Integrated Carbon Emissions and Carbon Costs for Bridge Construction Projects Using Carbon Trading and Tax Systems—Taking Beijing as an Example

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Abstract: Bridges are special infrastructures that emit large amounts of carbon dioxide from construction. Attention should be given to the carbon cost generated by the bridge, which includes its direct economic cost; the carbon cost is the largest driving force encouraging the enterprise to implement carbon emission reduction measures. In this study, the life cycle assessment (LCA) method is applied to carbon emissions in the bridge construction stage, which include emissions from material production, transportation and on-site construction; then, a carbon emission calculation model for the construction stage is established. Next, the carbon cost calculation model for the bridge in the construction stage is determined by combining the carbon pricing mechanisms of carbon emission taxing and trading to monetize carbon emissions. Finally, by taking a bridge in Beijing as an example, the carbon emissions in the bridge construction stage are calculated, and the carbon cost is calculated. The results show that carbon emission monetization is beneficial for clarifying the environmental impact of bridge construction; these calculations should be included in cost accounting.

Keywords: bridge; construction; carbon emissions; carbon cost

1. Introduction

It is reported by Intergovernmental Panel on Climate Change (IPCC) statistics that the construction industry consumes 40% of the world’s energy and produces 36% of global greenhouse gases [1]. The greenhouse gas emissions of the construction industry are far higher than those of the transportation and industrial sectors. Bridges are a resource- and energy-consuming infrastructure with the characteristics of high energy consumption, high carbon emissions and high resource consumption throughout their life cycle and are a massive source of CO₂ emissions in the construction industry [2]. In the past decade, the average annual rate of highway bridge construction in China has been 27,000 per year. By the end of 2021, there were 961,100 highway bridges nationwide, an increase of 48,300 over the end of the previous year; among them, there were 7417 extra-large bridges, 134,500 bridges, and nearly 820,000 medium and small bridges [3]. Thus, bridge construction in China is developing rapidly. At the same time, energy consumption is growing rapidly, greenhouse gas emissions are rising sharply, and the scale of bridge construction projects has caused major damage to the environment. Therefore, it is urgent to quantify the carbon emissions in the bridge construction stage and then monetize the carbon emissions, that is, to convert the external impact of carbon emissions into direct economic losses within the enterprise, to encourage the enterprise to take carbon emission reduction measures consciously.

Carbon emissions need to be monetized through a certain carbon pricing mechanism. Currently, there are two mainstream carbon pricing mechanisms—carbon tax and carbon...
trading. Carbon taxes refer to the government setting tax rates for greenhouse gas emissions, which are uniformly converted into carbon emissions to obtain direct taxes [4]. Sathre and Gustavsson [5] believe that environmental taxes can act as economic incentives to encourage companies to innovate and seek production methods that are economical and have little impact on the environment. In addition, Zhang and Wei [6] believe that the implementation of carbon emissions trading policies in countries around the world can effectively reduce global carbon dioxide emissions. Rogge et al. [7] believe that carbon emissions trading can encourage companies to use environmentally friendly technologies and innovations, thereby reducing carbon emissions. Implementing a carbon pricing mechanism will make greenhouse gas emissions a cost for enterprises. Enterprises can choose different resource inputs or products according to their own conditions to control greenhouse gas emissions, thereby curbing global warming.

The aims of this study are as follows. First, a carbon cost calculation model for bridge construction based on carbon trading and the carbon tax system is proposed. By quantifying the direct economic losses caused by carbon emissions, companies are encouraged to choose different resource inputs or products to control carbon emissions according to their own conditions. Second, taking an actual bridge in Beijing as an example, we comprehensively analyze the carbon emissions and carbon costs of the bridge construction stage, clarify the key stages of carbon emission control in the bridge construction stage, and help companies focus on the high carbon emission stage to formulate carbon emission reduction strategies.

2. Literature Review

2.1. Life Cycle Assessment of Bridges

The scale of bridge construction projects has caused significant damage to the environment. The life cycle assessment (LCA) method can be used to estimate life cycle environmental impacts, such as the carbon emissions of concrete structures [8,9]. During the life cycle of bridges, especially in the production stage of steel and concrete, a large amount of raw materials and fossil fuels are consumed, and then a large amount of greenhouse gases, such as CO₂, are emitted [10–13]. Itoh and Kitagawa [14] studied the carbon emissions of bridges in the three stages of material production, construction, reinforcement and maintenance, and the results showed that the material production stage has the most CO₂ emissions. The introduction of the LCA method in road environmental impact assessment has led to the gradual recognition of LCA as an effective means of comprehensively assessing the carbon emissions of complex transportation systems as part of the environmental assessment of highway infrastructure [15,16]. Jena et al. [17] assessed the environmental factors of pedestrian bridges using the LCA framework. Du et al. [18] calculated the carbon emissions of bridges using LCA through material fabrication, construction, use and maintenance, and end-of-life.

2.2. Environmental Costs and Carbon Costs

The global environmental pollution problem has become extremely serious, and the environmental quality is deteriorating [19]. The prominence of environmental problems has expanded the research scope of environmental costs, a concept that has emerged in recent years. Some scholars have defined this concept. Norris [20] stated that environmental costs include direct costs (such as the cost of waste disposal), indirect costs (such as the cost of environmental management systems), uncertain costs (such as fines) and costs that are difficult to determine (such as a company’s reputation). Senthil [21] developed a life cycle environmental cost analysis (LCECA) model to calculate the environmental cost of wastewater treatment, environmental management, taxes, restoration, energy use, and recycling costs. Ge et al. [22] improved the LCECA model and classified environmental costs into six categories, including resource consumption cost, pollutant emission control cost, pollutant treatment cost, environmental management cost, environmental damage costs and regeneration cycle cost. Other scholars have conducted quantitative research on environmental costs. Zhang [23] divided the generalized life cycle cost of buildings into
direct costs and environmental costs and established a calculation model for these costs; this model is also the first to quantify the environmental cost of buildings in China. Chen [24] determined the calculation method of different environmental impact cost indicators at each stage by analyzing the stage-specific types and characteristics of the environmental impact cost throughout the life cycle of bridge engineering, resulting in the establishment of an environmental cost analysis model for bridge engineering.

With the convening of the Copenhagen Climate Conference at the end of 2009, the concept and practice of a low-carbon economy rose to prominence, and the desire to develop a low-carbon economy caused research on environmental costs to gradually focus on the cost of carbon emissions. Carbon cost is an integral part of environmental cost. Due to the strong externality of environmental cost, carbon cost is difficult to measure. Carbon costs can reflect environmental problems as enterprise costs via carbon pricing mechanisms, which are beneficial for measuring internal enterprise expenditures. Therefore, this paper calculates the carbon cost of bridges to clarify the environmental impact of the bridge construction stage. In addition, the carbon cost calculated in this paper mainly refers to the carbon tax paid by enterprises to the taxation department and the cost of purchasing carbon emission rights in the carbon trading market. Luo et al. [25] and Gao [26] proposed a carbon cost accounting model of buildings under the carbon trading system and carbon tax system. Based on the accounting model, Xiao [27] chose a carbon pricing mechanism—a carbon tax mechanism—to monetize the carbon emissions and obtain the carbon cost of the building. Lu [28] divided the building life cycle cost system into two parts: the traditional building life cycle cost and the carbon emission cost, for which the carbon emission cost calculation method was based on the carbon tax policy. The above research shows that using the carbon taxing and trading systems to calculate construction carbon costs is reliable and applicable for calculating bridge carbon costs. However, to date, China lacks special research on bridge carbon costs. Therefore, it is necessary to establish a bridge carbon cost calculation model to clarify the bridge’s impact on the environment during the construction phase.

First, based on LCA and construction process estimation methods, this paper establishes a carbon emission calculation model for the bridge construction stage. Second, through the carbon taxing and trading mechanisms, the life cycle carbon emissions of bridges are converted into costs, and a bridge life cycle carbon cost calculation model under the two systems is established. Finally, by taking an actual bridge in Beijing as an example, the carbon emissions and costs of the construction stage are calculated, and the composition and proportion of each stage are analyzed.

3. Method
3.1. Calculation Model of Bridge Carbon Emissions
3.1.1. System Boundary

The bridge life cycle includes material production, construction (including material transportation and on-site construction), operation, maintenance and demolition stages [29], among which the first two stages involve materialization; the materialization stage is the calculation boundary of the bridge in this paper, as shown by the dashed line in Figure 1.

The environmental impact of the main materials and components required for bridge construction are considered in this study, and the research hypotheses are as follows: (1) We do not consider the carbon emissions from the construction of temporary pits in the riverbed because it is only a small fraction. According to the Pareto principle [30], only the construction activities that account for more than 80% of the total impact are considered. (2) Similarly, only the two main materials, steel bars and concrete, and seven types of components, such as bored piles, pier columns, abutments, tie beams, cover beams, main beams, and railings, are considered.
3.1.2. Bridge Carbon Emissions Calculation Method

To calculate the carbon emissions in the materialization stage of the bridge (as shown in Figure 1), the bridge construction stage is decomposed and analyzed according to the analysis results of the carbon emission factors during the construction period; from there, the entire bridge construction stage is divided into processes that are independent and have a unified quantitative expression of carbon emissions. Based on the LCA modeling method, a unit process carbon emission measurement model is established. Then, it is necessary to calculate the total carbon emissions in the bridge construction stage according to the inverse decomposition method [31]. This process yields the structural carbon emission universal measurement model for the construction stage of the bridge project, as shown in Figure 2:

**Figure 1.** Calculation boundary of carbon emissions of bridges (the dashed line is the research content of this paper).

**Figure 2.** Modeling idea of the bridge engineering materialization stage.
The bridge infrastructure projects are classified, and the unit process is divided according to the composition and construction characteristics of each infrastructure project.

The materials of the unit process within the boundary are analyzed and studied, and the lists of materials, off-site processing machinery and equipment, transportation vehicles, and on-site construction machinery are determined.

Based on the above list, a determination is made regarding whether upstream traceability is needed. If necessary, the corresponding substance list is updated according to the unit process traceability, and then the unit process list data are collected and calculated to obtain the demand for each substance in the list; if not, the unit process inventory data are directly collected and calculated to obtain the demands of each substance in the inventory.

The demands of each substance in the list are combined with the basic theory of carbon emission measurement to calculate and obtain the life cycle inventory data of the unit process.

The life cycle list data of each subproject, division, unit and construction phase in the construction stage from the bottom up are summarized and obtained.

The bridge carbon emission calculation model during the construction stage is as follows:

\[ E = E_{cl} + E_{ys} + E_{sg} \]  

In Equation (1), \( E \) is the total carbon emissions, and \( E_{cl}, E_{ys}, \) and \( E_{sg} \) are the carbon emissions in the bridge material production, transportation and on-site construction stages, respectively.

(1) Carbon emission calculation model in the material production stage

Bridge engineering requires many building materials to construct and produce abutments, beams, piers, piles and other components, and the production and processing of these materials produces considerable CO\(_2\).

The carbon emissions calculation model of building materials is as follows:

\[ E_{cl} = \sum_{j=1}^{n} \sum_{i=1}^{m_j} m_{ij} \cdot Q_i \cdot Z_i \]  

In Equation (2), \( m_{ij} \) is the quantity of type \( i \) building materials required for the construction of type \( j \) subsystem; \( Q_i \) is the fixed consumption of type \( i \) materials; \( Z_i \) is the carbon emission factor of type \( i \) building materials produced per unit mass; and \( \mu \) is the number of abutments, and beams of subsystems.

(2) Carbon emissions calculation model in the material transportation stage

The carbon emissions calculation model for transporting materials to the construction site is as follows:

\[ E_{ys} = \sum_{j=1}^{n} \sum_{i=1}^{c} \sum_{k=1}^{m_{ijk}} m_{ijk} \cdot Q_k \cdot l_{ik} \cdot U_k \]  

In Equation (3), \( m_{ijk} \) is the transportation volume of the \( j \) subsystem transporting the \( i \) materials by \( k \) transportation methods; \( Q_k \) is the shift quota of the \( k \) construction materials; \( l_{ik} \) is the average transportation distance (km) of the \( i \) building materials by the \( k \) transportation mode; and \( U_k \) is the carbon emission factor of the \( k \) transport mode.

(3) Carbon emissions calculation model in the on-site construction stage

The carbon emissions calculation model during the construction stage is as follows:

\[ E_{sg} = \sum_{j=1}^{n} \sum_{\beta=1}^{b} m_{j,\beta} \cdot Q_\beta \cdot R_\beta \cdot V(k) \]  

In Equation (4), \( E_{sg} \) is the carbon emissions generated by the mechanical equipment used in construction, \( m_{j,\beta} \) is the engineering quantity produced by the \( \beta \) mechanical equipment during the construction of subsystem \( j \); \( Q_\beta \) is the shift quota of the \( \beta \) mechanical equipment; \( R_\beta \) is the energy consumed by each shift of the mechanical equipment \( \beta \); and \( V(k) \) is the carbon emission factor of the \( k \) energy.
3.2. Calculation Model of the Carbon Costs of Bridges

Carbon cost is a branch of environmental cost. The carbon cost of a bridge refers to the direct economic expenditure paid by relevant enterprises due to carbon emissions at various stages of the bridge life cycle. The measurement of bridge carbon cost is based on carbon emissions, and the external impacts of bridge life cycle carbon emissions are transformed into the internal expenditure costs of relevant enterprises through the carbon pricing mechanism under certain systems. There are two mainstream carbon pricing mechanisms: carbon emissions trading and carbon taxation. This paper monetizes the carbon emissions of bridges under these carbon pricing mechanisms and calculates the carbon cost of bridges. Furthermore, the carbon cost in the construction phase is the only consideration in this study.

3.2.1. Main Bridge Carbon Cost

The main body of carbon cost refers to the enterprise that incurs the economic losses caused by CO$_2$ emissions, which can be determined by tracing the sources of carbon costs. Only by clarifying the main body of carbon costs can enterprises consciously control carbon emissions.

The carbon cost of material production mainly comes from the carbon emissions caused by raw materials and energy consumption in the process of material production and processing. Therefore, the carbon cost of the material production stage is borne by the material supplier.

The carbon cost of material transportation mainly comes from the carbon emissions of fuel consumption during material transportation. Therefore, at this stage, the carbon cost is also borne by the material supplier.

The carbon cost in the on-site construction stage mainly comes from the carbon emissions generated by the use of gasoline, diesel, coal and other fossil fuels for mechanical operation. Therefore, the enterprise bearing the carbon cost at this stage is the construction enterprise.

3.2.2. Carbon Cost Calculation Model for Bridges Based on the Carbon Taxing System

First, the carbon tax rate needs to be determined. Based on the analysis and research of previous scholars concerning the carbon tax rate of the construction industry in China, it is assumed that the bridge carbon tax can be levied by taking the estimated CO$_2$ emissions as the basis of the carbon tax calculations and implementing a fixed tax rate. By considering the influence of the carbon tax on energy demand at various stages of construction and comprehensively considering the influence of different carbon tax rates on macroeconomic and social welfare, Xiao [22] concluded that the reasonable carbon tax rates in the material production and transportation stage and the construction stage are 60–80 CNY/ton and 40–60 CNY/ton, respectively. Based on this research, this paper sets the carbon tax rate of each stage of bridge construction to the values shown in Table 1.

<table>
<thead>
<tr>
<th>Industry</th>
<th>Stage</th>
<th>Tax Rate (CNY/Ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridge construction</td>
<td>Material production stage</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Material transportation stage</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>On-site construction stage</td>
<td>50</td>
</tr>
</tbody>
</table>

Second, the carbon cost can be calculated according to the determined carbon tax rate. The carbon cost calculation formula of the bridge construction stage is as follows:

\[
C = C_1 + C_2 + C_3 \\
C_1 = E_{cl} \cdot 70 \\
C_2 = E_{ys} \cdot 70 \\
C_3 = E_{sg} \cdot 50
\]  

(5)

In Equation (5), $C_1$ represents the carbon cost of the material production stage based on the carbon tax, $C_2$ represents the carbon cost of the material transportation stage based
on the carbon tax, and \( C_3 \) represents the carbon cost of the on-site construction stage based on the carbon tax.

3.2.3. Carbon Cost Calculation Model of a Bridge Based on a Carbon Trading System

The carbon cost is the cost due to the carbon emissions exceeding the corresponding quota of the enterprise under the carbon emission trading system. Material suppliers are responsible for carbon emissions during material production and transportation; thus, the calculation formula is as follows:

\[
C_1 = \frac{E_1}{E_T} \cdot (E_T - E_{E1}) \cdot P_1 \\
\text{if } (E_T - E_{E1}) < 0, \quad C_1 = 0 \quad (6)
\]

In Equation (6), \( C_1 \) represents the carbon cost, and \( E_1 \) represents the carbon emissions in the material production and transportation stages. \( E_T \) represents the annual carbon emissions of the material suppliers (tons), \( E_{E1} \) represents the carbon allowances received by material suppliers from energy exchanges (tons/year), and \( P_1 \) represents the price of carbon allowances purchased by the material suppliers (CNY/ton).

The main body of carbon emissions in the on-site construction stage is the construction enterprise, and the calculation formula is as follows:

\[
C_2 = \frac{E_2}{E_T} \cdot (E_T - E_{E2}) \cdot P_2 \\
\text{if } (E_T - E_{E2}) < 0, \quad C_2 = 0 \quad (7)
\]

In Equation (7), \( C_2 \) represents the carbon cost, and \( E_2 \) represents the carbon emissions in the on-site construction stage. \( E_T \) represents the annual carbon emissions of the construction enterprise, \( E_{E2} \) represents the annual carbon allowances obtained by the construction unit from the energy exchange, and \( P_2 \) represents the carbon allowance price purchased by the construction unit.

According to the “quota verification method of key carbon emission units in Beijing” issued by the Beijing Environment Exchange, the carbon allowances of enterprises are estimated. The total amount of the annual carbon dioxide quota \( T \) of an enterprise is verified by the historical total emission method, and the calculation formula is as follows:

\[
T = A + N + \Delta \quad (8)
\]

In Equation (8), \( A \) is the quota of existing facilities, \( N \) is the quota of new facilities, and \( \Delta \) is the quota adjustment amount; the unit of measurement is tons.

To calculate the carbon emission allowances of enterprises, this paper only considers the carbon emission allowances of existing facilities. The calculation formula of the carbon allowance of an existing facility is as follows:

\[
A = E \cdot f \quad (9)
\]

In Equation (9), \( E \) is the average value of carbon emissions of the enterprise over the previous four years, and \( f \) is the emission control coefficient (92%).

4. Results and Discussion

4.1. Case Description

To illustrate the application of the above methods in assessing the carbon emissions and costs generated by bridges in the construction stage, the Beijing Lishui Bridge was selected as a case study, as shown in Figure 3. Lishui Bridge is located on Anli Road, crossing the Qinghe River. The bridge is an inclined bridge, the total length of the bridge is 120.05 m, and the span combination is \( 5 \times 22.0 \) m. The total width of the bridge is 50.0 m, which comprises the east side road bridge and the west side road bridge on its sides and the main road bridge in its middle. The main road bridge deck is 24.0 m wide, the auxiliary road bridge decks on both sides are 7.0 m wide, the sidewalks on both sides are 3.5 m wide, and the separation belt between the main road bridge and the auxiliary road bridge is 2.5 m wide.
The superstructure of the bridge is a simply supported T-beam made of 5-span, posttensioned, prestressed concrete, of which the auxiliary road bridges on both sides have 6 T-beams per span, and the main road bridge has 14 T-beams per span. The prefabricated width of the main beam is 1.2 m, and the beam height is 1.2 m. The distances between the main beams of the auxiliary road bridge and the main road bridge are 1.75 m and 1.80 m, respectively. Cast-in-place wing plates and cast-in-place beams are arranged between the beams. The piers of the lower bridge structure are piles connected to pier columns and ordinary reinforced concrete cover beams. The bridge abutment adopts the cover beam and pile foundation, and the pier column adopts the circular bridge pier with a diameter of 1.2 m. The main and auxiliary road bridge pier columns and abutment cover beams are independent, and the main road bridge cover beam is set with a 2 cm structural joint at the midline position. The bridge piers use ordinary plate rubber bearings, and the bridge abutments use skateboard rubber bearings. The design load level of the bridge is City-A, and the crowd load is 3.5 kN/m². The seismic fortification level is 8 degrees, and the design period is 50 years.

4.2. Carbon Emissions of the Case Bridge

The case bridge component information and carbon emissions are summarized in Table 2.

Table 2. Summary of component information and carbon emissions.

<table>
<thead>
<tr>
<th>Component</th>
<th>Number</th>
<th>Project</th>
<th>Material</th>
<th>Transportation</th>
<th>Mechanical</th>
<th>Single Summary</th>
<th>Total Carbon Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bored pile (C25)</td>
<td>73</td>
<td>Drilling, Cast-in-place concrete</td>
<td>1.91 × 10⁴</td>
<td>0.00</td>
<td>4.83 × 10³</td>
<td>6.74 × 10²</td>
<td>4.92 × 10⁴</td>
</tr>
<tr>
<td>Steel bars</td>
<td></td>
<td></td>
<td>1.31 × 10⁴</td>
<td>5.72 × 10²</td>
<td>2.20 × 10³</td>
<td>1.39 × 10⁴</td>
<td>1.01 × 10⁶</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
<td>2.66 × 10⁴</td>
<td>8.98 × 10⁵</td>
<td>5.77 × 10³</td>
<td>2.81 × 10⁴</td>
<td>2.05 × 10⁸</td>
</tr>
<tr>
<td>Pier column–cast-in-place (C35)</td>
<td>48</td>
<td></td>
<td>6.54 × 10⁵</td>
<td>2.54 × 10⁵</td>
<td>1.10 × 10⁵</td>
<td>6.90 × 10⁵</td>
<td>3.31 × 10⁷</td>
</tr>
<tr>
<td>Steel bars</td>
<td></td>
<td></td>
<td>1.19 × 10⁵</td>
<td>3.99 × 10⁵</td>
<td>2.74 × 10⁵</td>
<td>1.25 × 10⁵</td>
<td>6.01 × 10⁶</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
<td>9.25 × 10⁵</td>
<td>3.66 × 10⁷</td>
<td>1.58 × 10⁵</td>
<td>9.77 × 10⁵</td>
<td>5.86 × 10⁸</td>
</tr>
<tr>
<td>Abutment–cast-in-place (C35)</td>
<td>6</td>
<td></td>
<td>1.71 × 10⁴</td>
<td>5.75 × 10⁵</td>
<td>3.94 × 10⁵</td>
<td>1.80 × 10⁵</td>
<td>1.08 × 10⁷</td>
</tr>
<tr>
<td>Tie beam (C25)</td>
<td>12</td>
<td></td>
<td>6.11 × 10⁴</td>
<td>2.49 × 10⁵</td>
<td>7.01 × 10⁵</td>
<td>6.43 × 10⁵</td>
<td>7.71 × 10⁶</td>
</tr>
<tr>
<td>Steel bars</td>
<td></td>
<td></td>
<td>5.80 × 10⁵</td>
<td>1.95 × 10⁷</td>
<td>9.84 × 10⁵</td>
<td>6.10 × 10⁵</td>
<td>7.32 × 10⁷</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
<td>5.13 × 10⁵</td>
<td>2.07 × 10⁷</td>
<td>2.50 × 10⁷</td>
<td>5.36 × 10⁷</td>
<td>6.43 × 10⁸</td>
</tr>
<tr>
<td>Cover beam (C35)</td>
<td>12</td>
<td></td>
<td>4.84 × 10⁵</td>
<td>1.63 × 10⁷</td>
<td>1.02 × 10⁷</td>
<td>5.10 × 10⁷</td>
<td>6.12 × 10⁸</td>
</tr>
<tr>
<td>Steel bars</td>
<td></td>
<td></td>
<td>2.89 × 10⁴</td>
<td>1.07 × 10⁵</td>
<td>9.09 × 10⁵</td>
<td>3.09 × 10⁵</td>
<td>4.01 × 10⁷</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td>Install</td>
<td>1.20 × 10⁰</td>
<td>4.03 × 10⁵</td>
<td>3.94 × 10⁵</td>
<td>1.28 × 10⁵</td>
<td>1.66 × 10⁸</td>
</tr>
<tr>
<td>Prestressed reinforced concrete main beam (C45)</td>
<td>130</td>
<td></td>
<td>1.65 × 10³</td>
<td>8.98 × 10⁵</td>
<td>3.66 × 10⁵</td>
<td>1.10 × 10⁵</td>
<td>1.43 × 10⁷</td>
</tr>
<tr>
<td>Concrete bridge deck and asphalt</td>
<td>4180</td>
<td>Surface layer</td>
<td>1.21</td>
<td>8.10</td>
<td>0.69</td>
<td>9.99</td>
<td>4.18 × 10⁴</td>
</tr>
<tr>
<td>concrete bridge deck (C30)</td>
<td></td>
<td></td>
<td>1.13 × 10⁵</td>
<td>8.10</td>
<td>0.09</td>
<td>1.95 × 10⁵</td>
<td>8.16 × 10⁴</td>
</tr>
<tr>
<td>Trail (C30)</td>
<td>632</td>
<td>Low level</td>
<td>3.21 × 10⁷</td>
<td>2.09 × 10⁵</td>
<td>0.00</td>
<td>5.29 × 10⁵</td>
<td>3.35 × 10⁷</td>
</tr>
<tr>
<td>Brick</td>
<td></td>
<td></td>
<td>1.34 × 10⁷</td>
<td>6.48</td>
<td>1.59</td>
<td>1.35 × 10⁶</td>
<td>3.11 × 10⁷</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td>Steel bars</td>
<td>7.53 × 10⁵</td>
<td>2.54</td>
<td>0.17</td>
<td>7.80 × 10⁵</td>
<td>1.79 × 10⁷</td>
</tr>
<tr>
<td>Railing</td>
<td>460</td>
<td>Cast iron Columns and railings</td>
<td>2.35 × 10²</td>
<td>7.49</td>
<td>0.00</td>
<td>2.43 × 10²</td>
<td>1.12 × 10⁵</td>
</tr>
</tbody>
</table>

(1) Comparison of bridge carbon emissions in different stages
The carbon emissions of the case bridge at different stages are shown in Figure 4. The figure shows that the carbon emissions in the material production stage are the largest as they reach $7.96 \times 10^6$ kg, the carbon emissions in the construction stage are only $2.08 \times 10^5$ kg, and the carbon emissions generated by material transportation are $4.72 \times 10^5$ kg, which are probably 2.3 times greater than the carbon emissions in the construction stage. When considering the carbon emission proportions, the carbon emissions in the material production stage are as high as 92.1%, the transportation stage emissions are 5.5%, and the construction stage emissions are only 2.4%. These results occur because during the transportation and construction stages, only the carbon emissions generated by the fuel, electricity and other energy sources consumed by the transportation machinery and construction machinery are considered; the carbon emissions at the machinery manufacturing stage are not considered.

![Figure 4. Comparison of carbon emissions in different bridge stages.](image)

(1) Comparison of carbon emissions in different stages

The proportion of carbon emissions in different stages to total carbon emissions:

- Material production stage: 92.10%
- Transportation stage: 5.50%
- Construction stage: 2.40%

(2) Comparison of carbon emissions of different materials

As shown in Figure 5, this paper mainly considers the carbon emissions of the two main materials—steel bars and concrete—during the construction period. In the material production stage, the carbon emissions from steel bar production are approximately $4.94 \times 10^6$ kg, accounting for 62% of the carbon emissions throughout the material production stage; this amount is approximately twice the proportion of the carbon emissions from concrete production. This situation occurs because although the amount of concrete in the whole bridge is larger than that of steel, the carbon factor of steel is much larger than that of concrete. In the transportation stage, the carbon emissions from concrete transportation are approximately $1.04 \times 10^5$ kg, and the carbon emissions from steel bar transportation are approximately $1.67 \times 10^5$ kg. This phenomenon occurs because according to the “Construction Carbon Emission Calculation Standard”, the steel bar transportation distance is 500 km, which is much larger than that of concrete. The transportation distance is 40 km.

(3) Comparison of carbon emissions of different components

Figure 6 shows the carbon emissions of concrete and steel bars of different components during the material production and transportation stages. In the material production and transportation stages, the carbon emissions of steel bars for bored piles, main beams, tie beams, pier columns and concrete have high carbon emissions, while bridge abutments, cover beams, and railings have low carbon emissions.
Figure 5. Carbon emissions of different materials at different stages.

Figure 6. Comparison of carbon emissions of different components.

Figure 7. The carbon cost of the bridge construction stage under the carbon taxing system. CNY, and the carbon cost of on-site construction is 10,400 CNY.
4.3. Carbon Cost of the Case Bridge

4.3.1. Carbon Taxing System

According to the carbon emissions in each stage and Equation (5), the carbon cost of material production is 557,200 CNY, the carbon cost caused by transportation is 33,000 CNY, and the carbon cost of on-site construction is 10,400 CNY. Figure 7 shows the carbon cost of the bridge construction stage under the carbon taxing system.

As shown in Figure 7, the carbon cost of the bridge construction period mainly comes from the material production stage, accounting for 92.8%. The material production stage has the largest share of carbon costs, mainly because the carbon emissions in the material production stage are relatively large and the unit carbon price in this stage based on the carbon tax policy is relatively high.

4.3.2. Carbon Trading System

(1) Material production and transportation stage

The annual average carbon emissions of enterprises are obtained by querying the annual carbon emissions of the building materials used by steel and concrete enterprises; then, using the Beijing Environment Exchange’s quota verification method based on the total historical emissions, the enterprise’s total annual carbon emissions are obtained. Since there are many companies involved in this stage, it is not realistic to perform calculations for each company. Therefore, all building material production companies are combined into one and calculated as a single typical building material factory. The average annual carbon emissions are 774,000 tons. According to Equations (8) and (9), the carbon allowance of typical building materials factories at this stage based on data from 2020 is calculated as 712,100 tons. According to Equation (6), based on the average carbon trading price of 89.1 CNY per ton announced by the Beijing Environment Exchange on 3 June 2020, the carbon cost at this stage is 60,103.16 CNY.

(2) Construction stage

According to Equations (8) and (9) from the Beijing Environment Exchange carbon allowance calculation method, the carbon allowance of construction enterprises per year is 30,936.18 tons. According to Equation (7), based on the average carbon trading price of 89.1 CNY per ton announced by the Beijing Environment Exchange on 3 June 2020, the carbon cost is 1484.09 CNY. Figure 8 shows the carbon cost under the carbon trading system.
As shown in Figure 7, the carbon cost of the bridge construction is 30,936.18 tons. According to Equation (14), the carbon allowance of construction enterprises per year is 712,100 tons. The annual carbon emissions of the building materials used by steel and concrete enterprises; the carbon cost is transformed into the internal expenditure costs of relevant enterprises under the carbon taxing system. Although the difference between the carbon trading system is much smaller than that under the carbon taxing system, this is because under the carbon taxing system, all carbon emissions at each stage are involved in the calculations of carbon costs, while under the carbon trading system, companies obtain specific carbon allowances for free, and only the proportion of carbon emissions exceeding the carbon allowances participate in the calculations of carbon costs. Although the difference between the carbon costs of the two systems is nearly 9-fold, Figure 9 shows that the proportions of carbon costs in each stage of the construction period under the two different systems are not much different. The carbon cost in the material production stage accounts for a very high proportion of the carbon cost in the construction phase is the smallest.

4.3.3. Comparative Analysis of Carbon Costs in Different Systems

The proportions of carbon costs under different systems are shown in Figure 9.

![Comparative Analysis of Carbon Costs in Different Systems](image)

**Figure 9.** The proportions of carbon cost under the carbon taxing and trading systems.

Figures 7 and 8 show that the carbon cost under the carbon trading system is much smaller than that under the carbon taxing system. This is because under the carbon taxing system, all carbon emissions at each stage are involved in the calculations of carbon costs, while under the carbon trading system, companies obtain specific carbon allowances for free, and only the proportion of carbon emissions exceeding the carbon allowances participate in the calculations of carbon costs. Although the difference between the carbon costs of the two systems is nearly 9-fold, Figure 9 shows that the proportions of carbon costs in each stage of the construction period under the two different systems are not much different. The carbon cost in the material production stage accounts for the highest proportion, mainly because this stage exhibits the highest carbon emissions. The carbon cost in the construction phase is the smallest.

5. Conclusions

A bridge carbon emission calculation model is established in this paper based on the construction sequence method, and then the external impacts of bridge carbon emissions are transformed into the internal expenditure costs of relevant enterprises under the carbon taxing and trading systems. Using an actual bridge as an example, the carbon cost and emissions during its construction phase were calculated, and the calculation results were
analyzed. (1) The carbon emission calculation results show that the carbon emissions of the material production stage are the largest during the construction period of the bridge, accounting for 92.1% of the entire construction stage, and the carbon emissions generated by the production of steel bars account for 62% of the entire material production stage. The carbon emissions of the steel bars and concrete of the bored piles are the highest in the material production stage and the transportation stage, so it is necessary for the material manufacturing industry to take carbon reduction measures to control carbon emissions. (2) The carbon cost calculation results show that the carbon cost under the carbon taxing system is significantly higher than that under the carbon trading system, and the carbon cost in the material production stage accounts for a very high proportion of the carbon cost in the construction period, reaching approximately 98%. Therefore, monetizing carbon emissions is conducive to clarifying the environmental impact of bridge construction.

However, this paper also has various limitations. This paper only measures the carbon emissions and carbon costs during the bridge construction period, and in the future, the carbon emissions and carbon costs of the whole life cycle of the bridge can be studied. In addition, there are many types of building components and materials involved in a bridge, and it is difficult to quantify all materials and components in one study. Therefore, only the carbon emissions of key components and major materials are considered in this paper, and all components and materials can be quantitatively analyzed in the future.

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