Evaluating Life-cycle CO^2 Emissions of Prefabricated and Assembled Urban Tunnels

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Abstract

In order to comprehensively and quantitatively analyze CO_2 emissions characteristics of the entire life cycle of prefabricated urban tunnels, Based on life cycle theory, this paper divides the life cycle stages of prefabricated tunnels, and uses the carbon emission coefficient method and scenario assumption method to construct a CO_2 emissions measurement model for the life cycle of prefabricated urban tunnels. Use this model to calculate the CO_2 emissions of the Shanghai Zhuguang Road Tunnel throughout its life-cycle. The results show that the total CO_2 emissions of Zhuguang Road Tunnel throughout its life cycle are 88,657.96t, and CO_2 emissions intensity is 63.78t CO_2/m. CO_2 emissions in operation and maintenance stage and raw materials production stage are relatively large, accounting for 54.83% and 35.23 % respectively, CO_2 emissions can be reduced by choosing energy-saving equipment, reducing the waste of raw materials, promoting raw materials recycling and improving processing techniques.

Keywords

CO_2 emissions, Prefabricated urban tunnels, The life cycle.

1. Introduction

In order to relieve the pressure of urban land shortage and traffic congestion, improve the connectivity of local road networks, and realize the smooth traffic between regions, China has vigorously developed urban underground tunnel construction. Currently, the total number of underground road tunnels in Shanghai is about 100km[1]. The construction and operation of urban tunnels will consume a large amount of materials, resources and energy and produce a large amount of CO_2. With the increasing demand for construction, the accompanying carbon emission problem should not be underestimated.

In order to accelerate the construction of green and low-carbon transportation infrastructure, construction units have promoted application of prefabricated assembly technology to the field of urban tunnels construction in china. The prefabricated assembly technology is a kind of standardized prefabricated components produced in the factory and assembled on-site to form an overall structure [2]. Compared with traditional cast-in-place technology, prefabrication can improve construction quality, shorten construction period [3], and reduce materials and construction waste [4]. Therefore, the transition from traditional cast-in-place to fully prefabricated assembly is an inevitable trend for the future development of urban tunnel construction. At present, there are few studies on CO_2 emissions of the tunnel life cycle at home and abroad, and most scholars only study the part of the tunnel life cycle [5]. Li et al.[6] only considered the actual carbon emissions in the four stages of on-site construction. Considering off-site transportation, Chen [7]. Guo et al. [8] constructed a carbon emission model for each stage of road tunnel construction, operation, and maintenance, but did not consider the end of life stage of the tunnel. In general, the existing research has the problems of system boundaries, functional units and research hypotheses are not unified, life cycle division and measurement content are not comprehensive [9].

So far few scholars have built a CO_2 emissions calculation model for the entire life cycle of prefabricated tunnels. In this paper, the carbon emissions coefficient and scenario assumption method are used to quantify CO_2 emissions of prefabricated urban tunnels throughout the life cycle. This paper divides the life cycle stages of prefabricated tunnels based on life cycle theory, determines the

CO_2 emissions system boundaries and functional units, selects CO_2 emissions factors on the basis of existing research, and finally establishes a full life cycle CO_2 emissions measurement model and Shanghai Zhuguang Road Tunnel is used as a case for analysis.

2. CO_2 emissions measurement model of prefabricated urban tunnel

2.1 Definition of the life cycle scope of prefabricated urban tunnel

Relevant literature reading, expert interviews and on-site investigations have determined CO_2 emissions assessment scope of the life cycle of prefabricated urban tunnel, including raw material production, prefabricated component manufacturing, construction, operation and maintenance, end of life (EOL). In addition, it also includes transportation(T) stage,as shown in Fig.1. Due to the difficulty of data collection and the fact that CO_2 is the most important greenhouse gas, this paper only considers CO_2 emissions and does not measure other greenhouse gases.

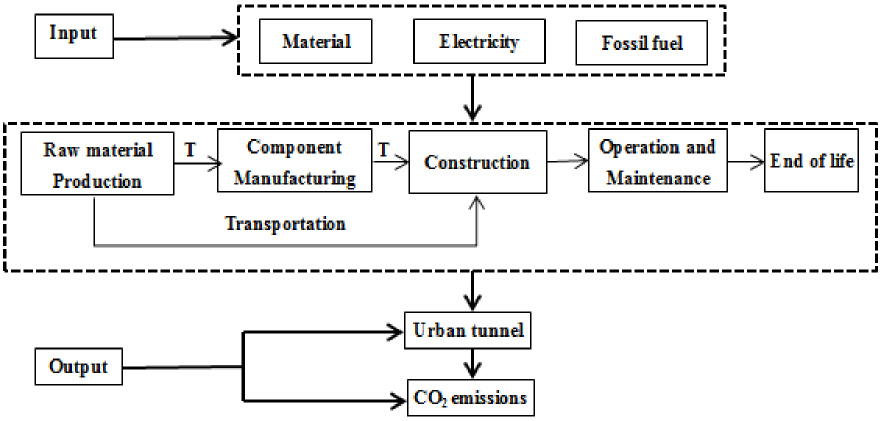

Fig. 1 The scope of CO_2 emissions of the life cycle of prefabricated urban tunnel

There is a big difference in total CO_2 emissions of prefabricated and assembled urban tunnels due to different lengths. In order to compare different typical cases of prefabricated and assembled urban tunnels, the functional unit of the study (ie carbon emission intensity) is determined as CO_2 emissions per meter of prefabricated and assembled urban tunnel (unit: tCO_2/m).

2.2 Selection of CO_2 emissions factors for prefabricated urban tunnel

The life cycle of prefabricated urban tunnel mainly involves CO_2 emissions factor data of building materials, energy and vehicle transportation. This article compares and selects from the life cycle assessment database, literature and research reports, and summarizes the CO_2 emissions factors required for CO_2 emissions analysis of prefabricated tunnel, The CO_2 emissions factors are shown in Table 1.

Table 1 CO_2 emissions factors of materials, energy and transport

Items		Unit	Emissions factors
Materials	C35 Concrete	kg/m^3	292.552[10]
	C50 Concrete	kg/m^3	403.141[10]
	C60 Concrete	kg/m^3	450.535[10]
	Steel	kg/t	3150[9]
	PVC	kg/kg	8.69[9]
Energy	Diesel	kg/kg	3.161[11]
	Gasoline	kg/kg	2.984[11]
	Electric Power（East China area）	kg/kwh	0.8046[12]
Transport	Highway (Diesel)	kg/(t· km)	0.1983[13]
	Highway (Gasoline)	kg/(t· km)	0.2004[13]
	Waterway	kg/(t· km)	0.0183[13]
	Railway	kg/(t· km)	0.00913[13]

2.3 Establishment of CO_2 emissions model for the life cycle of prefabricated urban tunnel

Table 2 Calculation formula of CO_2 emissions at each stage of prefabricated urban tunnel

Stage	Formula	Algebraic form	Definition
Raw material production	$P_r=\sum_{i=1}^{n} Q_i \times EF_i \times (1+\varepsilon_i)$	P_r	The CO_2 emissions during the raw material production stage
		Q_i	The amount of raw material *i*
		EF_i	The CO_2 emissions factor of raw material *i*
		ε_i	Depletion coefficient of raw material *i*
components manufacturing	$P_{cm}=\sum_{q=1}^{p}(U_q \times EF_q)+\sum_{d=1}^{f}(U_d \times EF_d \times H_d)$	P_{cm}	The CO_2 emissions from component manufacturing
		U_q	consumption of energy *q*
		EF_q	The CO_2 emissions factor of energy *q* usage
		U_d	Electric energy consumed by electrical equipment *d*
		EF_d	The CO_2 emissions factor of electricity usage
		H_d	Running time of equipment *d*
Transportation	$P_{tp}=\sum_{i=1}^{n}\sum_{j=1}^{z} Q_{ij} \times EF_j \times L_{ij} \times K$	P_{tp}	The CO_2 emissions from material and components transportation
		Q_{ij}	The transportation quantity of materials or pre-components *i* of the *j*th transportation scheme
		EF_j	The CO_2 emissions factor for transportation using the *j*th transportation method
		L_{ij}	The transportation distance of the *i*th materials or components using the *j*th transportation method
		K	Empty vehicle return coefficient, assuming full load transportation and empty return, the environmental load when empty is 0.67 times that of full load, K=1.67[14]
Construction	$P_{ct}=\sum_{q=1}^{p}(U_q \times EF_q)+\sum_{d=1}^{f}(U_d \times EF_d \times H_d)$	P_{ct}	The CO_2 emissions from construction stage
Operation and Maintenance	$P_{om}=P_{op}+P_{mt}$	P_{om}	The CO_2 emissions during the operation and maintenance stage
	$P_{op}=\sum_{d=1}^{f}(U_d \times EF_d \times H_d)$	P_{op}	The CO_2 emissions during the operational stage
	$P_{mt}=\{\sum_{i=1}^{n}(Q_i \times EF_i)+\sum_{q=1}^{p}(U_q \times EF_q)$	P_{mt}	The CO_2 emissions during the maintenance stage
	$+\sum_{d=1}^{f}(U_d \times EF_d \times H_d)\} \times D$	D	Maintenance times
End of life	$P_{eol}=P_{demo}+P_{disp}$	P_{eol}	The CO_2 emissions from the end of life
	$P_{demo}=\sum_{q=1}^{p}(U_q \times EF_q)+\sum_{d=1}^{f}(U_d \times EF_d \times H_d)$	P_{demo}	The CO_2 emissions from tunnel demolition
	$P_{disp}=\sum_{i=1}^{n} EF_{disp} \times W_i \times (1-R_i)$	P_{disp}	The CO_2 emissions from waste recycling or landfill
	$-\sum_{i=1}^{n} EF_i \times W_i \times R_i \times S_i$	EF_{disp}	The CO_2 emission factor of unit waste landfill
		W_i	The amount of waste *i*
		R_i	Recovery rate of raw material *i*
		S_i	Waste *i* recycling will save the proportion of CO_2 emissions from raw material *i* production

In this paper, CO_2 emissions coefficient method is adopted to calculate the carbon emission from prefabricated urban tunnel. CO_2 emissions during life-cycle of the prefabricated urban tunnel can be obtained by adding the CO_2 emissions generated at the six different stages of the tunnel. The calculation formula of CO_2 emissions at each stage is shown in Table 2.

3. Case analysis

3.1 Calculation of CO_2 emissions throughout the life cycle of Zhuguang Road Tunnel

This paper chooses Zhuguang Road tunnel in Shanghai as a case. Zhuguang Road tunnel is the first tunnel in China to adopt fully prefabricated assembly technology. It is constructed by using the earth pressure balance shield machine with a diameter of 14.45m. The prefabricated assembly rate is over 90% and it is a single-tube double-layer tunnel. The tunnel is divided into shield section and open cut section, with a total length of about 2.8km, among which the shield section is about 1.39km. The main prefabricated components include pipe segment, π-shaped pieces, column, lane plate, cover and anti-collision side stone, and the rest sections are underground cast-in-place concrete structure. The designed speed of Zhuguang Road tunnel is 40 km/h, the designed service life is 100 years, and the construction scale is two-way four lanes of motor vehicles.

By looking up the bill of quantities and investigating in the prefabrication plant and the construction site, we have obtained the raw materials, resources and energy consumption at each stage of the life cycle of the Zhuguang Road Tunnel. This paper only considers concrete, steel and PVC, and the other raw materials are not considered due to their small usage. The CO_2 emissions factor in Table 1 and formula in Table 2 are used to calculate the CO_2 emissions in each stage of life-cycle of the Zhuguang Road Tunnel. The results are shown in Table 3.

Table 3 CO_2 emissions and Percentage of CO_2 emissions of the life cycle of Zhuguang Road Tunnel at each stage

Stage		CO_2 emissions/t	Percentage/%
Raw material production		31233.78	35.23%
Prefabricated components manufacturing		339.50	0.38%
Transportation		618.84	0.70%
Construction stage		4959.04	5.59%
Operation and Maintenance stage	Ventilation system	13718.11	15.47%
	Lighting system	34068.64	38.43%
	Routine maintenance	820.07	0.92%
End of life		2899.97	3.27%
Total		88657.96	100.00%

3.2 Results and discussion

From the perspective of the entire life cycle of prefabricated urban tunnel, the total CO_2 emissions of Zhuguang Road Tunnel are 88657.96t, and the carbon emission intensity is 63.78 tCO_2/m. As can be seen from Table 3, CO_2 emissions in the operation and maintenance stage (54.83%) > raw material production stage (35.23%) > construction stage (5.59%) > end of life stage (3.27%) > transportation stage (0.70%) > prefabricated components production stage (0.38%). CO_2 emissions account for a large proportion in the operation and maintenance stage, the raw material production, while the rest stages are relatively small, accounting for only 9.94%. The following two stages are mainly analyzed:

CO_2 emissions in the operation and maintenance stage are the highest among all stages of the tunnel life cycle, mainly due to the large amount of electricity consumption. At this stage, it takes 24 hours to turn on the lighting equipment to facilitate vehicle traffic. Choosing energy-saving and emission-reducing lighting fixtures can effectively reduce CO_2 emissions at this stage.

The raw material production stage is also the key stage of emission reduction of Zhuguang Road tunnel. The total CO_2 emissions in this stage is 31233.78t, and CO_2 emissions intensity is 22.47tCO_2/m. According to Fig. 2, Steel and PVC (polyvinyl chloride) are the main CO_2 emissions sources. As an essential material in tunnel construction, Steel produces a large amount of CO_2. Therefore, the utilization rate of steel should be improved and waste should be reduced by rational use. Due to the heavy weight of the components, PVC core mode is adopted to reduce the quality of the components. However, due to the large CO_2 emissions factor of PVC compared with the steel, CO_2 emissions factor of PVC production should be reduced by improving the process. On the premise of satisfying the safety and durability of the structure, the use and waste of steel and PVC with high energy consumption and high pollution should be reduced as far as possible. Meanwhile, attention should be paid to the recycling and reuse of raw materials.

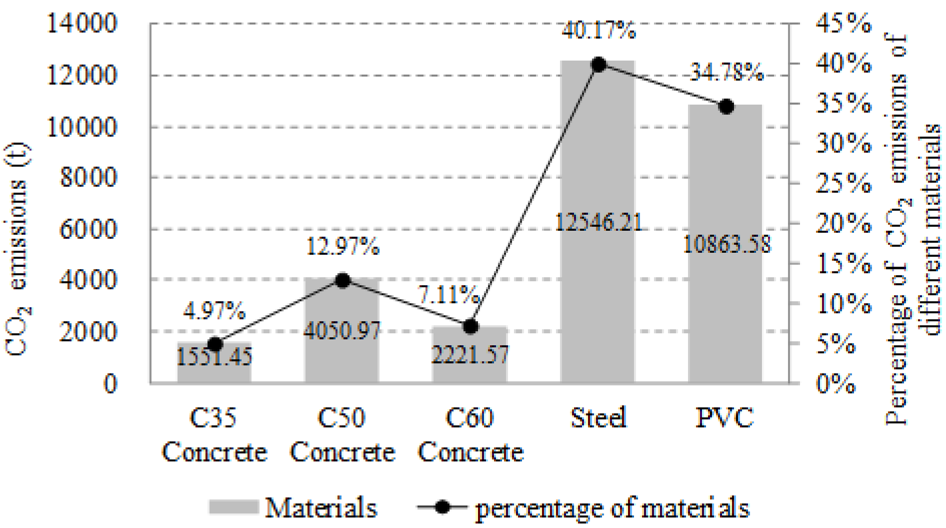

Fig. 2 CO_2 emissions of different materials in Zhuguang Road Tunnel during the raw material production stage

Zhuguang Road Tunnel produces a large amount of CO_2 during its entire life cycle. The CO_2 emissions generated during operation and maintenance and raw material production stage account for more than 90% of the entire life cycle of the tunnel. CO_2 emissions can be reduced by choosing energy-saving equipment, reducing the waste of raw materials, promoting raw materials recycling and improving processing techniques.

4. Conclusion

At first, this paper builds a CO_2 emissions measurement model for the entire life cycle of prefabricated urban tunnels, which is divided into six stages: raw materials production, Prefabricated components manufacturing, transportation, construction, operation and maintenance, and end of life. The measurement content includes CO_2 emissions generated by the consumption of building materials and prefabricated components, energy consumption of transportation vehicles, and mechanical equipment.

Secondly, the world's first double-layer fully prefabricated assembly tunnel—Shanghai Zhuguang Road Tunnel is selected as a case. According to the constructed CO_2 emissions measurement model, the carbon emission intensity of the light tunnels is calculated to be 63.78tCO_2/m. The stage with the largest carbon emissions throughout the life cycle of this case is the operation and maintenance stage, accounting for 54.83%; the second is the raw material production stage, accounting for 35.23%. Operation and maintenance and raw material production stage account for a relatively large proportion, which is the focus of our attention. We can reduce carbon emissions by selecting energy-saving equipment, reducing raw material waste, promoting raw material recycling, improving processing techniques, and adopting feasible new technologies and new processes.

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