of the rail cars to broadcast real-time news and weather conditions.

6 Workflow for vehicle comparison and selection

In the actual process to select metropolitan (suburban) rail vehicles, two steps should be taken to compare the vehicles' functionality and serviceability.

1) Functionality: The vehicle safety, speed, capacity, and other functional characters should be determined based on the design travel speed, station spacing, passenger flow volume, interoperability, and other requirements specified in the feasibility study report. If the metropolitan (suburban) railway is connected to the national railways, a vehicle model that is interoperable should be selected. Vehicle cost should also be compared to ensure comprehensive comparison and selection.

2) Serviceability: Based on the factors such as the railway line's travel time, passengers, and socio-economic and cultural development, the serviceability requirements for the vehicle should be determined, which include requirements for seat arrangement, toilets, and doors.

7 Conclusion

This paper studied the selection of metropolitan (suburban) rail vehicles. It summarized the experience of vehicle selection and analyzed the current status and trend of the industrial development in China. Moreover, it identified key factors in the selection of metropolitan (suburban) rail vehicles from two aspects (functionality and serviceability) and established the selection system. Vehicle functionality includes five factors, i.e., safety, speed, capacity, interoperability, and cost. Vehicle serviceability includes seat arrangement, toilets, doors, and other factors. This paper also proposed a workflow for vehicle comparison and selection to be used in the actual vehicle selection process. The technology for metropolitan (suburban) rail vehicle keeps developing, and vehicle technical specifications keep changing. The vehicle comparison and selection system established in this paper can provide technical reference for developing the industrial standardization system of metropolitan (suburban) rail vehicles.

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