

Research Article

Energy Consumption Analysis of High-Speed Trains under Real Vehicle Test Conditions

Qing Zhang ¹, Hongjun Yu,² Xin Su,² and Yao Li²

¹College of Engineering, China Agricultural University, Beijing 100083, China

²Beijing Institute of Space Launch Technology, Beijing 100076, China

Correspondence should be addressed to Qing Zhang; zhangqingbit@163.com

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The study collected statistics on the actual operation of national railway electric multiple units (EMUs) and compared the energy consumption of different EMU models at different speed levels. An important method for studying the relationship between speed and energy consumption of EMUs has been constructed based on group method of data handling to reflect how the energy consumption of different EMU models changes with speed. The energy consumption of CRH2 and CRH380A EMUs on flat and sloping lines was compared. Moreover, the start-up energy consumption of CRH2 and CRH380A EMUs was compared. The effect of the number of stops of CRH2 and CRH3 EMUs on energy consumption was analyzed. Furthermore, an idea for improving the general expression and calculation methods of traction energy consumption of EMUs was proposed. Finally, suggestions on the construction of a traction energy consumption information system were provided, and the selection of different high-speed EMU models and the reasonable determination of the operating speed were discussed.

1. Introduction

High-speed railways (HSRs) are the most favored mode of transportation for their high-efficiency and energy-saving features, which is an important reason that China attaches great importance to HSR development. Energy shortages, environmental pollution, and inflated energy prices have become major issues undermining national security, economic development, and the improvement of people's living standards. The demand for energy in China is high, whereas the carrying capacity of environment is low. Compared with roadways, civil aviation, and other transportation methods, railways are recognized as a greener and more popular transportation mode. Although the increase in railway speed and the large-scale operation of electric multiple units (EMUs) have improved transportation efficiency, there is an urgent need to accurately measure, analyze, and optimize the energy consumption of HSRs, which is also required for the HSR organization, cost accounting, transportation pricing, revenue settlement, etc. Therefore, the energy consumption of high-speed EMUs has become the focus of attention.

However, the effect of high operating speeds of EMUs on their energy consumption has not been elucidated. Therefore, the research on energy consumption of high-speed EMUs is of practical significance.

Three factors can affect the energy consumption of high-speed EMUs during their entire operation. The first factor is the type of EMUs. Different EMU models possess different traction characteristics, appearance, power, and energy efficiency, resulting in varying levels of energy consumption. The second factor is the operating conditions. The operating condition has the most prominent effect on the energy consumption of EMUs. It is a complex aspect dependent on a multitude of factors, such as slope, curve radius, train formation, operating speed, start/stop time, and regional climate and atmospheric pressure. Specifically, the energy consumption in the startup and operation processes shows different patterns, thus requiring that the energy consumption value is corrected according to the number of starts and stops. The third factor is the driver's operations, which affect the energy consumption during operation and braking. Depending on the drivers' proficiency levels, energy

consumption values may significantly differ on the same trip. If a driver is very familiar with the rail conditions, he/she can drive smoothly, which is conducive to energy saving.

EMUs currently in operation in China mainly include CRH1, CRH2, CRH3, CRH5, and CRH380. Table 1 shows the technical specifications of typical EMUs [1, 2]; China Railway Engineering Corporation, 2015; [3]).

Studies at home and abroad on energy consumption of EMUs involve three aspects: recording of energy consumption information, analysis and processing, and the optimization of driving operations to improve energy consumption management on a continuous basis. With respect to energy consumption information recording, the energy consumption information of EMUs in many countries can be recorded in real time and output centrally, which lays a foundation for further analysis and research. However, not all EMUs in China can automatically collect energy consumption information, and different EMU models measure energy consumption in different ways. CRH2, CRH380A, and CRH380AL EMUs can display power and energy consumption information and time, train speed (km/h), accumulative mileage (km), traction power (kWh) and regenerative power (kWh) in graphical interfaces. All displayed power values are accumulative value with an accuracy of 1 kWh, which provides a basis for data analysis of energy consumption, but all data are not recorded or can be only manually recorded. Other EMU models do not display energy consumption information at all. For example, CRH 5 EMUs are not equipped with any energy consumption metering devices. Voltage, current, and traction are displayed by analog clocks, which cannot accurately reflect energy consumption information. In addition, under normal operating conditions, they do not provide any data storage function or output interfaces for signals, such as voltage and current, and therefore cannot synchronize the speed and mileage information for postprocessing and analysis. If voltage transformers and current transformers are to be installed for energy consumption measurement, additional hardware must be installed and software be modified, and core components of the EMUs and intellectual property rights will be involved, which will increase the workload and complicate the procedure, making it difficult to implement. Due to the limited energy consumption measurement methods of EMUs, the analysis and management of the energy consumption of EMUs by operating units, such as the power management department of EMUs, are also relatively extensive. The electric power management department determines the electric power evaluation index for the locomotive crew based on the experience data obtained by four operators and the electric energy consumption index issued by the superior. For the CRH 2 EMU and its derivative models with electric meters, the locomotive crew will manually read the energy consumption data at the start and end of each trip, and then fill in the driver's declaration form. This method provides total energy consumption information that cannot be measured and analyzed by section. Other EMU models do not have electricity meters, and drivers rely on experience and assessment indicators to estimate and report energy

consumption data, which is even worse. Although some railway scientific research institutions and related companies have developed relatively mature EMU intelligent energy consumption monitoring devices and corresponding analysis systems, and have put them into application, they are not widely used due to such factors systems and policies. The locomotive depots of transportation bureaus (companies) cannot create a continuous and effective data record and analyze it. Currently, no energy consumption monitoring devices and software are specifically designed for EMUs. Therefore, the current management and analysis of the energy consumption of high-speed EMUs by operating units are in an extensive stage, not to mention in-depth research on optimized driving, energy saving, and consumption reduction. Although preliminary studies have been conducted on energy consumption information collection solutions for EMUs, implementing them is difficult because of the current EMU design and operational safety factors.

Previous studies on energy consumption of EMUs were mainly based on theoretical analyses of influencing factors. The impacts of EMU models and vehicle characteristics on energy consumption are beyond the control of the crew. In the same traction mode, different levels of manufacturing technology would result in varying traction performance, energy efficiency, braking characteristics, and on-board devices, therefore significantly varying energy consumption of different EMU models. There are few dedicated comparative studies on this aspect. This study is based on the statistical data of the EMU operations across the country and joint commissioning and trial runs before some new high-speed rails were put into operation. The real vehicle test method was used to compare and analyze the energy consumption of EMU models, and build different energy consumption models for EMUs under different conditions to provide a basis for identifying the energy consumption levels of different EMU models and EMU model selection in a scientific way.

The rest of this paper is structured as follows. Section 2 introduces the relevant literature of EMU energy consumption research. Section 3 presents the data source and model establishment. Section 4 further discusses the results of this study and proposes suggestions for further research. Finally, Section 5 presents the summary of the article.

2. Related Literature

The traction energy consumption of EMU trains is related to multiple factors [3], and the relationship between the traction energy consumption of EMU trains and the line conditions is useful for large-scale high-speed rail construction. There have been many theoretical studies and simulation-based calculations related to traction energy consumption in EMU trains [4]. Jørgensen and Sorenson [5] used some on-site measurement results of train operation within European cities, introduced the calculation method to determine the energy consumption and emissions for different trains under different operating conditions, and established empirical estimation equations for energy

TABLE 1: Technical specifications of typical EMUs.

Model	Power configuration	Maximum operating speed (km/h)	Weight (t)	Seating capacity
CRH1	6M2T	250	474	670
CRH2	6M2T	250	419.6	610
CRH3	4M4T	250	536	557
CRH5	5M3T	350	500	587
CRH380A	6M2T	380	415	494
CRH380AL	14M2T	380	897.3	1061
CRH380B	4M4T	350	522	490
CRH380BL	8M8T	380	956.7	1005

consumption and total emissions of different types of high-speed trains (e.g., Germany ICE, France TGV, Spain AVE, and UK APT in European countries). Based on the statistical data analysis of Swedish railways, Lukaszewicz [6] argued that the energy consumption of railway transportation is mainly affected by railway line parameters, rail types, mechanical and physical parameters, driving strategies, and external factors. He proposed a method for calculating the energy consumption, which considers parameters such as traction, speed, acceleration, idling rate, locomotive conversion efficiency, wheel radius, and transmission ratio equation. Lukaszewicz and Andersson [7] conducted simulation research on the Sweden “Gröna Tåget,” a green train demonstration project, aiming to develop a next-generation train to improve the specifications, procurement, and development capabilities for future high-speed trains in Sweden and the Nordic region as well as to boost economic efficiency, environmental performance, and attractiveness to passengers. Watson [8] estimated the energy consumption of modern European high-speed trains running on the proposed high-speed line 2 (HS2) between London and Birmingham in the United Kingdom and conducted simulations of three types of trains to analyze the contribution of each type to the difference in energy consumption with the reference train on HS2. Thus, the key features of vehicle design that can help reduce the energy consumption of the high-speed rail line were determined. These features can serve as a reference for mapping out alternative schemes for the HS2 trains to minimize the operating energy consumption and carbon dioxide emissions of HSRs. Yu [9] expounded that Japan has continuously optimized and modified the shapes and lengths of train heads and reduced the weight of trains in the past 20–30 years and has used variable voltage variable frequency converters to increase the train speed while reducing energy consumption by 40%. Xue et al. [10] proposed a calculation method for the energy consumption of EMUs by analyzing the effects of factors such as locomotive performance and line attributes on the energy consumption of train traction. Zhang [11] studied the effects of train types on energy consumption. Wang and Ding [12] discussed the effects of different types of trains on energy consumption from three aspects, namely the critical value of EMU regenerative braking, the main parameters of the train body, and comfort devices. They also indicated that models that can convert partial kinetic energy into electrical energy and feed it back to the catenary, or those with a lighter body, or those where the energy consumption of

comfort devices accounts for a small proportion of the total power are more energy efficient. Chen [13] used simulation methods to analyze the operating energy consumption of the train attributes of the EMU from the aspects of the traction/braking characteristics of the train and the running resistance of different EMU models. Wang [1] categorized the factors influencing EMU operation energy consumption into two types: infrastructure and transportation organization mode. The infrastructure-related operation energy consumption is related to train attributes and line conditions. Train attributes include traction power characteristics, unit basic resistance equations, vehicle-mounted support, and types of equipment and vehicles. Meanwhile, line conditions include line slope, curve radius, and station spacing. The transportation organization mode affects the energy consumption of EMU operations mainly through four factors, namely technical speed, stop schedule plan, full load rate, and formation plan. Tian [14] analyzed the traction characteristics of EMUs after detailing EMUs both at home and abroad. Through the correlation and comparison between the traveled mileage, time, speed, and energy consumption of EMUs, the optimal matching relationship between the operation and energy consumption of EMUs was obtained. Huang and Liu [15] proposed a traction energy consumption estimation method for long-distance and multioperation conditions to estimate the traction energy consumption of high-speed trains at different speed levels through direct operation modes. They compared the total traction energy consumption and traction energy consumption composition and running time at different speed levels to provide a basis for selecting the speed targets of high-speed EMUs. Based on the analysis of the current research on the effect of domestic and foreign train energy consumption, Wang [16] used computer simulation methods with Beijing–Tianjin Intercity Railway and Wuhan–Guangzhou High-speed Railway as examples, and selected EMU model, speed level, number of stops, and line conditions as four main factors affecting the energy consumption of EMU trains. Furthermore, after the simulation of the energy consumption of CRH2 and CRH3 EMU trains, the results showed that the effects of EMU model, speed level, number of stops, line conditions, etc. on the energy consumption of EMU trains were consistent with the result of theoretical analysis. Lv et al. [17] combined theoretical analysis with simulation experiments by setting up simulation environments with different parameters and quantitatively studied and compared the operation energy

consumption of different types of CRH EMUs under influencing factors such as train performance, operating conditions, and driver operations. Wang and Rakha developed an electric train energy consumption modeling framework that considered instantaneous regenerative braking efficiency in support of a rail simulation system [18]. Martinis and Corman reported that energy efficiency goals are one of the main drivers for the future development of planning and operations of transport systems and used practical test cases based on real onboard monitoring of electric trains in Switzerland to identify current and future challenges in improving the energy efficiency of train operations [19]. Furthermore, in our previous study related to energy consumption of EMUs [20], factors affecting the traction energy consumption of EMU trains are qualitatively and quantitatively analyzed to conserve energy and improve operational efficiency of high-speed railways. It is concluded that data mining is an effective method for analyzing EMU train energy consumption. Fu and Chen [21] used data analysis methods to find out the usage patterns of energy consumption and used the mixed integer programming model to obtain a solution that can balance passing capacity and energy consumption. Wang et al. [22] indicated that electricity generation mix structure and full load rate are important factors influencing the life-cycle energy consumption and greenhouse gas emissions of high-speed railway transportation. It is recommended to improve the coverage of HSR network, accelerate train upgrades, improve the full load rate of high-speed railway trains, and promote the low-carbon development of electricity supply to strengthen and realize the low-carbon advantage of high-speed railway transport mode in China. Magazzino and Giolli [23] analyzed the relation among railway networks, energy consumption, and real value added in the transport and communications sectors for Italy in the long term. It was found that railway networks represent a determinant of economic growth in the Italian case. Pan et al. [24] developed an integrated model to optimize the integrated timetable, which includes both the timetable and the train trajectory achieve the minimum electrical energy consumption. The results show that the proposed integrated model can achieve a reduction in total energy consumption for the entire line up to 14.3% compared with the previous optimization model. Kierzkowski and Haładyn [25] proposes a method of reconfiguring the train timetable, taking into account minimizing the globally consumed energy for traction purposes. It turned out that it is possible to achieve a global total energy demand reduction of up to 398 MWh/year. This proves the validity of using the proposed algorithm at the timetabling stage and extending its implementation to the entire network.

Many countries have carried out systematic, holistic, and continuous tracking of and studies on the EMU energy consumption, which have been verified through related tests and applied in production practices that have witnessed considerable reduction of the energy consumption. In the field of theoretical analysis, all data processing and analysis methods at home and abroad used conventional statistical analysis and data processing methods. The key is to

accurately collect and record basic information, apply the results to production practice through theoretical calculations, computer simulations, and other methods, and optimize operations to conserve power. However, domestic studies are inconsistent and unsystematic. In particular, due to the difficulty of dynamic data collection, most studies simply focus on analyzing and addressing specific problems. More importantly, most countries' power management and research projects focus on safety instead of reducing energy consumption and enhancing efficiency, which has impeded the application of energy research results.

3. Research Method

3.1. Statistics-Based Comparative Analysis of the Energy Consumption of Different EMU Models. To conduct a comparative analysis of the energy consumption of different EMU models, this study collected 175,198 statistical datasets, which were generated from August 2011 to December 2012, from China Railway Corporation's EMU operation database. After the incomplete datasets were filtered out, 158,689 datasets were left. Then, apparently unreasonable data, such as those with technical speed less than 100 km/h and unit consumption value below 100 kWh/10,000 ton-kilometers and over 1,000 kWh/10,000 ton-kilometers, were removed. A total of 146,322 datasets were left with an effective rate of 83.52%. The number of datasets of CRH2, CRH3, and CRH380 models was 7468, 12957, and 5208, respectively.

To ensure the comprehensiveness, validity, and accuracy of the collected data, operating speeds ranging from 100 to 300 km/h were classified in steps of 20 km/h or 10 km/h according to the distribution characteristics of the data and the EMU speed classification principle. Furthermore, lines with more data sample points (Beijing–Tianjin, Shanghai–Hangzhou, Wuhan–Guangzhou, and Zhengzhou–Xi'an) and four vehicle models (CRH2, CRH3, CRH380AL, and CRH380BL) were selected for regression analysis. The running resistance mainly incurs the traction energy consumption, and the resistance is usually a quadratic function of speed [26–28]; therefore, the energy consumption was fitted to the quadratic function of the operating speed based on the statistics of different EMU models on different lines. Taking the Beijing–Tianjin Intercity Railway and the Shanghai–Hangzhou High-speed Railway as examples, the energy consumption and speed relationship models for different EMU models were constructed based on statistical data. Table 2 presents the comparison between the actual statistical value and the calculated energy consumption value per 10,000 ton-kilometers by substituting the median value of each speed level into the model.

As shown in Table 2, the energy consumption per 10,000 ton-kilometers of EMUs significantly increased as the speed increased, whereas the increase rate in energy consumption decreased with the increase in operating speed. The average error between the model-calculated value and the actual statistical value was within 6%, indicating that each model effectively simulated the relationship between energy consumption and speed at different speed levels. From the

TABLE 2: Actual energy consumption values of different EMU models on the Beijing–Tianjin intercity railway and Shanghai–Hangzhou high-speed railway at different speed levels and the values calculated by the model.

Vehicle model and energy consumption model	Speed (km/h)	Beijing–Tianjin Intercity Railway		Error (%)
		Actual statistical energy consumption (kWh/10,000 ton km)	Model-calculated values (kWh/10,000 ton-kilometers)	
CRH2C $E = -0.0019v^2 + 0.3982v + 414.46$	160–180	454.7	453.3	0.32
	180–200	455.3	454.0	0.28
	200–220	455.9	454.0	0.42
	220–240	456.2	453.1	0.67
	240–260	453.7	451.5	0.48
	260–280	452.5	449.1	0.76
	100–160	319.2	319.2	0.0
CRH380AL $E = -0.0019v^2 + 0.8802v + 236.9$	160–180	332.5	331.6	0.3
	180–200	337.3	335.5	0.5
	200–220	338.4	338.0	0.1
	220–240	338.7	338.8	0.0
	240–260	338.9	338.2	0.2
	260–280	339.6	337.3	0.7
	100–120	462.8	456.2	1.4
CRH3 $E = -0.0023v^2 + 0.9656v + 377.79$	120–140	463.1	464.4	–0.3
	140–160	450.1	470.9	–4.6
	160–180	469.5	475.5	–1.3
	180–200	496.2	478.2	3.6
	200–220	489.6	479.1	2.1
	220–240	494.9	478.2	3.4
	240–260	502.1	475.4	5.3
	260–280	444.6	470.8	–5.9
	280–300	448.7	464.4	–3.5
	300–320	446.3	456.1	–2.2
320–340	451	446.0	1.1	
340–360	453.3	434.0	4.3	
Shanghai–Hangzhou high-speed railway				
Railway model and energy consumption model	Speed (km/h)	Actual statistical energy consumption (kWh/10000 ton km)	Model-calculated values (kWh/10,000 ton km)	Error (%)
CRH2C $E = -0.0134v^2 + 6.8872v - 505.14$	130–180	236	240.4	–1.9
	180–200	333.3	319.7	4.1
	200–240	349.6	361.5	–3.4
	240–300	379.9	377.5	0.6
CRH2B $E = 0.0094v^2 - 1.022v + 174.7$	120–140	200.7	200.7	0
	140–160	232.9	232.9	0
	160–200	295.3	295.3	0
CRH2E $E = -0.0038v^2 + 1.9845v + 30.285$	100–140	212.1	213.7	–0.8
	140–160	248.9	242.5	2.6
	160–180	251.4	257.8	–2.6
	180–220	276.8	275.2	0.6
CRH380AL $E = -0.001v^2 + 0.5644v + 256.04$	130–160	321.4	316.9	1.4
	160–180	310.9	323.1	–3.9
	180–200	331.1	327.2	1.2
	200–220	333	330.5	0.8
	220–240	332.2	333.0	–0.2
CRH380BL $E = -0.0078v^2 + 3.1976v + 74.682$	240–300	333.3	335.5	–0.7
	100–160	359	358.6	0.1
	160–180	384.5	392.9	–2.2
	180–200	417.8	400.6	4.1
	200–240	388.5	400.6	–3.1
	240–260	390.7	386.6	1.1

Note. CRH2C, CRH2B, and CRH2E fall into CRH2 series EMUs. The main difference lies in the power configuration and formation. CRH2C is 6M2T; CRH2B, and CRH2E are 8M8T; CRH2E is a full-row sleeper EMU train.

perspective of energy consumption statistics and energy saving of different EMU models at different speeds, the energy consumption of CRH2C and CRH3 EMUs on the

Beijing–Tianjin Intercity Railway was greater than that of CRH380AL EMUs; therefore, CRH380AL should be selected for operation. CRH2B or CRH2E EMU should be selected if

the target operation speed for the Shanghai–Hangzhou High-speed Railway is determined to be 200 km/h or less, whereas CRH380AL EMU should be selected for operation when the target speed is determined to be within 200–300 km/h.

3.2. Comparative Analysis of Energy Consumption of Different EMU Models Based on Real Vehicle Tests. To accurately analyze the relationship between the speed and energy consumption of different EMU models, this study conducted tests in combination with the step-by-step speed increase tests on passenger dedicated lines during their joint commissioning and trial runs by collecting energy consumption data from November 2011 to October 2012 at different speed levels of the CRH2 and CRH380A EMUs in real time. Thus, a large amount of valuable test data was collected for the study on the relationship between energy consumption and speed of EMUs.

3.2.1. Introduction to the Method and Process of Energy Consumption Information Collection. To collect the energy consumption data of EMU trains at different speed levels, the JVC GZ-HM30SAC HD flash memory camcorder and Sony P150 digital camcorder were used to continuously film the display and control screens in the EMU monitoring room. Currently, only CRH2 and its derivative CRH380A models are furnished with electricity consumption meters which can display power and energy consumption statistics and other information in real time. They can display time, train speed (km/h), cumulative driving mileage (km), traction power (kWh), regenerative power (kWh), and other information in the driver's cab and monitoring room graphically. The study collected data of the CRH2 and its derivative model CRH380A running on the lines using the step-by-step speed increase tests. According to the data requirements, the overall plans for the joint commissioning and trial runs of some lines were reviewed, and the following four lines for data collection were selected: Guangzhou–Shenzhen–Hong Kong Passenger Dedicated Line, Harbin–Dalian Passenger Dedicated Line, Shijiazhuang–Wuhan Section of Beijing–Guangzhou Passenger Dedicated Line, and Hefei–Bengbu Passenger Dedicated Line. Each speed level in each section of a line consists of one-way or round-trip speeds. A total of more than 1,000 GB of data was collected, and nearly 400 hours of footage were filmed (equivalent to 100,000 kilometers at an average speed of 250 km/h). The collected data were filtered, and data samples were selected for comparative analysis.

During the selection of data samples, other factors in addition to speed, such as slope and working conditions, which would impact the energy consumption of EMUs, were also kept as consistent as possible. Therefore, the study analyzed the table of slopes for each line to select a target section with a certain slope and calculated and compared the energy consumption in this section at different speed levels. The longer the selected section is, the better the calculation accuracy will be. Otherwise, the time that a train takes to pass through the section at a high speed would not be long enough for the power consumption value displayed on the

screen to change significantly, which may result in a reading error.

In addition, the EMU speed was not always maintained at the target speed level due to phase separation and line speed limitation. Instead, it went through a process of repeated accelerations, constant speed, and decelerations. A speed–mileage curve was generated by recording relevant information during the running of the train. A target section with a certain slope was selected to analyze the “speed–slope–traction energy consumption” relationship based on speed data on the curve and line data.

The power consumption value displayed on the screen is a cumulative value; therefore, the target section should be locked by calculating the difference in value between the start and end of the section. In particular, based on the slope table, station information (milestones at the centers of starting and ending stations), and broken chain table, the length of the target section from the starting to ending stations was calculated so as to lock the target section in the video and record the cumulative power values at the start and end of the target section; furthermore, the difference between the cumulative power values was considered the energy consumption in the section. However, the power values displayed on the screen was only accurate to one decimal place. To improve the calculation accuracy, this study estimated the power values to 2–3 decimal places based on the time when the displayed value changes so as to reduce statistical errors.

The energy consumption and passenger turnover at each speed level were combined to calculate the energy consumption (unit: kWh/100 seat-kilometers) of the target section at each speed level. Moreover, the size and trend of the sample data through graphs and tables were analyzed and compared.

- (i) The uphill and downhill energy consumption was compared to determine how the energy consumption changes with increasing speed on the same slope in the same section
- (ii) The energy consumption was compared to determine its changes on different slopes in the same section
- (iii) The energy consumption was compared to determine its changes on the same slope in different sections, and the reasons for the difference were analyzed
- (iv) The startup and end energy consumption of different EMUs on different lines was compared and related factors was analyzed

On the basis of the above-mentioned comparative analysis, the sample data were fitted to obtain a fitting equation and trend line of the speed–energy consumption relationship in each target section, and the dynamic relation between energy consumption and speed is further clarified.

4. Results and Discussions

4.1. Comparative Analysis of Traction Energy Consumption of Different EMU Models on Flat Slopes. To compare and

analyze the energy consumption of different EMU models on flat slopes, a 5-kilometer flat slope for CRH2 EMUs on the Guangzhou–Shenzhen–Hong Kong Passenger Dedicated Line and a 7.25-kilometer flat slope for CRH2 EMUs on the Harbin–Dalian Passenger Dedicated Line were selected. For CRH380A EMUs, a 6.5-kilometer flat slope on the Hefei–Bengbu Passenger Dedicated Line and a 10.3-kilometer flat slope on the Shijiazhuang–Zhengzhou section of the Beijing–Guangzhou Passenger Dedicated Line were selected. The energy consumption data of EMUs under the step-by-step speed increase tests on these flat slopes were recorded to calculate the energy consumption per 100 seat-kilometers of the EMUs on different lines. The calculation showed that the uphill or downhill energy consumption changed little with speed of each EMUs on each flat slope; therefore, the average value of the uphill and downhill speeds per 100 seat-kilometer was used, and statistical energy consumption values at different speed levels were fitted to a quadratic function of speed. Figure 1 presents the statistical values and the fitted values.

The errors between the statistical values and the calculated values based on the fitting quadratic function of energy consumption and the speed are within 9%.

The EMU traction energy consumption is closely related to the operation speed. It was previously indicated that the resistance of the EMU overcomes when running at a constant speed on a flat line has a quadratically increasing relationship with the operation speed [19, 29]. As with ordinary trains, the general equation for the basic resistance of EMUs per unit weight is as follows:

$$w_0 = a + bv + cv^2, \quad (1)$$

where w_0 is the basic resistance per unit weight (N/t); a , b , and c are the constants, which are determined by experiments; v is the EMU speed (km/h).

After comparing the statistical values of different EMU models at different speed levels with the calculated values by the resistance equation in Figure 1, we found that the error between the two fluctuates slightly, usually approximately 10%. Therefore, to obtain the traction energy consumption of other EMU models on flat slopes, theoretical extension calculations can be performed based on the resistance equation to calculate the traction energy consumption values at different speed levels.

Table 3 presents the basic resistance equations per unit weight of different EMU models [30].

Therefore, the resistance equation of the whole EMU train can be obtained by multiplying w_0 (N/t) by the weight (t) of the corresponding EMU and then obtain the work done by the rigid body as follows:

$$\begin{aligned} W_{\text{traction}} &= \int_C F_{\text{traction}} ds \\ &= \int_C F_{\text{traction}} ds \\ &= \int_C F_{\text{traction}} ds, \end{aligned} \quad (2)$$

where W_{traction} is the traction work (J), which can be converted into electric energy consumption unit kWh; F_{traction} is

the traction force (N); s is the trip distance (m). The traction work (in J) of the EMUs running at a constant speed on a 100 km flat line was calculated, and using the conversion equation (1) $J = 2.78 \times 10^{-7}$ kWh, the energy consumption was calculated. Moreover, as shown in Table 4, the study considered 90% efficiency of the traction motors to derive the formula for calculating the total energy consumption and average traction energy per seat (divided by the seat capacity).

Work against resistance is the most important factor affecting the EMU traction energy consumption; hence, the resistance equation is used to calculate the energy consumption of different EMU models on a flat and straight line, and the results are shown in Figure 2.

As shown in Figure 2, the energy consumption of CRH5 EMUs is the highest at each speed level below 250 km/h, which is followed by the energy consumption of CRH3, CRH380BL, CRH1, CRH380AL, and CRH2 EMUs.

From 200 km/h, the speed increases at a step of 10%, and the energy consumption growth rates per 100 seat-kilometers of each EMU model at each speed level are shown in Figure 3. The results show that as the speed increases by 10%, the energy consumption growth rate of each EMU models also increases but stably rather than drastically.

4.2. Comparative Analysis of Slope Traction Energy Consumption of Different EMU Models. The section between K2365+595 and K2372+155 on the Guangzhou–Shenzhen–Hongkong Passenger Dedicated line, which is about 6.5 km, was selected for the analysis. Table 5 shows the slope data of the downhill line of this section, while the slope data of the uphill line are the opposite of these data. Table 6 shows the energy consumption at different constant speeds of CRH2 EMUs passing through this uphill line.

Table 6 shows that as the speed increased, the corresponding uphill traction energy consumption value also increased. This is because when going uphill, the gravity force component of the train along the direction of the slope adds to the resistance. If the train runs at a constant speed at this time, a greater traction force needs to be exerted than when it is running at the same speed on a flat slope, resulting in higher energy consumption. By contrast, when the train moves downhill, the gravity force component of the train along the slope direction acts as the traction force. When the component force is greater than or equal to the resistance of the train at a certain speed, the traction force of the train itself can maintain the existing constant speed without any work. When the component force is less than the resistance of the train at a certain speed, the train's own traction force needs to do work to ensure the constant-speed operation at that speed; however, this work is smaller than the work required to maintain a considerable speed on a flat slope.

We assume that the train mass is M (t), the slope length is s (m), the slope gradient is θ , and the seating capacity is L . Then, the energy consumption can be calculated using the conversion (1) $J = 2.78 \times 10^{-7}$ kWh, and the traction motor efficiency is considered 90%. Then, the additional traction

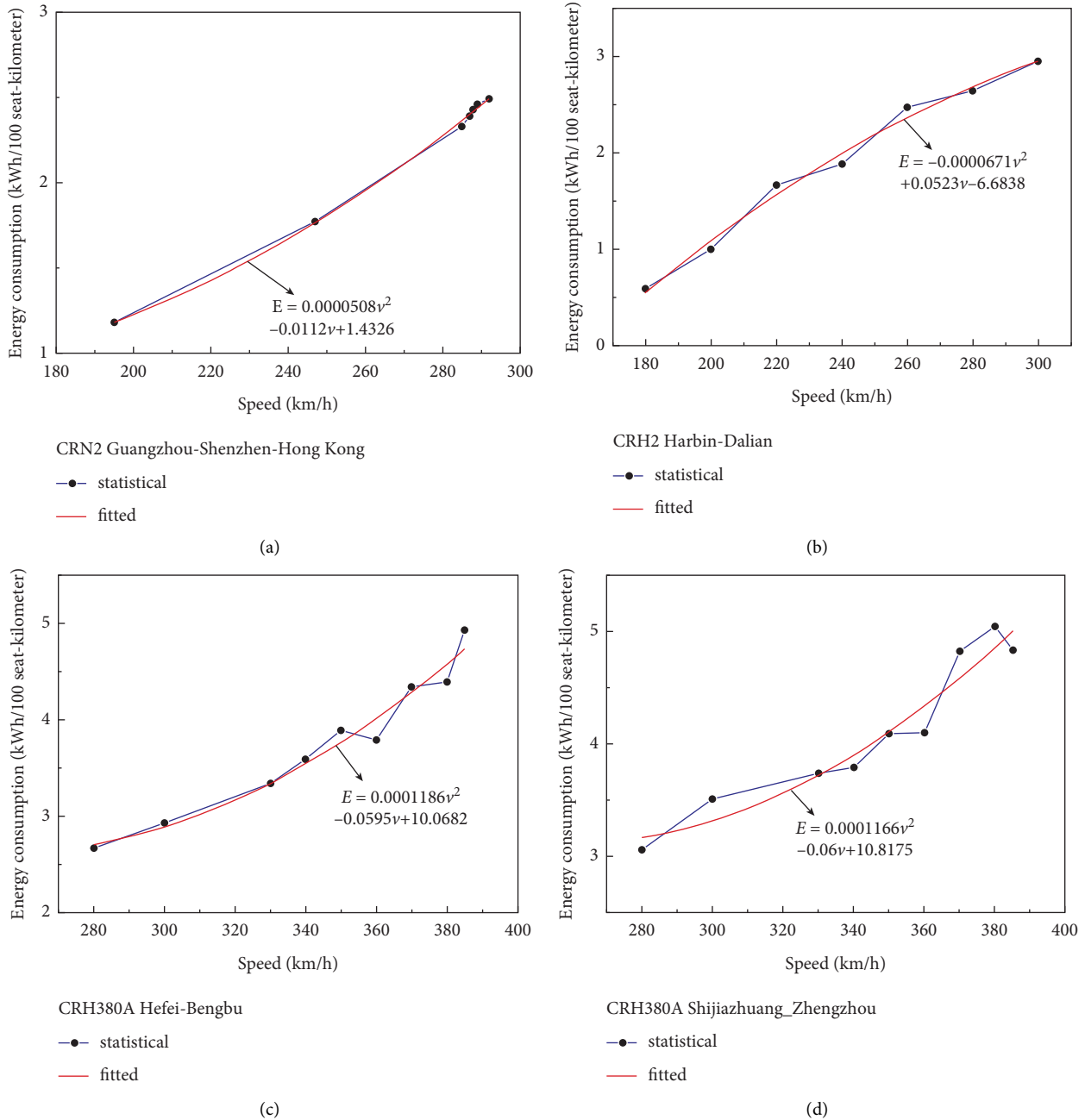


FIGURE 1: Statistical values of energy consumption and calculated values by fitting equations at different speed levels of CRH2 and CRH380A EMUs.

energy consumption of the EMU on the slope can be calculated as follows:

$$F = \frac{90\% \times (1000Mg \times s^2\theta) \times 2.78 \times 10^{-7}}{L} \quad (3)$$

Figure 4 shows the additional traction energy consumption caused by the changes in gravitational potential energy or slope in addition to the traction energy consumption required for maintaining a constant speed of different EMU models running on the flat slope and covering 10km uphill slopes of different gradients. The

additional traction energy consumption of different EMU models covering the same slope is different because of their different weights. That is, the additional traction energy consumption is directly proportional to the weight.

4.3. Comparative Analysis of Start-Up Energy Consumption of Different EMU Models. Based on the EMU joint commissioning and trial run plans, the start-up energy consumption data at different speed levels of the CRH2 EMU on the Harbin-Dalian Passenger Dedicated Line and CRH380A EMU on the Shijiazhuang-Wuhan Section of the

TABLE 3: Basic resistance equations and parameters of common EMUs per unit weight.

EMU model	Resistance equations
CRH1	$w_0 = 11 + 0.05316v + 0.00143v^2$
CRH2	$w_0 = 8.63 + 0.07295v + 0.00112v^2$
CRH3	$w_0 = 7.75 + 0.06237v + 0.00113v^2$
CRH5	$w_0 = 16.17 + 0.00098v + 0.00175v^2$
CRH380AL	$w_0 = 3.65 + 0.05157v + 0.00103v^2$
CRH380BL	$w_0 = 5.5 + 0.03622v + 0.0011v^2$

TABLE 4: Resistance-based equations for calculating the average traction energy consumption per 100 seats of EMUs on a flat and straight line.

EMU model	Average traction energy consumption per 100 seats of EC_{pc} (kWh)
CRH1	$EC_{pc} = 0.24 + 0.001161v + 0.00003122v^2$
CRH2	$EC_{pc} = 0.183 + 0.001549v + 0.00002378v^2$
CRH3	$EC_{pc} = 0.23 + 0.001852v + 0.00003356v^2$
CRH5	$EC_{pc} = 0.425 + 0.000026v + 0.00004601v^2$
CRH380AL	$EC_{pc} = 0.095 + 0.001346v + 0.00002689v^2$
CRH380BL	$EC_{pc} = 0.162 + 0.001064v + 0.00003232v^2$

Note. v refers to the EMU constant speed (km/h).

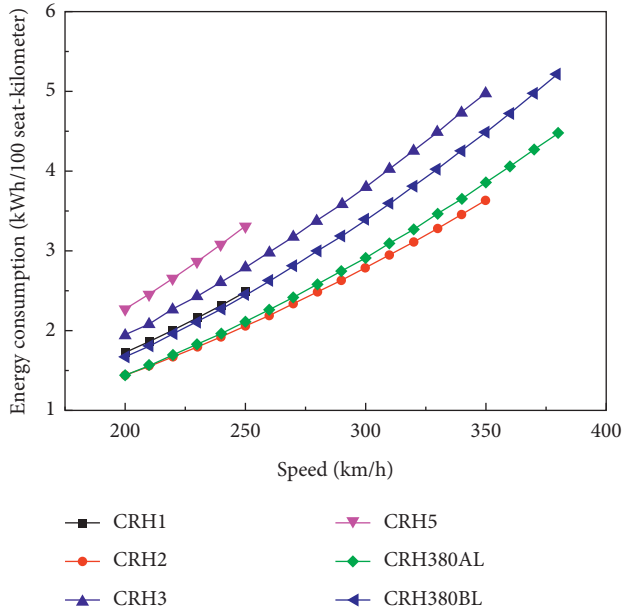


FIGURE 2: Energy consumption (kWh) per 100 seat-kilometer of different EMU models on a flat and straight line based on the resistance equation.

Beijing–Guangzhou Passenger Dedicated Line were collected during their joint commissioning and trial runs. The study converted the total start-up energy into energy consumption per 100 seat-kilometers for comparison. It used the start-up energy consumption as a dependent variable, and the target speed, corresponding time, and mileage as independent variables to build group method of data

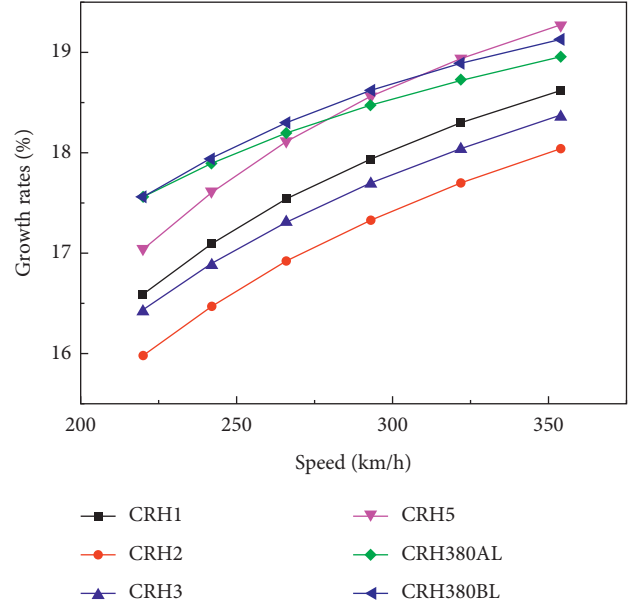


FIGURE 3: Energy consumption growth rate per 100 seat-kilometers of each EMU model (%) as the speed increases at 10% increment.

TABLE 5: Slope data of downhill lines between K2363 + 755 and K2373 + 355 (the slope data of uphill lines are the opposite).

Downhill slope (%)	Slope length (m)	End point mileage
-9.6	1840	K2365 + 595
0	1760	K2367 + 355
-5.3	987	K2368 + 342
-2	2613	K2370 + 955
-6	1200	K2372 + 155

TABLE 6: Traction energy consumption of CRH2 EMU in the downhill line at different constant speed levels.

No.	Speed (km/h)	Total energy consumption of traction (kWh)	Energy consumption (kWh/100 seat-kilometer)
1	195	70	1.75
2	247	101	2.52
3	291	124	3.10
4	300	137	3.42
5	308	145	3.62
6	329	149	3.72

handling (GMDH) models [31, 32] as in equations (4) and (5), respectively:

$$\begin{aligned}
 E_{CRH2} &= 2.064 - 0.01041v - 0.05222s + 0.00003521v^2, \\
 E_{CRH380A} &= 3.135 - 0.003207v - 0.1603s + 0.0003598vs,
 \end{aligned} \tag{4}$$

where E_{CRH2} and $E_{CRH380A}$ are the start-up energy consumptions of CRH2 and CRH380A, respectively, at different target speeds, and v , n , and s are the target speed, target speed-reaching time, and corresponding mileage, respectively. From equations (4) and (5), it can be seen that the

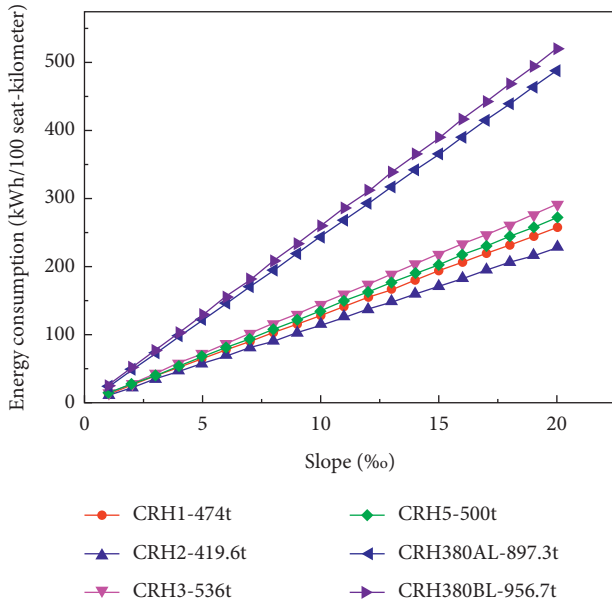


FIGURE 4: Additional traction energy consumption (kWh/100 seat-kilometer) plus the traction energy consumption required for maintaining a constant speed on the flat slope for various EMU models to cover 10 km downhill slopes at different gradients.

start-up energy consumptions of the two EMUs are mainly associated with the target speed and the mileage that EMUs travel to reach the target speed. Table 7 lists the start-up energy consumption of CRH2 EMU on the Harbin–Dalian Passenger Dedicated Line and CRH380A EMU on the Shijiazhuang–Wuhan Passenger Dedicated Line during their joint commissioning and trial runs. The energy consumption of CRH2 and CRH380A and the errors between them and actual energy consumption data are calculated using equations (4) and (5).

When the target speed is within 200–300 km/h, CRH2 EMUs had less start-up energy consumption than CRH380A (Table 7).

4.4. Comparative Analysis of Energy Consumption Related to the Number of Stops of Different EMU Models. On the Beijing–Tianjin Intercity Railway and the Wuhan–Guangzhou Passenger Dedicated Railway, the energy consumption related to the number of stops of CR2 and CRH3 EMUs was compared. Table 8 presents the energy consumption related to the number of stops per 100 seat-kilometers for different EMUs at different target speed levels. The EMU energy consumption E is the dependent variable, and the target speed v of the EMU and the number of stops p are the independent variables. The GMDH models for energy consumption for different EMUs on different lines were built (Table 8).

Table 8 shows that the energy consumption increased as the number of stops increased for the same EMU model running on the same line. The energy consumption increased with target speed; CRH2 consumed less energy than CRH3. For CRH2, energy consumption on the Wuhan–Guangzhou Passenger Dedicated Line was more

efficient than that on the Beijing–Tianjin Intercity Railway line. The first-order partial derivatives obtained for the energy consumption model E of both EMUs are increasing functions of the speed v or the number of stops p ; this implies that increase in the target speed or the number of stops results in higher energy consumption of any EMU. Therefore, the number of stops should be minimized for high-speed EMUs provided that the traffic demand can be met.

Previous studies on the energy consumption of EMUs mostly focused on the factors affecting the universality of EMUs, such as the impact of speed, line conditions, bridges, tunnels, wind force, and driving skills on energy consumption. This study focused on the basic rules of different types and energy consumption changes of EMUs, involving the design characteristics of EMUs. It is of guiding significance for different regions to choose and purchase appropriate EMUs according to different geographical characteristics, such as which EMUs are suitable for low energy consumption in plain areas, which EMUs are suitable for low energy consumption in high altitude areas, which EMUs are suitable for low energy consumption in high cold areas, and which EMUs are suitable for low energy consumption in high temperature areas. Therefore, it is pointed out that CRH5 is more suitable for operation in alpine areas due to the influence of vehicle technical characteristics and transportation organization, and CRH3 has better performance at higher speeds; in actual operation, it is very necessary to comprehensively consider various factors for vehicle type selection for different speed levels.

4.5. Ideas for Improving the Research on Traction Energy Consumption of EMUs

4.5.1. General Expression of EMU Traction Energy Consumption. The energy consumption of different EMU models based on joint commissioning and trial runs discussed in the previous sections was compared for flat lines and sloping lines. The traction energy consumption of the EMU on a flat straight line can be mainly expressed by the quadratic function of the speed, whereas the EMU on an uphill line requires more additional energy consumption to maintain the same speed. If the basic model of the relationship between speed and energy consumption on a flat line is established as $E = af(v)$, increasing the gradient factor F can lead to a general expression of EMU traction energy consumption, namely $E = af(v) + F$.

Taking the CRH2 EMU as an example, based on the data collected by the joint commissioning and trial runs on all flat and straight lines on the Guangzhou–Shenzhen Passenger Dedicated Line and Harbin–Dalian Passenger Dedicated Line, the relationship between speed and energy consumption on flat and straight lines can be established as $E = -0.00006v^2 + 0.047v - 5.7587$, which serves as the basic model. According to (3), increasing the gradient F can lead to the following general expression of CRH2 EMU traction energy consumption on common lines:

TABLE 7: Analysis of the start-up energy consumption of CRH2 and CRH380A EMUs.

EMU Model	Start-up energy consumption E (kWh/100 seat-kilometer)	Target speed v (km/h)	Speed-reaching time n (s)	Speed mileage S (km)	Model calculated value E' (kWh/100 seat-kilometers)	Model calculation error (%)
CRH2	1.03	200	236	7	1.02	-0.5
	1.02	220	257	8	1.06	3.94
	1.11	240	288	10	1.07	-3.46
	1.10	260	309	12	1.11	1.0
	0.91	280	340	19	0.92	0.82
	0.91	300	458	23	0.91	-0.13
CRH380A	2.23	200	41	2.9	2.24	0.33
	2.13	220	54	3.7	2.13	-0.03
	2.02	240	70	4.7	2.02	-0.11
	1.92	260	89	6.0	1.9	-1.0
	1.78	280	110	7.6	1.78	0.24
	1.68	300	134	9.5	1.68	-0.27
	1.58	320	159	11.7	1.58	0.02
	1.51	330	178	13.4	1.52	0.64
	1.46	340	203	15.7	1.45	-0.78
	1.42	350	220	17.3	1.42	-0.14
	1.24	360	349	24	1.24	0.15
	1.17	380	423	31.7	1.17	-0.08

TABLE 8: Energy consumption with respect to the number of stops for different EMU models on different lines.

Railway line and EMC model	Target speed v (km/h)	Number of stops (p)	Energy consumption E (kWh/100 seat-kilometers)	GMDH model
Beijing-Tianjin intercity railway CRH2	350	0	2.8502	$E = 1.452 + 0.003996v - 0.646p + 0.003998vp$
	350	1	3.6035	
	300	0	2.6504	
	300	1	3.2038	
Beijing-Tianjin intercity railway CRH3	350	0	3.6211	$E = 2.487 + 0.003241v - 0.202p + 0.003246vp$
	300	0	3.459	
	350	1	4.5553	
	300	1	4.231	
Wuhan-Guangzhou passenger dedicated railway CRH2	300	1	2.3111	$E = 0.4472 + 0.006006v - 0.01601p + 0.0002604vp$
	350	1	2.6244	
	300	5	2.5595	
	350	5	2.9249	

$$E = -0.00006v^2 + 0.047v - 5.7587 + \frac{90\% \times (1000Mg \times s^2 \theta) \times 2.78 \times 10^{-7}}{L} \quad (5)$$

where E is the energy consumption per 100 seat-kilometers (kWh); v is the speed (km/h); M is the EMU mass (t); g is the acceleration of gravity; s is the slope length (m); θ is the slope gradient.

4.5.2. Suggestions for Improving the Research Method of Traction Energy Consumption of EMUs. By and large, an error is inevitable between the statistical energy consumption values per 100 seat-kilometers of the EMU and the energy consumption values calculated using the resistance equation. This is because the statistical energy consumption

value is the actual energy consumption, whereas the resistance equation into which the average speed is substituted is calculated based on the assumption that speed is constant, which is not the case with actual operation conditions—the EMUs do not run at a constant speed. To improve the calculation accuracy of the energy consumption of the EMU, the EMU operations can be classified into two conditions, namely start-up acceleration and constant-speed operation, to calculate the energy consumption, respectively, and then the results are added. The calculation method for the constant-speed operation stage remains the same, with the speed indicator applied to the actual operating speed limit or the technical speed for the section [18]. In the start-up acceleration stage, the energy consumption of the section is obtained by integrating the speed, time, and mileage information at different points in time so as to approximate the actual energy consumption curve. However, the traction

energy consumption and the additional energy consumption due to the slope are not calculated during the deceleration and stop phase.

- (1) For the section where the EMU runs at a constant speed, the resistance equation is used for calculation:

$$\begin{aligned} E_1 &= F \cdot s + \sum M \times g \times s_1 \times \vartheta E_1 \\ &= F \cdot s + \sum M \times g \times s_1 \times \vartheta. \end{aligned} \quad (6)$$

- (2) For the section where the EMU accelerates, integral calculation is used:

$$E_2 = \int_{t_1}^{t_2} Fvdt + \sum M \times g \times s_1 \times \vartheta + 0.5Mv^2. \quad (7)$$

- (3) The traction energy consumption in the entire section is obtained as follows:

$$E = E_1 + E_2, \quad (8)$$

where F refers to the running resistance with speed (N); s is the running distance (m); M is the EMU mass measured in t; s_1 is the slope length (m); g is the acceleration of gravity; ϑ is the slope gradient.

The calculation method can be improved in terms of the pattern of traction work in the actual operation of the EMU than the calculation method of substituting the technical speed into the resistance equation.

However, to improve the EMU energy consumption calculation method, we must first of all improve the data collection method by building a real-time data collection system. At present, standard energy consumption collection and measurement devices are not available on China's EMUs. Therefore, energy consumption and speed data cannot be collected real time, and further analyses or applications cannot be realized. Hence, we should first improve the EMU data collection system to collect EMU energy consumption data in real time and dynamically. Currently, if the traction system of EMUs cannot provide network voltage and current data, voltage and current sensors can be inserted into the train's integrated traction circuit. The voltage and current signals on the high voltage can reflect the entire energy consumption of the train. If the on-board signals contain speed and mileage information (otherwise a speed sensor needs to be installed) and the EMU traction system can provide network voltage and current data, the IMC data collection system [33] can be used to collect data in a synchronous and high-speed manner and stored for a long time. The core real-time energy consumption data include time, speed, mileage, network voltage, and current. The time, speed, and mileage can be collected through the API of the locomotive LKJ monitoring system [34], whereas the network voltage and current can be provided by the core data of the traction system.

5. Conclusion

An important method for studying the relationship between speed and energy consumption of EMUs has been

constructed based on group method of data handling to reflect how the energy consumption of different EMU models changes with speed. However, for the lack of real-time collection devices for energy consumption data, errors in statistical data may exist, and the accuracy needs to be improved. The energy consumption data collected during the step-by-step speed increase tests in the joint commissioning, and trial runs were the only energy consumption information from real vehicle tests before the passenger dedicated lines were put into operation. According to the operational requirements, the speed in the joint commissioning and trial run increased step by step. Therefore, each speed level data can be collected, analyzed, and studied to obtain the energy consumption at different speed levels in a section, thus providing a reliable basis to study the relationship between speed and energy consumption. Establishing a model of the relationship between speed and energy consumption is a less-explored and important approach to expand the research on the energy consumption of EMUs.

Through a comparative analysis of the energy consumption of different EMU models at each speed level on the four lines, namely Guangzhou–Shenzhen–Hong Kong, Harbin–Dalian, Hefei–Bengbu, and Shijiazhuang–Wuhan section of Beijing–Guangzhou passenger Dedicated lines, and from the perspective of the relationship between the energy consumption and speed, we determined that the energy consumption increased on all lines as the speed increased gradually. The curve fitting equation of energy consumption on each line shows that the energy consumption-speed curve is in the rising section of the right side of the symmetry axis of the quadratic curve. Since the energy consumption of the EMUs increases with speed, the reasonable operating speed of EMU trains should be examined comprehensively in combination with transportation conditions, passenger flow demand, and economic benefits.

The study on the relationship between EMU speed and energy consumption is a systematic project. From the perspective of energy conservation, the energy consumption level of CRH380A EMU is significantly higher than that of CRH2, which is the most energy efficient EMU model within the comparable range at the same speed level. However, due to factors, such as technical characteristics of different EMU models and transportation organization, CRH5 EMUs are more suitable for operation in alpine regions, whereas CRH3 EMUs perform better at higher speeds. Therefore, we should comprehensively consider as many factors as possible when selecting EMU models for different speed levels during actual operations [30–33] [34].

Abbreviations

DIC: Diploma of imperial college
 EMU: Electric multiple units
 HSR: High-speed railways.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interests.

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