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The Calculation and Analysis of Carbon Emission in Traction Power Supply System of High-Speed Rail

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Abstract: It is necessary to provide technical reserves and path guidance for China's carbon neutral strategy, and study the rules of carbon emissions during high-speed rail operation. By comparing the carbon emission coefficient of different kinds of electric power at present, the appropriate carbon emission coefficient of electric power is selected to calculate the carbon emission. In high-speed railway, the boundary of traction power supply system is defined and the carbon emission calculation model of railway traction power supply system is established. The relationship between passenger transport turnover and traction carbon emission is analysed. The new theory is established, which is the decoupling of transport turnover, used in the "H" High-speed Rail. The data of 48 months from the year 2013 to 2016 were calculated and analysed. The indicator -- kgCO_2/(per·km) of carbon emissions per passenger turnover appeared to be meaningful for the future, that the average value is 0.037935, the standard deviation is 0.013791. The decoupling model shows the relationship between the growth rate of carbon emissions and the growth rate of turnover about "H" High-speed Rail in different months. It is obvious that April is the best whose increased turnover will not lead to increased carbon emissions; meanwhile, November is the worst.

Keywords: carbon emission; emission intensity; high-speed rail; the decoupling of transport turnover

1 INTRODUCTION

As of the end of 2021, the length of China's high-speed railway has exceeded 40000 kilometers, which is accounting for more than 66.7% of the world's total and the largest in the world. There is voluminous literature on energy consumption research on high-speed railways. It is a theoretical method to use simulation and analytical method to calculate the traction energy consumption of trains in the operation stage of high-speed railways [1]. From the perspective of railway operation phase, using the rated power and capacity of the locomotive to calculate carbon emission can be apparent as speculative algorithm [2]. The author compares high-speed railway with car and airline travel based on statistics of high-speed rail travel in the United States, and the result has shown that high-speed rail has a prominent emission reduction effect. The evaluation index used is carbon emission intensity, and the formula used is carbon emission per unit turnover [3]. In the above literature research, it is found that the boundary standards for the operation stage of the high-speed railway are very different. Due to the availability of data, the establishment of the carbon emission calculation model of the traction power supply system is calculated by the theoretical method of simulation operation and locomotive rated power, and at the same time understandings vary in terms of current carbon emission coefficients of electricity issued by the state. Passenger turnover refers to the index reflecting the passenger transport workload in a certain period of time. In China, passenger turnover is the main basis for making transportation plans. Therefore, we choose passenger turnover rather than passenger volume to explore the relationship between carbon emissions. Based on facts listed above, this thesis divides the boundary of high-speed railway traction operation, and collects, summarizes and compares the current power carbon emission coefficients in China, so as to facilitate researchers to choose appropriate power carbon emission coefficients, select the average carbon emission coefficient of regional power grids, and establish Carbon emission calculation model of traction operation and analysis model of carbon emission and turnover. The model of calculation is performed to obtain the key evaluation indicators with the obtained data of the actual power consumption of the "H" High-speed Rail. Yang, et al. [4-8], used the method of life cycle assessment to study the carbon emission of high-speed railway. The result showed that the operation stage was the highest carbon emission stage. Within the Divisia index, the Logarithmic Mean Divisia Index (LMDI) is extensively applied in factor decomposition of energy-related carbon emissions because it has the perfect decomposition and has no unexplained residuals [9, 10], which was first proposed by Wang and Zhang [11]. The LMDI method has served for researching carbon emission in different countries, such as France, Latin America and Ireland [12, 13]. Carbon emissions and economic analysis are also the focus of research in many European countries. If we can find some relationship between carbon emissions and railway passenger transport, it will help us to analyze the relationship between carbon emissions and society [14, 15].

2 DEFINITION OF TRACTION OPERATION BOUNDARY

Only electricity is used in the traction operation stage of the high-speed railway, and the system used is called the traction power supply system. Electricity can be transmitted from power station to traction substation specially set for high-speed railway through power transmission line; then, after the transformer converter of the traction substation, the required electric energy is provided to the electric load of the electric locomotive, thereby all other functions such as traction electric energy transmission and distribution are completed. It is just as shown in Fig. 1.

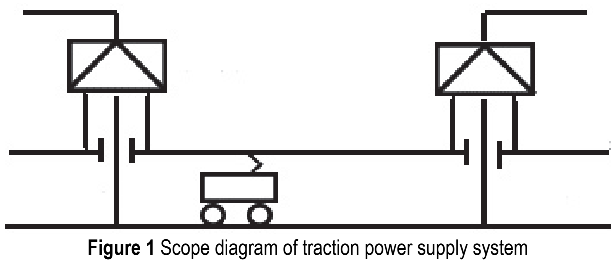

Figure 1 Scope diagram of traction power supply system

Considering electricity cannot directly give rise to carbon emissions, the carbon emissions in the traction operation phase of high-speed railways refer to the carbon emissions implied by the electricity consumed by the traction power supply system. More specifically, it refers to the carbon emissions generated by the consumed electricity when power plant produces traction power supply systems of high-speed railway.

3 CARBON EMISSION COEFFICIENT OF ELECTRICITY

When calculating carbon emission in the traction operation stage, it is necessary to select an appropriate power carbon emission coefficient. At present, there are the following types of electricity emission coefficients in China, as shown in Tab. 1.

Table 1 Comparison of emission coefficients of various types of electricity

Name		Category	Boundary calculating	Remarks
Grid average CO_2 emission factor at regional level		Emission	Ratio of CO_2 produced in an independent grid to total electricity generation	The regional grid is an independent grid
Grid average emission factor at Provincial level		Emission	The ratio of provincial carbon dioxide produced by power plants to the generated electricity	Administrative boundaries are different from grid boundaries
Grid Baseline Emission Factors at regional level	OM	Emission	Ratio of CO_2 produced by stand-alone grid to net on-grid electricity	exclude the power consumption and power plant line loss
	BM	Emission reduction	The ratio of the weighted sum of carbon emissions generated by a set of units in the area to the weighted sum of unit power generation	Exclude intro-regional wind electricity
Grid baseline emission factor of low carbon technology fossil fuel grid-connected power generation area in China		Emission reduction	The ratio of carbon dioxide produced by power plants to the total power generation of these power plants	Only consider power plants in the top 15% of effective power generation

The above comparison gives a conclusion that when calculating the carbon emissions implied in high-speed railway traction electricity, the average carbon dioxide emission factor of the regional power grid should be selected.

According to the division boundary of the power grid, China divides it into six regional power grids: North China Regional Power Grid, Northeast Regional Power Grid, East China Regional Power Grid, Central China Regional Power Grid, Northwest Regional Power Grid and Southern Regional Power Grid, excluding Tibet Autonomous Region, Hong Kong Special Administrative Region, Macao Special Administrative Region and Taiwan Province. The geographical boundaries of the regional grid are shown in Tab. 2.

The average carbon emission factors for regional power grids were determined by the National Development and Reform Commission Climate Change Division, which organized a study by the Centre for National Climate Change Strategy Research and international cooperation, used to account for the carbon emissions implied by electricity use. This refers to the ratio of all carbon emissions generated by generating electricity within the regional grid to those generated. The total amount of electricity in a regional power grid includes the amount transferred in or out. The specific calculation formula has been given by the National Development and Reform Commission.

Table 2 Geographical scope of regional grid

Grid Name	Provinces and Cities Covered
North China Regional Power Grid	Tianjin, Beijing, Hebei, Shanxi, Shandong, Inner Mongolia Autonomous Region
Northeast Regional Power Grid	Liaoning, Jilin, Heilongjiang
East China Regional Power Grid	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian
Central China Regional Power Grid	Henan, Hubei, Hunan, Jiangxi, Sichuan, Chongqing
Northwest Regional Power Grid	Shaanxi, Gansu, Qinghai, Ningxia Autonomous Region, Xinjiang Autonomous Region
Southern Regional Power Grid	Guangdong, Guangxi Autonomous Region, Yunnan, Guizhou, Hainan

The currently promulgated average carbon dioxide emission factors for China's regional power grids in 2010, 2011 and 2012 were published in 2013 and 2014, respectively, as shown in Tab. 3. The emission factors from 2013 to 2016 were calculated in accordance with the specific promulgated formulas. Data source: statistics of power generation, power consumption and fuel consumption in each region come from the query of the State Electricity Council; the calorific value data of coal comes from China Energy Statistical Yearbook; the emission coefficient and carbon oxidation rate of coal are from 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 2 Energy.

$$EF_{\text{grid},i} = \frac{Eu_{\text{grid},i} + \sum_j \left(EF_{\text{grid},j} \times E_{\text{imp},j,i} \right)}{E_{\text{grid},i} + \sum_j E_{\text{imp},j,i} + \sum_k E_{\text{imp},k,i}} + \frac{\sum_k \left(EF_k \times E_{\text{imp},k,i} \right)}{E_{\text{grid},i} + \sum_j E_{\text{imp},j,i} + \sum_k E_{\text{imp},k,i}} \tag{1}$$

$$Eu_{\text{grid},i} = \sum_u \left(FC_u \times NCV_u \times \frac{EF_u}{1000} \right) \tag{2}$$

$$EF_u = CC_u \times OF_u \times \frac{44}{12} \tag{3}$$

Among these data:

i: One of the Northeast, North, East, Central, Northwest and South regional power grids;

j: Other regional power grids that output net electricity to regional power grid i;

k: Other countries net exports electricity to regional grid i;

u: types of fossil fuels consumed for power generation.

$EF_{\text{grid},i}$: average CO_2 emission factor for regional grid i, Unit: $kgCO_2/kWh$;

$Eu_{grid,j}$: direct CO_2 emissions from power generation within the geographic area covered by the regional grid i (calculated by Eq. (2)), unit: tCO_2;

$EF_{grid,j}$: average CO_2 emission factor for district grid j that outputs net electricity to district grid i; unit: $kgCO_2/kWh$;

$E_{imp,j,i}$: the net electricity output from regional grid j to regional grid i, unit: MWh;

EF_k: the average CO_2 emission factor of power generation in country k that outputs net electricity to regional grid i, unit: $kgCO_2/kWh$;

$E_{imp,k,i}$: the net exported electricity from country k to regional grid i, MWh;

$E_{grid,i}$: the total annual power generation in the geographic area covered by the regional grid i, unit: MWh;

FC_u: consumption of fossil fuels u for power generation within the geographic area covered by grid i, unit: t or m^3;

NCV_u: Average lower calorific value of fossil fuel u, unit: GJ/t or GJ/m^3;

EF_u: CO2 emission factor for fossil fuel u (calculated from Eq. (3) unit: tCO_2/TJ;

CC_u: unit calorific value content of fossil fuel u, unit: tC/TJ;

OF_u: carbon oxidation rate of fossil fuel u, unit: %;

$\frac{44}{12}$: Conversion coefficient for carbon to carbon dioxide.

Table 3 Average emission factors of China's regional power grids in 2010, 2011 and 2012 / $kgCO_2/kWh$

Region \ Year	2010	2011	2012	2013	2014	2015	2016
North China Regional Power Grid	0.8845	0.8967	0.8843	0.8720	0.8600	0.8481	0.8364
Northeast Regional Power Grid	0.8045	0.8189	0.7769	0.7370	0.6992	0.6634	0.6294
East China Regional Power Grid	0.7182	0.7129	0.7033	0.6938	0.6845	0.6753	0.6662
Central China Regional Power Grid	0.5676	0.5955	0.5257	0.4641	0.4097	0.3617	0.3193
Northwest Regional Power Grid	0.6959	0.6860	0.6671	0.6487	0.6308	0.6135	0.5966
Southern Regional Power Grid	0.5960	0.5748	0.5271	0.4834	0.4432	0.4062	0.3727

4 TRACTION ELECTRICITY CARBON EMISSION ANALYSIS

Carbon emission analysis of high-speed railway traction electricity, including the calculation model of traction electricity carbon emission and the carbon emission analysis model.

4.1 Carbon Emission Calculation Model

The electricity consumption of the traction power supply system mainly includes the power consumption of the EMU (the air conditioner of the EMU, the interior lighting, the signal system, the catering service, etc.) and the loss of the feeder and the catenary. The power consumption of the entire traction power supply system can be obtained by data collection from the power consumption recorded by the traction substation for a period of time. Since some high-speed railway lines are long, large spanning and some even cross the boundaries of different power grid regions, so it is necessary to combine the average power consumption of different regional power grids to calculate carbon emissions. Assumptions: (1) All the energy consumed by the high-speed railway comes from the electricity consumed by the traction power supply system. (2) The electricity consumed by high-speed railways is calculated in a certain period in each power grid area. Taking a high-speed railway as the research object, the carbon emission calculation formula and expansion formula of the traction power supply system are as follows:

$$C = \sum_{i=1}^{m} E_{(n,m)} \times \alpha_{(n,m)} \tag{4}$$

$$= \frac{E}{P} \times \frac{P}{D} \times D \times \alpha \tag{5}$$

$$= \frac{E}{Q} \times P \times D \times \alpha \tag{6}$$

$$= \frac{E \times \alpha}{Q} \times P \times D \tag{7}$$

C: carbon emissions of a high-speed railway traction power supply system, unit: tCO_2;

m: Grid area spanned by high-speed rail;

v: velocity, unit: km/h;

t: time, unit: h;

$E(n, m)$: electricity consumed by traction power supply system in m regional grid in the nth year, unit: KWh;

$\alpha(n, m)$: the average carbon dioxide emission factor of the m regional grid in the nth year, unit: $kgCO_2/KWh$;

P: passenger volume of a high-speed railway in the nth year, unit: per;

D: the average passenger distance of a high-speed railway in the nth year, $D = v \times t$, unit: km;

Q: the passenger turnover of a certain high-speed railway in the nth year, $Q = P \times D$, unit: per·km;

$\frac{E}{Q}$: the traction power consumption per unit passenger turnover of a high-speed railway on the whole line in the nth year, unit: KWh/(per·km);

$\frac{E \times V}{Q}$: carbon emissions per unit passenger turnover of a high-speed railway on the whole line in the nth year, unit: $kgCO_2$/(per·km).

The Eq. (5) is extended in terms of carbon emission calculation model of the traction power supply system. Eq. (6) is to calculate the carbon emission from the perspective of per capita traction power consumption, and the per capita traction power consumption can be used as the per capita energy consumption evaluation index between different lines. Eq. (7) calculates carbon emissions from the perspective of the carbon emissions per unit passenger turnover; this indicator sums the carbon emissions generated by different power grid regions and the travel distance by passengers has also been considered; specifically, it means that Carbon emissions are implied in the amount of traction electricity consumed per kilometer when a passenger takes a high-speed rail.

4.2 Analysis Model for Carbon Emission

Taking advantage of the calculation model of high-speed railway traction carbon emissions and considering the relationship between traction carbon emissions and passenger volume, passenger turnover, and operating speed, it is proposed to use the methods listed in Tab. 4 for analysis.

Table 4 Traction carbon emission analysis indicators and methods

Dependent Variable	Evaluation indicators	Analysis Method
Passenger Capacity	Traction Power Consumption Per Capita (Carbon Emissions)	Mathematical Statistics
Turnover	Traction Power Consumption Per Unit Passenger Turnover (Carbon Emission)	Mathematical Statistics
	Decoupling Index	Turnover Decoupling Model

4.2.1 Mathematical Statistics

Mathematical Statistics is a branch of mathematics gradually formed under the development of probability theory aimed to study the laws of a large number of random phenomena and can be divided into two categories: descriptive statistics and inferential statistics. Descriptive Statistics refers to sorting, grouping, and calculating various characteristic indicators after collecting data, and using charts to gain a certain understanding of the phenomenon. Commonly used characteristic indicators are measures of centralized tendency - mean, median, mode and number of columns; measures of dispersion - range, variance and standard deviation.

4.2.2 Turnover Decoupling Model

Decoupling model of carbon emission turnover is derived from the decoupling theory which provides a description of the dependence between two subjects. It was firstly used in the physical world that refers to two or more physical relationships, which is extended to "decoupling"[16]. Later in 1966, some foreign scholars began to study the decoupling of environment relating to economic development and energy consumption [17]. Since then, decoupling theory has been extensively used in different fields to quantitatively describe the relationship between environment and economy. Tapio calculated the decoupling situation of the transportation industry in Europe and Finland and studied the decoupling indicators subdivided into 8 indicators such as weak decoupling, strong decoupling, and expanding connection, thus perfecting the decoupling theory [18]. Many domestic scholars focus on economic growth, energy consumption, urban and rural construction, etc, but less of them pay attention to transportation industry [19-22]. Currently, the research focus is paid on the relationship between carbon emissions from energy consumption and the economic growth and turnover of the transportation industry [23-25]. The relationship between tractive carbon emission and turnover can be assessed by using turnover decoupling model. The formula is as follows:

$$DI = \frac{\left(\mathrm{CO}_{2,s} - \mathrm{CO}_{2,s-1}\right) / \mathrm{CO}_{2,s-1}}{\left(Q_s - Q_{s-1}\right) / Q_{s-1}} = \frac{\Delta \mathrm{CO}_2 / \mathrm{CO}_{2,s-1}}{\Delta Q / Q_{s-1}} \tag{8}$$

DI: turnover Decoupling Index;

S: month in the observation period.

The decoupling index evaluation system in the Tapio model can be used in the evaluation of the turnover decoupling index. Tapio model evaluation index is the ratio of the rate of change of carbon dioxide to the rate of change of the GNP with a dimensionless unit change rate. The turnover decoupling model is also the ratio of two change rates, so the decoupling index of the Tapio model is used to guide the turnover decoupling index. The judging conditions for the turnover decoupling index are as shown in Fig. 2.

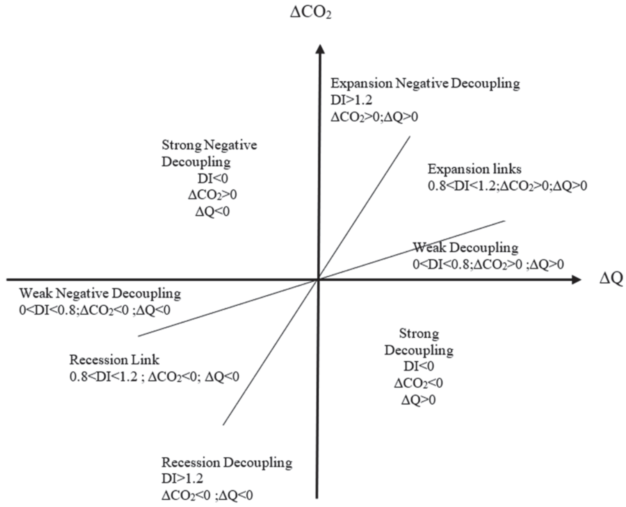

Figure 2 Area chart of turnover decoupling index

Terms in the turnover decoupling index area chart are explained as follows: decoupling means that when the growth rate of the turnover of a high-speed railway is positive, the growth rate of its carbon emissions from traction electricity is lower than the turnover growth rate. The most ideal state is that with the increase of high-speed railway turnover, the carbon emission decreases. According to Tapio decoupling index's judging criteria, it can be divided into strong decoupling and weak decoupling. Weak decoupling means that the growth rate of carbon emissions of high-speed railway traction is less than that of the turnover and the defined decoupling index is 0.8.

Negative decoupling refers to a state in which the growth rate of the carbon emissions from high-speed railway traction power consumption is higher than that of the turnover when the growth rate of the turnover of a high-speed railway is negative. The strong negative decoupling and weak decoupling are the worst case.

Link: the Tapio elastic coefficient is around 1.0 with a floating value of 0.2, so the turnover decoupling index is limited between 0.8 and 1.2. It is believed that the growth and decline of the turnover and the carbon emissions from high-speed railway traction are consistent. It can be divided into expansion and decline links.

Expansion negative decoupling and recession decoupling refer to the fact that when the growth rate of high-speed railway turnover is positive (negative), the growth rate of carbon emissions from high-speed railway traction is larger (smaller) than the growth rate of turnover, and the decoupling index is larger than 1.2. It can be concluded that the carbon emissions from high-speed railway traction and the turnover are strongly dependent.

5 EXAMPLE ANALYSIS

The "H" High-speed Rail has a design speed of 380 km/h. (currently operates at two speeds: 350 km/h for the Fuxing and 300 km/h for the Harmony). It has been working for nearly eleven years since its opening on June 30, 2011, 1318 km in length with 23 stations. It spans two major grid regions, North China and East China, and the classification of the 27 traction power supply stations by grid region is shown in Tab. 5. The names of the traction power supply stations in the table are internal names used by the railroad bureau for the convenience of statistical summary, and the corresponding regional grid average CO_2 emission factors need to be used when calculating carbon emissions.

Table 5 Traction substation located in the grid area

Grid Area	Traction Substation Name
North China	Liying, Weishanzhuang, Zhouliying, Zhangjiawo, Jinghai, Qingchi, Chengguan, Dezhou, Yucheng, Jigao, Taitie, Wangzhuang, Dongguo, Zhouying
East China	Xuzhou, Taogou, Guzhen, LiLou, Sangjian, Waipu, Nanjing South, Xiashu, Danyang, Zhenglu, Wuxi, Kunshan, Hongqiao

The data counted from each traction substation is organized as shown in Tab. 6, which shows that the annual traction power is increasing year by year.

Table 6 Power statistics of traction substation from 2013 to 2016 / KWh

Grid Area	2013	2014	2015	2016
North China	1240959257	1464568113	1674822198	1986291710
East China	1038727137	1279409556	1428133739	1696263242
Total	2279686393	2743977669	3102955937	3682554952

The number of passengers carried on the entire "H" High-speed Rail and the average distance carried are shown in Tab. 7.

5.1 The "H" High-Speed Rail Traction Carbon Emission Calculation

Combining the average CO_2 emission factors of the regional power grids in North and East China, the carbon emission of the "H" High-speed Rail traction carbon emission calculation can be calculated, and the data is shown in Fig. 3, the traction carbon emission of it is increasing year by year.

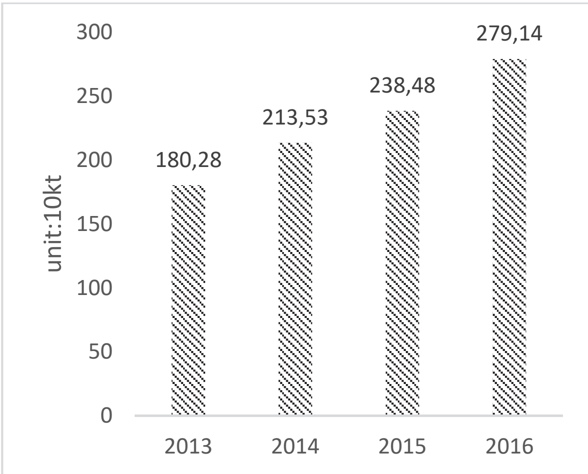

Figure 3 Carbon emission bar chart of the "H" High-speed Rail traction carbon emission calculation for four consecutive years

Table 7 Passenger volume (million) and average distance (km) of the "H" High-speed Rail from 2013 to 2016

Months	2013		2014		2015		2016	
	Passenger volume	Average distance	Passenger volume	Average distance	Passenger volume	Average distance	Passenger volume	Average distance
Jan	417.49	529.20	759.60	557.10	640.52	734.40	825.90	768.80
Feb	446.90	532.70	852.61	555.20	693.62	770.70	1062.20	807.00
Mar	483.98	535.60	882.12	526.90	831.03	743.00	1071.30	746.60
Apr	517.79	536.61	713.21	709.30	852.95	737.00	1205.10	745.70
May	526.03	535.74	734.74	706.90	869.68	735.10	1193.70	744.50
Jun	516.05	547.84	691.51	711.30	824.76	745.80	1179.20	755.20
Jul	632.99	592.07	843.19	612.91	1232.00	817.00	1400.60	793.50
Aug	648.76	588.39	859.68	623.06	1240.90	818.40	1434.40	785.80
Sep	568.88	552.12	740.07	569.50	1073.10	783.50	1247.60	781.40
Oct	493.54	553.90	614.50	640.00	1135.70	769.80	1361.10	790.10
Nov	429.19	535.50	539.16	638.00	946.30	745.70	1028.9	775.70
Dec	423.19	513.20	505.40	590.00	907.90	726.60	1020.5	762.40

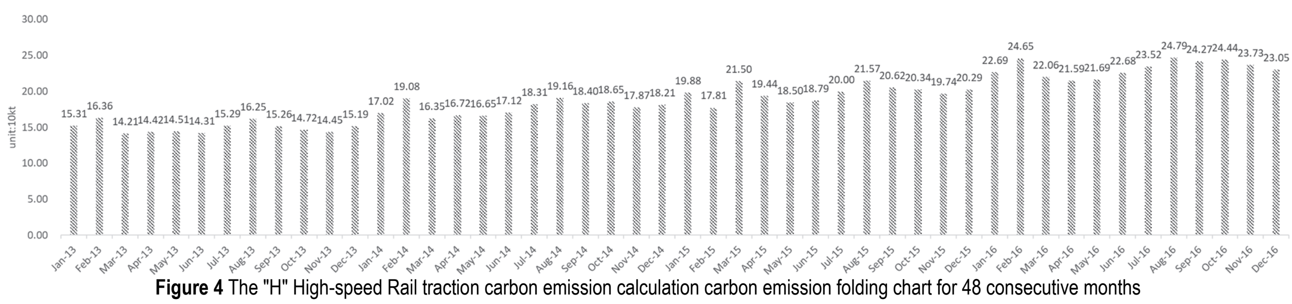

Figure 4 The "H" High-speed Rail traction carbon emission calculation carbon emission folding chart for 48 consecutive months

By calculating the carbon emissions of traction power for 48 months from 2013 to 2016 and drawing visual line graph as shown in Fig. 4, it is found that the monthly traction carbon emissions of the "H" High-speed Rail traction carbon emission calculation have the following patterns: the carbon emissions of the same month in different years are increasing; the traction carbon emissions of each month in a year show a wave shape, as shown in Fig. 5: February and September are the peak points of the wave shape, and May and November are the trough points of the wave shape.

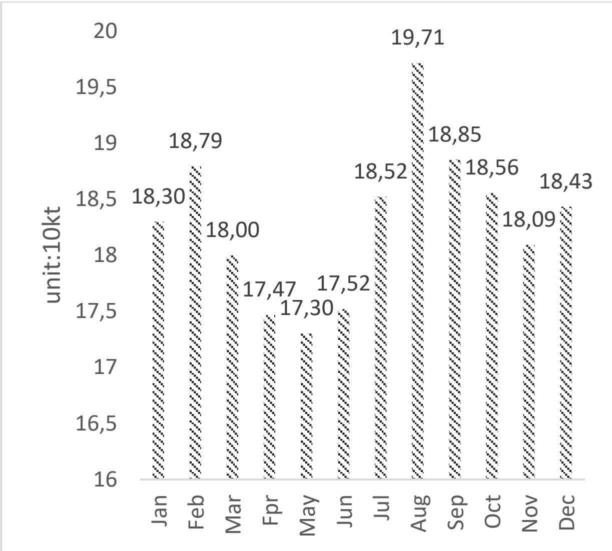

Figure 5 The "H" High-speed Rail traction carbon emission calculation of average carbon emissions by month

5.2 Analysis of Traction Carbon Emissions of the "H" High-Speed Rail Traction Carbon Emission Calculation

5.2.1 Analysis of Carbon Emissions Per Passenger Volume and Passenger Turnover

The monthly passenger volume, average distance, and traction carbon emissions for 48 months were used to determine the unit passenger traction carbon emissions, which were analysed numerically using "Statistical Product and Service Solutions", and the calculation results are shown in Tab. 8.

The study of carbon emissions per unit of passenger volume and turnover for each month, and the descriptive analysis of this data using "Statistical Product and Service Solutions". The results are shown in Tab. 9, and the line graph is shown in Fig. 6. It is found that the line graph of carbon emission per unit of passenger volume and turnover is in the shape of "V", and the highest value is generally reached in January and December of the year, while the lowest value is reached in July of the year.

Table 8 Analysis of carbon emission characteristics of traction per unit passenger volume for 48 consecutive months of the "H" High-speed Rail traction carbon emission calculation

Indicators	N	Mean	Max	Min	Std. Error
Traction carbon emissions per unit of passenger volume $kgCO_2$/per	48	24.393220	36.674307	16.232067	5.638886
Traction carbon emissions per unit of Passenger turnover $kgCO_2$/(per·km)	48	0.037935	0.069955	0.019868	0.013791

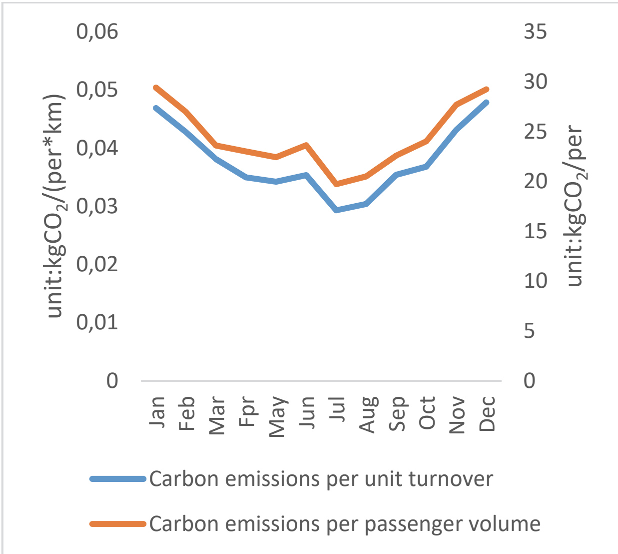

Figure 6 The "H" High-speed Rail traction carbon emission calculation of carbon emissions per unit of passenger volume (turnover) for each consecutive month folding line graph

When studying monthly carbon emissions per unit of passenger turnover and carbon emissions of traction, it is found that when carbon emissions per unit of passenger turnover are highest in each month of traction, carbon emissions per unit of passenger turnover are often neither the highest nor the lowest, but there is a certain delay, indicating that there is a certain link between turnover and carbon emissions.

Table 9 Characteristic analysis of traction carbon emissions per unit passenger volume by month for the "H" High-speed Rail traction carbon emission calculation

Months	Traction carbon emissions per unit of passenger volume $kgCO_2$/per				Traction carbon emissions per unit of Passenger turnover $kgCO_2$/(per·km)			
	Min	Max	Mean	Std. Error	Min	Max	Mean	Std. Error
Jan	22.4027	36.6743	29.3974	6.0083	0.0357	0.0693	0.0469	0.0152
Feb	22.3749	36.5984	26.9630	6.5748	0.0288	0.0687	0.0428	0.0179
Mar	18.5296	29.3699	23.5928	4.9396	0.0276	0.0548	0.0381	0.0117
Apr	17.9138	27.8433	22.9993	4.0648	0.0240	0.0519	0.0350	0.0119
May	18.1697	27.5883	22.4225	3.9226	0.0244	0.0515	0.0342	0.0119
Jun	19.2327	27.7219	23.6210	3.5620	0.0255	0.0506	0.0354	0.0109
Jul	16.2321	24.1480	19.7200	3.8438	0.0199	0.0408	0.0293	0.0104
Aug	17.2792	25.0495	20.5006	3.8296	0.0212	0.0426	0.0304	0.0105
Sep	19.2173	26.8241	22.5871	3.8429	0.0245	0.0486	0.0354	0.0125
Oct	17.9103	30.3475	24.0099	7.0202	0.0227	0.0538	0.0368	0.0162
Nov	20.8563	33.6738	27.6847	6.6761	0.0280	0.0629	0.0431	0.0171
Dec	22.3523	36.0410	29.2204	7.7957	0.0296	0.0700	0.0479	0.0207

5.2.2 Turnover Decoupling Analysis

Using the turnover decoupling model, the passenger turnover and carbon emissions of 48 months from 2013 to 2016 are analysed. The results are shown in Tab. 10 and Tab. 11, as shown in Fig. 7.

2013~2016, a total of 48 months, in January 2013 as the base period, leaving 47 study samples. During this period, the "H" High-speed Rail carbon emissions and passenger turnover showed eight relationships:

Decoupling is what we think is ideal. We consider that with the increase in turnover, carbon emissions will not increase rapidly. This is where energy-saving and emission reduction are most advantageous; we can seek the successful experience of energy-saving and emission reduction. This state accounted for a total of 42.56%, of which strong decoupling and weak decoupling accounted for half of the proportion, statistical decoupling state in the next month the number of repeated, we found that there were four occurrences in April, three occurrences in July and three occurrences in October, so we can focus on the operational status of these three months, including power plant power generation structure, traction power system specific use of electricity sector, passenger turnover and so on, in order to seek energy-saving and emission reduction of beneficial experience.

Table 10 Results of decoupling analysis of the "H" High-speed Rail traction carbon emission calculation turnover

Months	2013		2014		2015		2016	
	DI	Results	DI	Results	DI	Results	DI	Results
Jan	—	—	0.126596	Weak decoupling	0.158578	Weak decoupling	–3.1469	Strong-negative decoupling
Feb	0.880103	Expand the link	1.020551	Expand the link	–0.76466	Strong decoupling	0.24667	Weak decoupling
Mar	–1.47299	Strong decoupling	7.903673	Recession decoupling	1.337859	Negative decoupling of expansion	1.565295	Recession decoupling
Apr	0.19828	Weak decoupling	0.259754	Weak decoupling	–5.29477	Strong decoupling	–0.17492	Strong decoupling
May	0.463181	Weak decoupling	–0.15524	Strong decoupling	–2.86476	Strong decoupling	–0.42434	Strong-negative decoupling
Jun	–4.47602	Strong decoupling	–0.52645	Strong-negative decoupling	–0.41283	Strong–negative decoupling	22.26167	Negative decoupling of expansion
Jul	0.210302	Weak decoupling	1.372244	Negative decoupling of expansion	0.101342	Weak decoupling	0.148626	Weak decoupling
Aug	3.408069	Negative decoupling of expansion	1.284624	Negative decoupling of expansion	8.784217	Negative decoupling of expansion	3.805347	Negative decoupling of expansion
Sep	0.344274	Weak-negative decoupling	0.187875	Weak-negative decoupling	0.25537	Weak-negative decoupling	0.15519	Weak-negative decoupling
Oct	0.2726	Weak-negative decoupling	–0.20546	Strong decoupling	–0.34254	Strong decoupling	0.069558	Weak decoupling
Nov	0.114264	Weak-negative decoupling	0.332329	Weak-negative decoupling	0.154086	Weak-negative decoupling	0.112943	Weak-negative decoupling
Dec	–0.93041	Strong-negative decoupling	–0.14421	Strong-negative decoupling	–0.43344	Strong decoupling	1.134553	Recession link

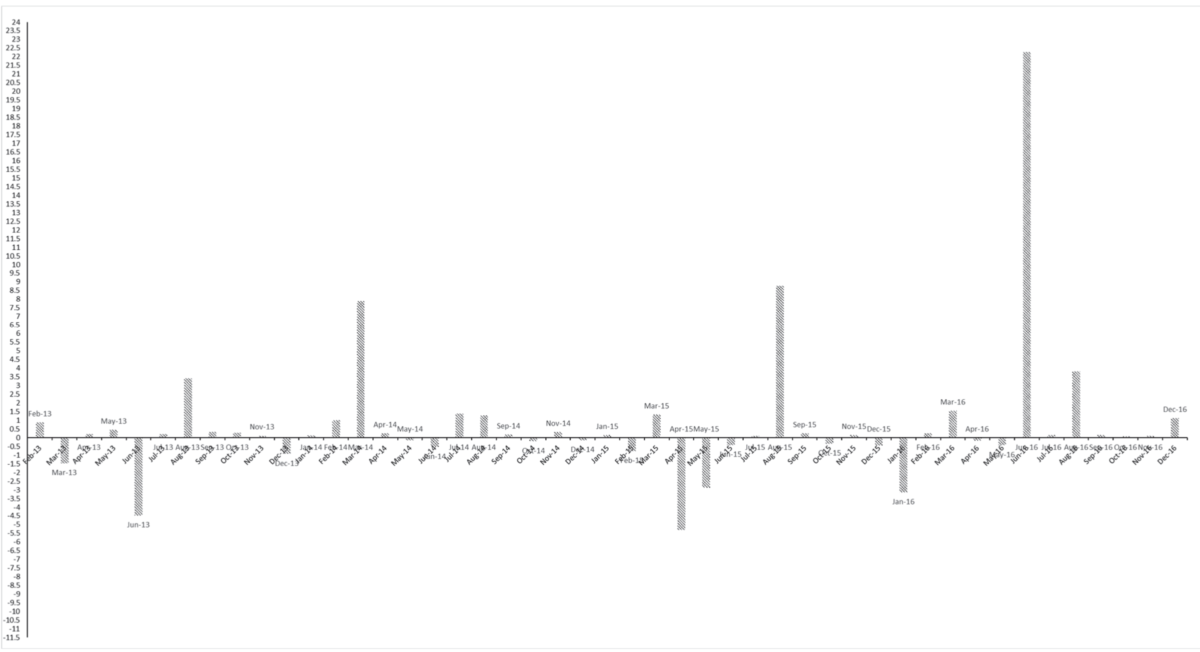

Figure 7 The track chart of turnover decoupling index

Table 11 Statistical results of decoupling of the "H" High-speed Rail traction carbon emission calculation turnover

Status		Date	Proportion
Decoupling	Strong	2013-3; 2013-6; 2014-5; 2014-10; 2015-2; 2015-4; 2015-5; 2015-10; 2015-12; 2016-4	21.28%
	Weak	2013-4; 2013-5; 2013-7; 2014-1; 2014-4; 2015-1; 2015-7; 2016-2; 2016-7; 2016-10	21.28%
Link	Expand	2013-2; 2014-2	4.26%
	Recession	2016-12	2.13%
Negative decoupling	Strong-negative	2013-12; 2014-6; 2014-12; 2015-6; 2016-1; 2016-5	12.77%
	Weak-negative	2013-9; 2013-10; 2013-11; 2014-9; 2014-11; 2015-9; 2015-11; 2016-9; 2016-11	19.15%
Negative decoupling of expansion		2013-8; 2014-7; 2014-8; 2015-3; 2015-8; 2016-6; 2016-8	14.89%
Recession decoupling		2014-3; 2016-3	4.26%

Negative decoupling means that the growth rate of carbon emissions is still greater than the growth rate of passenger turnover, which is the worst state and the key to energy-saving and emission reduction; this kind of state accounted for 31.92%, in which strong negative decoupling accounted for 12.77%, weak negative decoupling accounted for 19.15%. The number of repeated months under the negative decoupling state was found to be weak in November every year. Therefore, this is the key month for energy-saving and emission-reduction of high-speed railway.

The link state, the expanding negative decoupling state and the recessionary decoupling state can all reflect the dependence of the change rate of the "H" High-speed Rail carbon emissions on the change rate of passenger turnover, which account for a total of 25.49%. The number of duplicate months in the sample was found to occur four times in August and three times in March, two months that were the focus of attention. By showing that carbon emissions depend on turnover, and that the factors that affect passenger turnover can also affect carbon emissions, and that the factors that affect turnover are often macro-factors, this points out the direction for energy-saving and emission reduction of high-speed railway in the future.

From January to December, the track of turnover decoupling index shows a "M" track, that is, the two are related at first, and then the most favourable state of decoupling appears, slowly becomes connected state, until there is an adverse state, and then become connected state, and then there is a state of decoupling, and then slowly become connected state, the most adverse state.

6 CONCLUSION

The carbon emission of high-speed railway during traction operation was calculated by means of 48 months continuous observation of traction capacity and average grid emission factors in different regions. (1) The study found that the monthly tractive carbon emissions show a wave pattern during the year: the peak of the wave pattern is in February and September, and the trough of the wave pattern is in May and November. (2) The relationship between the increase of carbon emission and the increase of turnover is studied through the decoupling coefficient of turnover carbon emission; November is the worst month. (3) According to the decoupling model of passenger turnover, the relationship between the change rate of traction carbon emission and passenger turnover of Beijing-Shanghai high-speed railway is found. (4) The results of this study have contributed to the adjustment of high-speed rail transport plans, indicating the direction of time. In April, it would be feasible to increase transport without affecting the overall increase in carbon emissions, which would be conducive to economic activity, while in November it would be prudent to take a cautious approach to the transport plan because the increase in passenger turnover will quickly result in an increase in total carbon emissions. And the most important factors that affect passenger turnover are passenger volume and average distance. At the same time, the factors that affect the average transportation distance often include the territory scope, People's material living standard, the developed degree of tourism industry and the level of high-speed railway network, thus better energy-saving emission reduction is the future direction of research.

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