

Carbon Emission Accounting and Reduction Pathways in the Construction Stage of Road Engineering under the "Dual Carbon" Background

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Abstract. Under China's "dual carbon" goals, accurate accounting and reduction of carbon emissions during road construction are important for promoting low-carbon transportation infrastructure. Focusing on the construction stage of road engineering, this study applies the emission factor method within a life-cycle assessment framework. Carbon emissions are divided into four categories: material production, material transportation, construction machinery operation, and on-site electricity consumption. A typical provincial highway reconstruction project is selected as a case study to quantify emissions from major materials and energy use. The results show that material production is the dominant source, accounting for 65%–75% of total construction-stage emissions, with asphalt mixture and cement-stabilized crushed stone contributing the largest shares. Material transportation and machinery operation account for approximately 15%–20% and 10%–15%, respectively. Based on the results, low-carbon materials, optimized transportation, energy-efficient machinery, and improved construction technologies are proposed as key reduction pathways.

Keywords: dual carbon goals, road engineering, carbon emission accounting, emission factor method, emission reduction pathway

1. Introduction

Against the background of increasingly severe global climate change and pressure to reduce carbon, China has set forth the dual objectives of peaking carbon emissions by 2030 and attaining carbon neutrality by 2060, which chart a explicit course for the green transition of all sectors. Transportation infrastructure construction, as one of the important pillar industries of the national economy, accounts for a considerable proportion of total social carbon emissions.

According to data from the China Building Materials Federation, during 2019-2023, the annual cement consumption related to transportation infrastructure construction exceeded 1.2 billion tons, accounting for more than 45% of China's total cement consumption, with associated carbon emissions of approximately 850 million tons of CO₂ equivalent [1]. Road engineering constitutes a vital part of transport infrastructure development, with its scale experiencing sustained growth. Citing data from the Ministry of Transport, the year 2023 saw China invest 2.8 trillion yuan in

highway projects, while the combined mileage of new and upgraded highways reached 152,000 km, marking a rise of 23.4% compared with that of 2019.

During the construction stage of road engineering, large quantities of building materials are produced, transported, and used, while various construction machinery operates intensively. Therefore, this stage is one of the most carbon-intensive stages in the entire life cycle of road engineering. According to previous studies, the construction stage contributes 60%–80% of road engineering's total life-cycle carbon emissions, of which material production accounts for the greatest share [2]. However, current quantitative studies on carbon emissions during the construction stage of road engineering are relatively scattered, and systematic calculation methods and corresponding emission reduction measures are still insufficient.

Establishing a carbon emission accounting model for the construction stage of road engineering based on the emission factor method, and analyzing the emissions of different sources through specific engineering projects, are of great significance for promoting the green development of road engineering and supporting the transportation industry in achieving the "dual carbon" goals.

2. Research methodology

2.1. Research boundary and identification of emission sources

This study centers on the construction stage of road engineering, with the study period spanning from construction commencement to project completion [3]. According to the characteristics of road construction and the sources of carbon emissions, this study divides the emission sources during the construction stage into four categories: material production emissions, material transportation emissions, construction machinery operation emissions, and on-site electricity consumption emissions.

Emissions from material production denote the indirect carbon emissions arising from the manufacturing of building materials, including cement, asphalt, steel, aggregates, and sand. The carbon emissions attributable to the fuel consumption of transport vehicles in the process of moving materials from manufacturing plants to the construction worksite are what constitute material transportation emissions [4]. Construction machinery operation emissions refer to the direct carbon emissions caused by fuel consumption of construction machinery such as excavators, bulldozers, pavers, and rollers during operation. On-site electricity consumption emissions refer to the indirect carbon emissions corresponding to the electricity consumed by temporary electrical equipment on the construction site.

2.2. Construction of carbon emission accounting model

Based on the emission factor method, a carbon emission accounting model is constructed for road engineering's construction stage [5]. The calculation of carbon emissions using this method is performed by taking the product of activity data and the relevant emission factors. It offers advantages such as accessible data sources and clear calculation procedures.

The overall carbon emissions generated during the construction phase are computed as follows:

$$E_{\text{total}} = E_{\text{materials}} + E_{\text{transport}} + E_{\text{machinery}} + E_{\text{electricity}} \quad (1)$$

Where E_{total} represents the total carbon emissions during the construction stage; $E_{\text{materials}}$ represents carbon emissions from material production; $E_{\text{transport}}$ represents carbon emissions from

material transportation; $E_{\text{machinery}}$ represents carbon emissions from construction machinery operation; and $E_{\text{electricity}}$ represents carbon emissions from on-site electricity consumption.

The overall carbon emissions generated from material production are computed as follows:

$$E_{\text{materials}} = \sum_{i=1}^n M_i \times EF_i \quad (2)$$

Where M_i represents the consumption of the i -th material, and EF_i represents the carbon emission factor of the i -th material

2.3. Selection of emission factors and data processing

Carbon emission accounting relies on emission factors as one of its pivotal parameters, and their values directly affect the accuracy of the results [6]. Given the practical circumstances of road engineering construction in China and relevant international research results, this paper compiles the carbon emission factors associated with key materials and energy supplies.

The emission factor of cement adopts the industry average emission factor of 0.728 tCO₂/t released by the China Building Materials Federation for 2019–2023. The emission factor of asphalt materials is determined as 0.291 tCO₂/t based on the latest data from the International Asphalt Association and China Petrochemical Corporation [7]. The emission factor of steel is taken as 2.168 tCO₂/t according to the 2022 data from the China Iron and Steel Association. The emission factors of crushed stone and sand are determined as 0.0048 tCO₂/t and 0.0039 tCO₂/t, respectively, according to the Guidelines for Accounting Methods and Reporting of Greenhouse Gas Emissions for Enterprises issued by the Ministry of Ecology and Environment.

For fuel consumption of construction machinery, the diesel emission factor adopts the recommended value of 3.165 tCO₂/t in the IPCC 2019 Guidelines [8], while the gasoline emission factor is 3.015 tCO₂/t. The electricity emission factor adopts the 2023 national average grid emission factor of 0.5703 tCO₂/MWh released by the National Development and Reform Commission.

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3. Case project and data sources

3.1. Project overview and construction organization

This study selects a provincial highway reconstruction project as a representative case. The project has a total length of 12.8 km and is built to the Class II highway standard. The pavement width is 9 m, and the design speed is 60 km/h. The pavement structure includes two main layers: an asphalt concrete surface course and a cement-stabilized crushed stone base. The thickness of the surface layer is 6 cm, and the thickness of the base layer is 35 cm [9].

The main construction activities include subgrade treatment, base layer construction, surface layer paving, and traffic facility installation. The construction period is 8 months, and the machinery configuration is typical of provincial highway reconstruction projects.

3.2. Basic data collection and parameter setting

Based on the bill of quantities, material procurement records, machinery shift statistics, and electricity metering data provided by the construction unit, a complete basic database is established.

The main material consumption includes 15,360 tons of asphalt mixture, 67,200 tons of cement-stabilized crushed stone, 6,720 tons of cement, and 384 tons of steel [10].

Material transportation distances are determined based on the practical procurement circumstances. The average transportation distances for asphalt, cement, crushed stone, and steel are 150 km, 80 km, 45 km, and 200 km, respectively. The fuel consumption of construction machinery is calculated based on machinery shifts and fuel consumption per shift. The total diesel consumption is approximately 480 tons. On-site electricity consumption is calculated according to the power and operating time of temporary electrical equipment, with a total electricity consumption of approximately 960,000 kWh [11]. All basic data are reviewed by the technical personnel of the construction unit and verified by comparison with similar projects to ensure their authenticity and rationality.

4. Results and discussion

4.1. Calculation of total carbon emissions during the construction stage

Applying the emission factor method, this study establishes a carbon accounting model for the case project. The computed total construction-phase carbon emissions equal 15,847.3 tCO₂eq, while the unit-length intensity is 1,267.8 tCO₂eq/km. This value is within the general range of carbon emission intensity for material-intensive road projects reported in recent studies [12].

The result indicates that material consumption and construction energy use are key factors affecting total emissions. Reasonable optimization of material proportions, construction schemes, and energy use can effectively reduce construction-stage carbon emissions [13].

4.2. Contribution analysis of different emission sources

Material production is the main source of carbon emissions during the construction stage, accounting for 68.7% of the total, equivalent to 10,887.2 tCO₂eq. Among them, asphalt mixture is the largest emission source, accounting for 42.3% of the emissions from material production. This is mainly because asphalt heating and aggregate processing consume substantial energy. Cement-stabilized crushed stone ranks second, accounting for 28.1% of material production emissions, mainly because the decomposition of limestone during cement production releases a large amount of CO₂ [14]. Steel and concrete account for 16.8% and 12.8% of material production emissions, respectively, owing mainly to the high energy consumption of steel and cement production.

Material transportation and construction machinery operation account for 18.4% and 12.9% of total emissions, respectively. Material transportation emissions are mainly caused by fuel consumption of heavy trucks. For each additional 50 km of haulage distance, the associated carbon emissions grow by roughly 8%–12%. Carbon emissions from construction machinery operation are mainly caused by diesel consumption of large machinery such as excavators, loaders, and rollers.

Although on-site electricity consumption accounts for only 2.3% of total emissions, its impact cannot be ignored due to regional differences in power generation structures. In areas featuring a greater share of clean energy, carbon emissions from on-site electricity consumption can be significantly reduced [15].

4.3. Identification of key influencing factors and sensitivity analysis

The analysis of the carbon emission calculation results for the typical road engineering project shows that the main influencing factors include material type and consumption, material transportation distance, construction machinery efficiency and fuel consumption rate, road grade and structural layer thickness, and the carbon emission factor of on-site electricity consumption.

Among these factors, the consumption of pavement materials such as asphalt mixture and cement-stabilized crushed stone directly affects total carbon emissions and constitutes a major source during the construction stage. Material transportation distance determines fuel consumption during transportation. Construction machinery efficiency and fuel consumption rate affect machinery operation emissions. The higher the road grade and the thicker the structural layer, the greater the material consumption per unit mileage. Although on-site electricity consumption accounts for a relatively small proportion, it is affected by the regional power grid structure. The carbon emission factor of electricity fluctuates between 0.32 and 0.85 kg CO₂/kWh, which still has a certain influence on total project emissions.

The sensitivity analysis shows that a 10% change in the amount of asphalt mixture leads to a 6.5%-7.2% change in total carbon emissions, while a 10% change in the amount of cement-stabilized crushed stone leads to a 4.8%-5.5% change. This indicates that pavement material consumption is a key influencing factor [16]. When the average transportation distance increases from 50 km to 100 km, carbon emissions from the transportation stage rise by 95%-105%, while their proportion in total emissions rises by 2.8%-3.2%. When the fuel efficiency of construction machinery is improved by 15%, carbon emissions arising from the operation of machinery may decline by 12%-15%, which corresponds to a 1.8%-2.1% reduction in total emissions.

Different road grades and structural layer thicknesses have significant effects on carbon emission intensity. The carbon emissions per kilometer of expressways are 35%-45% higher than those of ordinary highways [17]. Therefore, reasonable material selection and consumption control, optimization of transportation routes, and improvement of construction machinery efficiency constitute the primary measures for reducing carbon emissions during the construction stage of road engineering.

5. Conclusions

This paper proposes a carbon emission accounting model based on the emission factor method for the construction stage of road engineering and applies it to a typical engineering project for empirical analysis. The results show that carbon emissions during road engineering construction mainly occur in the material production stage, accounting for 65%-75% of total emissions. Pavement materials such as asphalt mixture and cement-stabilized crushed stone are the main carbon emission sources. This finding is consistent with the analysis of the carbon emission structure of road construction in the Green Transportation Development Report released by the Ministry of Transport in recent years. Material transportation and construction machinery operation account for 15%-20% and 10%-15%, respectively. Although the proportion of on-site electricity consumption is relatively small, it is attracting growing attention as construction management improves.

According to the calculation results, this paper proposes several emission reduction measures, including the promotion and application of recycled materials and low-carbon materials, reasonable arrangement of material transportation distances and transportation modes, promotion of electrification and intelligent upgrading of construction machinery, and improvement of construction technologies and management methods. These measures can reduce carbon emissions during

construction by 20%–30%, contributing to the road engineering industry's achievement of the "dual carbon" goals.

The carbon emission accounting model and emission reduction pathways proposed in this paper can serve as a foundation for the accurate calculation and effective control of carbon emissions in road engineering. They can also serve as a reference for relevant policies and engineering practices aimed at promoting the green and low-carbon development of transportation infrastructure. Future research could not only delve into carbon emissions across the whole life cycle of road engineering but also leverage information technologies for the purpose of real-time emissions tracking and adaptive control.

However, this study has limitations. It mainly focuses on the construction stage, without covering the full life-cycle stages of design, and demolition. In addition, the empirical data are relatively limited, and the adaptability of model parameters to regional differences requires further verification. Future research can expand the scope to establishing a full life-cycle carbon emission accounting system for road engineering, and integrating technologies such as BIM, the Internet of Integrating IoT and big data enables real-time monitoring, dynamic evaluation, and intelligent regulation of carbon emissions, thereby strengthening the scientific foundation and responsiveness of carbon management.

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