Life cycle carbon emission of monorail transit and its comparison in operation stage with other city transit modes

Teng Li[1], Eryu Zhu[1]*, Haoran Liu[1]

[1]Dept. of Civil Engineering., Beijing Jiaotong University., Shangyuancun 3rd, Beijing, China, 100044
* Corresponding author, Eryu Zhu, Professor of Bridge Department, Beijing Jiaotong University, Ph. D, China.

Abstract. In this paper, carbon emissions of a monorail transit are calculated using the method of whole life cycle, which can be divided into four stages: material manufacturing stage, construction stage, operation stage and demolition stage. In the operation phase, the units are PKT (Passenger Kilometers Travelled) and VKT (Vehicle Kilometers Travelled), while in other three stages, the unit is 1 km. The results show that the carbon emissions from the 1km length monorail are 6271.204 tons. In addition, in the operation stage, it is found that the PKT index and VKT index of Chongqing monorail transportation are 0.07468 and 3.31933 respectively, far lower than those of subways in the same city. For PKT indicators of other rail transits, from small to large, they are light rail, tram, subway, APM and maglev. As for VKT indicators, from small to large, they are tram, light rail, subway, APM and maglev. The PKT index of Beijing subway is the lowest compared with that of other cities.

1 Introduction

In recent years, with the continuous increase of urban population density, the flow of people and goods between cities and the construction of rail transit are in full swing. However, with the continuous expansion of the construction scale of different types of rail transit, the topic of environmental pollution, which is closely related to the life quality of residents, begins to receive the close attention of the country and the society. The increasing carbon emission has posed a threat to human lives in the world. In this year, the concept of carbon neutrality and carbon peak was first written into the government work report in China [1]. Carbon peak means that China promises that carbon emissions will stop growing by 2030 and gradually decline after they peak. Carbon neutrality means that enterprises, groups or individuals calculate the total amount of greenhouse gas emissions directly or indirectly generated within a certain period of time, and then offset the carbon emission generated by themselves through plant afforestation, energy conservation and emission reduction, etc., so as to achieve the goal of zero emission.

According to statistics [2], carbon emission from China's transportation industry accounts for nearly 10% of China's total carbon emissions. And with the advancement of urbanization and industrialization, the carbon emissions from China's transportation industry will continue to increase. Therefore, the development of green transportation has a very great significance. However, there has been little analysis of the carbon emissions of different modes of transport. In this paper, carbon emissions from different urban transit modes are calculated and compared, including monorail transit, subway, maglev, APM and trams, to find a lower carbon emission transit mode, and to facilitate the adjustment of the urban rail transit system and urban sustainable development, and to provide suggestions for government policies.

2 Whole life cycle carbon emission

The carbon emission calculated in this paper is based on the method of whole life cycle, and the carbon emission of different traffic projects is divided into the following four stages: material manufacturing stage, construction stage, operation stage and demolition stage [3]. The corresponding list is established for each stage, and carbon emissions of each item in the list are calculated. The carbon emissions of the whole life cycle are obtained by summing up the carbon emissions of the four stages.

2.1. Carbon emission calculation methods in each stage

The calculation method of carbon emission in each stage [4] is as follows.

In the material manufacturing stage, the following formula is used:

$$M_c = \sum M_i \times C_i \tag{1}$$

M_c is the carbon emission in the production and processing stage of building materials; M_i is the consumption of the ith material in the production and processing stage of building materials; C_i is the carbon emission of the production process of unit building materials.

In the construction stage, greenhouse gas emissions mainly come from the transportation of materials and different construction works, and results are related to the transportation distance of building materials and the amount of works in each process. The following formula will be used to calculate carbon emissions in the construction stage:

$$C_c = \sum M_i \times C_{ti} \times L_i + M_p \times C_p \qquad (2)$$

C_c is the carbon emission in the construction stage; M_i is the amount of the ith material in the construction stage; C_{ti} is the carbon emission per unit transportation distance of the vehicle; L_i is the transportation distance. M_p is the amount of works in each process in the construction stage and C_p is the carbon emission generated by unit work in each process.

In the operation stage, energy consumption mainly comes from the electricity consumed during vehicle operation, while carbon emission mainly comes from electricity production. The following formula is used to calculate carbon emission in this stage:

$$O_c = \sum M_i \times C_i \qquad (3)$$

O_c is the carbon emission in the construction stage; M_i is the electricity consumed during operation in the life cycle of different urban transit modes, and C_i is the carbon emission generated by production of unit electricity.

In the demolition stage, the following formula is used to calculate carbon emission:

$$D_c = \sum M_i \times C_{ti} \times L_i + M_p \times C_p \qquad (4)$$

D_c is the carbon emission in the demolition stage; M_i is the amount of the ith material in the construction stage; C_{ti} is the carbon emission per unit transportation distance of the vehicle; L_i is the transportation distance. M_p is the amount of works in each process in the demolition stage and C_p is the carbon emission generated by unit work in each process.

2.2. Carbon emission factors

Energy consumption carbon emission factor refers to the amount of greenhouse gases associated with the consumption of unit mass energy, and is an important parameter representing the characteristics of greenhouse gas emissions of a certain energy type [5]. Carbon emission factors of IPCC 2006 [6] are used in this paper. The carbon emission factor of diesel is 3.16 kg CO_2 / kg. The average carbon emission factor of electricity production in China is 1.062 kg CO_2 / kilowatt-hour [7].

According to some research results [8-10], carbon emission from C40 concrete is 644.59 kg/m^3; carbon emissions of 1-ton large size steel, medium and small size steel and steel wire are 20344.4 kg/ton, 16883.7 kg/ton, 16706.3 kg/ton, respectively.

Carbon emissions in different works are mainly from the electricity consumption and diesel consumption from various construction machinery and equipment. Carbon emission of concrete construction process per unit volume [11] is shown in the following table:

Table 1. Carbon emission of concrete construction per unit volume.

Procedure（kg / m^3）	CO_2	NO_X	Carbon Equivalent
Template Works	46.975	0.377	159.321
Steel Works	13.947	0.427	141.193
Concrete Works	3.166	/	3.166
Earth Works	8.89	/	8.89

2.3. Carbon emission from material transportation

In the material transportation process, carbon emissions are mainly caused by the energy consumed by transportation vehicles. Road transportation is the most common solution and the fuel of road vehicle is mainly diesel. In this paper, the specific assumptions for material transportation are as follows: for concrete, 8 square concrete mixers are used, and the fuel consumption per 100 km is 35L. As for other building materials such as steel, 20-ton freight vehicles are used, and the fuel consumption per 100 km is 30L. It is assumed that the round-trip transport distance of concrete is 30km, that of steel is 60km and that of earthwork is 15km. In the structural demolition stage, only the removal of major

materials such as concrete and steel are considered. It is assumed that the average transport distance of steel is 60km, and the transport distance of waste concrete is 30km.

3 Estimation of life-cycle carbon emissions from monorail transit

In this paper, 1km is selected as a functional unit to carry out a theoretical analysis of carbon emissions of monorail transit in the four stages. A monorail transit line in China is selected for analysis. The cross section of concrete PC guideway running by the train is I-shaped, 850mm wide, and 1.5m high. The structure is shown in the figures below [12]:
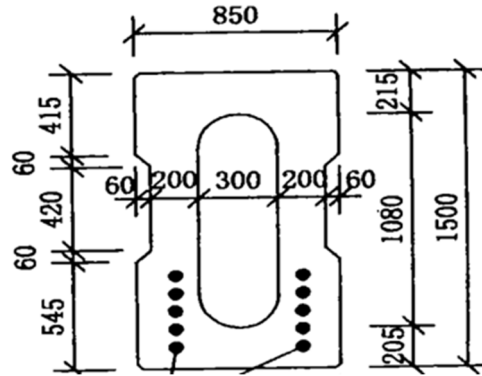
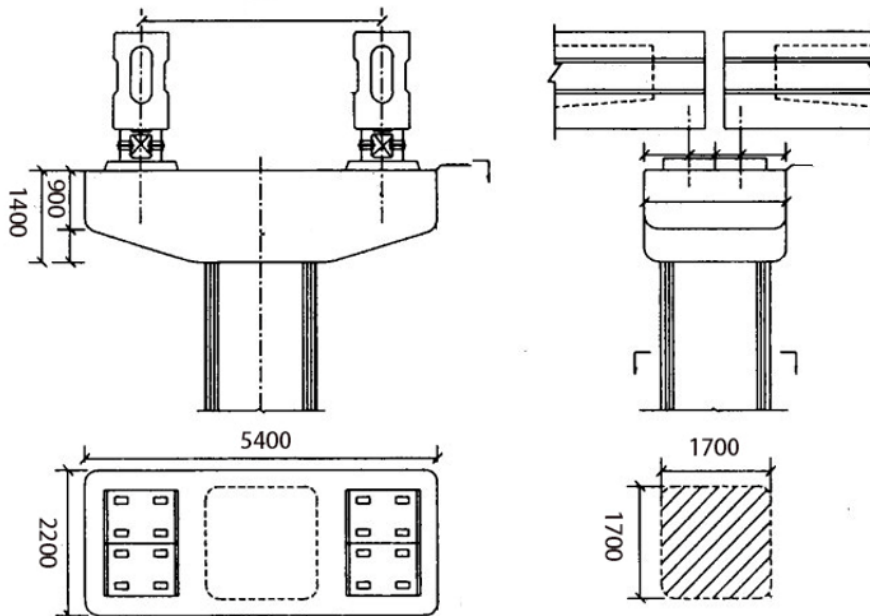**Figure 1.** Cross section of monorail guideway

Figure 2. T –shaped pier of monorail.

Assuming the length of a span is 25 m and the bridge pier height is 9 m. There are 41 piers in 1 km length bridge and the concrete volume of two guideways, 41piers, 41 cover beams are 1912.8 m³, 1066.4 m³ and 598.477 m³, respectively. Assuming the C40 concrete and 10 bunches of 3 - 7 Φ 5 steel strands are used in the guideway. Total steel strand volume in 1 km guideway is 8.2 m³. Total mass of 1 km steel strand is 64370 kg. Assuming the reinforcement ratio of compression members is 0.2%, and reinforcement ratio of flexural members is 0.2% too. Total steel mass is 56169.53 kg. Assuming the spread foundations and piles are used and each pier has a single row of three piles, with diameter of each pile 100 cm. Assuming the depth is 12 m. The volume of concrete or earth is 1158.66 m³. Assuming the pile reinforcement ratio is 0.2%, then the steel quantity is 18190.96 kg.

In all, total concrete volume is 4736.36 m³. Total quantities of steel rebar and strand are 74360.49 kg and 64370 kg, respectively. And total earth volume is 1158.66 m³. Based on the above carbon emission factors, carbon emissions from the material manufacturing stage, construction stage and material transportation in the construction stage are shown in **Table 2**, **Table 3** and **Table 4**, respectively.

Table 2. Carbon emissions of monorail transit in material manufacturing stage.

	Concrete (m³)	Steel strand (kg)	Steel reinforcement (kg)	Sum
Carbon Emission （kg）	4736.36	64370	74360.49	2659720.5

Table 3. Carbon emission of monorail transit in construction stage.

	Template work	Steel work	Concrete work	Earth work	Sum
Carbon Emission （kg）	222490.5	1934874.1	14995.3	10300.5	2182660.4

3

Table 4. Carbon emissions from transportation in material manufacturing stage.

	Earth	Steel	Concrete	Sum
Carbon Emission（kg）	246.11	346.81	16826.78	17419.69

Annual power consumption data and passenger and vehicle data are obtained from China Urban Rail Transit Yearbook 2019 [13] and the carbon emission of one-year operation of the monorail line is 333633.8 kg. Assuming the life cycle of monorail is 100 years. Carbon emission of Chongqing monorail Line 2 is 1063884 kg per kilometer.

The carbon emission of structure demolition mainly comes from the on-site demolition process. The total concrete volume of 1 km was calculated before as 4736.36

m^3. Since the carbon emission per cubic meter of concrete removal is 69.82 kg [4], we can obtain that the total carbon emission in the demolition process is 330692.66 kg. According to the assumption of transportation of the removed material, carbon emission from this process is 16826.78 kg.

Based on the above calculation, the whole life-cycle carbon emission of 1km monorail transit is shown in the following table:

Table 5. Life cycle carbon emissions of monorail transit.

	Materials Manufacturing Stage	Construction Stage	Operation Stage	Demolition Stage	Sum
Carbon Emission（kg）	2659720.5	2200080.09	1063884	347519.44	6271204.03

4 Operation stage carbon emissions of different urban rail transit modes

In this stage, we used two new units, passenger kilometers traveled (PKT) and vehicle kilometers traveled (VKT). Data from China Urban Rail Transit Yearbook 2019 [13] are used. In order to eliminate the influence of geographical factors, the operation data of rail transits in multiple cities are compared in this paper. The energy consumption data of monorail transit - metro (Chongqing),

metro - maglev transit (Changsha), metro - maglev -APM (Shanghai), metro - tram (Shenyang), metro - light rail (Changchun), metro – rapid rail transit (Qingdao) and metro -APM (Guangzhou) during the operation stages are included. Then the carbon emission factor of electric power is considered to calculate the carbon emissions. The results are shown in **Figure 4** to **Figure 11**. The unmarked bars in **Figure 4** to **Figure 11** represent local subways. **Figure 3** shows the section of a typical subway tunnel. It can be seen that the section size is much larger than that of the monorail bridge guideway.
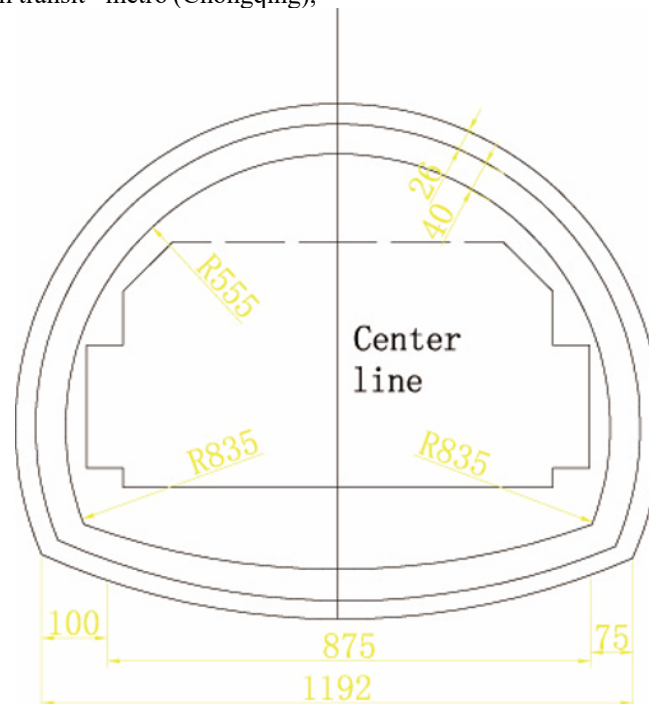

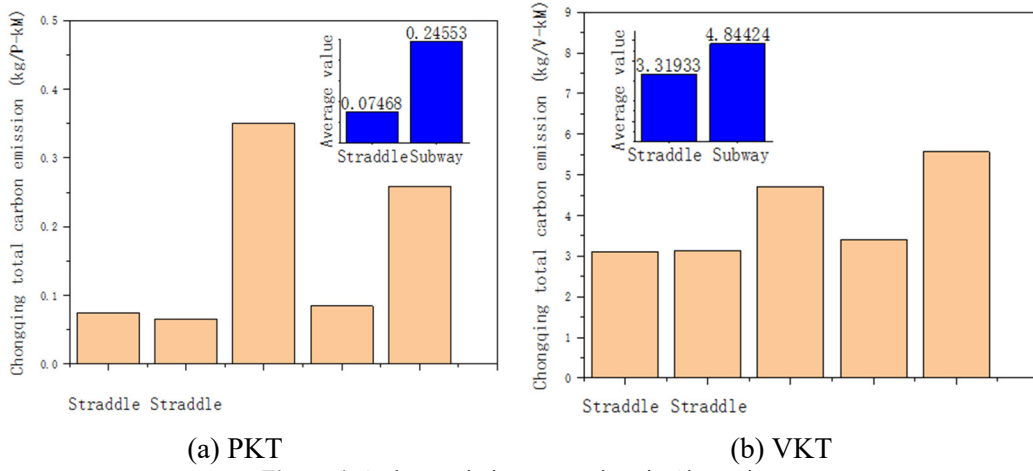**Figure 3.** Typical subway tunnel cross section (Unit: cm).

(a) PKT   (b) VKT

Figure 4. Carbon emission comparison in Chongqing.

(a) PKT   (b) VKT
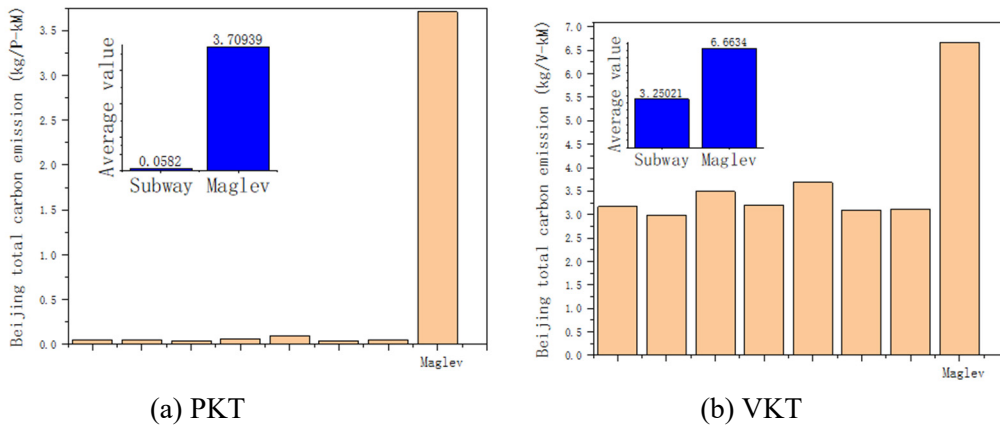
Figure 5. Carbon emission comparison in Beijing.

(a) PKT   (b) VKT
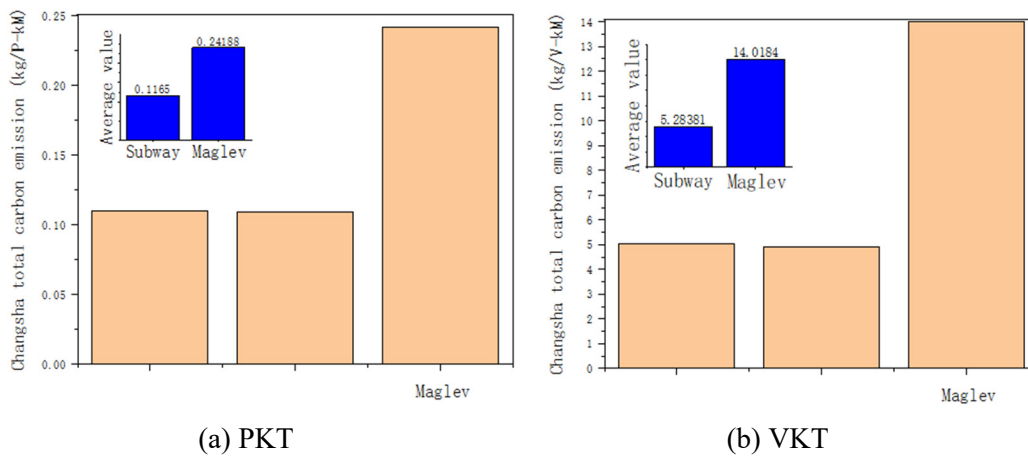
Figure 6. Carbon emission comparison in Changsha.

(a) PKT

(b) VKT
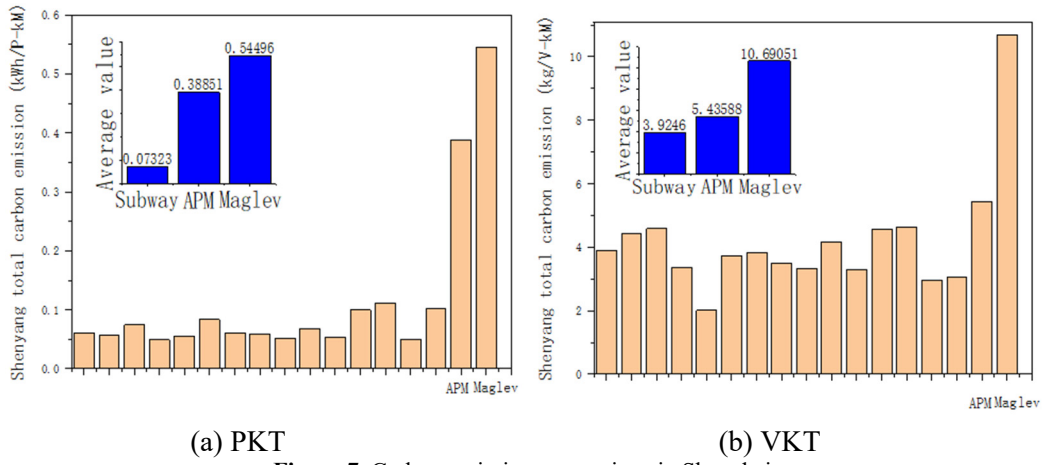
Figure 7. Carbon emission comparison in Shanghai.

(a) PKT

(b) VKT
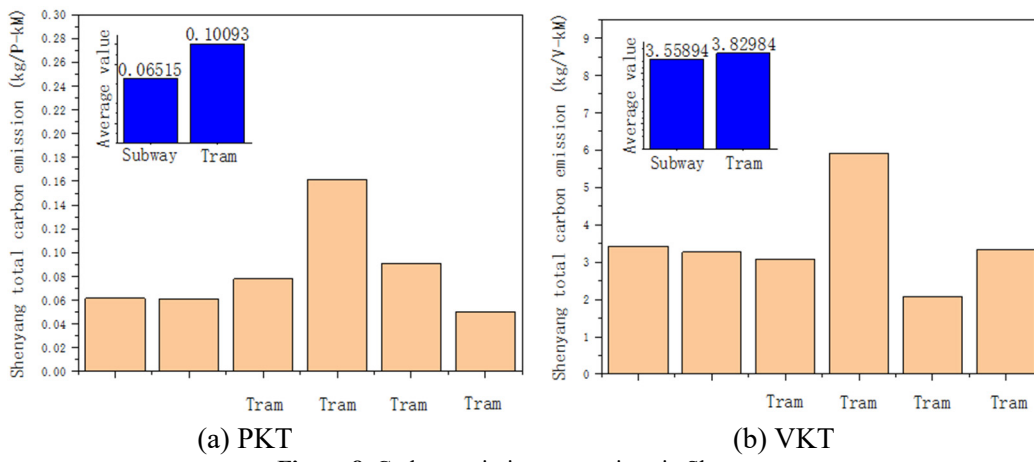
Figure 8. Carbon emission comparison in Shenyang.

(a) PKT

(b) VKT
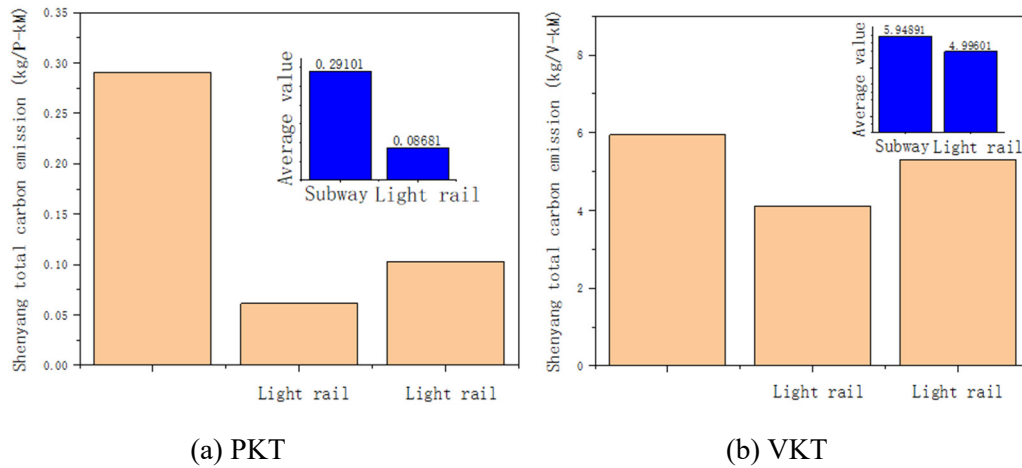
Figure 9. Carbon emission comparison in Changchun.

(a) PKT (b) VKT
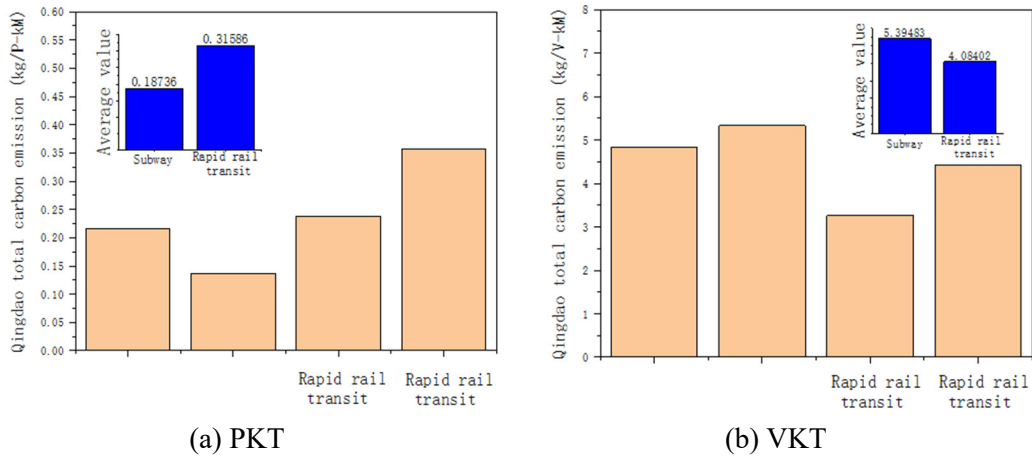
Figure 10. Carbon emission comparison in Qingdao.

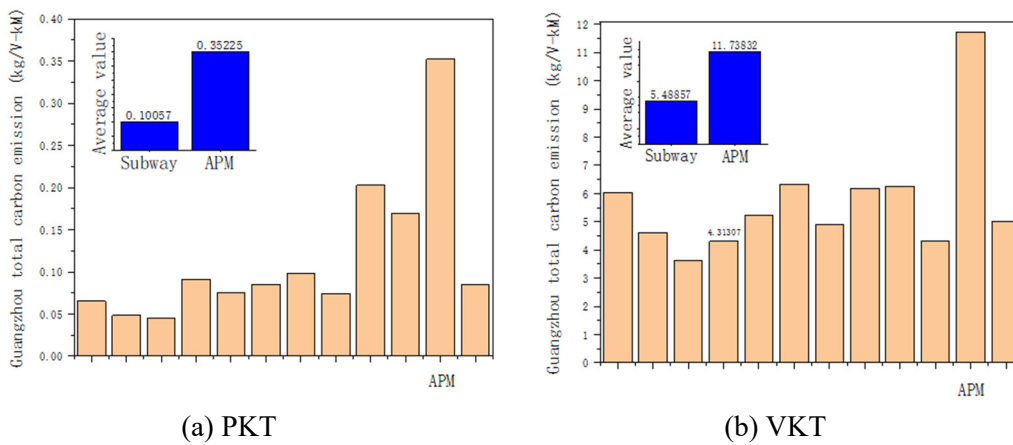(a) PKT (b) VKT

Figure 11. Carbon emission comparison in Guangzhou.
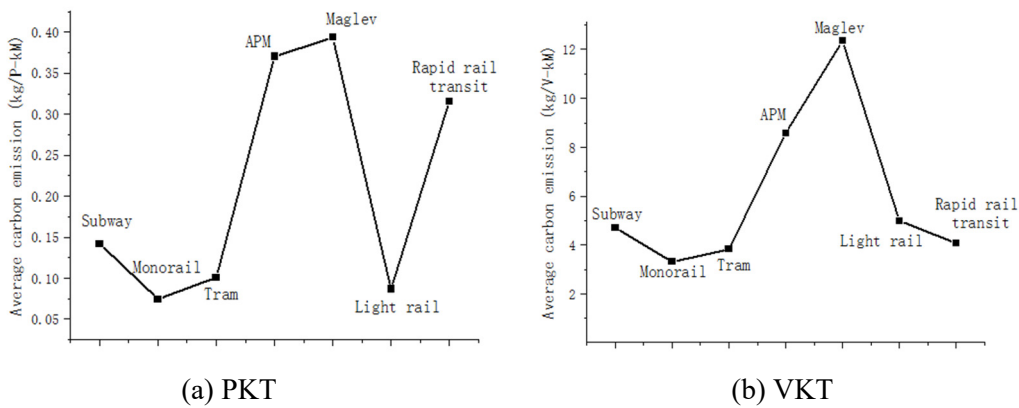

(a) PKT (b) VKT

Figure 12. Average carbon emission.

Subway is still the main rail transit form in each city. It can be seen that the carbon emissions (PKT and VKT) of Chongqing monorail transit during operation are much smaller than those of local subways. According to the data of Beijing and Changsha, we find that the carbon emission of maglev is much higher than that of subway, and the VKT indexes of the two maglev lines are more than 10. According to the data of Shanghai, we find carbon emissions of the APM line are between subway and maglev traffic, but VKT index is also over 5. As can be seen from the data of Guangzhou, the VKT index of APM

is more than 11, almost reaching the carbon emission of maglev. In addition, we can also see that the carbon emission of tram operation is slightly higher than that of subway, while the carbon emission of light rail is lower than that of subway. The PKT index of urban rapid rail transit is higher than that of subway, while the VKT index is lower than that of subway. Compared with other cities, the PKT index of Beijing subway is the lowest, which also reflects the congestion degree of Beijing subway vehicles. The number of passengers in the same vehicle increases greatly, leading to the low per capita value. As shown in

Figure 12, for different forms of rail transit in various cities, the ranking of PKT index from small to large is monorail, light rail, tram, subway, APM and Maglev. For VKT indicators, the ascending order is monorail, tram, light rail, subway, APM and maglev.

5 Conclusion

The final results show that the carbon emissions from the 1km length monorail are 6271.204 tons. Among them, carbon emission from the material manufacturing stage is 265.972 tons; carbon emission from the construction stage is 2,200.08 tons; carbon emission of the 100-year operation stage is 1063.884 tons, and the carbon emission in the demolition stage is 347.519 tons.

By comparing the carbon emissions in the operation stage, it is found that the PKT index and VKT index of Chongqing monorail transportation are 0.07468 and 3.31933 respectively, far lower than those of subways in the same city. For PKT indicators of other rail transit modes, from small to large, they are light rail, tram, subway, APM and maglev. As for VKT indicators, from small to large, they are tram, light rail, subway, APM and maglev. Compared with other cities, Beijing's metro has the lowest PKT index.

Acknowledgments

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