Measurement and Improvement Pathways of Low-Carbon Efficiency in the Transportation and Logistics Sector under China's Dual-Carbon Goals

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Abstract: Under China's advancing dual-carbon strategy, the transportation and logistics sector remains a major source of energy consumption and carbon emissions. Assessing its low-carbon efficiency is therefore essential for facilitating the sector's green transition and supporting sustainable regional development. Using panel data for the cities of Henan Province from 2014 to 2023, this study constructs an evaluation framework for low-carbon logistics efficiency that incorporates inputs, desirable outputs, and undesirable outputs. A super-efficiency slacks-based measure SE-SBM model and a DEA-Malmquist productivity index are employed to assess transportation and logistics efficiency from static and dynamic perspectives, respectively. Nevertheless, the sector's total factor productivity exhibited a modest and fluctuating upward trend over the study period. Technological change was the principal driver of productivity growth, while fluctuations in pure technical efficiency and scale efficiency constrained the overall improvement. Accordingly, this study proposes measures to optimize the transport structure, accelerate technology-enabled upgrading, promote regional coordination and place-based development, and strengthen the policy framework. These measures are intended to facilitate the high-quality and low-carbon transformation of Henan's transportation and logistics sector.

Keywords: Carbon Peaking and Carbon Neutrality Goals; Henan Province; Transportation and Logistics; Low-Carbon Efficiency Measurement

1. Introduction

Against the global backdrop of climate change mitigation and sustainable development, China has established the strategic goals of achieving carbon peaking and carbon neutrality. These goals have accelerated the systematic green transformation of the country's economic and social systems. As a major energy-consuming and carbon-emitting sector, transportation and logistics will have a direct bearing on the achievement of these national strategic goals. Accurately measuring its low-carbon efficiency, identifying the sources of efficiency variation, and developing feasible improvement pathways are therefore urgent practical tasks. Within the broader context of low-carbon transition and coordinated regional development, increasing attention has been devoted to the measurement, determinants, and spatial heterogeneity of logistics efficiency. The relevant literature can be broadly classified into three strands: efficiency measurement, influencing factors, and regional disparities. The first strand focuses on methodological approaches and predominantly applies nonparametric techniques, including data envelopment analysis DEA, three-stage DEA, SBM-DEA, super-efficiency SBM models, and DEA-Malmquist productivity indices [1-7].The second strand examines the determinants of logistics efficiency and identifies logistics infrastructure, informatization, government support, technological progress, foreign investment, economic development, and human capital as major explanatory factors [8-9].The third strand investigates regional heterogeneity in logistics eco-efficiency, with particular attention to the Yellow River Basin, the southeastern coastal region, the Beijing-Tianjin-Hebei region, and the Yangtze River Delta, and proposes region-specific improvement strategies [10-13].These studies have established a theoretical foundation and analytical framework for research on low-carbon logistics efficiency. They also provide a basis for further investigation of its spatiotemporal dynamics and underlying mechanisms. Building on this literature, the present study applies a super-efficiency SBM model to evaluate the static level and cross-city disparities of low-carbon logistics efficiency under multiple input and output factors. A DEA-Malmquist productivity index is further used to examine changes in low-carbon logistics efficiency across different periods and to identify the internal sources of efficiency improvement or deterioration. This integrated framework combines static cross-sectional assessment with dynamic intertemporal analysis. The study also extends the unit of analysis from regional and interprovincial logistics systems to the city level, thereby broadening the empirical scope for measuring low-carbon logistics efficiency and assessing the potential for carbon emissions reduction.

2. Research Design

2.1 Methods

2.1.1 Static Evaluation Model

The static evaluation model estimates the low-carbon efficiency of the logistics sector within a given period. The resulting efficiency score reflects the overall performance of the logistics system in terms of resource utilization and emissions performance during that period. By characterizing the relationship between the inputs and outputs of each decision-making unit (DMU), the model determines whether a DMU lies on the efficient frontier. Under conventional data envelopment analysis (DEA), a DMU with an efficiency score of 1 is considered to lie on the production frontier. onventional DEA and SBM models, however, assign the same score to all frontier-efficient DMUs and therefore cannot distinguish their relative performance. To address this limitation, Tone extended the SBM framework and developed the super-efficiency SBM (SE-SBM) model. By evaluating an efficient DMU relative to a reference set from which that DMU is excluded, the SE-SBM model permits efficiency scores above unity and enables the ranking of DEA-efficient units [14,15]. Assuming that the K th DMU is efficient, the SE-SBM model is specified as follows:

$$\delta^* = \min \frac{1+\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1-\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{rk}^g}-\sum_{p=1}^{s_2}\frac{s_p^b}{y_{pk}^b}\right)} \quad \text{s.t.} \begin{cases} \sum_{j=1,j\neq k}^{n}\lambda_j x_{ij} - s_i^- \le x_{ik} \, (i=1,2,\dots m) \\ \sum_{j=1,j\neq k}^{n}\lambda_j y_{rj}^g + s_r^g \ge y_{rk}^g \, (r=1,2,\dots s_1) \\ \sum_{j=1,j\neq k}^{n}\lambda_j y_{pj}^b + s_p^b \ge y_{pk}^b \, (p=1,2,\dots s_2) \\ \lambda_j \ge 0, s_j^- \ge 0, s_r^g \ge 0, s_p^b \ge 0 \end{cases} \tag{1}$$

Here: δ^* denotes the efficiency score, and the DMU is considered efficient when $\delta^* \geq 1$ .The parameter λ_j denotes the weight assigned to reference DMU , and n is the total number of DMUs. The variable x_{ik} denotes the i th input of DMU K, and m is the number of input indicators. The variable ; y_{rk}^g denotes the r th desirable output of DMU K, and s_1 is the number of desirable-output indicators. The variable y_{pk}^b denotes the p th undesirable output of DMU K, and s_2 is the number of undesirable-output indicators. Finally, s_i^- denotes the slack, or redundancy, in input i; S_r^g denotes the shortfall in desirable output r; and S_p^b denotes the redundancy in undesirable output p.

2.1.2 Dynamic Evaluation Model

To examine how the low-carbon efficiency of the transportation and logistics system evolves over time, this study combines the Malmquist productivity index with DEA to construct a DEA-Malmquist index model. The model captures dynamic changes in productivity and helps identify the patterns and trends underlying efficiency improvement. The Malmquist index measures the intertemporal change in total factor productivity (TFP). It can be decomposed into technological change (TC) and technical efficiency change (EC).TC captures shifts in the production frontier between periods and thus reflects the contribution of technological progress to productivity growth.EC measures changes in the relative efficiency of production units between two adjacent periods and is influenced by technology application, management, resource allocation, and other factors. To further identify the mechanisms underlying efficiency dynamics, EC can be decomposed into pure technical efficiency change (PC) and scale efficiency change (SC).

Calculation of the Malmquist index requires an input distance, Following the productivity analysis framework developed by Caves et al., input and output variables are incorporated into the DEA model to characterize dynamic changes in TFP [16]. Given the requirements of the present study, the Malmquist index is calculated using observations from periods t and t+1, where x denotes inputs and y denotes outputs. The index is expressed mathematically as follows:

$$M^{t,t+1}=\sqrt{\frac{D^{t}\left(x^{t+1},y^{t+1}\right)}{D^{t}\left(x^{t},y^{t}\right)}\cdot\frac{D^{t+1}\left(x^{t+1},y^{t+1}\right)}{D^{t+1}\left(x^{t},y^{t}\right)}} \quad (2)$$

In this expression, D denotes the relevant distance function evaluated with respect to the technology in period (t) or period (t+1).The Malmquist index can be decomposed into EC and TC as follows:

$$M^{t,t+1}=\frac{D^{t+1}\left(x^{t+1},y^{t+1}\right)}{D^{t}\left(x^{t},y^{t}\right)}\cdot\sqrt{\frac{D^{t}\left(x^{t+1},y^{t+1}\right)}{D^{t+1}\left(x^{t+1},y^{t+1}\right)}\cdot\frac{D^{t}\left(x^{t},y^{t}\right)}{D^{t+1}\left(x^{t},y^{t}\right)}} \quad (3)$$

$$EC=\frac{D^{t+1}\left(x^{t+1},y^{t+1}\right)}{D^{t}\left(x^{t},y^{t}\right)} \quad (4)$$

$$TC=\sqrt{\frac{D^{t}\left(x^{t+1},y^{t+1}\right)}{D^{t+1}\left(x^{t+1},y^{t+1}\right)}\cdot\frac{D^{t}\left(x^{t},y^{t}\right)}{D^{t+1}\left(x^{t},y^{t}\right)}} \quad (5)$$

After further decomposing EC, the Malmquist index can be expressed as follows:

$$M^{t,t+1}=EC\times TC=PC\times SC\times TC \quad (6)$$

A value of PC greater than 1 indicates an improvement in pure technical efficiency and reflects more effective application of science and technology under the corresponding production mode. A value of SC greater than 1 indicates an improvement in scale efficiency and an efficiency advantage associated with the corresponding input-output scale, thereby contributing to TFP growth. Conversely, a value of PC or SC below 1 indicates deterioration in the corresponding efficiency component and may contribute to a decline in TFP. The Malmquist index also indicates the direction of efficiency change over time. An index value greater than 1 indicates productivity improvement, a value equal to 1 indicates no material change, and a value below 1 indicates productivity deterioration.

2.2Indicator Selection and Data Sources

2.2.1 Indicator Selection

The construction of a low-carbon logistics efficiency evaluation system requires indicators grounded in an appropriate theoretical framework and established disciplinary practice. Following a systematic review of major domestic and international studies, this research adopts the three-dimensional framework of resource inputs, desirable outputs, and undesirable outputs. The frequency with which individual indicators have been used in previous studies is also considered. Accordingly, the number of employees in the logistics sector, fixed-asset investment in the logistics sector, and the mileage of graded highways are selected as input indicators. The value added of the logistics sector, freight volume, and freight turnover are selected as desirable-output indicators. Carbon dioxide emissions from the logistics sector are included as the undesirable-output indicator [8,17-29].The complete indicator system is reported in Table 1.

Table 1. Selection of Input-Output Indicator System

Indicator Type	name of index	Indicator Description	unit
	Number of employees in the logistics industry	Input of labor factors	thousands of people
Input Indicator	Fixed asset investment in the logistics industry	Input of capital factors	Billion yuan
	Total mileage of national highways	Input of material and other resources	kilometre
	Value added produced by the logistics industry	Reflecting the industry's achievements	Billion yuan
Expected Output Indicator	quantity of shipments	Represents the results of transportation activities.	tonnes
	turnover of freight traffic	A comprehensive reflection of transportation achievements	Billion-ton kilometers
Unexpected Output Indicator	Carbon dioxide emissions from the logistics industry	Representing environmental pollution	tonnes

(1) Input indicators. Input indicators refer to the resources that must be consumed or allocated to achieve specified output objectives and thus reflect the costs incurred in the production process. The number of employees in the logistics sector directly reflects the dependence of transportation and logistics activities on labor resources. Fixed-asset investment in the logistics sector indicates the sector’s capacity for technological upgrading and infrastructure renewal. The mileage of graded highways reflects the dominant role of road transportation in Henan Province’s freight structure and captures the most fundamental infrastructure

factor with the greatest influence on carbon emissions from transportation and logistics activities.(2) Desirable-output indicators. Desirable-output indicators refer to outcomes with positive value that are pursued during production or operation and represent the intended direction of efficiency improvement. The value added of the logistics sector measures its direct contribution to the national economy and reflects the actual value created by the sector. Freight volume directly indicates the carrying capacity of the regional logistics network and the efficiency of freight circulation and is an important measure of basic logistics service capacity. Freight turnover combines freight volume with transportation distance and serves as a comprehensive indicator of the freight transportation workload completed within a given period, thereby reflecting the overall scale and volume of transportation activities.

(3) Undesirable-output indicator. Undesirable-output indicators refer to adverse outcomes that are inevitably generated during production or operation and should be minimized. Carbon dioxide emissions from the logistics sector are incorporated into the evaluation system as an undesirable output. This indicator reflects the carbon emissions pressure imposed on the environment by logistics operations and represents the principal environmental cost of logistics activities.

2.2.2 Data Sources

This study uses panel data covering seven indicators for the cities of Henan Province from 2014 to 2023. Data on the number of employees in the logistics sector, total fixed-asset investment in the logistics sector, mileage of graded highways, value added of the logistics sector, freight volume, and freight turnover were primarily obtained from the Henan Statistical Yearbook, the China Energy Statistical Yearbook, and statistical yearbooks or bulletins issued by relevant local governments. Specifically, data for the transportation, storage, and postal services sector were extracted from these sources.

Carbon emissions data were obtained from the Emissions Database for Global Atmospheric Research (EDGAR). A geographically weighted allocation method was applied, together with a carbon-intensity correction coefficient of 1.3, to estimate and aggregate logistics-related carbon emissions within the administrative boundaries of each city. The resulting carbon dioxide emissions are reported in Table 2.During data collection, missing observations for certain years or cities were reasonably imputed using a combination of interpolation and moving-average methods to ensure the continuity and reliability of the dataset.

Table 2. CO2 emissions from the logistics industry in various cities of Henan Province, 2014 - 2023(Unit: ten thousand tons)

DMU	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Zheng zhou	710.9	667.8	663.8	663.5	680.2	764.8	738.4	739.5	717.6	728.5
Kaifeng	126.8	127.5	121.9	120.2	122.8	120.4	121.6	125.4	124.3	131.1
Luoyang	434.3	432.3	424.1	424.7	423.4	410.6	402.7	408.1	402.4	431.1
flatiron	420.1	396.7	392.6	392.1	390.7	391.9	389.5	407.6	395.9	402.1
Anyang	341.2	320.2	311.9	310.1	327.6	334.9	337.9	363.3	362.2	383.4
Hebi	96.8	131.7	128.2	130.8	135.9	134.7	133.2	144.7	133.7	137.8
Xinxiang	282.5	324.2	309.5	304.8	312.1	307.6	311.7	321.9	317.4	330.7
Jiaozuo	257.5	299.4	258.7	264.9	276.6	307.7	336.1	364.7	362.9	373.0
Pu Yang	88.2	88.1	86.5	84.5	124.1	122.5	124.3	129.2	127.6	132.6
Xuchang	186.8	178.4	177.4	177.6	131.9	181.5	182.3	191.1	185.9	191.6
Louhe	80.3	81.9	77.5	75.3	77.2	75.5	76.9	77.9	76.9	81.4
Sanmenxia	133.8	126.4	144.1	169.7	173.4	171.6	168.7	182.3	181.7	189.7
Nam Duong	500.8	485.6	489.2	480.9	488.5	491.8	534.3	572.3	545.4	558.7
Shangqiu	245.1	227.3	223.7	224.8	234.2	245.2	243.8	257.5	253.9	246.7
Xinyang	256.8	249.7	248.7	248.5	254.2	254.8	254.5	263.9	256.6	269.5
Zhoukou	95.2	96.0	96.1	106.7	131.5	133.8	135.1	155.7	151.8	158.5
Zhumadian	161.9	164.0	158.3	156.9	161.8	157.9	158.2	163.3	161.8	171.4
Jiyuan	237.3	222.1	220.5	220.3	227.0	229.8	230.6	241.0	234.1	239.9

3. Carbon Efficiency Analysis

3.1 Static Measurement of Low-Carbon Efficiency in Transportation and Logistics

Using the super-efficiency SBM framework, this study employs the SBM model implemented in MATLAB R2021b to measure the low-carbon logistics efficiency of 18 prefecture-level cities in Henan Province based on panel data from 2014 to 2023. The SBM results show that the number and distribution of decision-making units with an efficiency score of 1 fluctuate across cities and years. To further distinguish the relative performance of efficient cities, the cities with overall efficiency scores greater than 1 in 2023, the most recent year of the study period, are selected and ranked using the super-efficiency SBM model. The measurement results are presented in Table 3 and Figure 1.

Table 3. Analysis of Super-Efficiency SBM Measures in Selected Valid Cities of Henan Province in 2023

DMU	Comprehensive Technical Efficiency	pure technical efficiency	Scale Efficiency
Zheng zhou	1.14	1.28	0.89
Hebi	1.19	1.30	0.92
Jiaozuo	1.15	1.34	0.86
Pu Yang	1.06	1.07	0.99
Louhe	1.19	1.39	0.86
Shangqiu	1.18	1.21	0.97
Zhoukou	1.40	1.43	0.98
Jiyuan	1.08	1.65	0.66

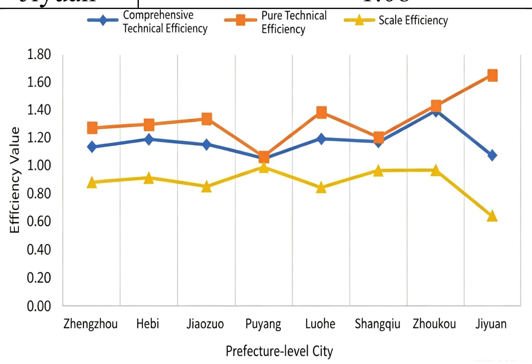

Figure 1. Analysis of Super-Efficiency SBM Measurements in Selected Valid Cities in Henan

As shown in Table 3 and Figure 1, cities with relatively high super-efficiency scores generally exhibit high technical efficiency but uneven scale efficiency, indicating that improvements in technological quality and operational efficiency have yet to be fully coordinated with the appropriate scale of operation. Zhoukou, for example, ranks among the leading cities in both overall technical efficiency and pure technical efficiency, demonstrating substantial advantages in logistics resource allocation and technology application. Although its scale efficiency remains below the optimal value of 1, it is still relatively high, indicating a strong capacity for low-carbon logistics operations. Puyang, Shangqiu, and Hebi achieve high overall and pure technical efficiency while maintaining scale efficiency above 0.90, suggesting a relatively high degree of coordination between technological performance and operational scale. Zhengzhou, Jiaozuo, and Luohe record scale-efficiency scores above 0.85, reflecting comparatively strong scale performance. However, their scores remain below the efficiency frontier, particularly in Zhengzhou, indicating further scope for optimizing intensive and low-carbon development. Jiyuan achieves the highest pure technical efficiency, demonstrating the most effective use of technology among the evaluated cities. Its relatively low scale efficiency, however, reveals considerable potential for improving scale allocation, as its technological advantages have yet to be fully translated into overall efficiency.

3.2 Dynamic Analysis of Low-Carbon Efficiency in Transportation and Logistics

3.2.1 Temporal Analysis

To better capture the evolutionary trend of low-carbon efficiency in Henan’s transportation and logistics industry over time, the Malmquist index model is adopted to analyze the changes in the province’s transportation and logistics efficiency from 2014 to 2023, with the results presented in Table 4.

Table 4. Total Factor Productivity and Its Components in Henan Province’s Transportation and Logistics Sector, 2014-2023

Period	EC	TC	PC	SC	TFP
2014-2015	0.96	1.11	0.95	1.01	1.07
2015-2016	1.09	0.93	1.08	1.01	1.01
2016-2017	1.00	1.06	1.00	1.01	1.06
2017-2018	1.02	1.03	0.99	1.02	1.04

2018-2019	1.02	1.10	1.05	0.98	1.12
2019-2020	1.03	1.03	1.03	0.99	1.06
2020-2021	0.94	1.06	0.97	0.97	0.99
2021-2022	1.00	1.09	0.97	1.03	1.09
2022-2023	0.96	1.05	0.95	1.01	1.00
Mean	1.00	1.05	1.00	1.00	1.05

As shown in Table 4, total factor productivity in Henan Province's logistics sector generally increased from 2014 to 2023, with an average Malmquist index of 1.05. This result indicates an average annual increase of approximately 5.0% in the overall efficiency of the provincial logistics system and reflects a substantial improvement in low-carbon efficiency over the study period. Among the components of the Malmquist index, the technical efficiency change index averaged 1.00, suggesting that changes in technical efficiency made only a limited contribution to total factor productivity growth. Its relatively small fluctuations indicate a slight positive contribution overall. By contrast, the technological change index averaged 1.05 and constituted the primary driver of total factor productivity growth. This finding suggests that Henan's logistics sector made positive progress in

technological innovation, equipment renewal, and process improvement, which played a critical role in enhancing sectoral efficiency. The pure technical efficiency change index averaged 1.00. Although management and organizational efficiency fluctuated in certain years and exerted a slight restraining effect on overall efficiency, its general performance remained favorable. The scale efficiency change index averaged 1.05, exceeding the benchmark value of 1.00, indicating that improvements in returns to scale contributed positively to efficiency growth. The expansion of operational scale and the optimization of resource allocation partly compensated for deficiencies in pure technical efficiency.

The annual trends indicate a generally favorable improvement in the low-carbon efficiency of Henan Province's transportation and logistics sector. Total factor productivity reached relatively high levels during 2017-2018 and 2021-2022, accompanied by marked increases in the technological change index. These twperiods may have coincided with concentrated policy stimulus, infrastructure development, or increased investment in informatization. In comparison, total factor productivity reached its lowest level during 2020-2021, indicating potential risks to productivity growth that impeded efficiency improvement. This decline may have been associated, to some extent, with the public health emergency during that period.

3.2.2 Spatial Analysis

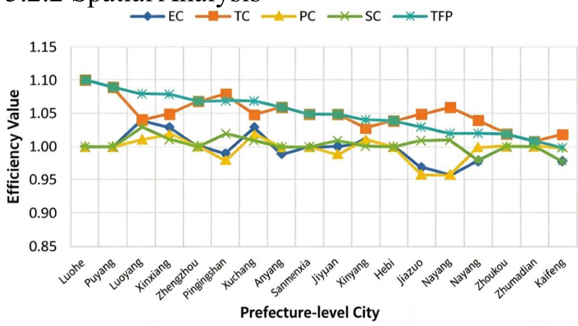

Figure 2. Trends in Total Factor Productivity and Its Composition across Cities in Henan Province, 2014-2023

Owing to differences in industrial structure, policy support, resource endowments, and other factors, the low-carbon efficiency of the logistics sector exhibits pronounced spatial heterogeneity across regions. To investigate regional disparities in efficiency within Henan Province and their possible causes, the average logistics efficiency levels of the 18 prefecture-level cities are compared horizontally based on the DEA-Malmquist model results, followed by an analysis of their spatial distribution characteristics. The estimated total factor productivity of each city in Henan Province from 2014 to 2023 is presented in Table 5, and the corresponding trends are illustrated in Figure 2.

Table 5. Total Factor Productivity and its Components across Cities in Henan Province, 2014-2023

DMU	EC	TC	PC	SC	TFP	sort
Louhe	1.00	1.10	1.00	1.00	1.10	1
Pu Yang	1.00	1.09	1.00	1.00	1.09	2
Luoyang	1.04	1.04	1.01	1.03	1.08	3

Xinxiang	1.03	1.05	1.02	1.01	1.08	4
Zheng zhou	1.00	1.07	1.00	1.00	1.07	5
flatiron	0.99	1.08	0.98	1.02	1.07	6
Xuchang	1.03	1.05	1.02	1.01	1.07	7
Anyang	0.99	1.06	1.00	1.00	1.06	8
Sanmenxia City	1.00	1.05	1.00	1.00	1.05	9
Jiyuan	1.00	1.05	0.99	1.01	1.05	10
Shangqiu	1.01	1.03	1.01	1.00	1.04	11
Xinyang	1.00	1.04	1.00	1.00	1.04	12
Hebi	0.97	1.05	0.96	1.01	1.03	13
Jiaozuo	0.96	1.06	0.96	1.01	1.02	14
Nam Duong	0.98	1.04	1.00	0.98	1.02	15
Zhoukou City	1.00	1.02	1.00	1.00	1.02	16
Zhumadian	1.00	1.01	1.00	1.00	1.01	17
Kaifeng	0.98	1.02	1.00	0.98	1.00	18

As shown in Table 5 and Figure 2, the total factor productivity values of all cities exceed 1, indicating that the transportation and logistics systems across Henan Province generally improved in efficiency during the study period and achieved positive progress in low-carbon transformation. Technological change is also greater than 1 in most cities, confirming its central role in driving efficiency improvement and highlighting the substantial contribution of technological renewal, equipment upgrading, and information technologies to the decarbonization of logistics systems. Nevertheless, the magnitude of efficiency growth varies across cities. Luohe, Puyang, Luoyang, and Xinxiang exhibit particularly strong improvements, with total factor productivity values ranking among the highest in the province. These cities generally possess a well-developed logistics foundation, a relatively high level of industrial agglomeration, or strong policy support, making them important regional pillars of low-carbon logistics development in Henan Province. By comparison, cities such as Kaifeng record relatively limited growth in technological change and weaker performance in scale efficiency or technical efficiency, indicating further scope for improving resource allocation and management practices.

Overall, the dynamic analysis reveals a clear improvement in the low-carbon efficiency of the logistics sector across Henan Province, although substantial regional disparities remain.

3.3 Analysis of Results

A systematic assessment of the carbon efficiency of Henan Province's transportation and logistics sector from both static and dynamic perspectives yields the following findings.

(1) The overall low-carbon efficiency of Henan Province's transportation and logistics sector remains relatively low. The static analysis indicates that overall technical efficiency is substantially constrained by pure technical efficiency, suggesting considerable room for improvement in logistics technologies, management capabilities, and informatization in some cities. Although certain cities exhibit relatively high scale efficiency, their technical efficiency has not improved correspondingly, preventing resource inputs from being effectively converted into environmentally desirable outputs.

(2) The efficiency of Henan Province's transportation and logistics sector generally increased from 2014 to 2023. The dynamic analysis shows an overall upward trend in low-carbon efficiency over the ten-year period. However, fluctuations and delayed effects associated with technological change resulted in moderate volatility and limited growth in the efficiency index. These findings indicate that the sector still lacks sufficient momentum for technological innovation and green transformation and also demonstrate the critical role of management and organizational capacity in improving low-carbon efficiency.

(3) Considerable differences in low-carbon logistics efficiency exist among cities. Core cities such as Zhengzhou and Luoyang benefit from the concentration of resources and policy support and have consistently ranked among the provincial leaders in efficiency. By contrast, Zhoukou, Sanmenxia, and several other cities have remained at relatively low efficiency levels because of weaker infrastructure and less

diversified industrial structures. Regional coordination therefore requires further improvement, together with stronger infrastructure connectivity and more effective integration of regional resources.

4. Strategies for Improving Carbon Efficiency in Transportation and Logistics

Based on the measurement and analysis of transportation and logistics carbon efficiency in Henan Province, improvement pathways are proposed from four perspectives: transport structure optimization, technology-enabled development, regional coordination, and policy and institutional support.

4.1 Pathway 1: Optimizing the Transport Structure and Advancing Green Transformation

Given the current overdependence of the logistics sector on road transportation and its relatively high carbon intensity, energy-intensive industries should be encouraged to prioritize lower-carbon transport modes, including railways, waterways, and multimodal transportation. Such measures would facilitate a greener and more intensive freight transport structure. Incentive policies, such as green freight subsidies and preferential access for low-carbon vehicles, should also be introduced to accelerate the transition from high-emission transport modes to cleaner alternatives and promote structural decarbonization throughout the sector.

The green logistics infrastructure system should be further improved through the wider adoption of new-energy equipment, including electric freight vehicles and hydrogen-powered trucks. Dedicated corridors for new-energy vehicles and green transport hubs should also be developed to systematically strengthen the low-carbon resilience and operational performance of the logistics network.

4.2 Pathway 2: Improving Efficiency through Technology-Enabled Development

The adoption of intelligent logistics equipment and systems should be accelerated, alongside the active development of intelligent transportation systems. Big data, the Internet of Things, and related technologies can be used to optimize road-network operations and reduce the carbon emissions associated with traffic congestion. Through the coordinated development of green infrastructure and technology-enabled services, a province-wide public service platform for smart logistics should be established to improve transportation and distribution efficiency, facilitate resource sharing, and enhance resource utilization.

4.3 Pathway 3: Strengthening Place-Based Development and Regional Coordination

A regional development mechanism characterized by core-city leadership and progressive diffusion should be established. In Henan Province, high-efficiency hub cities such as Zhengzhou and Luoyang should fully leverage their advantages in transportation connectivity, policy support, capital concentration, and innovation resources. Industrial-chain collaboration, regional logistics alliances, and shared information platforms can facilitate resource integration and complementary development, thereby improving the overall operational efficiency of the transportation and logistics system.

Differentiated development strategies should also be implemented according to local conditions. Zhoukou can capitalize on Zhoukou Port to attract leading enterprises, strengthen inland waterway transportation, and improve its multimodal transport network, thereby reducing energy consumption and enhancing system resilience. Puyang, Xinxiang, and similar cities should focus on the intelligent and digital transformation of logistics services and use technological upgrading to improve logistics operational efficiency.

4.4 Pathway 4: Strengthening Policy Institutions and Market Mechanisms

A dedicated plan for the green transformation of the transportation and logistics sector should be formulated, accompanied by a sectoral carbon emissions accounting system and supporting incentives. A cross-departmental coordination mechanism should also be established to integrate the responsibilities of transportation, energy, environmental protection, finance, and other relevant authorities. Enhanced information sharing and policy coordination would support a multi-stakeholder governance framework, strengthen collective carbon-reduction capacity, and systematically improve the low-carbon efficiency of the transportation and logistics sector.

5. Conclusions

Taking Henan Province's transportation and logistics sector as the research object, this study constructs a theoretically grounded evaluation indicator system and selects representative input and output variables to objectively reflect the sector's actual performance in resource utilization, output efficiency, and carbon emissions constraints. Efficiency evaluation models are then employed to systematically assess low-carbon efficiency from both static and dynamic perspectives. The results reveal that the overall level of low-carbon efficiency remains relatively low and that substantial disparities exist across cities. On the basis of these findings and the associated influencing factors, targeted recommendations are proposed to improve carbon efficiency in the transportation and logistics sector.

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