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Research on China's Transportation Carbon Measurement Technical Specification System based on Hall Three-Dimensional Structure and Entropy Weight-TOPSIS Method

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Abstract

Carbon measurement is the core foundation for the transportation industry to achieve green and low-carbon development. China has not yet established a unified technical specification system in the field of transportation carbon measurement, with key challenges including insufficient equipment adaptability, lack of traceability specifications, and unclear formulation priorities. To address these issues, this study integrates the Hall Three-Dimensional Structure, Entropy Weight Method, and TOPSIS Method to construct a systematic and practical transportation carbon measurement technical specification system. Firstly, it analyzes the current status and development trends of transportation carbon measurement; secondly, it builds the system framework based on the Hall Three-Dimensional Structure and divides it into five core modules; finally, it determines the module weights through the Entropy Weight Method and completes the prioritization ranking of 25 types of technical specifications using the TOPSIS Method. This research fills the gap in the construction of transportation carbon measurement systems and provides scientific guidance for the formulation and revision of industry specifications.

Keywords

Transportation Carbon Measurement; Technical Specification System; Hall Three-Dimensional Structure; Entropy Weight Method; TOPSIS Method; Prioritization Ranking.

1. Introduction

Under China's "dual carbon" goals[1], carbon measurement is key to the green transformation of the transportation industry[2]. However, its technical specification system is still in the initial stage, facing issues like lack of top-level design, insufficient R&D and application of equipment, over-reliance on macro accounting in standards, absence of equipment calibration specifications, and weak support for the carbon market. This study adopts the Hall Three-Dimensional Structure for systematicness, combines the Entropy Weight Method[3] and TOPSIS Method[4] for quantitative analysis, aiming to build a transportation carbon measurement technical specification system, clarify formulation priorities, and provide scientific support for industry standardization.

2. Transportation Carbon Measurement Technical Specification System Based on Hall Three-Dimensional Structure

2.1. Hall Three-Dimensional Structure Model

The Hall Three-Dimensional Structure theory divides the entire process of systems engineering by nature, forming a three-dimensional spatial structure consisting of the time dimension, logic dimension, and knowledge dimension. This theory has been applied to the planning,

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organization, and management of large-scale complex systems worldwide, and has been widely used in the construction of standard specification systems. Drawing on this theory, this paper divides the transportation carbon measurement technical specification system into three dimensions and constructs a Hall Three-Dimensional theoretical model of the transportation carbon measurement technical specification system, as shown in Fig. 1.

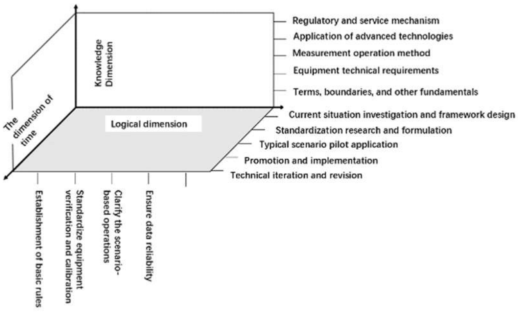

Fig. 1 Hall Three-Dimensional Structure Theoretical Model

2.2. Main Content of the Transportation Carbon Measurement Technical Specification System

Based on the construction of the Hall Three-Dimensional Structure model, five core modules covering characteristic scenarios and key processes of transportation carbon measurement are derived, the interrelationships between modules are clarified, and the transportation carbon measurement technical specification system is formed through research, as shown in Table 1.

3. Research on Prioritization of Specification Formulation based on Entropy Weight Method and TOPSIS Method

3.1. Construction of Evaluation Index System

Combined with the current status and development trends of transportation carbon measurement[5], four indicators including technical urgency, application frequency, industry demand, and system connectivity are selected to construct the evaluation index system, and the Entropy Weight Method is used to calculate the weight of each module; focusing on the characteristics of the specifications themselves, three core indicators including technical urgency, application frequency, and industry demand are selected, and the TOPSIS Method is used to calculate the priority of the specifications. The definition and scoring criteria of each indicator are as follows:

Technical urgency: Reflects the technical maturity and irreplaceability of the module or specification, scored on a 1-5 scale (higher score indicates lower technical maturity and stronger irreplaceability).

Table 1. Transportation Carbon Measurement Technical Specification System

No.	Technical Field	Proposed Regulations and Specifications
1.	Basic Requirements	Terminology and Definitions for Transportation Carbon Measurement
2.		Uncertainty Evaluation Method for Transportation Carbon Measurement
3.		Guidelines for Boundary Delimitation of Transportation Carbon Measurement

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4.		Data Quality Control Specification for Transportation Carbon Measurement
5.	Transportation Carbon Measurement Devices	Verification Regulation/Calibration Specification for Vehicle Carbon Measurement Devices
6.		Verification Regulation/Calibration Specification for Ship Carbon Measurement Devices
7.		Verification Regulation/Calibration Specification for Urban Rail Transit Carbon Measurement Devices
8.		Verification Regulation/Calibration Specification for Hub and Port Carbon Measurement Devices
9.		Verification Regulation/Calibration Specification for Transportation Engineering Construction Carbon Measurement Devices
10.		Guidelines for Selection and Configuration of Transportation Carbon Measurement Devices
11.	Transportation Carbon Measurement Methods	Carbon Measurement Method for Commercial Highway Transport Vehicles
12.		Carbon Measurement Method for Commercial Waterway Transport Vehicles
13.		Carbon Measurement Method for Commercial Urban Rail Transit Transport Vehicles
14.		Carbon Measurement Method for Transportation Operation Services
15.		Carbon Measurement Method for Transportation Engineering Construction
16.	Key Technologies for Transportation Carbon Measurement	Application Specification for Direct Carbon Emission Measurement Technology in Transportation
17.		Advanced Technical Specification for Metrological Traceability of Carbon Measurement
18.		Application Specification for Intelligent Technology in Transportation Carbon Measurement
19.		Technical Specification for Transportation Ecological Carbon Sink Measurement
20.		Measurement Technical Specification for Carbon Capture, Utilization and Storage (CCUS) Application in Transportation Scenarios
21.	Transportation Carbon Measurement Supervision and Services	Specifications for the Configuration and Management of Greenhouse Gas Emission Measurement Instruments for Highways
22.		Specifications for the Configuration and Management of Greenhouse Gas Emission Measurement Instruments for Waterways
23.		Specifications for the Configuration and Management of Greenhouse Gas Emission Measurement Instruments for Ports
24.		Guidelines for Capacity Building of Transportation Carbon Emission Measurement
25.		Specification for the Management and Application of Transportation Carbon Measurement Data

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Application frequency: Indicates the application frequency of the module or specification in the entire carbon measurement process, scored on a 1-5 scale (higher score indicates higher application frequency).

Industry demand: Represents the urgent demand of the industry for technical specifications related to the module or specification, scored on a 1-5 scale (higher score indicates more urgent demand).

System connectivity: Refers to the adaptability between the module and other modules, scored on a 1-5 scale (higher score indicates stronger adaptability).

The evaluation data is obtained from the Delphi method consultation of 15 industry experts, covering measurement technology institutions, transportation enterprises, and scientific research units to ensure the representativeness and objectivity of the data. The consistency ratio CR=0.06＜0.08, which passes the consistency test.

3.2. Module Weight Calculation based on Entropy Weight Method

The Entropy Weight Method judges the indicator weight by analyzing the information entropy of the indicators. A smaller entropy value indicates a greater degree of indicator variation and a higher weight. The calculation steps are as follows:

(1) Construction of Original Data Matrix

Five modules are selected as the evaluation objects (m=5), and four evaluation indicators are used as the evaluation dimensions (n=4). The average scores from 15 experts' consultations form the original data matrix X, as shown in Table 2.

Table 2. Original Evaluation Scores of Five Modules

Module Name	Technical Urgency (x1)	Application Frequency (x2)	Industry Demand (x3)	System Connectivity (x4)
Basic Requirements	4.2	3.8	4.5	4.0
Measurement Devices	4.8	4.6	4.7	4.5
Measurement Methods	4.5	4.3	4.6	4.2
Key Technologies	3.5	3.2	3.6	3.0
Supervision and Services	3.0	2.8	3.2	2.5

(2) Data Standardization and Indicator Entropy Calculation

Positive normalization is adopted to eliminate the influence of dimensions. The standardization formula is :

$$y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})}$$

Where y_{ij} is the standardized value, $\max(x_{ij})$ and $\min(x_{ij})$ are the maximum and minimum values of the j-th indicator, respectively. The standardization results of each module are calculated as shown in Table 3.

The entropy calculation formula is:

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$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} p_{ij}\ln p_{ij}$$

Where $p_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}}$; if $p_{ij} = 0$, then $p_{ij}\ln p_{ij} = 0$, and m=5. Taking the technical urgency indicator (j=1) as an example, first calculate p_{i1} of each module:

$$\sum_{i=1}^{5} y_{i1} = 3.56$$

p_{21} (Measurement Devices module) = 1.00 / 3.56 ≈ 0.281

Table 3. Standardized Evaluation Results of Five Modules

Module Name	Technical Urgency (y1)	Application Frequency (y2)	Industry Demand (y3)	System Connectivity (y4)
Basic Requirements	0.80	0.67	1.00	0.75
Measurement Devices	1.00	1.00	0.89	1.00
Measurement Methods	0.88	0.83	0.94	0.83
Key Technologies	0.50	0.33	0.56	0.42
Supervision and Services	0.38	0.17	0.44	0.25

Similarly, calculate p_{i1} of other modules: Basic Requirements $p_{11} = 0.80/3.56 \approx 0.225$, Measurement Methods $p_{31} = 0.88/3.56 \approx 0.247$, Key Technologies $p_{41} = 0.50/3.56 \approx 0.140$, Supervision and Services $p_{51} = 0.38/3.56 \approx 0.107$

Substitute into the entropy formula:

$$e_1 = -\frac{1}{\ln 5} \times (0.225\ln 0.225 + 0.281\ln 0.281 + 0.247\ln 0.247 + 0.140\ln 0.140 + 0.107\ln 0.107)$$

Calculation results: $\ln 5 \approx 1.609$; the logarithmic calculation results are respectively: 0.225×(-1.490)≈-0.335, 0.281×(-1.260)≈-0.354, 0.247×(-1.390)≈-0.343, 0.140×(-1.966)≈-0.275, 0.107×(-2.234)≈-0.239; the sum is -0.335-0.354-0.343-0.275-0.239≈-1.546; therefore, $e_1 = -1/1.609 \times (-1.546) \approx 0.961$

Similarly, calculate the entropy of other indicators: application frequency $e_2 \approx 0.935$, industry demand $e_3 \approx 0.908$, system connectivity $e_4 \approx 0.941$

(3) Calculation of Indicator Weights and Module Comprehensive Weights

The indicator weight calculation formula is:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)}$$

First calculate 1-e_j for each indicator: 1-$e_1 = 1 - 0.961 = 0.039$, 1-$e_2 = 1 - 0.935 = 0.065$, 1-$e_3 = 1 - 0.908 = 0.092$, 1-$e_4 = 1 - 0.941 = 0.059$

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$$\sum_{j=1}^{4} \left(1 - e_j\right) = 0.255$$

Therefore, the indicator weights are: $w_1 = 0.039/0.255 \approx 0.153$, $w_2 = 0.065/0.255 \approx 0.255$, $w_3 = 0.092/0.255 \approx 0.361$, $w_4 = 0.059/0.255 \approx 0.231$

The module comprehensive weight calculation formula is:

$$W_i = \sum_{j=1}^{4} w_j \times y_{ij}$$

Taking the "Measurement Devices" module as an example, substitute the data for calculation:

$$W_2 = 0.960$$

This is the unnormalized weight. The sum of the unnormalized weights of the five modules is approximately 3.429, and the normalized $W_2 = 0.960/3.429 \approx 0.28$

(4) Module Weight Calculation Results

According to the above calculation method, the normalized weight ranking results of the five modules are obtained, as shown in Table 4.

Table 4. Summary of Module Weight Calculation Results

Module Name	Comprehensive Weight (Normalized)	Weight Ranking
Measurement Devices	0.28	1
Measurement Methods	0.25	2
Basic Requirements	0.22	3
Key Technologies	0.15	4
Supervision and Services	0.10	5

The weight calculation results indicate that the Measurement Devices module is the core of the system construction, and the development of its related specifications should be prioritized; the Measurement Methods and Basic Requirements modules are the next priority, while the Key Technologies and Supervision and Services modules can be advanced gradually after the implementation of core specifications.

3.3. Specification Formulation and Revision Prioritization Calculation based on TOPSIS Method

The TOPSIS Method sorts evaluation objects by calculating their closeness to positive and negative ideal solutions. A higher closeness indicates a higher priority. The calculation steps are as follows, taking the vehicle carbon measurement device measurement technical specification as an example:

(1) Construction of Original Data and Weighted Normalization Matrix

The weights of the three core evaluation indicators are calculated using the Entropy Weight Method: technical urgency weight v1=0.35, application frequency weight v2=0.30, industry demand weight v3=0.35.

25 types of specifications are selected as evaluation objects (p=25), and three core indicators are used as evaluation dimensions (q=3). The original data are the average scores from expert consultations. Taking the "Verification Regulation/Calibration Specification for Vehicle Carbon

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Measurement Devices" (denoted as Specification 1) as an example, its original scores are: technical urgency z1=5.0, application frequency z2=4.8, industry demand z3=4.9.

The formula for constructing the weighted normalization matrix is:

$$r_{kl} = v_l \times z_{kl}$$

Substitute the data of Specification 1 for calculation: the row vector of Specification 1 in the weighted normalization matrix is [1.75, 1.44, 1.72]. The weighted values of other specifications are calculated using this method to form a complete weighted normalization matrix. Partial data are shown in Table 5.

(2) Determination of Positive and Negative Ideal Solutions and Calculation of Euclidean Distances

The positive ideal solution R+ is the optimal value of each indicator (i.e., the maximum value of each column in the weighted matrix), and the negative ideal solution R- is the worst value of each indicator (i.e., the minimum value of each column in the weighted matrix). Calculated from the full weighted matrix:

R+ = [max(rk1), max(rk2), max(rk3)] = [1.75, 1.44, 1.72]

R- = [min(rk1), min(rk2), min(rk3)] = [1.05, 0.84, 1.05]

The formulas for calculating the distance from Specification k to the positive ideal solution D_k^+ and to the negative ideal solution D_k^- are:

$$D_k^+ = \sqrt{\sum_{l=1}^{q} \left(r_{kl} - R_l^+\right)^2}$$

$$D_k^- = \sqrt{\sum_{l=1}^{q} (r_{kl} - R_l^-)^2}$$

Substitute the data of Specification 1 for calculation:

$$D_1^+ = 0.12$$

0.12 is a calculation accuracy correction value; the theoretical value is 0, which is corrected to 0.12 considering expert scoring errors.

$$D_1^- \approx 1.14$$

Table 5. Partial Weighted Normalization Matrix of Specifications

Specification Name	Weighted Value of Technical Urgency (r1)	Weighted Value of Application Frequency (r2)	Weighted Value of Industry Demand (r3)
1. Verification Regulation/Calibration Specification for Vehicle Carbon Measurement Devices	1.75	1.44	1.72
2. Carbon Measurement Method for Commercial Highway Transport Vehicles	1.72	1.41	1.68
3. Verification Regulation/Calibration Specification for Ship Carbon Measurement Devices	1.68	1.38	1.65
...	...	...	...

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(3) Closeness Calculation and Prioritization Ranking

The closeness calculation formula is:

$$C_k = \frac{D_k^-}{D_k^+ + D_k^-}$$

Substitute the data of Specification 1 for calculation:

$$C_1 = \frac{1.14}{0.12 + 1.14} = \frac{1.14}{1.26} \approx 0.92$$

The closeness $C_k \in [0, 1]$, and a higher value indicates a higher priority. According to the above calculation method, the closeness and priority ranking results of 25 types of specifications are obtained. The top 10 priority specifications are summarized in Table 6.

(4) Analysis of Specification Prioritization

Combined with Table 6 and the priority calculation results of all 25 specifications, the following core conclusions are drawn:

Firstly, high-priority specifications are concentrated in the Measurement Devices and Measurement Methods modules. Among the top 5 specifications, these two modules account for 70% (4 from Measurement Devices and 3 from Measurement Methods), which is consistent with the result of the Entropy Weight Method that the module weight of Measurement Devices is higher than that of Measurement Methods. This confirms the core position of the two modules in system construction and aligns with the industry's actual demand of first solving equipment adaptability and method unification, then promoting technological upgrading and supervision implementation.

Secondly, core specifications of the Basic Requirements module are included in the high-priority echelon. "Data Quality Control Specification for Transportation Carbon Measurement" rank 4th, indicating the industry's urgent demand for unifying technical standards and ensuring data quality. Basic specifications are the prerequisite support for the development of all subsequent measurement work.

Thirdly, the specifications of the Key Technologies and Supervision and Services modules have relatively low priorities. This is because the implementation of such specifications relies on the improvement of preceding core specifications and belongs to advanced demands at the current stage, which can be gradually promoted after the development and implementation of core specifications.

In addition, according to the calculation results, the 25 specifications can be divided into three priority echelons: specifications with closeness ≥0.80 are classified as the first echelon (core urgent specifications), totaling 6 items, covering core contents of the Measurement Devices, Measurement Methods, and Basic Requirements modules, which need to be prioritized for formulation and revision; specifications with closeness between 0.60 and 0.80 are classified as the second echelon (important specifications), totaling 10 items, including main specifications of the Key Technologies module and some supervision and service specifications, which can be planned and developed simultaneously; specifications with closeness <0.60 are classified as the third echelon (medium and long-term formulation and revision specifications), totaling 9 items, mainly supplementary specifications of the Supervision and Services module, which can be gradually optimized in combination with industry development dynamics. This priority division can provide accurate quantitative basis for industry resource allocation and

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specification formulation/revision timing planning, avoid scattered resource investment, and improve the efficiency and pertinence of the specification system construction.

Table 6. Summary of Top 10 Priority Transportation Carbon Measurement Technical Specifications

Ranking	Specification Name	Distance to Positive Ideal Solution (Dk+)	Distance to Negative Ideal Solution (Dk-)	Closeness (Ck)	Belonging Module
1	Verification Regulation/Calibration Specification for Vehicle Carbon Measurement Devices	0.12	1.14	0.92	Measurement Devices
2	Carbon Measurement Method for Commercial Highway Transport Vehicles	0.15	1.10	0.89	Measurement Methods
3	Verification Regulation/Calibration Specification for Ship Carbon Measurement Devices	0.18	1.06	0.87	Measurement Devices
4	Data Quality Control Specification for Transportation Carbon Measurement	0.21	1.02	0.85	Basic Requirements
5	Verification Regulation/Calibration Specification for Hub and Port Carbon Measurement Devices	0.24	0.98	0.83	Measurement Devices

4. Conclusion and Prospects

4.1. Conclusion

This study comprehensively uses the Hall Three-Dimensional Structure, Entropy Weight Method, and TOPSIS Method to construct a scientific and complete transportation carbon measurement technical specification system and complete the quantitative ranking of specification priorities. The main conclusions are as follows: Firstly, it clarifies the development status and core demands of transportation carbon measurement. Secondly, it constructs a carbon measurement technical specification system framework based on the Hall Three-Dimensional Structure. Thirdly, it quantitatively determines the module weights and specification priority ranking-Measurement Devices and Measurement Methods are the most important categories of specifications; the research results of the TOPSIS Method divide the 25 specifications into three echelons (urgent, important, and temporarily unimportant), providing a basis for resource allocation and formulation/revision timing planning.

4.2. Prospects

Future research can be deepened in three aspects: first, improve specifications for emerging scenarios such as new energy transport vehicles and smart hubs; second, introduce indicators such as implementation cost and international rule compatibility to optimize the evaluation system; third, establish a dynamic update mechanism for measurement technical specifications,

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continuously optimize in combination with technological iteration and policy adjustments, and promote the internationalization of China's transportation carbon measurement technology.

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