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How to scientifically guide expressway construction carbon emission reduction: the establishment and application of a carbon emission accounting and evaluation system

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Amid global climate change, reducing carbon emissions from expressway construction is crucial for achieving carbon peaking and neutrality goals. However, the existing expressway carbon emission accounting and assessment methods remain inadequate, failing to accurately characterize the level of carbon emissions and hindering the systematic promotion of low-carbon emission reduction work. Thus, a systematic carbon emission accounting and evaluation system is built by defining the emission boundaries during the construction period of expressways extensively, integrating the CRITIC method and the Hemming proximity Degree theory, and combining these with the "14th Five-Year Plan." Five typical sections in Hunan Province were selected to carry out empirical research. Key findings reveal significant disparities in carbon emissions across sections: S4 and S5 were rated Grade C (high emissions), whereas S1, S2, and S3 achieved Grade B (moderate emissions). The materialization stage was identified as the dominant source, contributing over 90% of the total across all sections. Its emissions were dominated by cement production, which contributed 27.10%. And steel-related materials (e.g., carbon steel reinforcement and plain carbon steel) contributed approximately 12% each of the materialization-stage total. Besides, transportation and construction stages accounted for only 2.18% and 2.69%, respectively. Notably, the carbon loss stage caused by vegetation clearance also constituted a significant emission source, especially the shrubs and scrub in S4, where it accounted for 47.9% of the total carbon emissions from all sections during the carbon loss stage. Critical section-specific hotspots included: the extensive use of steel supports in tunnel-intensive sections such as S2; high-strength cement and prestressed steel strands in bridge-dominant sections such as S4 and S5; transport activities in S2; and substantial diesel consumption in earthwork-heavy sections such as S1 and S2. These results comprehensively assess the carbon emissions of these projects during the construction process and clarify the advantages and shortcomings of each section. The system can scientifically guide the targeted

carbon emission reduction work during the expressway construction period, and provide scientific decision-making support for the preparation of expressway construction carbon emission accounting and evaluation standards.

KEYWORDS

expressway, construction, carbon emission accounting, carbon emission evaluation, carbon emission reduction

1 Introduction

China's expressways have evolved from transportation routes to symbols of national strength, distinguished by world-class standards and leading-edge construction technology (Government of China, 2023). By the end of 2024, the total length of China's road network is projected to reach 5.49 million kilometers, including 190,700 km of expressways, accounting for around 50% of the global total and ranking first in the world (Ministry of Transport of the People's Republic of China, 2025). However, the continuous expansion of expressway construction has also led to significant carbon emission pressures. In response, the state explicitly calls for accelerating the establishment of carbon accounting standards and low-carbon technical specifications in key industries, such as transportation and construction (National Development and Reform Commission of the People's Republic of China, 2023). Thus, the critical challenge is to establish a scientific accounting and evaluation system for expressway carbon emissions, essential for quantifying its environmental impact and guiding the industry towards green and low-carbon transformation.

Current research on expressway carbon emissions, both domestically and internationally, primarily focuses on the development of stage-specific quantitative standards and the analysis of emission characteristics. For example, in 2024, China Highway Survey and Design Association (2024a) released a group standard applicable to carbon emission calculations during expressway construction, which includes the material production, material transportation, and construction stages. In 2025, Tianjin Municipal Housing and Urban-Rural Development Commission (2025) also issued an industry standard, mainly applicable to carbon emission accounting during the construction of new, renovated, or expanded expressway projects at various levels within Tianjin. Its stage delineation similarly includes material production, transportation, and construction. In the theoretical research domain, numerous scholars have employed the life cycle assessment (LCA) approach to systematically analyze carbon emissions from expressways. Dos Santos and da Silva Rêgo (2025) developed a stochastic LCA model to estimate greenhouse gas emissions in Brazilian federal expressway projects, which covers the material production, transportation, and construction stages, and proposed that low-carbon development in the pre-design stage could be achieved by optimizing key disciplines and high-impact materials. Studies by Huang et al. (2024) and Gao et al. (2024) both identified material production as the primary source of carbon emissions, with this stage accounting for over 90% of the total in both studies. Liu et al. (2019a) defined system boundaries comprising four emission stages: upstream (material production), on-site (construction activities), off-site (mixture production), and transportation (material transport), providing a comprehensive assessment of CO₂ emission impacts during the construction of a mountain expressway. Current carbon emission assessments for

expressway construction often overlook carbon sink losses resulting from vegetation clearance, focusing primarily on emissions from material production, transportation, and construction consumption. However, empirical evidence reveals that such carbon sink losses are non-negligible. As demonstrated in Australia's Roe Highway Extension project, the carbon sink loss caused by vegetation clearance was nearly equivalent to the total carbon emissions from building material production and transportation (EPA Western Australia, 2012).

In addition, numerous standards and studies have adopted comprehensive evaluation methods to assess the green and low-carbon performance of expressway construction. China Highway Survey and Design Association (2024b), in 2024, establishes an evaluation system comprising 11 indicators across five categories: top-level planning and process control, carbon emissions and reduction, ecological protection and carbon sequestration, resource conservation and utilization, and technological innovation and application. The green and low-carbon construction level is determined through scoring based on this indicator system. Other studies have focused primarily on expressway service areas, employing similar methods by selecting multi-dimensional evaluation indicators related to carbon emissions for scoring, rating, or quantitative analysis (China Transportation Association, 2022; Jiangsu Renewable Energy Association, 2025). Similarly, Bujang et al. (2018) developed an assessment framework for green expressway development in Malaysia, evaluating four critical dimensions: environmental management, economic resource utilization, innovative technological solutions, and erosion control mechanisms in road construction projects. Building on existing policies, Li et al. (2020) incorporated the five core mandates for green expressway construction issued by the Ministry of Transport. Using the G1 method (order relation analysis), they assessed a civil engineering project in Hainan and identified suboptimal green construction performance, particularly in ecological conservation. Additionally, Wang et al. (2023) introduced several characteristic indicators for bridges and tunnels covering construction energy consumption control, resource utilization technology, construction techniques, and project management. By applying an improved analytic hierarchy process and a grey-fuzzy comprehensive evaluation method, they concluded that the green and low-carbon performance of the Huang'an Expressway construction project was excellent.

Overall, significant progress has been made in addressing carbon emissions during expressway construction. However, several critical issues persist in current research and practice: 1) Incomplete accounting boundaries: existing carbon emission accounting systems omit emissions resulting from vegetation clearance, leading to fragmented statistical scope and an inability to fully reflect the actual carbon emission of expressway projects; 2) Lack of objectivity and scientific rigor in evaluation frameworks: current

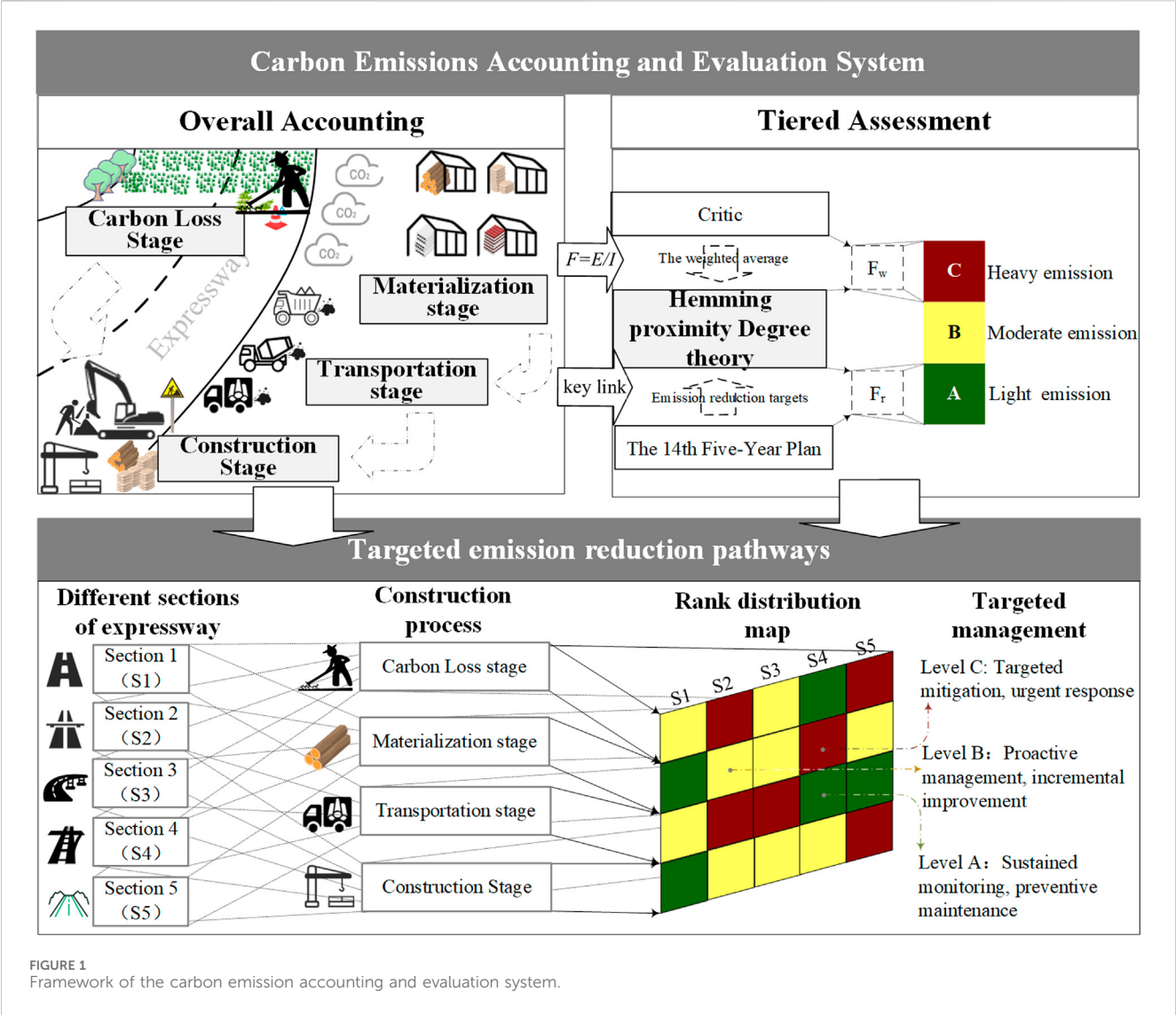


FIGURE 1 Framework of the carbon emission accounting and evaluation system.

assessment methods are either limited to quantitative emission analysis or comprise multi-indicator evaluation systems that lack uniform and objectively grounded scoring criteria. Additionally, A recently issued national policy further emphasizes the need to rationally decompose carbon emission targets and establish a comprehensive carbon evaluation mechanism (General Office of the State Council, 2024). Addressing these gaps and aligning with national policy, a carbon emission accounting and evaluation framework was proposed. It aims to improve the boundaries, methodologies, and standards of carbon accounting, bridge the evaluation gap in the expressway industry, accurately reflect emission levels, facilitate low-carbon emission reduction efforts, and enhance policy optimization and corporate decision-making.

2 Methodology

The framework of the carbon emission accounting and evaluation system during the expressway construction period is shown in Figure 1.

2.1 Method of carbon emission accounting

The temporal boundary was defined as the period from construction commencement to project completion. Carbon accounting was conducted in accordance with the ISO 14064 standard, which covers the global warming impacts of seven major greenhouse gases (International Organization for Standardization, 2018). Given its dominant role, carbon dioxide equivalent (CO₂e) was adopted as a unified metric for assessing the greenhouse effect (Committee for the preparation of the Second National Assessment Report on Climate Change, 2011). With reference to relevant studies (Liu et al., 2019b; Bao et al., 2025; Wang et al., 2015), carbon emissions during expressway construction can be further categorized into the following three stages: materialization of building materials, transportation of materials, and the construction stage. The specific calculation formulas for each stage are presented below.

The materialization stage covers raw material mining, transportation, industrial processing and prefabricated components manufacturing. As is shown in Equation 1:

$$E_m = \sum_{i=1}^n Q_i \times EF_i \quad (1)$$

where E_m is the carbon emissions of materialization stage (tCO₂e); Q_i is the consumption of i -th building materials in the materialization stage (t); EF_i is the carbon emission factor of i -th building materials in the materialization stage (tCO₂e/t).

The transportation stage includes the multi-stage operation flow of expressway construction materials transportation: secondary processing and transportation at off-site distribution centers, prefabricated components delivered to the site, construction machinery and equipment transfer, and on-site materials deployment. As is shown in Equation 2:

$$E_t = \sum_{j=1, k=1}^n D_j \times A_{jk} \times M_k \quad (2)$$

where E_t is the carbon emissions of transportation stage (tCO₂e); D_j is the consumption of j -th building materials in the transport (t); A_{jk} is the average transport distance of the k -th transport mode of the j -th building materials (km); M_k is the carbon emission factor of transport distance per unit weight under the k -th mode of transport (tCO₂e/(t·km)).

Within the defined temporal boundary, carbon emissions during the construction stage are primarily attributed to the operation of construction machinery, on-site personnel activities, and energy consumption by temporary facilities. Among these, emissions from construction worker's commuting are neglected due to limited data availability and their relatively low contribution. As is shown in Equation 3:

$$E_c = \sum_{l=1}^n AC_l \times EF_l \quad (3)$$

where E_c is the carbon emissions of construction stage (tCO₂e); AC_l is the l -th energy consumption during construction (t or kWh); EF_l is the carbon emission factor of the l -th energy (tCO₂e/TJ or tCO₂e/MWh).

The above accounting boundary was limited to the physical construction activities of the project, and did not account for ecosystem carbon sink losses caused by vegetation clearance. Thus, a vegetation clearance carbon loss stage (hereinafter referred to as the carbon loss stage) was introduced. Based on the significance of carbon sink contribution and data availability, four vegetation types were selected: coniferous forest, and broad-leaved forest, which are characterized by the highest carbon density, as well as shrubs and scrub, and crops, which cover the largest area. This classification system is consistent with the land-type categories used in engineering environmental impact assessments, ensuring that activity data are practically relevant and enhancing the accuracy and reliability of carbon sink loss calculations. The accounting formula is presented in Equation 4:

$$E_v = \sum_{i=1}^n F_i \times S_i \times T \quad (4)$$

where E_v is the carbon emissions of carbon loss stage (tCO₂e); F_i is the annual carbon sequestration per unit of land area of the i -th vegetation (tCO₂e/hm²·a); S_i is the unit of land area of the i -th

vegetation (hm²); and T is the years between the clearing of vegetation on the expressway and the completion of the construction (a).

In summary, the formula for calculating the sum of their carbon emissions is shown in Equation 5:

$$E = E_m + E_t + E_c + E_v \quad (5)$$

where E is the total carbon emissions during expressway construction.

Since project management generally adopts mileage as the benchmark for progress control, and the total carbon emissions are difficult to reveal the emission characteristics of key processes, the carbon emission intensity indicator per unit mileage (F) is introduced as a subsequent evaluation indicator, and shown in Equation 6:

$$F = E/I \quad (6)$$

where F is the carbon emission intensity of expressway construction projects (tCO₂e/km); I is the mileage of expressway construction projects within the scope of accounting (km).

2.2 Carbon emission evaluation system

The Hemming proximity theory can be employed to quantify the contribution of individual indicators within a comprehensive evaluation system (Peng et al., 2019). Based on this theoretical framework and guided by policy planning objectives, a tiered evaluation standard was developed for carbon emissions in expressway construction projects, establishing a comprehensive carbon emission assessment system. Consider a set of n samples (sections) to be evaluated and p indicators (key links), which together form an original index data matrix (x_{ij}). The specific steps are as follows (a worked example is provided in the Supplementary Material):

Step 1: Calculation of Hemming proximity Degree

The Hemming proximity Degree consists of the weights of the constituent elements and their corresponding degrees of affiliation, as shown in Equation 7:

$$\rho_{Hr} = 1 - \sum_{j=1}^n W_j |u_{ij} - u_j| \quad (7)$$

where ρ_{Hr} is the Hemming proximity Degree, W_j denotes the objective weight of the j -th evaluation indicator (key link).

The degree of affiliation can be obtained by Equation 8:

$$u_j = \frac{\sum_{i=1}^n u_{ij}}{n} \quad (8)$$

where u_j is the comprehensive affiliation degree of the j -th key link; u_{ij} is the affiliation degree of carbon emission intensity at the j -th key link of the i -th section, determined by evaluation indicators, namely, $u_{ij} = \frac{\min F_j}{F_{ij}}$, where F_j is the carbon emission intensity of the j -th key link of all sections; F_{ij} is the carbon emission intensity of the j -th key link of the i -th section.

To objectively quantify the relative importance of multidimensional elements of expressway construction carbon emissions, the CRITIC method was introduced. By analyzing the

standard deviation (reflecting variability) and correlation coefficient (reflecting conflict) of the indicator data, the method generates objective weights with mathematical reproducibility, which is especially suitable for revealing the intrinsic correlation and dynamic change characteristics among carbon emission indicators (Chen et al., 2022).

1. Standardized processing: Raw indicators are divided into two types, positive and reverse, and different types of indicators need to be processed differently. The accounting formula is presented in Equation 9:

$$\begin{cases} z_{ij} = \frac{x_j - x_{\min}}{x_{\max} - x_{\min}}, \text{positive indicators} \\ z_{ij} = \frac{x_{\max} - x_j}{x_{\max} - x_{\min}}, \text{reverse indicators} \end{cases} \quad (9)$$

where x_j is the raw data of the j -th evaluation indicator of all sections, and $x_{\min}$ and $x_{\max}$ are the minimum and maximum values of the j -th evaluation indicators of all sections, respectively.

2. Calculate indicator variability is presented in Equation 10:

$$S_j = \sqrt{\frac{\sum_{i=1}^n (z_{ij} - \bar{z}_j)^2}{n-1}} \quad (10)$$

where S_j is the standard deviation of the j -th indicator, where $\bar{z}_j = \frac{1}{n} \sum_{i=1}^n z_{ij}$.

3. The amount of information in each attribute is shown in Equation 11:

$$C_j = S_j \times \sum_{i=1}^p (1 - r_{ij}) \quad (11)$$

where C_j indicates the influence of the j -th evaluation indicator on the whole comprehensive evaluation indicator system; r_{ij} indicates the correlation coefficient between the evaluation indicators i and j , measured using the Pearson correlation coefficient.

4. Objective weighting coefficients is presented in Equation 12

$$W_j = \frac{C_j}{\sum_{j=1}^p C_j} \quad (12)$$

where $\sum_{j=1}^p W_j = 1$.

Step 2: Establishment of tiered evaluation criteria

To quantify the impact of each element, the Hemming proximity Degree of each element is used as the weight for the evaluation indicator (F_{ij}), and the weighted average is used to obtain the value of the comprehensive evaluation range of the evaluation system (the boundaries of moderate and heavy emissions). The accounting formula is shown in Equation 13:

$$F_w = \frac{\sum_{i=1}^n (F_i \times \rho_{Hr})}{\sum_{i=1}^n \rho_{Hr}} \quad (13)$$

where F_w is the weighted average value of carbon emission intensity during the construction period of the expressway; F_i is the carbon emission intensity of the i -th section.

The Outline of the 14th Five-Year Plan explicitly sets a binding target to reduce carbon emission intensity per unit of GDP by 18%

compared to 2020 levels (The Fourth Session of the 13th National People's Congress, 2021).

Algorithmically, the boundary values for emission reduction targets in carbon emission evaluation - such as the thresholds between moderate and light emission levels - can be determined using Equation 14.

$$F_r = F_w \times (1 - 18\%) \quad (14)$$

where F_r is the expressway emission reduction target threshold value.

2.3 Data sources

1. Activity data: Material consumption, transportation distances, and energy consumption data were obtained from contractor-provided documents, including bills of quantities, shop drawings, price lists, and procurement logs (Tables 1, 2). The area of vegetation that has been cleared was determined using spatially explicit green space planning maps and phytoremediation inventories supplied by the builder and planner (Table 3).
2. Carbon emission factors: Carbon emission factors of energies and materials were primarily selected from the International Energy Agency (2019), and supplemented by China Highway Survey and Design Association (2024a). Notably, the electricity emission factor is set at 0.5366 kg CO₂/kWh (General Office of the Ministry of Ecology and Environment, 2024), and the vegetation-related carbon emission factors are shown in Table 4.

2.4 Data quality control

To ensure the accuracy and reliability of the research data, the following data quality control measures were implemented:

1. Data source prioritization: on-site measured data > as-built documents > design documents > engineering quota standards > authoritative databases > peer-reviewed literature data.
2. Data cross-verification: for key materials and energy consumption data, cross-verification was performed using multiple independent sources (e.g., design documents, procurement records, and energy bills) to enhance accuracy.
3. Uncertainty specification: all referenced or estimated data were clearly labeled with their source types, and potential uncertainties were analyzed and discussed to improve transparency and credibility.

3 Empirical analysis

3.1 Case study

Hunan Province in China is one of the first low-carbon pilot provinces, with a geographic gradient of plains-hills-mountains

TABLE 1 List of material consumption.

Material type	Unit	Material consumption				
		S1	S2	S3	S4	S5
C15 Concrete	m ³	0.0	35054.1	25276.5	46.5	15196.1
C20 concrete	m ³	29960.0	45454.2	41107.0	9023.5	58634.0
C25 Concrete	m ³	42870.0	61931.7	21377.0	6409.5	23947.3
C30 Concrete	m ³	113950.0	155260.3	116773.2	25625.8	98170.5
C35 Concrete	m ³	0.0	103820.4	59494.0	1034.0	24957.8
C40 Concrete	m ³	36670.0	26632.3	26477.5	48.5	21565.9
C45 Concrete	m ³	0.0	22617.3	13505.5	0.0	0.0
C50 concrete	m ³	111100.0	155137.1	71051.5	1479.0	39990.8
Petroleum Asphalt*	t	2054.8	1278.4	1002.1	1809.5	972.0
Modified Asphalt*	t	2917.4	1847.9	2907.8	2615.5	1643.8
Cement	t	145467.6	350000.0*	223644.9	368340.0	111359.5
Fly ash	t	67607.5	31000.0*	28506.2	64443.5*	19000.0*
Sand and gravel	t	363446.3	590068.2	85172.4	35941.3	270023.0
Crushed stone	t	499738.6	733198.9	649414.7	60574.6	495638.0
Carbon Steel Rebar	t	21872.2	38353.1	16562.0	15910.0	21288.0
Steel Pipe	t	741.4	2333.0	559.5	521.4	131.0
Seamless Steel Pipe	t	265.7	98.5	1569.0	215.5	723.0
Steel Skeleton	t	1143.6	623.9	406.0	2840.0	291.0
Medium Sections	t	265.3	179.7	215.0	227.9	218.5
Steel Plate	t	1052.0	903.0	1107.0	26.0	665.0
Prestressing strand	t	27586.0	17440.9	338.0	15.9	1243.0
Large steel sections	t	5793.9	5267.9	5180.0	6670.0	932.0
Plain Carbon Steel	t	42611.9	854.1	27780.0	66060.0	640.0
Galvanized wire mesh	t	32.6	29.4	72.6	38.8	19.4
Explosives	t	1302.6	913.6	353.6	29.7	448.0
Detonators	t	42.0	29.4	30.2	71.0	12.7
Polyethylene tube	kg	85.2	71.4	69.4	76.4	63.3
High-density polyethylene material	t	1321.2	781.8	1024.0	1658.0	467.0
Rigid polyvinyl chloride pipe	kg	59270.0	49385.0	48580.0	39370.0	18593.8
Water stops	t	311.5	757.4	32.5	350.0	148.0
Polystyrene foam board	t	15720.0	8628.5	8984.0	19860.0	2306.6
Nonwoven Fabric	t	270.0	184.5	331.0	177.0	76.6
Geotextile	t	70.5	26.7	83.3	30.1	20.7
Geocell	t	599.1	287.7	34.7	61.8	19.7
SBS waterproofing membrane	m ²	721.0	638.0	1187.0	1383.6	839.0
Hot Bitumen Coating	m ²	7307.0	5914.5	5585.0	6619.0	3981.0
Culvert anticorrosion layer	m ²	7460.0	5647.3	5130.0	6416.0	3012.2

The symbol “*” indicates that the value is derived from the calculation of “Highway Engineering Budget Quota (JTG/T 3832–2018)” (Ministry of Transport of the People’s Republic of China, 2018), while the symbol “#” indicates the engineering design value.

TABLE 2 List of energy consumption.

Energy type	Unit	Energy consumption				
		S1	S2	S3	S4	S5
Diesel	t	3412.57	2639.91	1187.15	1228.34	418.00
Gasoline	t	956.47	758.46	58.33	0.00	0.00
Liquefied petroleum gas	t	36.86	27.84	0.00	0.00	0.00
Natural gas	t	0.00	0.00	14.22	0.00	0.00
Acetylene	t	0.10	0.20	0.00	0.00	0.00
Electricity	kWh	11258586.00	22422731.67	2346000.00	2334276.00	10800000.00

The unit of energy consumption provided by each construction unit is different, so the unified treatment unit is t. Moreover, the density of gasoline and diesel is about 0.73 kg/L and 0.84 kg/L, respectively.

TABLE 3 List of vegetation clearance.

Vegetation type		Carbon loss area/hm ²				
		S1	S2	S3	S4	S5
Permanent work	Coniferous forest	22.41	24.48	3.16	31.40	5.18
	Broad-leaved forests	10.70	16.32	5.17	0	17.42
	Shrubs and scrub	1.46	1.80	2.44	824.80	4.52
	Crops	13.79	20.50	13.2	73.30	39.18
Temporary Works	Coniferous forest	15.60	11.60	0.31	0	3.13
	Broad-leaved forests	4.40	7.40	1.76	0	9.38
	Shrubs and scrub	7.90	5.90	0.56	208.20	8.08
	Crops	31.40	25.40	2.89	0	5.47

TABLE 4 Vegetation-related carbon emission factors.

Vegetation type	Carbon emission factors/ tCO ₂ e·hm ⁻² ·a ⁻¹
Coniferous forest (Zhang, 2025)	6.58
Broad-leaved forest (Zhang, 2025)	6.68
Shrubs and scrub (Wang, 2024)	2.52
Crops (Deng, 2024)	1.78

Given that the carbon sequestration capacity of vegetation types varies across different geographical locations, the values used are consistent with the study area (Hunan province) to minimize data uncertainty.

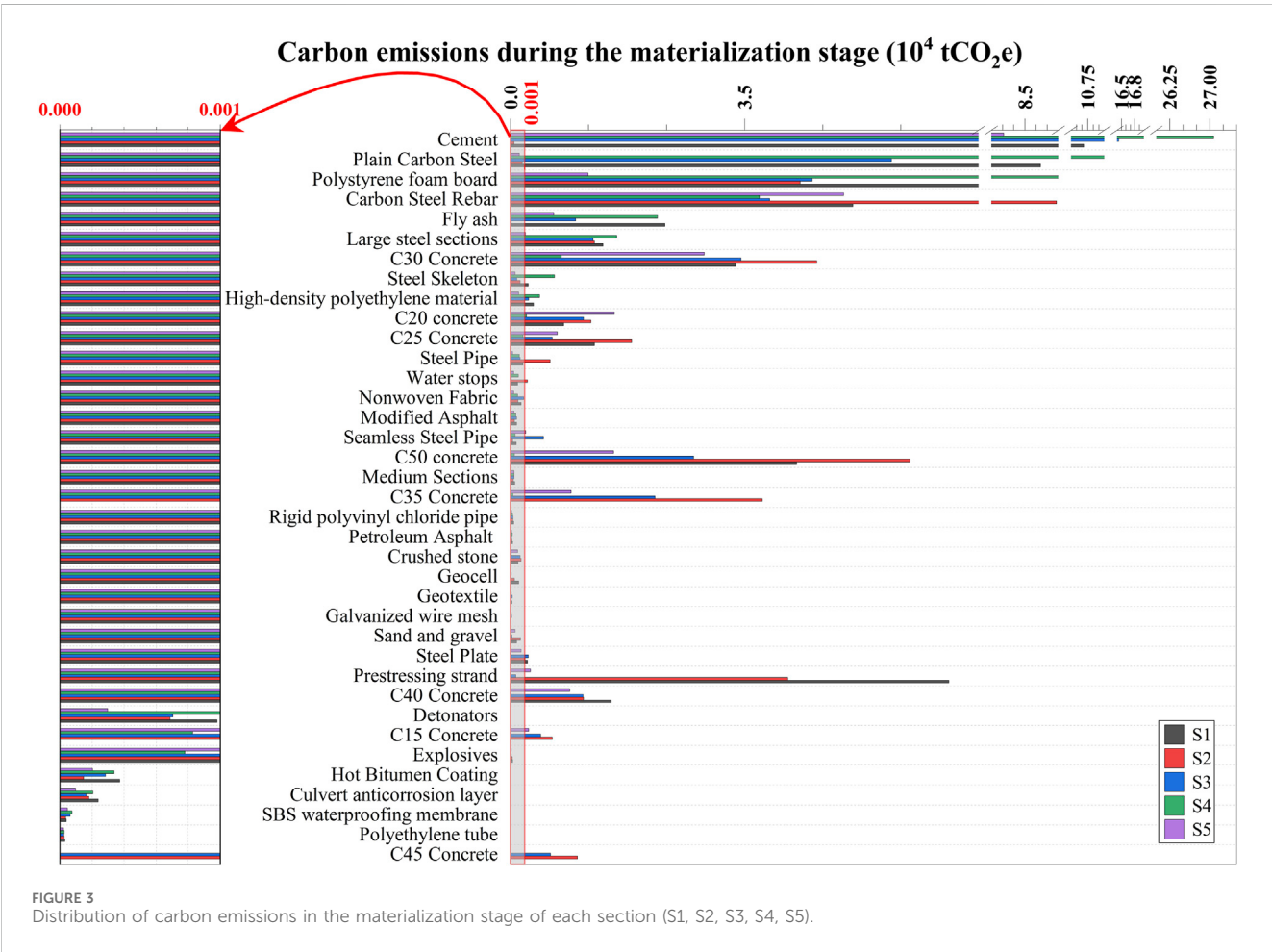
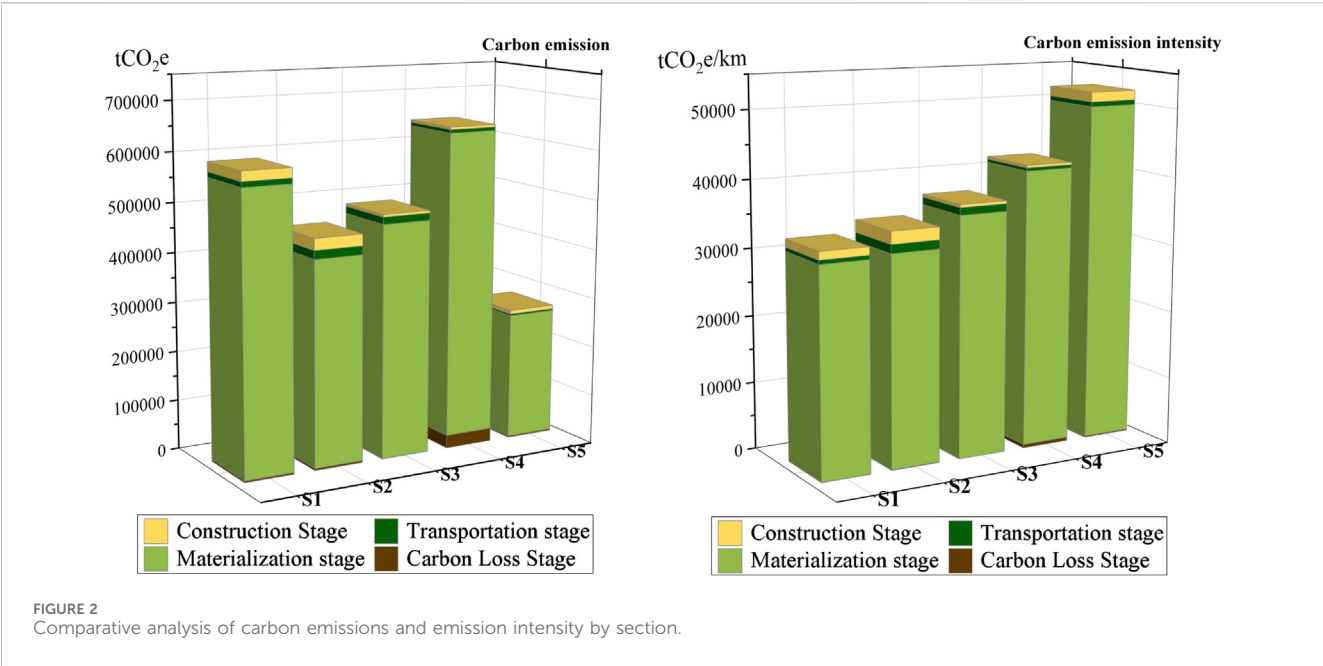
(National Development and Reform Commission of the People’s Republic of China, 2023; People’s Government of Hunan Province, 2020). Due to the availability of data, five construction sections were selected as empirical cases, named S1, S2, S3, S4, and S5, and the length of civil construction in each section was 18.212 km, 13.2 km, 13.127 km, 14.994 km, and 5.1 km, respectively. In parallel, the spatial scopes of the five sections were the land requisition and relocation work, the roadbed works, the bridge and culvert work (the roadbed works), and the bridge and culvert

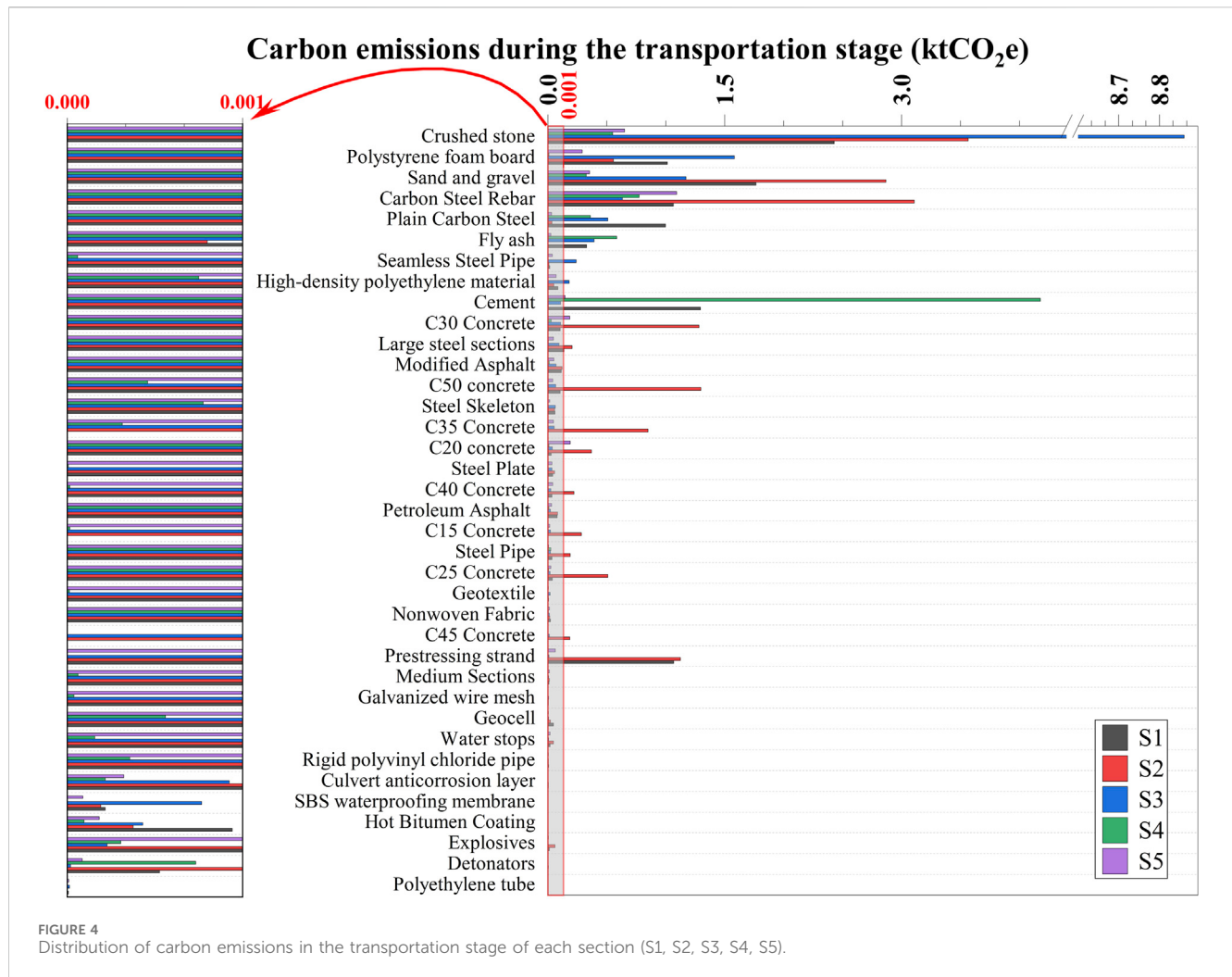
work (the bridge and culvert works). Works, bridge and culvert works (including T-beam fabrication), interchanges, culverts and tunnels, connection works, and large-scale temporary facilities within the scope of the section.

3.2 Analysis of the results of carbon emissions during expressway construction

As shown in Figure 2, the highest carbon emissions during civil construction of the expressway are observed in S1 and S4, each exceeding 590,000 tCO₂e. Emissions in all sections are predominantly attributed to the materialization stage, accounting for over 90% of the total, with S4 having the highest proportion at 96.80%. These results highlight the materialization stage as a critical focus for emission reduction, with substantial mitigation potential. Although emissions during the construction stage are comparatively lower, they remain non-negligible, particularly in S2 and S1. Moreover, emissions in the carbon loss stage also warrant attention in certain sections, such as S4.

Despite having high total emissions, S1 demonstrated lower carbon emission intensity, suggesting either a larger project scale or better management practices. In contrast, S5, with the lowest total emissions, exhibited the highest emission intensity, indicating





potential inefficiencies in technology or management per unit of activity. This section focuses solely on the analysis of total carbon emissions, as carbon emission intensity will be employed as a core indicator in subsequent evaluations for a more comprehensive and equitable assessment of emission levels across sections.

3.2.1 Materialization stage

At the materialization stage (Figure 3), carbon emissions from engineering materials are significant across all sections (S1 to S5), with major contributions from steel, construction raw materials, concrete, plastics and other chemical materials. Cement, as a fundamental building material, is the largest source of carbon emissions, accounting for 27.10% of the total, followed by various types of concrete (23.20%), which may be attributed to its extensive use in construction and energy-intensive production process. Furthermore, steel-based materials, including carbon steel rebar (prominently in S2, S1, and S5), prestressed steel strands (mainly used in pre-tensioned concrete in S1 and S2), and plain carbon steel (used for reinforcement and structural purposes, especially in S4, S1, and S3), also contribute substantially to carbon emissions. Specifically, carbon steel reinforcement and plain carbon steel account for approximately 266,725.44 tCO₂e and 282,789.26 tCO₂e, respectively, indicating considerable environmental pressure from their use in construction.

It is noteworthy that polystyrene foam boards contribute 12.07% of the total emissions across all sections. Although auxiliary materials and accessories such as high-density polyethylene, water stops, and non-woven fabrics have relatively low individual emission factors, their widespread use in construction projects results in non-negligible cumulative emissions. The proportional contribution of each material varies by project section. For instance, fly ash in S1 and S4, steel skeleton in S4, geocells in S1, and steel pipes in S2 require targeted emission reduction strategies.

3.2.2 Transportation stage

In the transportation stage (Figure 4), there are large differences in the carbon emissions generated by different project materials, while the transport of construction raw materials (57.05%), steel (23.24%), and concrete (11.75%) is the main source of carbon emissions. Of the emissions in construction raw materials, the transportation of crushed stone is particularly significant, reaching 16,134.43 tCO₂e, especially in S3. Cement follows, accounting for 10.8% of total transport-related carbon emissions. Additionally, attention must be paid to the transport carbon emissions associated with steel products such as carbon steel reinforcing bars, prestressed steel strands, and plain carbon steel. However, greater emphasis should be placed on identifying and

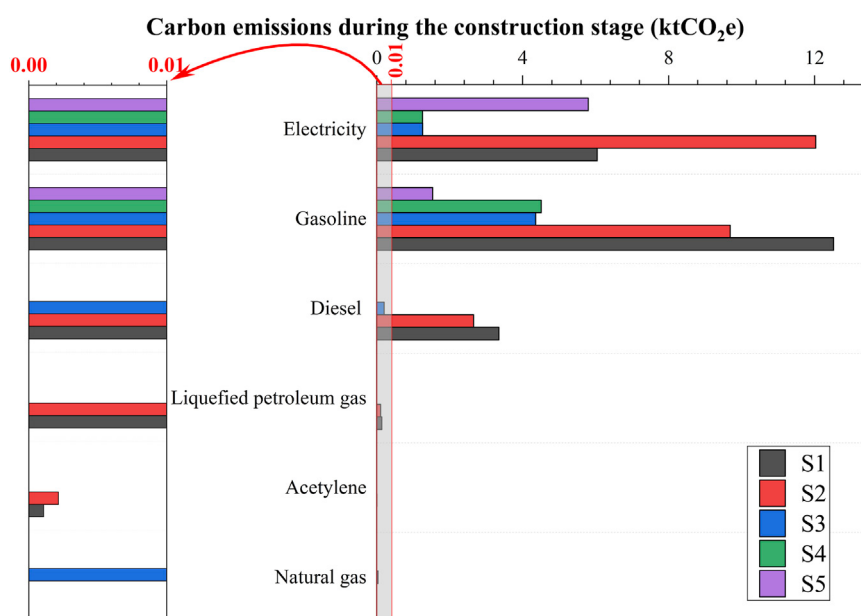


FIGURE 5
Distribution of carbon emissions in the construction stage of each section (S1, S2, S3, S4, S5).

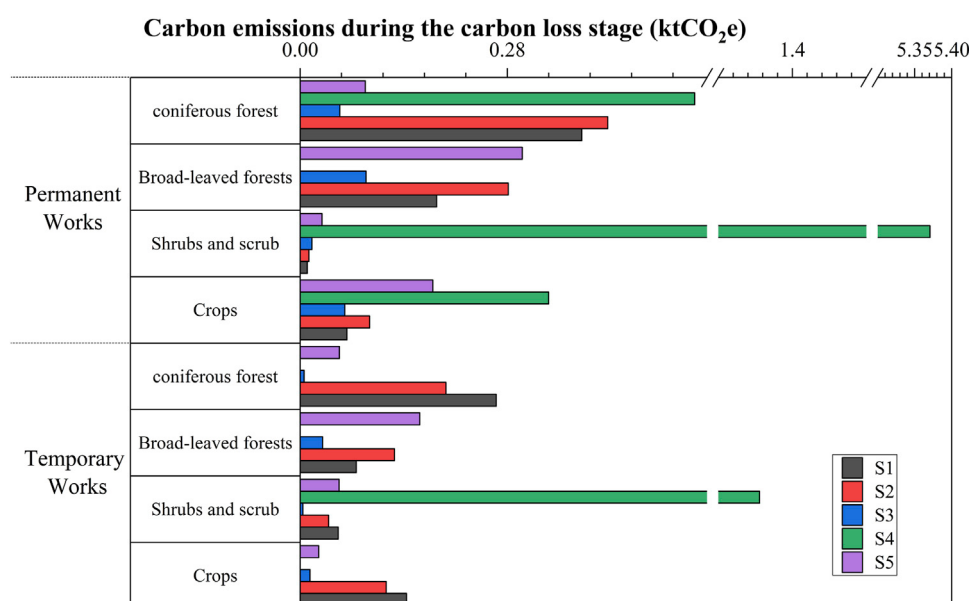


FIGURE 6
Distribution of carbon emissions in the carbon loss stage of each section (S1, S2, S3, S4, S5).

mitigating high-carbon-emission hotspots in material transportation across the sections. Key concerns include the transport of cement in S4 (due to its extensive use) and S1 (which had long haul distances due to a lack of local suppliers); crushed stone and sand in S1 (as the high tonnage of these materials makes them sensitive to transport distance), S2, and S3; prestressed steel strands in S1 and S2 (which are typically produced in centralized plants requiring long-distance transport); plain carbon

steel in S1 (due to its extensive use in structural frames and reinforcements, resulting in high total tonnage and long-haul transportation); carbon steel reinforcing bars in S2, S1, and S5 (as they are the primary steel material for concrete reinforcement, with massive consumption volume leading to significant transport emissions); and polystyrene foam boards in S3 and S1 (whose extremely low density and bulky volume result in poor transportation efficiency, and are in relatively large quantities).

TABLE 5 Recategorizing Key Links Across Sections and Within Stages.

Materialization stage		Transportation stage	Construction stage			
Material type	Key link	Key link	Energy type		Key link	
C15 Concrete	Concrete	Concrete Transport	Diesel		Diesel	
C20 concrete			gasoline		Other Fossil Fuels	
C25 Concrete			Liquefied petroleum gas			
C30 Concrete			Natural gas			
C35 Concrete			Acetylene			
C40 Concrete			Electricity		Electricity	
C45 Concrete						
C50 concrete						
Cement	Cement	Construction Raw Materials				
Fly ash	Fly ash					
Petroleum Asphalt	Other construction raw materials					Carbon loss stage
Modified Asphalt			Vegetation type		Key link	
Sand and gravel			Permanent works	Coniferous forest	Permanent works	
Crushed stone						Broad-leaved forests
Carbon steel reinforcement	Carbon steel reinforcement					Shrubs and scrub
Steel Pipe	Other Steel Materials	Crops				
Seamless steel pipe		Temporary Works	Coniferous forest	Temporary Works		
Steel Skeleton			Broad-leaved forests			
Medium Sections			Shrubs and scrub			
Steel Plate			Crops			
Prestressing strand	Prestressing strand					
Large steel sections	Large steel sections					
Plain Carbon Steel	plain Carbon Steel					
Galvanized wire mesh	Galvanized wire mesh					Processed Iron
Explosives	Pyrotechnic products					Pyrotechnics
Detonators						
Polystyrene foam board	Polystyrene foam board					Plastics and other chemical materials
Polythene tube	Other plastics and chemical materials					
High density polythene material						
Rigid polyvinyl chloride pipe						
Water stops						
Non-woven fabric						
Geotextile						
Geocell						
SBS waterproofing membrane						
Hot Bitumen Coating						

(Continued on following page)

TABLE 5 (Continued) Recategorizing Key Links Across Sections and Within Stages.

Materialization stage		Transportation stage	Construction stage	
Material type	Key link	Key link	Energy type	Key link
Culvert body anti-corrosion layer				

TABLE 6 The weighting factors for key link.

Stage	Key link	Weights
Materialization stage	Concrete	0.0346
	Cement	0.0496
	Fly ash	0.0505
	Other construction raw materials	0.0334
	Carbon Steel Reinforcement	0.0379
	Prestressing strand	0.0481
	Large steel sections	0.0451
	Plain Carbon Steel	0.0537
	Other Steel Materials	0.0343
	Galvanized wire mesh	0.0444
	Pyrotechnic products	0.0378
	Polystyrene Foam Board	0.0467
	Other plastics and chemical materials	0.0340
Transportation stage	Concrete Transport	0.0351
	Construction Raw Materials	0.0431
	Steel	0.0331
	Processed Iron	0.0375
	Pyrotechnics	0.0362
	Plastics and other chemical materials	0.0382
Construction stage	Diesel	0.0496
	Other Fossil Fuels	0.0501
	Electricity	0.0388
Carbon loss stage	Permanent Works	0.0476
	Temporary Works	0.0407

3.2.3 Construction stage

During the construction stage (Figure 5), the carbon emission structures of different sections exhibit significant variations. Overall, the proportion of direct carbon emissions from energy combustion varies considerably across sections, with diesel consumption contributing to nearly half of the energy combustion carbon emissions, with proportions particularly high in S3 and S4 at 74.43% and 78.26%, respectively. On the other hand, indirect carbon emissions from purchased electricity also constitute a notable share, with S5 having the highest proportion at 79.07%, followed by S2 at 49.15%. It can be seen that S1, S3, and S4 rely more heavily on diesel consumption,

whereas the carbon emissions of S2 and S5 originate primarily from purchased electricity.

3.2.4 Carbon loss stage

Figure 6 illustrates that the loss of forest, shrubs, and scrub had a particularly significant impact on carbon emissions, with permanent works contributing more significantly than temporary works. Among these, the carbon sink loss due to shrubs and scrub reduction accounted for the highest proportion (64.00% in permanent works, and 55.30% in temporary works), indicating that shrubs and scrub destruction were a major contributor to total emissions in these projects. Further analysis revealed that S4 accounted for 96.94% of the total shrubs and scrub loss during the carbon loss stage across all five sections. Carbon sink loss from forest land reduction ranked second (27.38%). Although the reduction of cropland was relatively minor overall, it still represented a considerable proportion in certain sections, such as S5 (22.99%) and S3 (27.14%). Although the carbon loss stage constitutes a relatively small proportion of total emissions (0.2%–1.2%), its impacts, should the system boundary not be time-constrained, are irreversible and long-lasting.

3.3 Delineation of criteria for tiered evaluation

Capitalizing on the types of stages in the civil construction process and the proportion of their carbon emissions, the key links in each stage of the expressway construction period are regrouped (Table 5), and the weights of the key links were calculated using the CRITIC method (Table 6), which facilitates the subsequent assessment work.

Harnessing the carbon emission accounting results of the five sections, the weighting coefficients of each key link, and the carbon emission grading evaluation model, the three-level evaluation standard of carbon emission intensity and their key links during expressway construction is generated, as shown in Table 7, in which level A indicates light emission, level B indicates moderate emission, and level C indicates heavy emission.

3.4 Graded assessment results and analysis of carbon emission levels

As shown in Figure 7, the overall carbon emission levels of each section are moderate to low, indicating that construction units still need to strengthen comprehensive carbon emission management. Notably, S4 and S5 exhibit relatively high overall carbon emissions, necessitating stricter control measures. It is noteworthy that although S1 (Grade B) has higher carbon emissions than S5 (Grade C), its

TABLE 7 Evaluation classification criteria for key link.

Stage	Key link	Level A	Level B	Level C
		Unit: tCO ₂ e/km		
Overall situation		[0, 32427.07)	[32427.07, 39545.21)	[39545.21, + ∞)
Materialization stage	Concrete	[0, 8089.47)	[8089.47, 9865.21)	[9865.21, + ∞)
	Cement	[0, 8446.24)	[8446.24, 10300.29)	[10300.29, + ∞)
	Fly ash	[0, 778.85)	[778.85, 949.82)	[949.82, + ∞)
	Other construction raw materials	[0, 204.42)	[204.42, 249.29)	[249.29, + ∞)
	Carbon Steel Reinforcement	[0, 4081.47)	[4081.47, 4977.40)	[4977.40, + ∞)
	Prestressing strand	[0, 1264.42)	[1264.42, 1541.98)	[1541.98, + ∞)
	Large steel sections	[0, 671.44)	[671.44, 818.83)	[818.83, + ∞)
	Plain Carbon Steel	[0, 2960.30)	[2960.30, 3610.12)	[3610.12, + ∞)
	Other Steel Materials	[0, 606.93)	[606.93, 740.16)	[740.16, + ∞)
	Galvanised wire mesh	[0, 6.14)	[6.14, 7.49)	[7.49, + ∞)
	Pyrotechnic products	[0, 11.98)	[11.98, 14.61)	[14.61, + ∞)
	Polystyrene Foam Board	[0, 3222.33)	[3222.33, 3929.67)	[3929.67, + ∞)
	Other plastics and chemical materials	[0, 379.24)	[379.24, 462.49)	[462.49, + ∞)
Transportation stage	Concrete Transport	[0, 86.20)	[86.20, 105.12)	[105.12, + ∞)
	Construction Raw Materials	[0, 372.27)	[372.27, 453.98)	[453.98, + ∞)
	Steel	[0, 167.90)	[167.90, 204.75)	[204.75, + ∞)
	Processed Iron	[0, 0.19)	[0.19, 0.23)	[0.23, + ∞)
	Pyrotechnics	[0, 0.97)	[0.97, 1.18)	[1.18, + ∞)
	Plastics and other chemical materials	[0, 56.78)	[56.78, 69.24)	[69.24, + ∞)
Construction stage	Diesel	[0, 391.55)	[391.55, 477.49)	[477.49, + ∞)
	Other Fossil Fuels	[0, 71.36)	[71.36, 87.03)	[87.03, + ∞)
	Electricity	[0, 424.07)	[424.07, 517.16)	[517.16, + ∞)
Carbon loss stage	Permanent works	[0, 98.15)	[98.15, 119.70)	[119.70, + ∞)
	Temporary Works	[0, 34.39)	[34.39, 41.94)	[41.94, + ∞)

overall emission performance remains better than the latter. And each section should formulate specific emission reduction measures and plans targeting key high-emission processes:

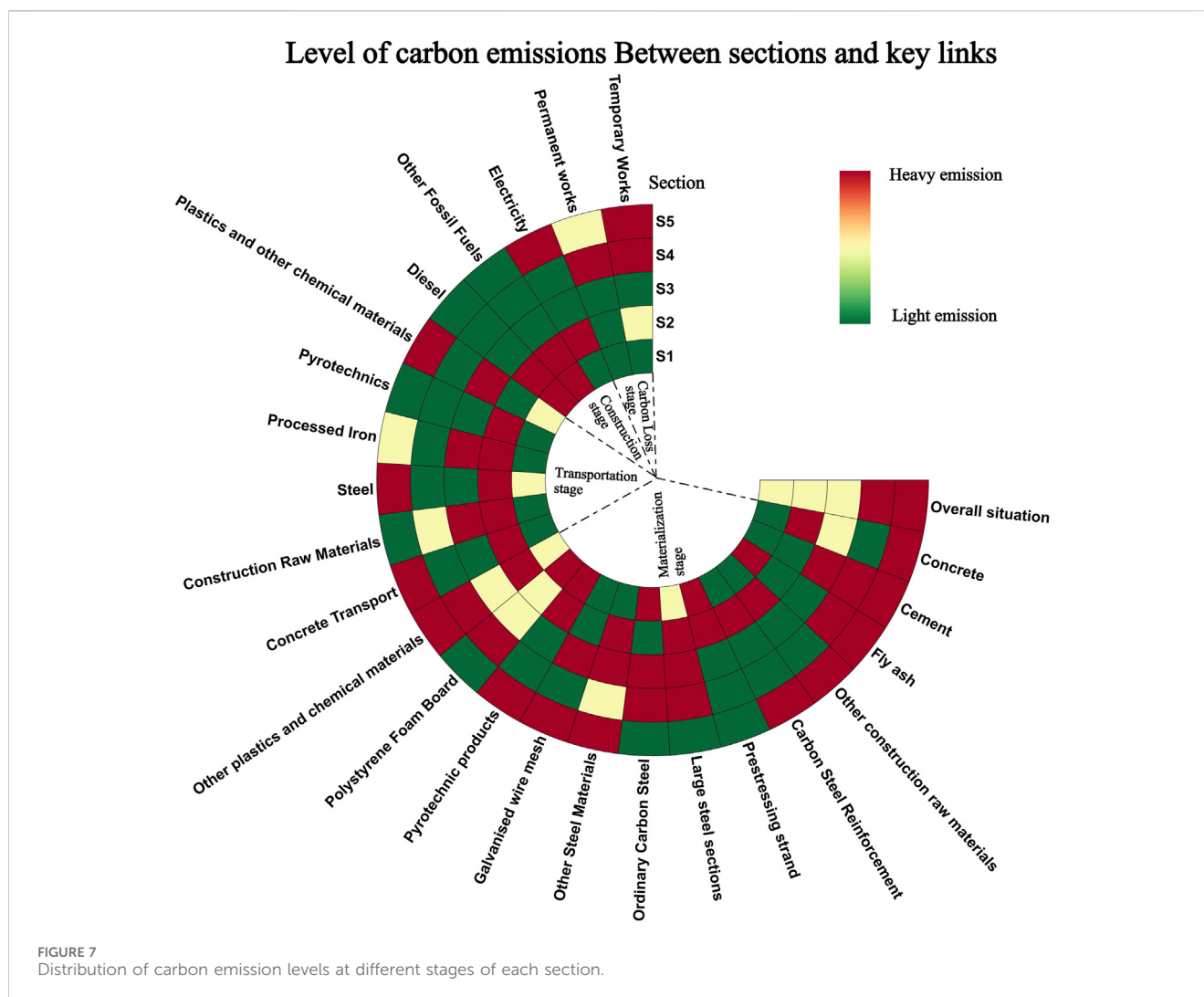
During the materialization stage, materials such as cement, fly ash, and plain carbon steel exhibited high-level emissions across multiple sections. In particular, steel materials (e.g., carbon steel reinforcement, prestressed steel strands, and large-section steel) generally showed high carbon emission levels. Most materials presented moderate and heavy emissions in S2 and S5. For instance, cement in S2, S3, S4, and S5 mostly fell into Grade B or C; fly ash was graded C in S1, S4, and S5, highlighting the significant contribution of these specific materials. Significant steel-related emissions in S2 and S4 further highlight the considerable impact of material selection and usage on carbon emissions.

In the transportation stage, S4 performed the best (only building material transport (Grade B) did not achieve Grade A), whereas most building material transportation in S2 showed high emission levels

(with only plastics and other materials (Grade A) not classified as Grade C). S3 and S5 also exhibited moderate to high emissions across multiple materials, indicating a need to optimize transportation modes and routes to reduce carbon emissions during transport.

During the construction stage, all processes in S2 were associated with high-level emissions. The fossil energy consumption in S1 and the electricity consumption in S5 performed poorly (Grade C). In contrast, all processes in S3 and S4 achieved Grade A, indicating excellent performance. It is recommended that construction units implement tailored communication and coordinated emission reduction based on site-specific management plans.

In the carbon loss stage, most permanent and temporary works were graded A or B, with S1 and S3 both showing light emissions. This suggests that these sections likely avoided areas with high vegetation coverage during planning and design, thereby reducing damage to ecosystems and loss of carbon sinks. However, both permanent and temporary works in S4, as well as temporary works



in S5, were graded C. It is advised that the corresponding construction parties optimize project site selection prior to construction and implement ecological compensation measures.

Furthermore, S4 had the highest number of links in light emission level, yet its overall carbon emission was Grade C (while S2 showed the opposite pattern). It can be seen that although most links in S4 were well controlled, a few critical links (such as cement, fly ash, plain carbon steel, large section steel, polystyrene foam boards, and vegetation clearance) exhibited exceptionally prominent emission levels, which dominated and elevated the overall average. This indicates that the carbon emission level of each section is primarily governed by a limited number of high-emission, high-weight links.

4 Discussion

4.1 Comprehensive analysis and discussion

4.1.1 Materialization stage

To identify key factors for emission reduction in the materialization stage and evaluate the influence of parameter

uncertainty, a plus or minus 30% sensitivity analysis was performed on the carbon emission factors of six key materials accounting for 75% of total emissions. The results reveal significant variations in the impact of different materials on overall emissions. As shown in Figure 8, the carbon emission factor of cement is the primary driver, as a plus or minus 30% in its value leads to approximately plus or minus 15% variation in total emissions. It is followed by steel (including plain and carbon steel reinforcement). These findings suggest that construction units should prioritize low-carbon cement (e.g., through solid waste admixtures) and green steel procurement to achieve deep emission reductions in the materialization stage.

Moreover, the bridge-tunnel ratio across sections decreases in the order: S5 (89.14%) > S4 (83%) > S2 (75.99%) > S3 (64.13%) > S1 (43.92%). In S2, which has a higher tunnel proportion, tunnel support requires significant amounts of steel and concrete. In contrast, S4 and S5 are bridge-intensive, necessitating large quantities of high-grade cement, prestressed steel strands, and carbon steel reinforcement. The high bridge-tunnel ratio creates structurally rigid material demand, leading to consistently high carbon emissions during the materialization stage. It is recommended that key sections such as S4 and S5 focus on

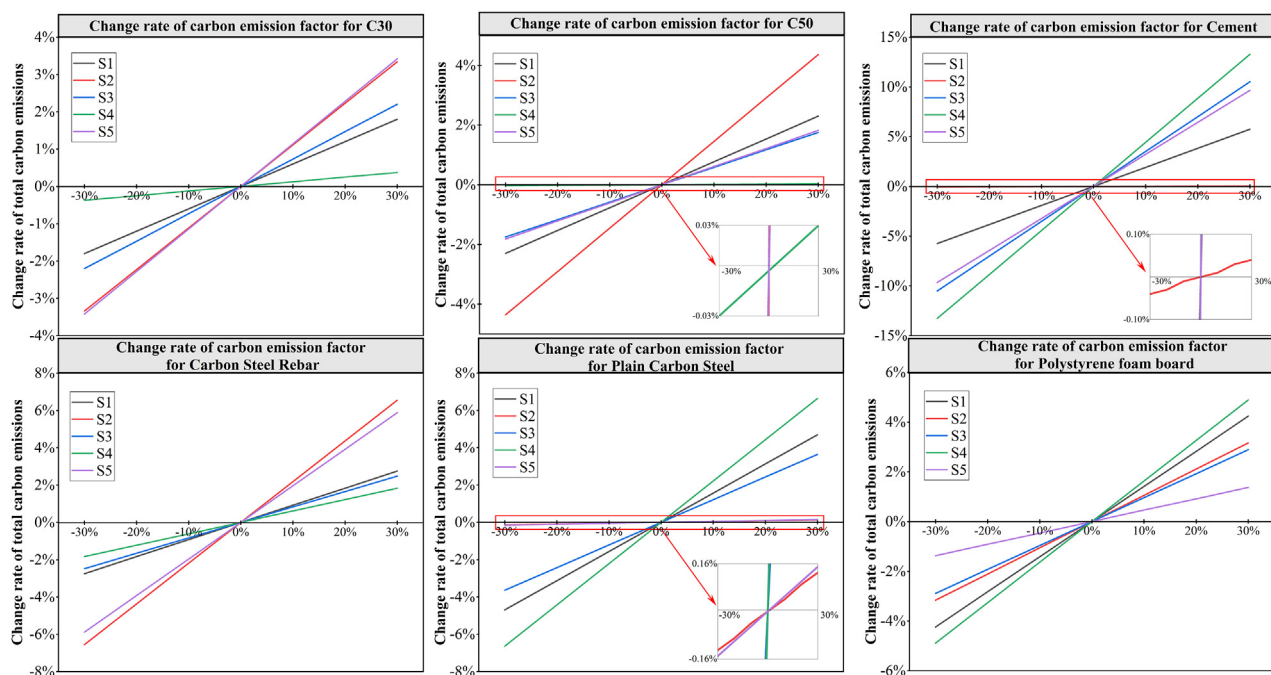


FIGURE 8
Sensitivity analysis of carbon emissions from key construction materials during the materialization stage.

adopting efficient construction techniques, utilizing low-carbon building materials, and optimizing in-tunnel energy management. Particular attention should be given to S5, which borders a 4A-level scenic area and faces stricter construction requirements. This is a significant factor contributing to its higher carbon emission levels (Grade C), making it a critical consideration for future carbon assessments. The low bridge-tunnel ratio in S1 provides an inherent advantage that contributed to its Grade B performance, reflecting lower demand for carbon-intensive materials such as cement and steel. However, its failure to achieve Grade A indicates substantial potential for improving management refinement. Although lower project complexity facilitates emission reduction, proactive management measures remain essential to achieve optimal performance. Additionally, bulk auxiliary materials such as polystyrene foam boards exhibiting a notable impact due to their extensive use in sections including S4 and S1 (e.g., for tunnel insulation and subgrade antifreeze), leading to significant contributions to the total carbon emission. This underscores that non-structural auxiliary materials cannot be overlooked when used at large scales. Most critically, the overall lag in the S5 performance highlights the inherent drawbacks of the industry's conventional high-carbon development model. Its multiple Class C ratings in the materialization stage stem directly from adherence to a cost-driven procurement model, which lacks carbon emission criteria in supplier selection and relies heavily on traditional carbon-intensive materials.

4.1.2 Transportation stage

According to Equation 2, the weight of materials transported, the transport distance, and the carbon emission intensity are the

three key controlling factors for carbon emissions in expressway construction material transport.

Given that the total material weight is a fixed requirement of the project design, two representative parameters were introduced (Table 8): the weighted average transport distance, defined as the average distance that materials are transported, weighted by the proportion of each material type; and comprehensive emission intensity, defined as the overall average carbon emissions produced per unit of material transported. This enables a quantitative assessment of the overall impact of transport distance and emission factors on carbon emissions. Six variation ranges (plus or minus 10%, plus or minus 20%, plus or minus 30%) were established to conduct quantitative analysis of carbon emissions during the transportation stage.

Figure 9 demonstrates that variations in transport distance and carbon emission intensity exert an identical linear effect on total carbon emissions. Notably, under the most extreme variations in S2 and S3, a 30% reduction in the weighted average transport distance would correspondingly decrease transportation stage carbon emissions by approximately 5,157.2 tCO₂e and 4,342.65 tCO₂e, respectively. Importantly, during the pre-construction stage, S4 (the construction site has the richest building materials around), and S5 conducted extensive surveys of the surrounding areas, identified a variety of local cement and sand-gravel suppliers, and utilized these local resources during the construction period. This strategy was effectively implemented during construction, significantly reducing the demand for long-distance material transport. Although this proportion is relatively small compared to the materialisation stage, it clearly demonstrates that measures such as optimising logistics, prioritising locally

TABLE 8 Representative parameter values for each section during the transportation stage.

Parameter name	Unit	S1	S2	S3	S4	S5
Comprehensive carbon emission intensity	kgCO ₂ e/(t·km)	0.136246	0.144595	0.148935	0.152545	0.136167
Weighted average transportation distance	km	40.31428	41.87469	50.04875	59.98043	16.33147

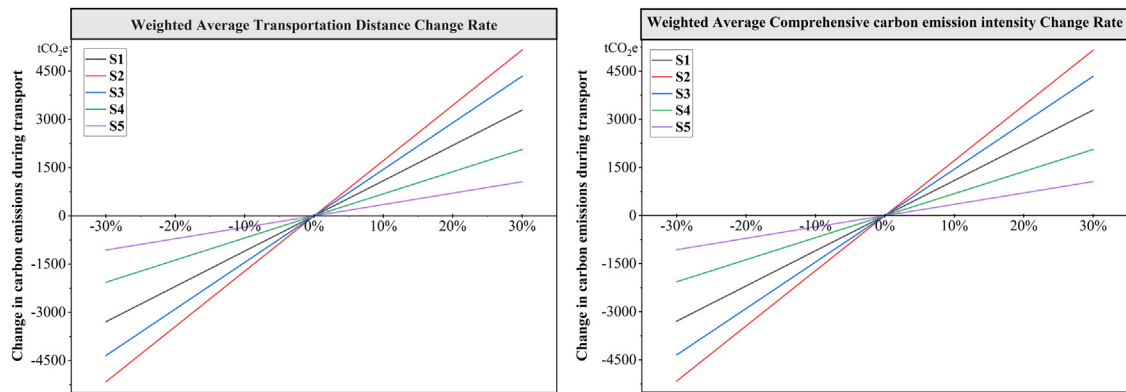


FIGURE 9 Sensitivity analysis of carbon emissions from key parameters during the transportation stage.

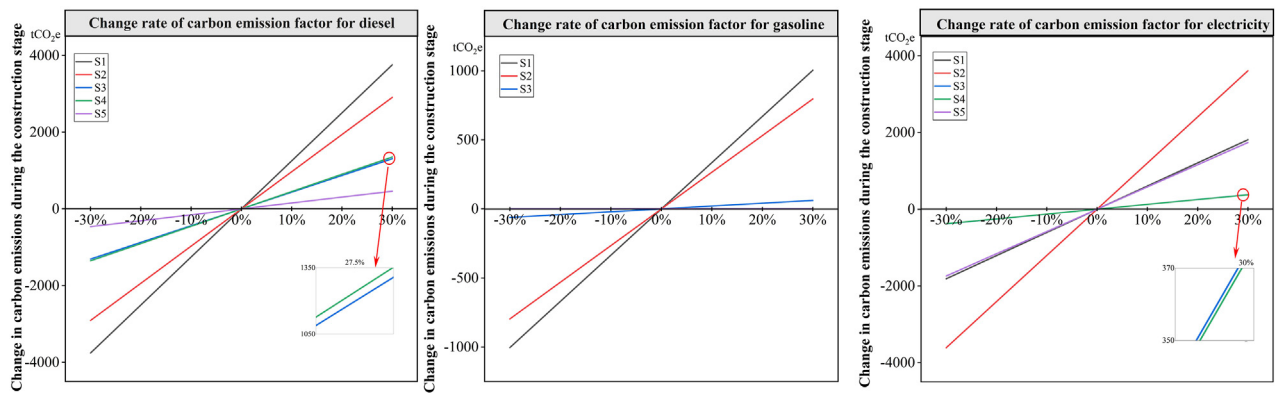


FIGURE 10 Sensitivity analysis of carbon emissions from key energy consumption during the construction stage.

sourced building materials, or establishing on-site aggregate processing stations/mixing plants can yield definite, quantifiable emission reductions. Similarly, with transport distances unchanged, reducing the comprehensive carbon emission factor by 10%–30% could decrease transportation stage carbon emissions by approximately 1,096.56 tCO₂e to 3,289.68 tCO₂e (S1). This demonstrates that upgrading to cleaner transport modes, such as switching to LNG lorries and hydrogen-fueled heavy-duty trucks, also holds significant emission reduction potential. This is particularly evident in regions with adverse geographical conditions (S2 and S3), where conventional mitigation strategies are often constrained. Such transitions not only overcome infrastructural and topographic limitations but also align

economic feasibility with environmental sustainability, thereby facilitating low-carbon transformation.

4.1.3 Construction stage

Sensitivity analysis of carbon emissions during the construction stage, as shown in Figure 10, indicates that diesel and electricity consumption are the primary driving factors, with S2 exhibiting the maximum potential variation of up to about 3,000 tCO₂e, and collectively these two factors constitute the majority of emissions in this stage. While gasoline consumption has a relatively limited impact, it remains non-negligible. Therefore, emission reduction strategies should prioritize efficiency improvements and clean energy alternatives for diesel-powered machinery, along with

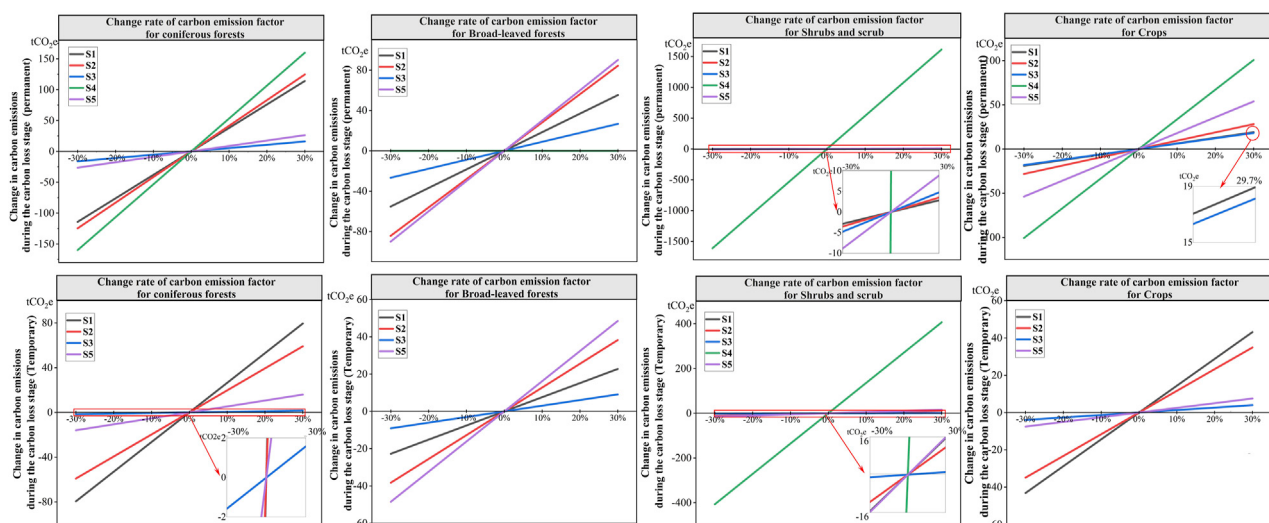


FIGURE 11
Sensitivity analysis of carbon emissions from different vegetation types during the carbon loss stage.

energy-saving measures for on-site electrical equipment and the integration of cleaner grid electricity; gasoline consumption management can be considered a secondary focus.

Specifically, S2 and S5 exhibit significant reliance on electricity. Investigations revealed the presence of gassy tunnels, particularly in S2, where high electricity consumption is likely associated with specialized requirements such as tunnel ventilation, explosion-proof lighting, and safety monitoring. This highlights the practical challenges of transitioning energy structures under specific engineering and safety constraints. In contrast, S3 and S4 are highly dependent on diesel, owing to the extensive use of diesel-heavy machinery in earthworks, transportation, and land grading, as well as the reliance on diesel generators in areas without grid access. Notably, although both S1 and S3 involve large earthwork volumes, S1 received a Grade C in diesel-related emissions, while S3 achieved a Grade A. This disparity primarily stems from differences in equipment efficiency and emission control management: S3 likely employed newer, low-emission machinery and implemented stricter operational protocols, whereas S1 relied on less efficient equipment with inadequate mitigation measures. Although project complexity and environmental requirements contribute to higher emissions, the absence of effective management measures remains one of the fundamental causes of their Grade C ratings. These two energy-use patterns demonstrate that without fundamental changes in energy structure and material selection, it remains difficult to break away from the high-carbon dilemma, whether the dependency is on diesel or carbon-intensive electricity.

4.1.4 Carbon loss stage

Figure 11 presents a sensitivity analysis of carbon emission factors across all five sections. The study systematically varied these factors to assess their impacts during both permanent and temporary carbon loss stages for different vegetation types. Additionally, the results revealed that the carbon emission response intensity during the permanent work was significantly stronger than that during the temporary work. Notably, shrub and

grassland vegetation in S4 exhibited the most pronounced sensitivity (with a variation of plus or minus 1,611.24 tCO₂e), far exceeding that of other vegetation types and sections. Both coniferous and broadleaf forests showed relatively high linear responses across all sections in the permanent work, whereas croplands demonstrated low or negligible sensitivity in most sections during the temporary work. Marked differences in sensitivity were observed among sections, with S4 being the most sensitive overall. Further analysis indicated that although the emission levels of S4 during materialization and construction stages were comparable to those of other high-carbon sections, it received a carbon rating of C in the carbon loss stage. Critically, carbon emissions from shrubs and scrub accounted for 59.99% of the total carbon emissions across all five sections. This may be primarily attributable to insufficient ecological baseline surveys and carbon sink assessments during the feasibility study and route selection stages, which led to the route passing through an area with exceptionally high shrub and scrub coverage. Consequently, extensive and irreversible carbon sink losses occurred. This case demonstrates that adhering to a conventional planning approach that prioritizes “engineering feasibility” over “ecological impact” may result in sharply rising hidden carbon costs, where carbon sink losses could even offset the emission reduction benefits achieved through energy-saving efforts.

4.2 Limitations and future prospects

It is important to note the inherent limitations of this work. First, the emission factors used in the carbon quantification model, although derived from authoritative sources, still involve certain uncertainties. Second, the research scope is limited to the construction projects and does not cover the full life-cycle stages, such as raw material production, transportation, road use, and maintenance, resulting in an incomplete evaluation system. What's more, although the five expressway sections investigated are representative to some extent, the limited sample size may affect

the generalizability of the weighting results. Additionally, inconsistencies in data quality across sections, with some data originating from engineering records and others estimated based on quotas, introduce substantial uncertainty and reduce the reliability of cross-section comparisons.

Future research should be enhanced in the following aspects:

- 1) expanding the system boundaries to include material production, transportation, and maintenance stages for constructing a comprehensive life-cycle carbon emission assessment model;
- 2) increasing sample size and geographic coverage to include projects from diverse regions and climatic conditions to improve the applicability and robustness of the model;
- 3) standardizing and digitalizing carbon emission monitoring at construction sites to ensure data authenticity, accuracy, and traceability;
- 4) integrating advanced technologies to develop dynamic carbon emission monitoring and intelligent evaluation platforms for real-time calculation and optimized regulation, such as artificial intelligence and big data;
- 5) establishing more scientific evaluation indicators, such as “carbon emission intensity per unit bridge-tunnel ratio,” to enable fairer assessment of projects with varying engineering complexities; and
- 6) enhancing carbon modeling of transportation processes by incorporating route optimization simulations to accurately quantify the impact of transport distance and energy consumption on emissions, thereby supporting more targeted emission reduction strategies.

5 Conclusion

Expressway construction involves high energy and material consumption, posing a significant environmental threat. To facilitate a holistic understanding of carbon emissions and scientifically guide the carbon reduction strategies during expressway construction, a systematic methodology for accounting and evaluation is proposed by adopting the Hemming proximity Degree theory and CRITIC method, combined with the 14th Five-Year Plan objectives. To demonstrate the applicability of the methodology, a case study was conducted on five sections during the construction period of expressways in Hunan Province, China.

The results reveal that S4 had the highest carbon emissions at 631,681.24 tCO₂e, while S5 had the lowest, accounting for 10.92% of the total emissions across the five sections. Moreover, the materialization stage was identified as the primary source of carbon emissions, accounting for over 90% of the total across all sections. Cement production contributed significantly, constituting 27.10% of the materialization-stage emissions, with S3 and S4 being the major contributors. Carbon steel reinforcement (notably in S2, reaching 89,746 tCO₂e) and plain carbon steel (S4 alone accounting for 47.89% of the materialization-stage emissions from the five sections) each contributed approximately 12% to this stage. In contrast to the dominant materialization stage, the transportation stage (2.18%) and construction stages (2.69%), while contributing a smaller share of emissions, introduce considerable uncertainty into the overall carbon accounting. Additionally, within the defined accounting boundary, the loss of carbon sinks resulting from vegetation clearance was incorporated. Although its proportional

contribution appears limited within the short-term scope, its long-term impact, particularly in S4, should not be overlooked and should be optimized during the preliminary design stage.

Another major contribution is the systematic integration of carbon emission intensity into the life-cycle assessment of expressway construction, alongside the proposal of a practical three-tier evaluation criterion (Grade A, B, and C) aligned with China’s “14th Five-Year Plan” emission reduction goals. The results indicate that S4 and S5 exhibited relatively severe carbon emission levels (Grade C), while S1, S2, and S3 demonstrated moderate emission levels. Currently, carbon emissions are highly concentrated in the following areas: the materialization stage of S5, S2, and S4, the transportation stage of S2 and S5, fossil fuel usage in S2 and S1, and the carbon loss stage in S4. It is recommended that the relevant sections systematically adopt low-carbon materials, optimize transportation schemes, promote clean energy, and increase vegetation compensation to achieve overall emission reduction. The carbon emission quantification model and comprehensive evaluation system built offer a systematic approach to assessing emission levels during expressway construction. The model is applicable in scenarios where complete carbon emission inventory data are available and can be adaptively adjusted to different contextual characteristics, demonstrating strong generalizability and extensibility. It also provides a transferable methodological framework for carbon emission assessment in similar engineering environments.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary Material](#), further inquiries can be directed to the corresponding author.

Author contributions

MX: Formal Analysis, Investigation, Project administration, Visualization, Writing – review and editing. YL: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review and editing, Writing – original draft. YW: Supervision, Writing – review and editing. TZ: Investigation, Project administration, Visualization, Writing – review and editing. JW: Data curation, Investigation, Writing – review and editing. LY: Data curation, Software, Writing – review and editing.

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Conflict of interest

Authors MX, YL, and TZ were employed by China Railway Chengdu Research Institute of Science and Technology Co., Ltd.

Author YW was employed by China Railway Research Institute Group Co., Ltd. Authors JW and LY were employed by China Railway Communications Investment Group Co., Ltd.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2025.1665509/full#supplementary-material>

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