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Carbon emission reduction potential of urban rail transit in China based on electricity consumption structure

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ABSTRACT

With the rapid development of rail transit, a vast amount of electric power is consumed each year. However, the generation of electricity, and especially coal power generation, is an important source of greenhouse gases. Therefore, it is very important to analyze the potential of carbon emission reduction of urban rail transit based on specific electricity consumption structures. In this study, 18 cities in China were taken as the research object, and backward analysis was used to analyze the proportion limit of coal power consumption for rail transit in each city under three scenarios from 2015 to 2017. By comparing the limit value with the actual coal power consumed by urban rail transit, we analyzed the potential carbon emission reduction of rail transit relative to other traffic modes. The study results supported several conclusions. First, the traffic demand is in direct proportion to the carbon emission reduction potential in rail transit. Second, for cities with high coal power consumption, the development of ground bus transit is more conducive to achieving carbon reduction targets compared with rail transit. Finally, promoting the development of rail transit technology and lowering the energy consumption per capita unit travel distance are the fundamental ways to increase the emission reduction potential of rail transit. Therefore, as a modern transportation tool, rail transit is not an absolute emission reduction advantage for all cities. A city needs to analyze its own resource structure and travel demand together, set up suitable traffic modes to realize green growth and sustainable development.

1. Introduction

With the increasingly prominent traffic problems globally, the priority development strategy of public transport, especially rail transit, has been adopted by many countries. Rail transit has been vigorously promoted because of its characteristically large transport volume and low pollution potential. According to the China Urban Rail Transit Association, a total of 34 cities in mainland China had opened urban rail transit at the end of 2017, totaling 165 lines and total annual traffic volume of 18.5 billion passengers. The total length of operation lines reached 5033 km, 3884 km (77.2%) of which involved subways.

Rail transit is an important part of an urban passenger transport system, and plays a great role in relieving urban traffic congestion. However, urban rail transit operations rely mainly on power resources; with the increase in operating rail length, energy consumption is increasing (Sun et al., 2018). According to the statistics of the China Urban Rail Transit Association, the energy consumption of rail transit in China reached 12.226 billion kWh in 2017. China predominantly generates electricity by burning coal; therefore, the large amount of electricity consumed by rail transit results in large amounts of greenhouse gases from the electricity generation process (Dong et al., 2018). Because of the development of urban rail transit and the huge increase of carbon emissions, the economic cost and the aggravation of environmental pollution have restricted green growth and sustainable development of cities in China and elsewhere (Song et al., 2018). Reducing the carbon emissions of rail transit systems has become a problem of widespread concern in recent years. Therefore, whether rail transit has more emission reduction advantages than other traffic modes is a question worthy of further examination.

The carbon emissions arising from the consumption of electric energy in rail transit mainly come from coal power generation, and there are great differences in the power supply structure in various regions of China (Chen et al., 2018). The north of China is rich in mineral resources and relies heavily on coal power. By comparison, water resources in the south of China are abundant, and hydropower occupies an important position in the region's power structure. The cleanliness (in terms of environmental emissions) of power in different regions is not the same (Pei et al., 2015). Therefore, the carbon emissions from the generation of electric power that is consumed by rail transit are also very different throughout China.

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At present, there are relatively few studies on carbon emissions from urban rail transit. In particular, there is no effective method for the specific calculation of rail transit carbon emissions. A quantitative calculation of these emissions can result in greater objectivity and comprehensively reflect the impact of rail transit system on urban green development. Furthermore, in the future construction of low carbon cities, quantitative carbon emission accounting can be used to evaluate the potential of carbon emission reduction in rail transit (Ning et al., 2015). Therefore, a key objective of this study was to quantitatively analyze the emission reduction potential of urban rail transit in China under different power consumption structures compared with other traffic modes.

The innovations made by this research are threefold. First, we selected 18 cities in China to carry out the comparative analysis of carbon emission reduction potential of rail transit, not only analyzing the influence of regional characteristics, but also analyzing the influence of the development maturity of rail transit. This approach provides a theoretical basis for the low carbon development of rail transit in different regions. Second, we compared and analyzed the potential for reducing rail traffic emissions under different combinations of traffic modes, the results of which will help cities establish the proper mix of traffic modes. Third, we used backward analysis to determine the coal power proportion limit in the electricity consumption of different cities. This approach was a more scientific and reasonable way to analyze the influence of power structure on carbon emission from the consumer side, and the quantitative result provides a city a certain intuitive understanding of the emission reduction potential in rail transit.

This paper is organized as follows. The related literature review is briefly discussed in Section 2. The methods and data for evaluating the emission reduction potential of rail transit are presented in Section 3. Section 4 contains a comparative analysis of emission reduction potential of rail transit and other traffic modes in each city. Finally, conclusions and policy implications are discussed in Section 5.

2. Literature review

In order to realize the emission reduction targets of transportation system, many countries have formulated a series of emission reduction strategies, of which the development of rail transit is an important measure. In general, rail transport system has less carbon intensity than other modes of transport (Kato et al., 2011; Wang et al., 2018). At present, rail transit has become an important part of the public transport development in many countries, including the United States, China, Canada, Brazil, etc. (Cascetta and Pagliara, 2008). With the development of electric rail technology, more and more cities are developing the rail transit system based on electric power, because compared with other traffic modes, rail transit has absolute advantages in reliability, safety, energy efficiency, congestion relief, and environmental pollution reduction (Electris et al., 2009). Some scholars believe that transport electrification is very important for energy transformation and mitigation of climate change (McCollum et al., 2014; Sakthivel et al., 2018). Chen & Whalley (2012) analyzed Taipei's traffic data, found that the opening of Taipei's rail transit significantly reduced carbon monoxide emissions, which indirectly suggested that rail transit could reduce energy consumption and greenhouse gas emissions from automobiles. Andrade and D’Agosto, 2016calculated the energy consumption and emission reduction of Rio Metro Line 4, and forecasted the potential for Line 4 in 2016–2040 compared to other traffic modes, the study found that Line 4 reduced 55,449 tons of carbon emissions each year. Li et al. (2018) used LCA method to define the system boundary of the Shanghai metro, and collated resource inputs and emission outputs lists based on the actually observed data. Moreover, the greenhouse gas emissions of rail transit in different regions of the world were compared and analyzed. According to the comparison results, although there was still a lot of space for emission reduction in rail transit, the intensity of carbon emission relative to other traffic modes was low.

Some studies also believe that the development of urban rail transit provides a more effective and safe traffic mode, but it is not yet known whether rail transit can effectively curb the consumption of vehicle energy and reduce the carbon emissions in cities (Lin and Du, 2017). Chaturvedi and Kim, 2015 believed that in the long run, the development of global traffic patterns would shift to a public rail transit system based on electric power, which would achieve a reduction of 5%–20% in the final consumption of the transportation sector and a simultaneous reduction of 8%–49% in traffic carbon emissions. However, as the share of rail transit increases, the carbon emissions of the transportation sector would shift to the electricity production sector. They found that if rail transit reached 50% in the transportation system, the overall carbon emission of the society would only decrease by 1% due to the 11% increase in carbon emissions from the electricity production sector. With the different electric power structures in different regions, the development of rail transit has different effects on the carbon emissions of each region.

With the rapid development of rail transit, electricity consumption is also increasing. According to statistics, The London Metro consumes more than 1 TW h of electricity each year, accounting for 2.8% of the city's total consumption, and it is the largest consumer of electricity in London (LU, 2008). In addition, New York consumes 3.4 TW h (MTA, 2008) each year, and Hong Kong consumes 1.4 TW h annually (MTR, 2012). According to the current development trend, China's rail transit will reach comparable levels in terms of energy consumption and greenhouse gas emissions (Yang et al., 2017). Depending on the proportion of fossil fuels in the power sources structure, these electricity production processes may generate more or less greenhouse gas emissions (Zheng, 2013). However, it is necessary to compare this amount of emissions with emissions from other modes of transport when the rail transit system is not yet implemented, and analyze whether rail transit is more advantageous than other modes of transport (Andrade and D’Agosto, 2016).

Among cities with different power consumption structures, there is a great difference in the potential for carbon emission reduction in rail transit (Chen et al., 2017). The proportion of coal power in electricity consumption, which is a main source of carbon emissions, has become the key parameter in the analysis of rail transit emission reduction potential; however, a quantitative study on this parameter is not yet available. Affected by urban attributes, rail transit maturity, and other factors, there are differences in the proportion limit of coal power consumption in different regions. Therefore, determining the proportion of coal power consumption in different electric power structures, and then analyzing the carbon emission reduction potential of rail transit in a city under different scenarios is an urgent need. The results can be more pertinent and scientific than those obtained through other approaches, and can provide a practical basis for cities to establish appropriate traffic modes.

3. Methods and data

3.1. Carbon emission measurement method

Traffic carbon emissions mainly refers to mobile source emissions. Compared to fixed source emissions from industry and construction, traffic carbon emissions have greater uncertainties in measurement, emission characteristics and evolution trends. According to the IPCC Guidelines for *National* Green*house Gas Inventories* (IPCC, 2006), the calculation methods for mobile source carbon emissions can be classified into a top-down model and a bottom-up model.

The top-down model is based on energy consumption and energy conversion factors to calculate carbon emissions from transportation, as described by Eq. (1). In Eq. (1), E represents the traffic carbon emissions, i is the type of fuel, EF_i is the carbon emission factor, and V_i denotes the fuel consumption.

$$E = \sum_i EF_i \times V_i \tag{1}$$

The carbon emissions of rail transit need to be calculated based on the amount of electricity consumed, and the CO2 production is mainly concentrated in the coal power generation. Different power structures in various regions, CO2 generated by the same electricity consumption is not the same. Most of China are dominated by coal power, and in a few areas hydropower and wind power are the main components. Hydropower, wind power and natural gas power belong to clean power sources, the resulting of CO2 can be negligible. Therefore, the paper mainly considers the CO2 produced in the power generation with coal as the source, specific see *Eq.* (2). E is the CO2 emission of rail transit, D is the electricity consumption of rail transit, P is the proportion of coal power in each region, and C is the CO2 emission factor of coal power generation. It should be noted that P is the proportion of coal power in the rail transit electricity consumption, which is based on the consumption side, taking into account the regional electricity trading.

$$E = D \times P \times C \tag{2}$$

The bottom-up model is based on the "activities-traffic-weight-density-fuel consumption" concept of Schipper et al.(2000), and uses different travel modes, vehicle types, ownership, travel distance, unit fuel consumption and other data to measure transport energy consumption. The basic bottom-up model is described by *Eq.* (3). E represents the traffic carbon emissions, i represents the vehicle type (such as cars, buses, motorcycles, diesel locomotives, steam locomotives, ships, aircraft, etc.), j is energy type (such as gasoline, diesel, kerosene, natural gas, etc.), t is traffic type (such as roads, railways, aviation, water transport, etc.) V_{ijt} is the number of vehicles i that use energy source j for traffic type t, D_{ijt} is the distance traveled by vehicle i using energy j for traffic type t for a certain period of time, C_{ijt} is the average energy consumption of the vehicle i using the energy source j for traffic type t, and F_{ijt} denotes the carbon emission factor of the vehicle i using the energy source j for traffic type t. As Eq. (3) indicates, carbon emissions are related to the traffic type, travel distance and energy type.

$$E = \sum_i \sum_j \sum_t V_{ijt} \times D_{ijt} \times C_{ijt} \times F_{ijt} \tag{3}$$

Due to the availability of data, this method can only be carried out in a small area and cannot be widely promoted. Therefore, this paper measures the carbon emissions from the perspective of residents based on the factors such as the travel volumes, the travel structure, and the per capita travel distance, as shown in *Eq.* (4).

$$E = \sum E_i = \sum N \times S_i \times T_i \times M_i \tag{4}$$

Where E_i is the carbon emissions of traffic mode i; N is the total travel volume of residents; S_i is the proportion of traffic mode i; T_i is the per capita travel distance of traffic mode i; M_i represents the carbon emission per capita unit travel distance for traffic mode i. According to the 1999 American Energy Foundation, CO2 emission factors for different modes of transport are seen (Table 1).

3.2. Data

According to the statistics of the China Urban Rail Transit Association, 34 cities in mainland China opened rail transit, which had been put into operation by the end of 2017. Since the time frame for our study was 2015–2017, the selected samples had opened and operated rail transit at the end of 2014. According to statistics, as of the end of 2014, 22 cities in China have opened and operated rail transit. However, due to the individual cities just put into operation, the data is missing, we finally select 18 cities as research objects. This paper collects and collates data on rail transit passenger volume and rail transit electricity consumption in 18 cities in China from 2015 to 2017 (Table 2). The rail transit electricity consumption is calculated according to the passenger volume and the energy consumption per capita kilometer announced by the China Urban Rail Transit Association.

Table 1
CO2 emission factors for different modes of transport (kg/pkm).

Traffic mode	Walk	Bicycle	Ground bus	Taxi	Car
CO2 emission factors	0	0	0.0198	0.1400	0.1160

Rail transit has a huge capacity to transport large numbers of users, but also consumes a large amount of power resources at the same time. As can be seen from Table 2, the annual electricity consumption of each city generally exceeds 100 million kWh; the greatest electricity consumer (Shanghai) reached 2 billion kWh, and Beijing's consumption is about to exceed 2 billion kWh. With the explosive growth of urban rail transit, how to make urban rail transit more energy saving has become a problem that many cities must face. The energy saving problem of urban rail transit is no longer just a traffic problem. The huge consumption of power resources has made rail transit an invisible shackle on urban development. Because China derives most of its power from coal, the large consumption of electricity power results in large greenhouse gas emissions. Therefore, from the perspective of the whole society, whether rail transit has the advantage of reducing emissions relative to other modes of transportation needs further examination.

4. Results and discussion

Since the 18 cities have developed rail transit at different times, and the population sizes are also different, there is uneven development of rail traffic in each city. The electricity consumption and the carbon emissions are not at an order of magnitude. For example, the annual passenger volumes exceed 1 billion in Beijing and Shanghai. Some small cities have the passenger volume less than 1 million. It is likely to ignore certain rules if the cities are not distinguished in analysis. Therefore, the18 cities were classified into three categories based on their annual rail transit passenger volumes (Table 3).

4.1. Analysis of electric power structure in different regions of China

In recent years, China's power industry has made great achievements, especially the popularization of electrification. However, some studies show that China's energy efficiency is lagging behind and the power structure is unreasonable (Pan and Zhang, 2016). The power structure of a country is closely related to its own primary energy structure and government policies, and the primary energy structure is related to the country's resource conditions and resources import (Liu et al., 2016). China's coal resources are abundant, and the proportion of coal power is dominant (Yang et al., 2018). However, China has a wide geographical area, the natural resources of various regions are very different, for example, the southwest is rich in water resources, and hydropower accounts for a large proportion. Under the restriction of carbon emission reduction, as the main source of greenhouse gas, coal power has become the object of strict control, and the clean power sources such as hydropower, wind power have been included as key power sources for popularization (Chen et al., 2016).

Rail transit consumes a large amount of electricity power every year. Due to the different power structures, even if different cities consume the same amount of electricity, there is a difference in their carbon emissions. Therefore, to analyze the emission reduction potential of rail transit in various regions, it is necessary to clarify the power sources contributing to electricity generation-consumption, and especially the proportion of coal-based power consumption. However, mutual power resources among China's various regions are traded very frequently. For example, Beijing generated 42.1 billion kWh of electricity in 2015, but the city's actual electricity consumption reached 95.272 billion kWh, with electricity purchased from other regions reaching 53.272 billion kWh (National Bureau of Statistic of China

Table 2
Descriptive analysis of rail transit passenger volume and electricity consumption in 18 cities in China.

	Passenger volume(Ten thousand people)				Passenger volume(Ten thousand kwh)			
City	Mean	S.D.	Max	Min	Mean	S.D.	Max	Min
Beijing	361776.60	18444.30	377790.60	341610.00	187864.65	17100.20	198753.23	168155.16
Shanghai	333557.73	24160.52	353769.00	306798.00	197775.23	19356.38	210506.72	175500.33
Tianjin	31575.03	3279.81	35155.00	28715.00	32875.10	5537.16	37967.53	26980.67
Chongqing	68966.33	5540.84	74309.50	63247.00	48624.24	5607.77	52320.38	42171.71
Guangzhou	254698.30	23354.59	280561.20	235151.00	119873.16	18356.04	135527.35	99670.52
Shenzhen	122303.87	26465.34	144621.80	93066.00	84470.51	24736.01	109351.82	59882.41
Nanjing	84158.43	13071.86	97741.40	71666.00	49489.12	5065.51	54045.47	44034.60
Suzhou	17843.97	6101.59	24841.30	13633.00	16607.16	9817.46	26316.23	6684.79
Wuxi	8241.90	1004.54	9233.60	7225.00	13392.81	530.53	14004.46	13057.48
Shenyang	30397.20	1881.28	31910.90	28291.00	13690.63	2404.65	15244.58	10920.85
Dalian	13235.77	2264.67	15719.80	11286.00	9536.99	2606.14	11085.76	6528.12
Chengdu	56120.80	22139.81	78212.30	33933.00	39623.91	14429.18	52977.70	24318.08
Xi'an	44550.87	14039.92	60534.00	34209.00	21696.43	6509.89	28539.92	15581.44
Changsha	15928.97	7470.44	23346.80	8407.00	13838.27	4408.00	18399.68	9601.65
Kunming	9897.13	2252.03	12483.10	8367.00	11819.37	2488.52	14688.39	10245.98
Hangzhou	27736.23	5867.35	33985.90	22346.00	25012.54	2984.23	28118.81	22167.53
Ningbo	8325.83	3990.74	11233.40	3776.00	16507.09	5577.96	21026.18	10273.00
Qingdao	2583.40	3496.37	6573.20	54.00	15922.16	23671.40	43144.06	175.44

Sources: Statistical Analysis Report of Urban Rail Transit in 2017 released by the China Urban Rail Transit Association.

(NBSC, 2015). Thus, it is not scientifically accurate to use simply the proportion of coal power generation when analyzing the emissions attributable to urban rail transit in Beijing. Instead, we need to know the proportion of coal power in the electricity consumption of rail transit. Unfortunately, China lacks official data related to power source structures contributing to power consumption in all regions. Therefore, backward analysis was used to calculate the proportion limit of coal power consumption by urban rail transit, and then analyze the reduction potential of rail traffic in each city.

4.2. Scenario analysis

The above discussion shows that rail transit in each region consumes huge amounts of electricity each year, and greenhouse gases emitted during the generation of electricity cannot be ignored. If other factors, such as traffic congestion, are not taken into account, only the reduction of traffic-related carbon emissions is the target. Thus, we assumed that these rail transit-developed cities do not, in fact, have rail transit, and transferred to other traffic modes the (hypothetically displaced) passengers that would have been carried by rail transit. The question then is how do the carbon emissions arising from these displaced passengers differ from those arising from the actual rail traffic. We used scenario analysis to explore this problem.

We assumed that the passengers who actually use rail transit will be transferred to cars, ground buses, taxis, and bicycles. Walking as a travel mode was ignored because walking is suitable only for individuals that need to travel a short distance; such individuals have significantly different characteristics from the group of people that utilize rail transit (Geng et al., 2016). In addition, the characteristics of people that travel by rail transit are similar to those that travel by ground bus. Therefore, it was assumed that most of the passengers who travel by rail transit transferred to the ground bus, and we designed three types of scenarios to apportion the rail travelers to other modes (Table 4).

Table 4
scenario design.

	Scenario 1	Scenario 2	Scenario 3
Car	30%	20%	10%
Ground bus	50%	65%	80%
Taxi	15%	10%	5%
Bicycle	5%	5%	5%

According to *China Big Data Report on Urban Travel Radius in 2017*, Beijing's average travel distance is 9.3 km, followed by Shanghai 8 km, Shenzhen 7 km, and Guangzhou 6.5 km. Therefore, we assume that the average travel distances of cars and taxis are 10 km, and the travel distance of ground bus is 8 km. Since bicycle travel does not produce carbon emissions, the distance traveled by bicycles is not considered here. According to *Eq.* (4), CO2 emissions under each scenario can be obtained (Fig. 1).

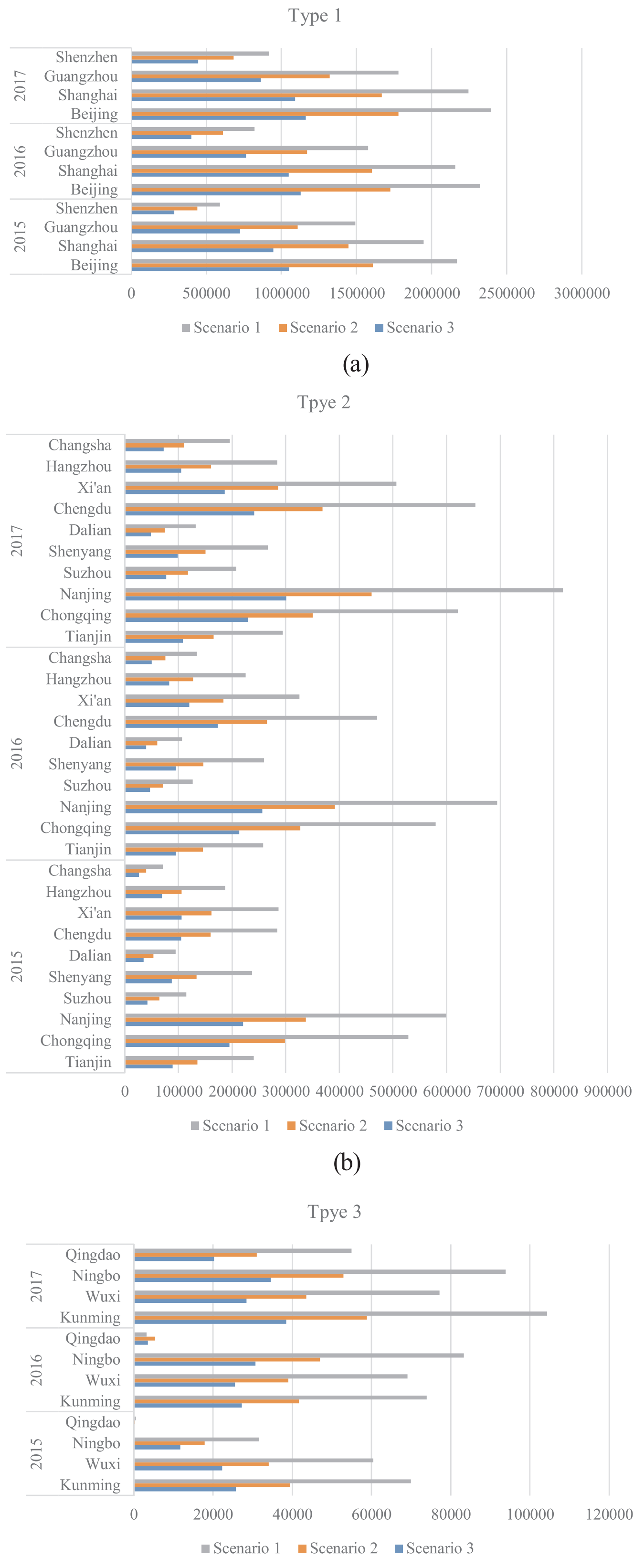
From Scenario 1 to Scenario 3, the proportion of ground bus gradually increases, the proportion of cars and taxis decreases, and the CO2 emissions are gradually reduced. Due to the different development maturity of rail transit in the three types of cities, the passenger volume varies greatly, and there is also a big gap in carbon emission.

In Type 1 cities, CO_2 emissions from three cities (excepting Shenzhen) exceed 500,000 metric tons in all three scenarios, and the carbon emissions from Shanghai are the largest. As the vehicular traffic in these cities increases, carbon emissions also increase. These cities are the most developed cities in China, with a high degree of socio-economic development and a high density of urban populations. Traffic demand in these cities is growing rapidly, and traffic energy consumption is increasing dramatically; therefore, greenhouse gases are increasing rapidly.

In eight of the Type 2 cities (excepting Chongqing and Nanjing), the CO_2 emissions in the three scenarios are controlled to less than 500,000 metric tons. Rapid development of rail transit in Nanjing and Chongqing has resulted in relatively large passenger volume. From the trend of development, because these cities are classified as having

Table 3
City classification.

Type	City	Passenger volume
Type 1	Beijing；Shanghai；Guangzhou；Shenzhen	> 1 billion people
Type 2	Tianjin；Chongqing；Nanjing；Suzhou；Shenyang；Dalian；Chengdu；Xi'an；Hangzhou；Changsha	100 million -1 billion people
Type 3	Kunming；Wuxi；Ningbo；Qingdao	< 100 million



(a)

(b)

(c)

Fig. 1. CO2 emissions under different scenarios in each city.

rapidly developing rail transit, the annual passenger volume has increased in the past 3 years, and the corresponding growth rate of carbon emissions under the three scenarios is relatively rapid.

The development of rail transit in Type 3 cities has occurred later than in other cities, and the amount of rail passenger transport is small. The corresponding carbon emissions are generally controlled to less than 100,000 metric tons. Qingdao has the least emissions, but also has the fastest growth rate. Qingdao's rail transit started operation in 2015, leading to its small passenger volume of rail transit. However, the energy consumption of infrastructure construction management at the early stage is relatively large. Compared with other cities, Qingdao has less passenger traffic, but energy consumption has not been significantly reduced. Therefore, Qingdao's rail transit carbon emissions are higher than those of other travel modes. Guiding residents to choose rail transit is an effective measure to improve the energy efficiency of Qingdao's transportation system and reduce carbon emissions. More publicity and learning are needed to improve residents' low carbon capacity (Wei et al., 2018).

The carbon emissions for the three scenarios are shown in Fig. 1 and provide a baseline for the analysis of the carbon emission reduction potential of rail transit in each city. If the actual carbon emissions of rail transit exceed this baseline, the other traffic modes have greater carbon emission reduction advantages. Otherwise, rail transit is more conducive to carbon reduction. Moreover, the smaller are the carbon emissions of rail transit compared to the baseline, the greater is the carbon emission reduction potential of urban rail transit.

4.3. Analysis of emission reduction potential of rail transit

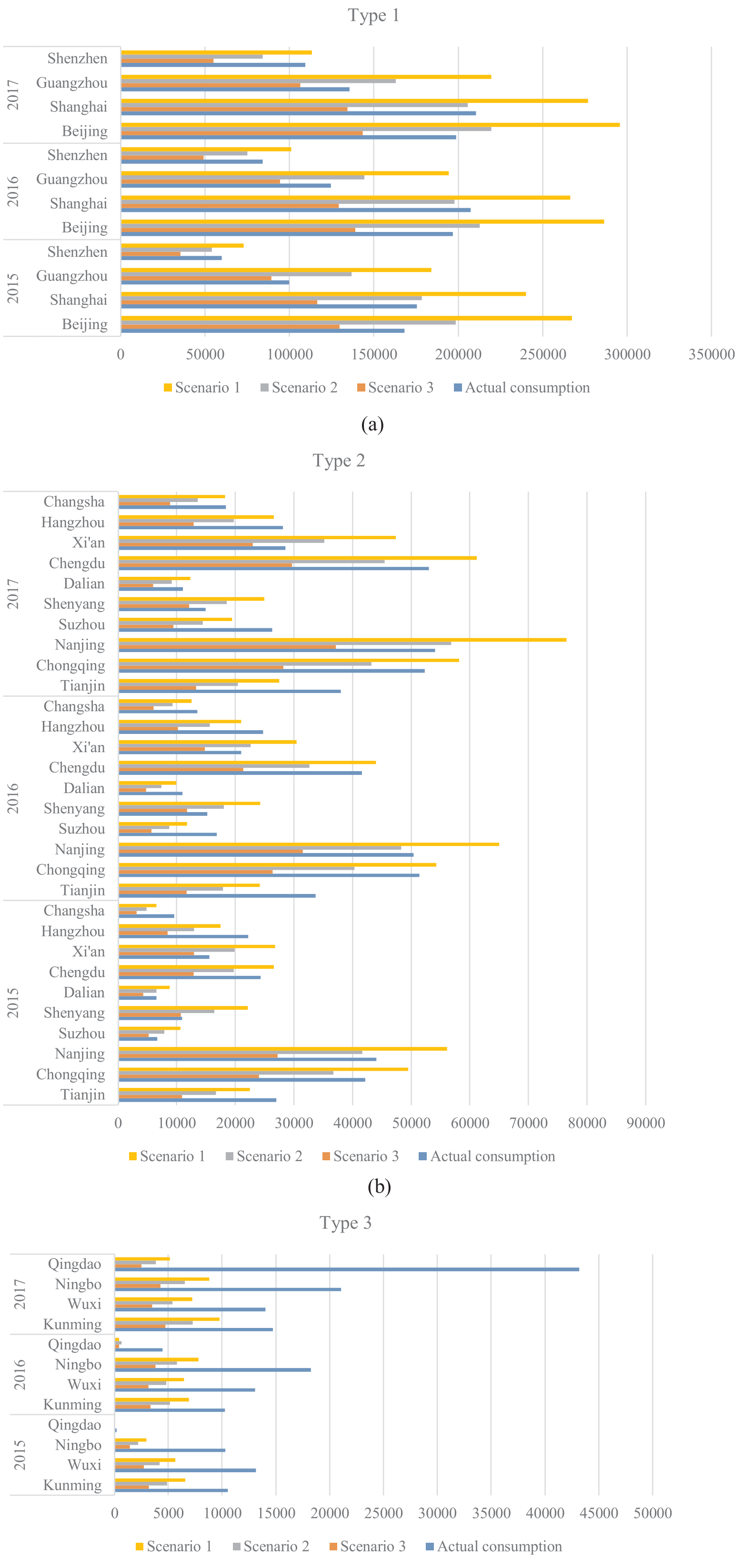
4.3.1. The electricity consumption under different scenarios

Since the urban rail transit system mainly consumes power resources, this paper mainly considers the carbon emissions from electricity consumption. We assume that the carbon emissions generated by the rail transit system all come from coal power. With the development of clean technologies, CO2 emission factors of coal power generation are also declining. According to Zhao et al. (2017), the factor selected in this paper is 0.81 kg/kWh. In the case of known carbon emissions of 3 scenarios, according to *Eq.* (2), the corresponding theoretical values of coal power consumption for rail transit under the 3 scenarios can be calculated in reverse (Fig. 2).

There is a large difference in carbon emissions under different scenarios, and coal power consumption is relatively high in areas with large carbon emissions. Scenario 1 consumes the most coal power, which is followed by Scenario 2.Scenario 3 with the highest proportion of ground buses consumes the least amount of coal power. The consumption of coal power also varies in the three types of cities. In the cities of type 1, the annual coal consumptions of rail transit are basically maintained at more than 500 million kWh, the cities of type 2 are between 100 and 500 million kWh, and the cities of type 3 are controlled within 100 million kWh.

Comparative analysis of the coal power consumption in actual rail transit and the theoretical consumption under each scenario, we find that the actual consumption are greater than those of other traffic mode in scenario 3. It means that if the power consumption source is all coal power, the carbon emission reduction potential of rail transit is smaller than that of ground bus, therefore, it is necessary to consider the proportion of coal power consumption in each city when analyzing the potential of carbon emission reduction in urban rail transit. In scenario 2, the actual coal power consumptions of rail transit in half cities of the type 1 are less than the theoretical consumption. But in type 2 cities, especially in type 3 cities, the actual consumptions of rail transit in most cities are higher than those of the other traffic mode. This means that the carbon reduction advantages of these urban rail transit need to be based on lower proportion of coal power consumption. In scenario 1, rail transit has carbon emission reduction advantages in almost all cities.

Therefore, we can conclude that the advantages of carbon emissions reduction in rail transit have a higher requirement for coal power consumption in each city. Especially for small and medium-sized cities



(a)

(b)

(c)

Fig. 2. The electricity consumption under different scenarios.

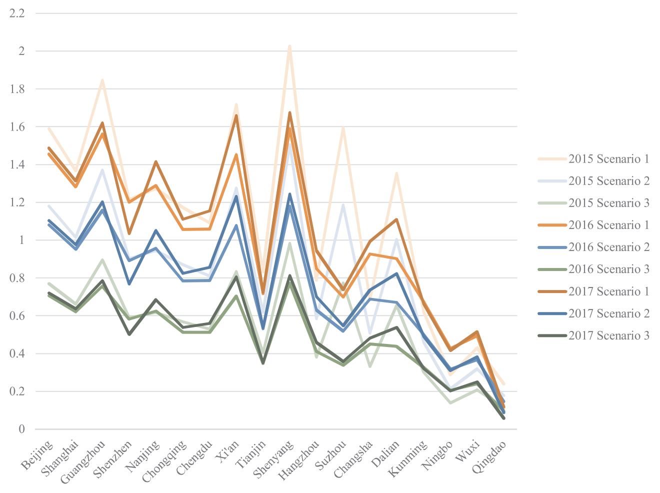


Fig. 3. The proportion limit of coal power consumption of urban rail transit in China.

with low traffic demand, the development of rail transit cannot effectively achieve the purpose of carbon emission reduction. For cities with high rail transit demand, the coal power consumption of rail transit is large, while the energy efficiency of rail transit is high, which in turn increases the carbon emission reduction potential of rail transit.

4.3.2. Analysis on proportion limit of coal power consumption of rail transit

Taking into account that the urban rail transit electricity consumption was differ by orders of magnitude, to facilitate the comparison among cities, we calculated the proportion of coal power consumption to the actual power consumption of rail transit (Fig. 3). The proportion is the limit value of coal power in the electric consumption structure of urban rail transit under the corresponding scenario. If the actual proportion of coal power of urban rail transit is lower than the limit value, the development of urban rail transit is conducive to the realization of carbon emission reduction targets. Conversely, a city was not suited to the development of rail transit only by considering carbon emission reduction targets.

First, from the numerical analysis, if the limit value exceeded 1, the development of rail transit had great potential for carbon emission reduction. Even if all the electricity consumed is derived from coal, rail transit will have greater emission reduction advantages than other traffic modes. As can be seen from Fig. 3, cities with a limit value greater than 1 were mainly concentrated in Scenario 1, and a few cities in Scenario 2 had a value greater than 1; however, these results were mainly related to our scenario design. In Scenario 1, the proportion of car transit among travel modes was relatively high, and the proportion of ground bus transit was relatively low. Because the highest carbon emission intensity is associated with cars, and ground buses have low carbon emission intensity (Zhang et al., 2018). This result was similar to those reported in many studies (Geng et al., 2018; Song et al., 2016). Encouraging green travel and reducing the proportion of cars is a low-carbon transport development strategy that many cities prefer to adopt. However, the comparison between different modes of public transport still needs further analysis. The results from Scenario 3 showed that the majority of the proportion limits of coal power consumption by urban rail transit were below 0.8; that is, in most cities where the proportion of coal power consumption exceeded this limit, the development of ground bus transit offered greater advantages in carbon emission reduction. However, for a coal-power dominated country such as China, it was very difficult to reduce the proportion of coal power consumption. Thus, for most cities, the potential for carbon emissions reduction from rail transit was limited. Rail transit is a recognized green travel tool with large volume and little pollution. However, we found that in some cities that have just opened rail transit, although passenger volume is small, the energy consumption, such as rail maintenance and station electricity, is fixed and huge. In addition, the energy consumed by rail transit does not have pollution during the use phase. However, from the perspective of life cycle, coal power generation in China as a coal power-based country emits a large amount of greenhouse gases at the electricity production stage (Hao et al., 2017). Therefore, under the premise of low carrying rate, the rail transit of some cities has no emission reduction advantage compared with other travel modes.

Second, analysis of specific cities showed that the proportion limit of coal power for rail transit in Type 1 cities was generally higher than that of Type 2 cities. Likewise, the proportion limit of Type 2 cities was higher than that of Type 3 cities. These results meant that as the rail transit passenger volume increased, the potential for carbon emission reduction also increased. This is mainly due to the fact that the energy input in the early stage of rail transit is established, including the energy consumption of infrastructure construction and the energy consumption of the platform. The marginal energy consumption of rail transit passengers is almost negligible (Liu et al., 2017). Therefore, the greater the passenger volume of rail transit, the less energy consumption per capita of the rail transit, improves the energy efficiency of urban rail transit, and thus increases the carbon emission reduction potential. The development of rail transit in Type 1 cities was relatively mature and had high operational efficiency. The proportion limit of coal power consumption in the four Type 1 cities was relatively high, and (compared to other types of cities) these cities could more easily achieve actual proportions below the limit value, indicating that the potential for developing rail transit carbon emission reduction was relatively large in such cities. Type 1 cities had high levels of economic development, large population densities, and a rapid increase in transportation demands, resulting in traffic congestion, increased air pollution, and serious contradictions between transportation supply and demand, which severely restricted the sustainable development of these cities (Peng et al., 2017). Therefore, rail transportation with the characteristics of safety, efficiency, large transportation capability, and lower land use demands, was an effective solution to the contradiction between the supply and demand of transportation in big cities, and fundamentally relieved the pressure on urban traffic. Rail transit is also the consensus approach of major cities in the world for solving traffic problems and building low-carbon cities (Lin and Du, 2017).

Rail transit in Type 2 cities was in a stage of rapid development. In most cities, the proportion limits under Scenario 3 were relatively low (except for Xi'an and Shenyang). However, for cities such as Chengdu and Chongqing, where hydropower resources were relatively abundant, even if the limit value was relatively low, it could nevertheless achieve the purpose of reducing emissions from rail transit. The two cities of Xi'an and Shenyang had special characteristics, and the proportion limits of coal power was relatively high. Shenyang, in particular, had the highest limit value of all cities for all three scenarios. These results may be related to the characteristics of Chengdu and Chongqing, where systematic transportation planning and the effectiveness of transportation operations have greatly reduced the unit energy consumption of residents (Ning et al., 2018). Type 3 cities had the lowest proportion limit of coal power consumption (< 0.6). Compared with the actual proportion of coal power consumption, Type 3 cities had limited carbon emission reduction potential for rail transit; in fact, rail transit generated more carbon emissions than other traffic modes in these cities. This was mainly due to the fact that rail transit was still in its initial development stage, with few operating lines and residents' dependence on rail transit was not high. In addition, some small and medium-sized cities had fewer private cars than other cities, and ground buses could fully meet the travel demand. The scale of rail transit construction far exceeds the actual traffic demand, or the cost of the construction of local rail transit is too high (Bu et al., 2018), restricting the rail transit carbon emission reduction effect.

Finally, most cities exhibited the largest rail transit potential in 2015, followed by that in 2017 and finally for 2016. The reason for these differences was that the energy consumption of per capita unit travel distance was lowest in 2015 and highest in 2016. According to relevant research, the energy consumption of urban rail transit trains is mainly (55%) due to gaining traction. In addition, the distance between urban subway stations was relatively short, such that trains started and braked frequently, which accounted for 40% of tractive power consumption. Furthermore, if the track itself has a slope, braking energy consumption is higher than on a flat track (Zhao and Deng, 2013). Therefore, promoting the technological progress of rail transit, rationally planning the lines and reducing the energy consumption of per capita unit travel distance are key actions to reduce the energy consumption and increase the carbon emission reduction potential of rail transit.

5. Conclusions and implications

5.1. Conclusions

This study compared the carbon emission reduction potential of urban rail transit and other traffic modes in China. The main conclusions of this study are as follows.

1) The traffic demand is in direct proportion to the potential for carbon emission reduction in rail transit. For cities with large traffic demand, the development of rail transit can effectively promote the attainment of low-carbon status. However, for cities with relatively low traffic demand, the potential for the reduction of carbon emissions from rail traffic is limited.
2) For cities with high coal power consumption, the development of ground bus transit is more conducive to achieving carbon reduction targets than rail transit. Compared with Scenario 3, the proportion of coal power consumption in most cities must be lower than 0.6. In fact, some cities needed to have a value less than 0.4 to realize emission reduction advantages.
3) Promoting the development of rail transit technology and lowering the energy consumption per capita unit travel distance are the fundamental ways to increase the emission reduction potential of rail transit. The electricity consumption structure and traffic mode cannot be changed in the short term. Only from the internal optimization of a rail transit system can the carbon emission reduction potential be improved.

5.2. Implications

The following implications can be drawn from the conclusions of this paper.

(1) A city needs to make a reasonable rail transit development plan according to its own traffic demand, and it must not blindly invest in the construction of rail transit. Passenger volume is an important factor in measuring the suitability of rail transit. Due to the large pre-investment, long construction cycle, and high exit costs of rail transit, it is necessary to ensure that passenger volume is sufficient to sustain profitable operation. If the size of the urban population is small, the development of rail transit will only bring great financial and energy pressure to the local government. (2) Cities must make full use of regional resource advantages to promote the coordination of urban low carbon construction and transportation development goals. Full consideration of city heterogeneity is the premise of the development of rail transit, and the local energy structure has a great impact on the emission reduction potential of rail transit. Cities should take advantage of their own resources and give full play to the advantages of clean energy.

(3) All regions must give attention to developing a more perfect energy management system while increasing the technical investment in rail transit. Reasonable scheduling and scientific management are the key to improving energy efficiency and reducing carbon emissions in rail transit. With the rapid development of large data technology, an urban rail transit system should have the capacity for monitoring, data collection, statistical analysis, and prediction of energy consumption.

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