Calculation Method of Carbon Emission during the Construction of Highway Tunnel in Mountainous Areas

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Abstract. In this paper, a tunnel in the Nantian Expressway project is selected as an example of carbon emission calculation under the background of the carbon peaking and carbon neutrality goals. In view of the lack of research on carbon emissions in tunnels in our country, a brief analysis and calculation framework is formulated to study the carbon emissions in the tunnel construction stage. In construction stage carbon emissions are divided into three sources and three corresponding calculation models are proposed. The carbon emission inventory obtained on construction site. Various types of carbon emission factors are determined by compiling related documents and regulations. Then the contribution of different materials and machinery to carbon emission is clarified. Finally, according to the calculated results, energy-saving and emission-reduction plans based on carbon emission evaluation are provided, which provide scientific basis for the green emission reduction construction of tunnel construction.

Keywords: carbon emission; tunnels; calculation

1 Introduction

By the end of 2020, the total mileage of expressways in operation in China is 5.1981 million kilometers, including 21,316 tunnels with a total operating mileage of 21.9993 million linear meters. Centralized carbon emissions are generated from all stages from the tunnel construction to the operation and management, due to limited space, special structure and complex facilities. Tunnel construction has higher energy consumption and raw material density than others during expressway construction, which causes worse greenhouse gas emission. Due to massive carbon emission, the transportation industry is an important link in realizing the national plan of carbon emission peaking and carbon neutrality. As critical positions on expressways, tunnels' carbon emission reduction is particularly important.

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2 Analysis and calculation of carbon emission during the tunnel construction stage

2.1 Calculation framework

At present, there is no unified calculation method for carbon emissions in transportation industry, but there are two calculation procedures used internationally, one is the "top-down" at the macro level, by which different forms of energy consumption and their corresponding carbon dioxide emission factors are calculated according to the total energy consumption measurement; The other is the "bottom-up” at the micro level, by which the carbon emissions of sub-sectors are summarized as the main basis. The "bottom-up” calculation procedure includes three specific methods: traffic mileage, total energy consumption and vehicle stock. However, the "top-down" calculation procedure is more convenient and accurate for the tunnel construction stage. Many scholars have studied the evaluation index system based on carbon emissions of tunnels. Chen[1] optimized design scheme for tunnels with ultra-small interval based on carbon emission evaluation. By taking the carbon emission model of tunnel construction as the breakthrough point, the study focused on green and low-carbon optimization of multi-arch tunnel structure and construction method. Chen[2] optimized design scheme for expressway tunnels with large span based on carbon emission evaluation, and selected the bench cut method for construction with good results, and technical, economic and environmental benefits on the premise of ensuring safety of tunnel construction. Feng[3] concluded that research on objectives of life cycle comprehensive value evaluation of extra-long highway tunnel needs to be determined by quantitative indicators, and establish a comprehensive evaluation index system, so as to provide a standard for evaluating whether the design scheme of highway tunnel is scientific and reasonable, and provide a basis for the life-cycle optimization design and the optimization of construction technology of highway tunnel. However, many studies have not put forward a unified definition and calculation model of tunnel carbon emission accounting.

In order to study the calculation method of carbon emissions of tunnels, detailed analysis steps should be followed. In the stage of tunnel construction, the emission of construction raw materials production, the emission of energy consumption of equipment and machinery during transportation, and energy consumption of construction machinery during construction (including excavation, ventilation, lighting, etc.) are taken into account in carbon emission calculation. The schematic diagram of carbon emission model path during tunnel construction is as follows:

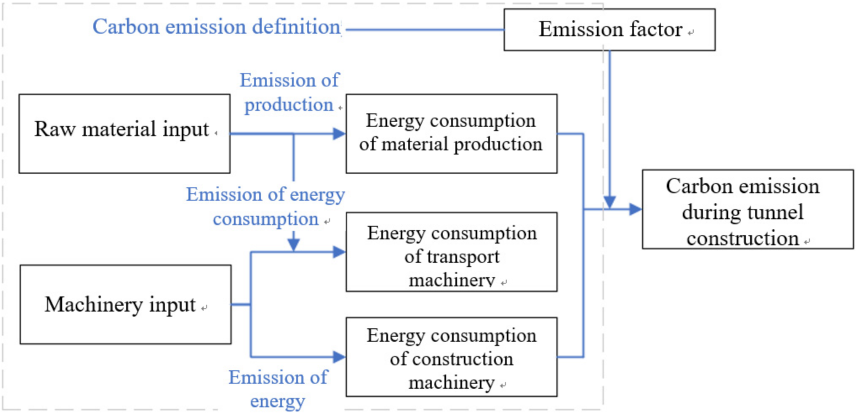

Fig. 1. The calculation framework of carbon emission for tunnel construction

2.2 Carbon emission definition

First, the types of carbon emission gases should be defined. There are six greenhouse gases to be accounted: CO2 (carbon dioxide), CH4 (methane), N2O (nitrous oxide), HFCs (hydrofluorocarbons), SF6 (sulfur hexafluoride), and PFCs (perfluorocarbons). Compounds other than carbon dioxide should be converted to CO2 equivalent as the basic unit, measured uniformly and calculated in accordance with the standards set by Intergovernmental Panel on Climate Change.

2.3 Carbon emission path

Construction material input inventory

. One of the source paths of tunnel carbon emission is construction materials. Most of raw materials are put into the construction site after production. The inventory is put forward according to different construction materials, commonly including cement, steel, sand, polyethylene, etc.

$$E_M = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} M_i \times f_i$$

E_M: Total carbon emission of construction materials, in t CO_{2eq};
M_i: Consumption of construction material i (i=1, 2, 3, n), in t;
f_i: Carbon emission factor of construction material i, in t $CO_{2eq/t}$;

Energy consumption inventory of transport machinery

. One of the source paths of energy consumption of transport machinery. Since half of raw materials are not produced on the construction site and need to be transported to the site for use, the carbon emissions generated during transport should be included. Transport machinery includes: construction waste loader, concrete carrier, etc.

$$E_T = \sum_{i=1}^{n} E_t = \sum_{i=1}^{n} V_i \times f_i$$

E_T: Total carbon emission of transport machinery, in t CO_{2eq};
E_t: Carbon emission of transport machinery, in t CO_{2eq};
V_i: Energy consumption of transport machinery i (i=1, 2, 3, n), in t;
f_i: Carbon emission factor of energy i, in t $CO_{2eq/t}$;

Energy consumption inventory of construction machinery

. One of the source paths of energy consumption of construction machinery. The energy consumed by various construction machinery during construction includes electric energy, diesel, gasoline, etc. Construction machinery includes: power supply machinery, drilling jumbo, wet shotcreting trolley, lining trolley, shotcrete machine. Other environmental equipment for lighting and ventilation, such as axial flow fan, is also considered.

$$E_C = \sum_{i=1}^{n} E_c = \sum_{i=1}^{n} P_i \times f_i$$

E_C: Total carbon emission of all construction machinery on site, in t CO_{2eq};
E_c: Carbon emission of some kind of construction machinery, in t CO_{2eq};
P_i: Energy consumption of construction machinery i (i=1, 2, 3, n), in t;
f_i: Carbon emission factor of energy i, in t CO_{2eq}/t;

3 Calculation example of carbon emission from tunnel construction

3.1 Project overview

In this paper, Lasuo Tunnel of Nandan-Tian'e Expressway is taken as an example for carbon emission calculation. The entrance of Lasuo tunnel of Nandan-Tian'e Xialao Expressway is located in Lasuo Village, Chengguan Town, Nandan County. There is a village road near the tunnel entrance with mediocre traffic condition, and there is no road near the tunnel exit with poor traffic condition. Lasuo is a separated long tunnel located in the slope zone of the transition from Yunnan-Guizhou Plateau to the hills in Northwest Guangxi. The whole site tilts from northeast to southwest, with rolling mountains, and belongs to the karst-erosional landform unit. The entrance is located below the steep slope, with a natural grade of 25° ~ 70°: the tunnel trunk crosses the ridge, and the highest point is 941.20m above sea level; The exit is located below the slope, with a natural grade of 35° ~ 55°. The altitude of the site is 719.5 ~ 941.2m, with a relative altitude difference of 221.7m; The altitude of the tunnel axis section is 777.6 ~ 938.0m, with a relative altitude difference of 160.4m. The starting and ending pile Nos. of the left line are ZK3 + 107 ~ ZK4 + 636, the design length is 1,529, and the maximum burial depth is about 156m; The starting and ending pile Nos. of the right line are YK3+065 ~ YK4+634, the design length is 1,569m, and the maximum burial depth is about 149.8m.

3.2 Carbon emission calculation inventory

The usage amount in Table 1 and Table 2 is from the investigation records of tunnel construction site. The carbon emission factors are obtained from government organizations, relevant institutions and professional literatures, and mean the greenhouse gas emission per unit input expressed in carbon dioxide equivalent. According to the calculation, the total carbon emission during the tunnel construction stage is 2.34 × 104 t.

Table 1. Carbon emission of main construction materials of tunnel

Materials	***Usage amount***	***Carbon emission factor/(kg CO_{2eq}/unit^{-1})***	***Emission/t CO_{2eq}***
Concrete	93249 m^3	260.2*	5613.59
Cement	152 m^3	0.525*	0.08
Reinforcement bar	465503 kg	2.364*	11000.45
Steel plate	2172975 kg	2.526*	5488.94
Steel tube	24624 kg	2.504*	61.66
Total	\	\	12264.71

* data from reference 4&5

Table 2. Carbon emission of main machinery and equipments of tunnel

Materials	***Energy***	***Usage amount***	***Carbon emission factor/(kg CO_{2eq}/unit^{-1})***	***Emission/t CO_{2eq}***
Power supply machinery	Electric energy	6563.04 mWh	0.972	6379.275
Secondary lining trolley	Electric energy	372.9 mWh	0.972	362.4588
Intelligent spray curing trolley	Electric energy	8.864 mWh	0.972	8.615808
Construction waste truck	Diesel	200.56 t	2.171	435.3968
Loader	Diesel	161.75 t	2.171	351.1547
Jumbolter	Diesel	5.37 t	2.171	11.65043

Materials	***Energy***	***Usage amount***	***Carbon emission factor/(kg CO_{2eq}/unit^{-1})***	***Emission/t*** CO_{2eq}
Concrete carrier	Diesel	459.6 t	2.171	997.7843
Concrete pump	Electric energy	93.23 mWh	0.972	90.6147
Axial flow fan	Electric energy	2606.4 mWh	0.972	2533.42
Total	\	\	\	11170.37

* data from reference 6&7

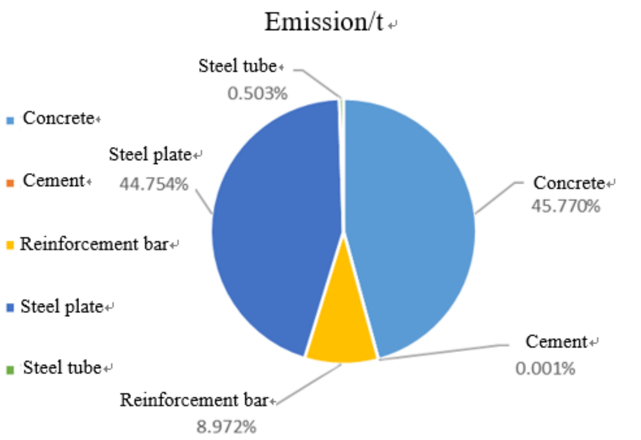

Fig. 2. Proportion of tunnel carbon emission in materials

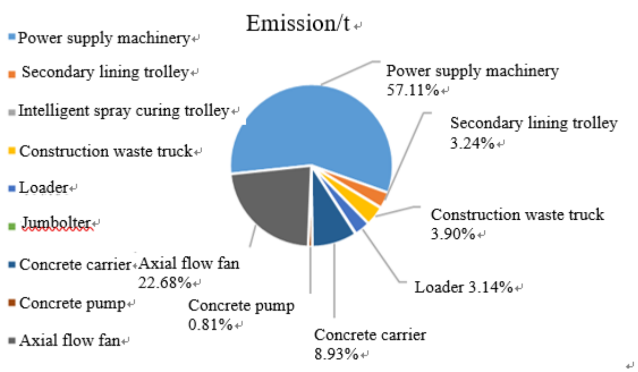

Fig. 3. Proportion of tunnel carbon emission in equipment

The usage amount in Table 1 and Table 2 is from the investigation records of tunnel construction site. The carbon emission factors are obtained from government organizations, relevant institutions and professional literatures, and mean the greenhouse gas emission per unit input expressed in carbon dioxide equivalent. According to the calculation, the total carbon emission during the tunnel construction stage is 2.34 × 104 t.

As shown in Fig. 2, among various construction materials, the carbon emissions of concrete and steel plate account for the largest of about 45%, and that of some materials account for less than 0.1%. Construction materials that have little impact on the total carbon emissions, such as sand and PVC pipes, are not listed. As shown in Fig. 3, electric energy accounts for 84% of the carbon emission of energy, and the carbon emission of diesel accounts for 16%. In details, the lighting and ventilation equipment mainly uses electric energy, the construction machinery such as secondary lining trolley mainly consumes electric energy, and the transportation machinery such as loader and construction waste truck are mainly powered by diesel. Therefore, the use of construction machinery such as secondary lining trolley powered by electric energy accounts for the largest proportion of carbon emission. According to the comparison between Table 1 and Table 2, the carbon emission from raw material input accounts for about 50%, which is similar to that generated during construction. This demonstrates that raw materials and construction machinery contribute almost the same to carbon emission and should be given the same attention in emission reduction.

4 Conclusion and future work

As an important position in transportation and highway construction, the carbon emission of tunnel directly affects the total carbon emission of transportation. However, there are few studies on the carbon emission of tunnel industry, and a unified standard system has not been formed, which results that the development of tunnel energy conservation and emission reduction plans lacks relevant data support, it is difficult to formulate optimization plans, and the improvement of economic benefits and environmental benefits are impeded. The main conclusions can be summarized as follow:

(1) In the life cycle of tunnel construction, two types of carbon emission sources should be considered. One is the carbon emission from raw materials input, and the other is the carbon emission generated by electricity and fuel consumption of machinery during construction.

(2) In the calculation of carbon emissions, material usage and energy consumption are the most important. Most of carbon emission from raw materials is generated form their production. Their emissions are determined based on the amount of construction materials used and their carbon emission factors. The carbon emissions of construction machinery mainly come from raw material transport machinery and that generated in the construction process. The carbon emission of raw material transport machinery can be determined by freight volume, haul distance, transport mode, etc. In order to simplify and obtain accurate data, the carbon emission is obtained by recording the energy consumption of transport vehicles in this paper.

(3) The carbon emission factor is also an essential value in calculating carbon emissions. The carbon emission factor is selected from the values set or mentioned by the

government, organizations or relevant literatures, combined with differences in local energy structure, etc.

(4) By calculation above, high carbon emissions in the life cycle of tunnel construction are shown, and the carbon emissions generated by both raw materials and construction machinery account for a half. In the optimization scheme of tunnel construction based on carbon emission assessment, both should be considered for energy conservation and emission reduction. Therefore, Between the two types of energy (electric power and diesel), the electric power usage and carbon emission account for about 80%, mainly from lighting, ventilation and construction machinery at the construction site. For energy conservation and emission reduction, this power consumption equipment should be optimized first.

In terms of the future work, according to the model of tunnel construction stage, efforts should be made to raw materials and equipment operation. Firstly, the usage of raw materials should be minimized by improving the utilization efficiency and recovery rate of raw materials, for example, optimizing the temporary support structure of the tunnel during excavation and reducing the waste caused by the demolition of abandoned buildings. Secondly, the overall construction efficiency should be improved, the excavation steps should be optimized, and the construction time should be shortened to reduce the operation time of all kinds of construction equipment, to directly reduce carbon emissions. Thirdly, clean power generation, such as photovoltaic power and wind power, can be used to clean the source of electric power.

Combined with an actual tunnel construction case, this paper adopts the "top-down" method to calculate the carbon emissions in the life cycle of tunnel construction and puts forward the calculation model of tunnel carbon emissions, which provides a reference for low-carbon tunnel construction based on carbon emissions assessment. However, due to the different energy structures and construction technologies in different regions, key parameters such as carbon emission factors should be studied further to match different construction site conditions.

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