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CARBON UNLOCKING EFFICIENCY STUDY BASED ON SUPER-EFFICIENCY SBM-MALMQUIST

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Abstract. Carbon Neutrality goals and Sustainable Development Goals (SDGs), as new requirements for global development at this stage, have raised higher requirements for achieving the coordination of economic efficiency and ecological development of transportation infrastructure, especially highways. To promote the achievement of Carbon neutrality goals and SDGs, this research intends to study the effect of highways on the efficiency of carbon unlocking in each province. In this paper, we take China as an example, use the data of 18 listed highway companies and their provinces from 2010–2021 to conduct the study, measure the static carbon unlocking efficiency by using the super-efficiency SBM model with undesirable outputs, combine with the Malmquist index model for the decomposition of the efficiency and the dynamic analysis, and use the Tobit regression model to analyze the factors affecting the carbon unlocking efficiency. The results show that (1) From a static perspective, the carbon unlocking efficiency shows a steady upward trend, and the carbon unlocking efficiency has been in a state of low efficiency in general, with obvious regional differences. (2) From a dynamic perspective, carbon unlocking efficiency changes are relatively flat, and the carbon unlocking efficiency change index is in the rising stage, relying on technical efficiency can effectively improve the level of carbon unlocking efficiency. (3) The regional economic level, industrial structure, and urbanization level have a significant positive correlation with carbon unlocking efficiency, while the level of scientific and technological development and the level of opening up have a negative effect.

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1. Introduction

The 20th Congress of the Communist Party of China proposed that the active and steady promotion of carbon peaking and carbon neutrality requires the three-pronged efforts of a competent government, an effective market, and technological innovation. At the 75th session of the United Nations General Assembly, China formally proposed achieving carbon peaking by 2030 and carbon neutrality by 2060. One of the fundamental objectives of the dual carbon target setting is fundamentally changing China's high-carbon development model [1]. As the primary source of carbon emissions after energy, transportation is crucial in achieving dual carbon goals. As an essential part of the transportation industry, promoting the green and low-carbon development of transportation

Keywords. Carbon unlocking efficiency, highway, super-efficiency SBM-Malmquist model, Tobit regression.

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infrastructure is the basis for attaining low-carbon development in the transportation industry. The highway is limited by its long construction cycle, large investment scale, and high carbon emission characteristics. It leads to path dependence and incremental marginal benefits, making it locked in a high-carbon development mode. The construction and operation stage of the highway will bring about a large amount of carbon emissions while bringing about the sustained growth of the national economy. It will increase with the increase of transportation infrastructure. At the same time, with the continuous development of the future society, the demand for transportation infrastructure will also grow rapidly. The comprehensive benefits of highways need to coordinate the relationship between economic and environmental benefits, and the key to carbon unlocking efficiency is to maintain the increase in economic benefits of highways while reducing regional carbon emission intensity to get rid of the carbon lock-in effect.

Spanish scholar Unruh first proposed the concept of "carbon lock-in" [2]. He believes the high dependence on fossil energy has locked the industrial economy in a carbon-based technology system, hindering the development of low-carbon technologies. The increasing returns to scale generated by path dependence has promoted the synergistic evolution of carbon-based technologies and institutions, thus forming a "technology-institutional complex". In recent years, domestic and foreign scholars have carried out a series of studies on the driving mechanism, relevant theoretical connotation, causes, and carbon unlocking path of carbon lock-in "technology-institution" co-evolution. David argues that carbon lock-in is the result of path dependence in social change, and the current path dependence can be broken through institutional innovation [3]. Trencher argues that carbon lock-in refers to a rigid path-dependent process that relies on traditional fossil energy consumption and can be seen as a self-perpetuating inertia in utilizing energy and generating carbon emissions [4]. Karlsson R argues that the centralized system and the expansion effect of heavily polluting enterprises unique to developing countries eventually lead to technology lock-in and path dependence [5]. Regarding the causes of carbon lock-in, domestic and foreign scholars believe that carbon-based technologies are the direct cause of carbon lock-in. In contrast, the institutional system formed around carbon-based technologies in social production further strengthens the carbon lock-in situation. Thus, carbon lock-in results from the joint carbon-based technology-institutional system [6,7]. Li redefined carbon lock-in from the perspective of carbon-based technology corpora and pointed out the relationship between the evolution of carbon-based technology corpora, revealing the formation mechanism of carbon lock-in [8]. Driscoll studied the transportation industry and found that the leading causes of carbon lock-in in the large road transportation industry are path dependence and incremental payoffs of scale [9]. Zhu analyzed the causes of carbon lock-in from the perspectives of technology and institutions and argued that the formation of carbon lock-in has gone through three stages of dual evolution of technology, institutions, and technological institutions [10]. Seto identified three main types of carbon lock-in: technology lock-in, institutional lock-in, and behavioral lock-in, and described their evolutionary processes [11]. Wang evaluated the impact of carbon lock-in on China's manufacturing industry and believed that industrial structure and economic scale were the main reasons for regional carbon lock-in in the high-carbon manufacturing industry, and the lock-in intensity continued to increase [12]. Niu measured and analyzed the level of carbon lock-in effect in China by constructing a carbon lock-in effect measurement index system and found that the institution and technology constrain each other's influence, contributing to the formation and development of carbon lock-in [13,14].

On how to remove carbon lock-in, Urnuh believes that escaping carbon lock-in requires the intervention of external factors, and the government's formulation of relevant policies can directly or indirectly affect carbon lock-in [15]. The transformative policy concept of carbon unlocking is not a problem that can be solved by the traditional scientific agenda alone but requires cooperation between industries, policymakers, and other subjects [16,17]. Scholars such as Mattauch and Kakuhl have explored possible paths to carbon unlocking from a cost-benefit perspective, suggesting that policy subsidies and taxes are proposed to be beneficial to enhancing technological efficiency. The government can provide policy subsidies to enterprises that adopt low-carbon technologies to encourage popularizing low-carbon technologies [18,19]. Tang argued that technological innovation could curb carbon emissions while promoting economic development [20]. Xu argued that technological progress and institutional innovation could not only directly produce a certain degree of unlocking effect on the carbon lock-in situation in China but also indirectly produce a more significant unlocking effect through optimizing the industrial structure and improving energy consumption [21]. Zhang believes that the realization of a low-carbon economy must achieve carbon unlocking. There are two paths to achieve carbon unlocking, one is institutional change and technological innovation, and the other is a low-carbon shift in consumption preferences and patterns [22]. Xu explored the impact of the industrial transfer on carbon lock-in in China and found that technological progress has direct and indirect carbon unlocking effects. Energy structure, trade openness, and fiscal spending exacerbate the carbon lock-in dilemma [23]. By measuring the industrial carbon unlocking efficiency (ICUE) of 30 provinces in China, Li found that energy utilization rate, foreign direct investment, and industrial enterprise scale promoted the growth of ICUE. Energy structure had a negative impact on ICUE in each province [17]. Jin believes that the fossil-based dirty regime is ahead of the invention of the clean system. The dirty history has generated path dependence, making the economy locked in the existing dirty growth system, that is, carbon lock-in. Turning to a clean system can accelerate society to eliminate the carbon lock-in effect [24]. Zhao believes that innovative city construction can significantly improve carbon emission efficiency, which is conducive to enhancing carbon unlocking efficiency [25]. From the existing literature, the path to carbon unlocking is mainly technological progress and institutional innovation, and the corresponding economic measures can also indirectly remove carbon lock-in.

By combing the existing research results, the current carbon lock-in mainly focuses on the "technology-institution" double lock-in. However, the formation and evolution of carbon lock-in is an extremely complex process. Only considering the influence of technology and institution on carbon lock-in is too single to reflect the reality reasonably. In recent years, scholars have further explored the carbon unlocking path from the economic level and argued the relationship between the economic system and carbon unlocking. In order to achieve carbon unlocking of transportation infrastructure, in addition to technical and institutional factors, economic factors are also necessary. Economic carbon unlocking is essential for achieving medium and high carbon unlocking levels [26]. Chen selected indicators from the three aspects of transportation infrastructure technology, institution, and economy to construct a carbon lock-in coupling evaluation index system and explored the spatial correlation pattern of carbon lock-in in China's inter-provincial transportation infrastructure [27]. Liang argues that both central and local governments are the leading promoters of regional carbon unlocking, and regional carbon lock-in faces the influence of factors at the macro level, such as technology, institution, and economy [28]. By analyzing the entry measures taken by the UK, Japan, and the US in the past two decades, Hu found that government funds and financial innovation have made significant contributions to the country's carbon emission reduction [29]. The common practice of economic measures for carbon emission reduction is to combine low-carbon funds with low-carbon industries. Increasing financial support for low-carbon technologies and energy is the main factor in reducing the promotion of carbon emission reductions [30,31]. Government subsidy strategies based on the level of carbon emission reduction can effectively drive low-carbon enterprises to reduce carbon emissions further [32]. Based on fully considering the existing research, combined with the characteristics of transportation infrastructure, this paper attributes the formation mechanism of carbon lock-in to technology lock-in, institution lock-in, and economic lock-in. It is believed that in the process of carbon lock-in formation of transportation infrastructure, technology, institution, and economic factors depend on each other and restrict each other, forming a lock-in complex of technology-institution-economy.

In summary, the quantitative analysis of carbon lock-in and carbon unlocking has been based on a large number of studies at the domestic and international levels. Still, few scholars have focused on the carbon unlocking of transportation infrastructure. In this paper, referring to the concept of carbon unlocking efficiency proposed by Jijian Zhang, we believe that carbon lock-in is essentially a combination of "institutional, technological and economic" factors [33]. To explore the practical path to achieve carbon unlocking, it is necessary to analyze the efficiency of each element in promoting the carbon unlocking process. Therefore, this paper first uses the undesirable output super-efficiency SBM model to measure the carbon unlocking efficiency of the provinces where 18 high-speed public listed companies were located from 2010 to 2021. Secondly, the Malmquist model measures carbon unlocking efficiency's spatial and temporal dynamic changes. Finally, the Tobit regression model is used to analyze the factors affecting the efficiency of carbon unlocking.

This study measured the carbon unlocking efficiency in different provinces by constructing the evaluation index system of carbon unlocking efficiency. It analyzed the dynamic influence mechanism of the carbon unlocking efficiency as a whole. By analyzing the differences in carbon unlocking efficiency between different provinces and regions, this paper puts forward a carbon unlocking strategy suitable for the economic development status and infrastructure construction development level of different regions, which is helpful to promote the realization of China's dual carbon goal. The main contributions and innovations of this paper are as follows: (1) Previous studies on carbon lock-in and carbon unlocking have focused on the fields of industry and manufacturing. Most of the research in the field of transportation is also concerned with the means of transportation. This article is the first to study the impact of the construction and operation of highways by listed companies in the field of transportation infrastructure on the efficiency of carbon unlocking. By calculating the carbon unlocking efficiency in different provinces, this paper fully analyzes the differences and causes of the carbon unlocking efficiency in different regions and puts forward corresponding suggestions to provide a basis for improving the carbon unlocking efficiency. (2) This paper proposes measuring carbon unlocking efficiency using the super-efficiency slacks-based measure (Super-efficiency SBM) model based on the undesirable output under the assumption of variable returns to scale to overcome the shortcomings of the traditional data envelopment analysis model. At the same time, carbon emissions are included in the negative output as undesirable output indicators, which enhances the scientificity of the model results.

2. Methods and data

2.1. Carbon unlocking efficiency measurement model

2.1.1. Super-efficiency slack-based measurement model

Data envelopment analysis (DEA) was first proposed by Charnes as a management efficiency evaluation model defined for management efficiency [34]. At present, most scholars use DEA model to study the total factor productivity. DEA method and its model evaluate the relative effectiveness of comparable units of the same type according to multiple input indicators and multiple output indicators, which can be used to measure the efficiency of multi-input and multi-output. In the DEA method, Charnes Cooper Rhodes (CCR) and Banker Charnes Cooper (BCC) are the two most common models, which are commonly used to study multi-objective decision-making under multiple input-output. The disadvantage is that the relaxation of variables is not considered, which makes the obtained efficiency have some deviation. Traditional DEA models such as the CCR and BCC models measure efficiency values in both radial and angular terms without taking into account input and output slack. In order to compensate for the shortcomings of the traditional DEA model, Tone [35] proposed the SBM model based on undesirable output, using non-radial measures to solve the problem of ignoring input and output slack variables in the traditional DEA model. However, because the SBM model takes values between 0 and 1, the standard efficiency model is prone to the problem of simultaneous multiple decision-making units are efficient, resulting in the data on the frontier surface cannot be compared. Therefore Tone [36] proposed the super-efficient SBM model, which can make comparisons in efficient decision-making while dealing with undesirable outputs, effectively compensating for the shortcomings of the standard efficiency model. The significant advantage of the undesirable output super-efficiency SBM model is that it can decompose and sort the effective decision-making units while considering the undesirable output, thus improving the accuracy and practicability of the efficiency evaluation. The carbon unlocking efficiency referred to in this paper needs to take into account the non-desired outputs, *i.e.*, carbon emissions, pollution of the environment, in addition to the economic benefits of the desired outputs from the highway.

Therefore, in this paper, referring to the solution of the SBM model proposed by Tone, the super-efficiency SBM model for undesirable output is:

$$
\begin{aligned}
\min \rho = {} & \frac{1+\dfrac{1}{m}\sum_{i=1}^{m}\dfrac{s_i^-}{x_{ik}}}{\left(1-\dfrac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1}\dfrac{s_r^{g+}}{y_{rk}^g}+\sum_{r=1}^{q_2}\dfrac{s_r^{b-}}{y_{rk}^b}\right)\right)} \\
\text{s.t.} \quad & \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j - s_i^- \leq x_{ik}; \\
& \sum_{j=1,j\neq k}^{n} y_{rj}\lambda_j + s_r^{g+} \geq y_{rk}^g; \\
& \sum_{j=1,j\neq k}^{n} y_{tj}^b - s_t^{b-} \leq y_{tk}^g; \\
& 1-\frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1}\frac{s_r^g}{y_{rk}^g}+\sum_{r=1}^{q_2}\frac{s_r^b}{y_{rk}^b}\right) > 0 \\
& s^- > 0, s^b > 0, s^g > 0, \lambda > 0 \\
& i = 1,2,\ldots,m;\ r = 1,2,\ldots,q; \\
& j = 1,2,\ldots,n;\ j \neq k.
\end{aligned}
$$

In the formula, assume that there are n decision units, X_i and Y_i denote the input and output quantities of the DMU of the decision unit, respectively. Among the Q outputs, there are q_1 desired outputs y^g and q_2 non-desired outputs y^b. s^-, s^g, and s^b denote the slack of input elements, desired outputs and non-desired outputs, respectively. λ is the weight vector and the objective function ρ is with respect to s^-, s^b, s^g and has values between 0 and between 1. x_{ij} is the i-th input of the j-th DMU and y_{rj} is the r-th output of the j-th DMU. When ρ is greater than or equal to 1, it means that the decision unit is effective; when ρ is less than 1, it means that the decision unit is relatively ineffective and there is room for improvement of the input-output relationship.

2.1.2. Malmquist index model

Because the super-efficiency SBM model of undesired output cannot directly measure the dynamic change of carbon unlocking efficiency, it can only analyze the efficiency value of the decision-making unit from a static perspective. Therefore, in order to explore its dynamic change, it is necessary to introduce the Malmquist index model.

This paper analyzes the Malmquist index proposed by Fare [37]. Specific to the research of carbon unlocking efficiency, the Malmquist index is decomposed into two parts: technical efficiency (EFFCH) change and technical (TECHCH) change. The values of EFFCH change and TECHCH can be greater than 1, less than 1, or equal to 1, indicating that the efficiency has improved, decreased, or remained the same compared to the previous year. The calculation formula is as follows:

$$
\begin{aligned}
\text{TFPCH} &= M(x^{t+1}, y^{t+1}, x^t, y^t) \\
&= \left[\frac{D^t(x_{t+1}, y_{t+1})}{D^t(x_t, y_t)} \times \frac{D^{t+1}(x_{t+1}, y_{t+1})}{D^{t+1}(x_t, y_t)}\right]^{\frac{1}{2}} \\
&= \frac{D^{t+1}(x_{t+1}, y_{t+1})}{D^t(x_t, y_t)} \times \left[\frac{D^t(x_{t+1}, y_{t+1})}{D^{t+1}(x_{t+1}, y_{t+1})} \times \frac{D^t(x_t, y_t)}{D^{t+1}(x_t, y_t)}\right]^{\frac{1}{2}} \\
&= \text{EFFCH} \times \text{TECHCH} = \text{EFFCH} \times \text{PECH} \times \text{SECH}.
\end{aligned}
$$

In the formula, $D^t(x_t, y_t)$ is the t period technology level to represent the current period management efficiency level; $D^t(x_{t+1}, y_{t+1})$ is the t period technology level to represent the $t+1$ period management efficiency level;

$D^{t+1}(x_{t+1}, y_{t+1})$ is the t period technology level to represent the current period management efficiency level; $D^{t+1}(x_t, y_t)$ is the $t+1$ period technology level to represent the t period management efficiency level.

If TFPCH > 1, it means that the productivity management efficiency level is improved; when TFPCH < 1, it means that the productivity management efficiency level keeps decreasing. After decomposing TFPCH, we can get the EFFCH index and the TECHCH index. EFFCH responds to whether the existing technology is effectively used in the decision unit. If EFFCH > 1, it means that the level of technology has been better improved within this decision unit in two adjacent periods; TECHCH represents the impact of technological progress on production efficiency, and if TECHCH > 1, it means that technological innovation has been achieved, because EFFCH can be further decomposed into scale technical efficiency (SECH) and pure technical efficiency (PECH).

2.2. Tobit regression model

To comprehensively and deeply analyze the influencing factors and influence the degree of carbon unlocking efficiency, this study establishes a Tobit regression model with the influencing factors as independent variables and the efficiency value obtained by the DEA model as dependent variables. Considering that the explained variable is the efficiency value calculated by the DEA model, and it is between $[0, 1]$, which belongs to the truncated data, if the ordinary least squares method is used for regression, it may lead to the deviation of parameter estimation and inconsistency. Therefore, this paper chooses the Tobit model for regression analysis. The basic form of the Tobit model is as follows:

$$\begin{aligned} y^* &= \beta x_i + \mu_i \\ y_i^* &= y_i, y^* > 0; \\ y_i^* &= 0, y^* \leq 0. \end{aligned}$$

In the formula, y^* is the potential dependent variable. When the potential variable is less than or equal to 0, it is truncated at 0, and the explained variable is equal to 0. When the latent variable is greater than 0, the explained variable is equal to itself. y_i is the observed actual dependent variable, x_i is the independent variable, β is the correlation coefficient vector, μ_i is independent and $\mu \sim N(0, \sigma^2)$.

2.3. Index selection

The connotation of the carbon unlocking efficiency index is the pursuit of a balance between socioeconomic and ecological, and environmental benefits [33]. Not only the economic benefits generated during the construction and operation of the highway, *i.e.*, the desired output, need to be considered. It is also necessary to consider the undesirable outputs, *i.e.*, carbon emissions, generated during the construction and operation process.

The system of indicators of inputs and outputs needed to construct the carbon unlocking efficiency in this paper is listed in Table 1. Carbon lock-in is essentially a "technology-institution" double lock-in caused by the high dependence on fossil energy in the process of economic development in industrialized countries. There is an apparent input-output relationship between carbon locking in a country or a region [21]. The highway has the characteristics of high carbon emissions, large investment scale, a long construction period, and a great influence on the carbon emissions and carbon lock in the surrounding area after the completion of the construction. The existing "technology-institution" lock-in cannot fully reflect the formation process of carbon lock-in in transportation infrastructure [38]. Therefore, on the basis of the original technology and institution lock-in, this paper adds the economic impact of carbon unlocking. Based on the three perspectives of technology, institutions and economics, the indicators needed are considered to include inputs, expected outputs and undesirable outputs.

In terms of institutional inputs, low-carbon regulations are the number of low-carbon regulations introduced by provincial governments during the year. After the government introduces low-carbon regulations, various industries will also introduce corresponding industry-specific laws, regulations and norms. Although the norms of other industries do not directly constrain the highway industry, they will have spillover effects and will have an impact on the low-carbon atmosphere and low-carbon habits of the whole society, so that the highway industry and related enterprises are correspondingly affected. Therefore, we believe that only statistics of highway industry regulations are incomplete, and the role of low-carbon system is overall.

In terms of technology investment, select the R&D expenditure of industrial enterprises above the designated size in the region and the number of invention patents applied. Statistical enterprises mainly focus on high-tech material research and development, high-tech equipment manufacturing, high-tech and other related enterprises. These enterprises will invest in research on low-carbon technology and low-carbon materials, and the results generated by the above R&D investment will be applied in the stages of highway construction, construction, operation, and maintenance, thus having an impact on the carbon unlocking. Traditional highway companies are usually construction companies that invest less in R&D and usually purchase low-carbon technologies directly for use. The low-carbon technological innovation of highways and the overall technological development of industry have formed an inseparable whole, so this paper selects the industrial enterprises above the regional scale to carry out research on technological inputs.

In terms of economic inputs, low-carbon government spending is the government's investment in environmental pollution. The government's treatment of the environment is a comprehensive treatment, rarely targeting a specific industry or region for pollution control. The government's investment in pollution control reflects the willingness and importance of local governments to control the environment; Subsidies are a common tool used by the Chinese government to promote low-carbon production. Regarding low-carbon subsidies, we selected the leading domestic highway construction and operation companies, for which subsidies account for most of the industry. Therefore, we believe it reflects the level of government subsidies for highway companies.

As for expected output and undesirable output, the goal of carbon unlocking is to reduce carbon dioxide emissions as much as possible and improve emission reduction efficiency without affecting economic development, that is, how to reduce carbon emissions (undesirable output) while increasing Gross Domestic Product (expected output). Therefore, we select the Gross Domestic Product of each province in China as the desired output to reflect the impact of carbon unlocking on economic development; At the same time, due to the dynamic nature of transportation, the regional transportation system will dynamically share the pressure of transportation, the carbon emissions of highways are constrained by the local transportation system, and the reduction of carbon emissions from highways will have an overall impact on regional carbon emissions. If the carbon emissions of highways are controlled separately, it may lead to the transportation demand that should be borne by highways to be borne by national highways, railroads, etc., resulting in the overall carbon emissions of the society being raised while the carbon emissions of highways are lowered. So the regional carbon emission is chosen as the undesirable output.

The details are shown in Table 1. Descriptive statistics of input and output variables are shown in Table 2.

2.4. Data

This paper measures the carbon unlocking efficiency values with the provinces where the listed highway companies are located and takes 2010–2021 as the study period. In the process of data selection, highway-related data mainly come from listed companies of highways in each province, because the construction and operation of highways in each province in China are mostly in the hands of provincial state-owned enterprises. Therefore, by counting the data of provincial highway enterprises, it can well reflect the impact of highway construction and operation on the province's carbon unlocking and the province's low-carbon investment. The statistical data are obtained from the China Statistical Yearbook, China Energy Statistical Yearbook, financial annual reports of listed companies, and provincial statistics from the National Research Network and other relevant literature. In order to eliminate the effects of inflation, technology funding, government low-carbon spending, government low-carbon subsidies, and regional development level are adjusted to constant 2010-based prices. The regional carbon emissions data were calculated using the carbon emission factor method according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and with reference to Du [39].

In this paper, 18 listed highway companies are selected as research objects. In the process of selecting the sample data, national transportation infrastructure construction and construction investment enterprises such

TABLE 1. Carbon unlocking efficiency evaluation index system.

Indicators	Category	Specific indicator composition	Indicator interpretation
Input	Institutional inputs	Low-carbon regulations	Low-carbon regulations introduced by the government during the year (X_1)
	Technical inputs	Technical funding	R&D expenditure of industrial enterprises above regional scale (X_2)
		Technology patents	Number of invention patents applied by industrial enterprises above regional scale (X_3)
	Economic inputs	Government low-carbon spending	Government investment in pollution control (X_4)
		Government low-carbon subsidies	Enterprises receive government subsidies related to highways (X_5)
Output	Expected output indicator	Regional development level	Regional GDP per capita for the year (Y_1)
	Undesirable output Indicator	Carbon emission	Regional carbon emissions (Y_2)

TABLE 2. Descriptive statistics of input and output variables.

Indicators	Variable	Unit	Observations	Mean	Standard deviation	Min	Max
Input	X_1	Regulation	216	31.63	29.57	0	155
	X_2	10 000 yuan	216	5 320 656.39	5 489 488.27	355 405	21 878,151
	X_3	Patent	216	20 437.53	30 040.99	296	139 727
	X_4	10 000 yuan	216	1 580 601.90	1 024 483.33	86 580.64	5 902 756.29
	X_5	10 000 yuan	216	2281.73	6592.083	0	41 731.79
Output	Y_1	Yuan	216	48 749.23	18 921.20	20 219	103 306.99
	Y_2	Metric ton	216	458.08	329.319	121.98	2021.90

as China Railway Engineering Group Corporation and China Communications Construction Group Corporation were excluded. The selected enterprises are provincial transportation infrastructure-related enterprises invested and held by each province's State-owned Assets Supervision and Administration Commission. According to our data combing, most provinces have only one transportation infrastructure state-owned holding enterprise.

The main business of the selected listed companies is transportation infrastructure construction, investment, operation, and other related fields. The actual controllers of these companies are usually the Provincial State-owned Assets Supervision and Administration Commission (acting as the government investment function). The government's subsidies for transportation infrastructure are generally issued as subsidies to enterprises. At the same time, most of these enterprises are the benchmark enterprises of transportation infrastructure in the province. Their business behavior will cause similar enterprises in the province to learn and participate in the construction of transportation infrastructure there. Therefore, the attitude of enterprises towards low-carbon technology and carbon unlocking reflects the situation of provinces to a certain extent.

TABLE 3. Carbon unlocking efficiency of each province from 2010 to 2021.

Province	Company	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Guangdong	Guangdong Provincial Expressway Development Co., Ltd	0.224	0.243	0.227	0.250	0.249	0.253	0.275	0.277	0.261	0.262	0.238	0.241
Hunan	Hunan Investment Group Co., Ltd	0.174	0.198	0.198	0.239	0.261	0.275	0.277	0.268	0.260	0.274	0.285	0.315
Shanxi	Shanxi Road and Bridge Co., Ltd	0.193	0.221	0.224	0.235	0.230	0.234	0.214	0.214	0.254	0.256	0.262	0.346
Guangdong	Dongguan Development (Holdings) Co., Ltd	0.225	0.242	0.225	0.248	0.245	0.250	0.273	0.275	0.260	0.243	0.245	0.255
Hunan	Xiandai Investment Co., Ltd	0.174	0.183	0.205	0.235	0.259	0.273	0.276	0.261	0.245	0.273	0.283	0.306
Tianjin	China Merchants Expressway Network Technology Holdings Co., Ltd	0.863	0.935	1.001	1.008	1.010	1.026	1.015	1.053	1.057	0.648	0.819	1.005
Anhui	Anhui Expressway Co., Ltd	0.140	0.148	0.188	0.181	0.183	0.189	0.210	0.181	0.192	0.247	0.265	0.281
Henan	Henan Zhongyuan Expressway Co., Ltd	0.135	0.162	0.170	0.191	0.214	0.216	0.204	0.216	0.198	0.202	0.194	0.214
Fujian	Fujian Expressway Development Co., Ltd	0.366	0.404	0.416	0.460	0.484	0.496	0.531	0.550	0.555	0.655	0.583	0.603
Hubei	Hubei Chutian Expressway Co., Ltd	0.188	0.225	0.248	0.279	0.295	0.299	0.312	0.314	0.325	0.346	0.328	0.361
Chongqing	Chongqing Road and Bridge Co., Ltd	0.214	0.262	0.290	0.336	0.374	0.392	0.421	0.470	0.423	0.505	0.517	0.554
Jiangxi	Jiangxi Ganyue Expressway Co., Ltd	0.135	0.172	0.178	0.199	0.222	0.236	0.259	0.223	0.214	0.266	0.270	0.310
Shandong	Shandong Hi-speed Co., Ltd	0.239	0.260	0.255	0.252	0.252	0.246	0.233	0.248	0.234	0.233	0.194	0.217
Guangxi	Guangxi Wuzhou Communications Co., Ltd	0.129	0.177	0.189	0.216	0.229	0.253	0.248	0.247	0.268	0.261	0.274	0.289
Jiangsu	Jiangsu Expressway Co., Ltd	0.325	0.323	0.317	0.353	0.352	0.377	0.351	0.390	0.388	0.407	0.315	0.369
Guangdong	Shenzhen Expressway Co., Ltd	0.211	0.242	0.225	0.249	0.249	0.253	0.266	0.262	0.249	0.336	0.245	0.236
Sichuan	Sichuan Expressway Co., Ltd	0.130	0.166	0.188	0.202	0.218	0.224	0.232	0.220	0.222	0.254	0.240	0.267
Jilin	Jilin Expressway Co., Ltd	0.274	0.324	0.353	0.386	0.415	0.414	0.448	0.421	0.426	0.268	0.331	0.346
Eastern Region	–	0.350	0.379	0.381	0.403	0.406	0.415	0.420	0.437	0.429	0.398	0.377	0.418
Central Region	–	0.177	0.204	0.221	0.243	0.260	0.267	0.275	0.262	0.264	0.267	0.277	0.310
Western Region	–	0.157	0.202	0.222	0.251	0.273	0.290	0.300	0.312	0.304	0.340	0.344	0.370
Mean	–	0.243	0.274	0.285	0.308	0.320	0.329	0.337	0.339	0.336	0.330	0.327	0.362

3. Result and discussion

3.1. Static evaluation of carbon unlocking efficiency

Based on data from listed highway companies from 2010 to 2021, the analysis was conducted using the super-efficiency SBM model and Maxdea software. For comparison, the 18 highway-listed companies were divided into eastern, central, and western regions according to the regions they belonged to (based on the regions they belonged to in their provinces and cities, including 7 highway-listed companies in the east, 8 in the central region and three in the west). The regional differences and characteristics of carbon unlocking efficiency were comparatively analyzed (Tab. 3).

As a whole, the carbon unlocking efficiency has been on a steady upward trend from 2010 to 2021, but the increase is low, *i.e.*, from 0.243 in 2010 to 0.362 in 2021, and the carbon unlocking efficiency as a whole has gone up by 11.9%. Although the carbon unlocking efficiency has increased during these nine years, its value did not exceed 1, which indicates that the carbon unlocking is still inefficient. In terms of DEA effectiveness, only Tianjin reaches effective in 2021. The differences in efficiency values between regions show a tendency to widen and then narrow. In 2010, the highest efficiency value was 0.863 for Tianjin and the lowest efficiency value was 0.129 for Guangxi province, with a difference of 0.734. The highest efficiency value in 2018 was 1.057 for Tianjin and the lowest was 0.192 for Anhui province with a difference of 0.865 between them. By 2021 the highest efficiency value of 1.005 for Tianjin differed from the lowest efficiency value of 0.214 for Henan province. The variability between regions was gradually narrowing and stabilizing.

From the perspective of China's three major regions, there are pronounced regional differences in the carbon unlocking efficiency, and the overall trend of high carbon unlocking efficiency in the eastern region and low

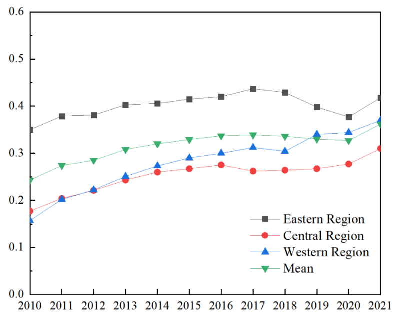

FIGURE 1. Carbon unlocking efficiency in three regions from 2010 to 2021.

carbon unlocking efficiency in the central and western regions. The change trend can be seen in Figure 1. From 2010 to 2021, the trend of carbon unlocking efficiency in the eastern, central, and western regions is different, which may be related to the level of economic development and related legal policies in each region. The carbon unlocking efficiency in the east shows a steady upward trend and is greater than the national average. It may be because the eastern region has a higher level of economic development, a higher degree of attention to low-carbon development, and a positive response to the national call to promote the low-carbon transformation of highways, so the corresponding carbon unlocking efficiency is higher. The carbon unlocking efficiency in the central region was slightly lower than the average during the study period. It may be due to the rapid economic development in the central region in recent years and the large proportion of the secondary industry, which aggravated the carbon lock-in dilemma in the region, resulting in higher carbon emissions. While the government carries out environmental supervision in these areas, it will lead to an increase in the cost burden of enterprises. In a short time, it can not consider the innovation and utilization of low-carbon green technologies for highways, so the corresponding carbon unlocking efficiency is low. Although the starting point of carbon unlocking efficiency in the western region is low, it has a good momentum of development. It may be that with the steady growth of China's Western development strategy, the economic development of the region has ushered in a significant acceleration, and the carbon emissions are high. The scale of highways in the western region is smaller than that in the eastern and central regions, and the difficulties in promoting the low-carbonization of highways are smaller. Hence, the carbon unlocking efficiency is higher than that in the central region. The value of carbon unlocking efficiency in the Eastern Region decreased from 0.437 in 2017 to 0.429 in 2018. This decline may be due to the rapid development of transportation infrastructure, resulting in a large amount of pollution and carbon emissions during the whole life cycle of highways. The average carbon unlocking efficiency increased from 0.327 in 2020 to 0.362 in 2021. This increase may be due to the government and enterprises actively promoting the low-carbon development of highways, which has improved the efficiency of carbon unlocking accordingly.

3.2. Dynamic evaluation of carbon unlocking efficiency

To further analyze which decomposition efficiency affects the carbon unlocking efficiency, the Malmquist index model is additionally introduced in this paper. Using Maxdea software to measure and analyze the Malmquist productivity index of each province and city from 2010 to 2021, the technical efficiency (EFFCH) and technical progress efficiency (TECHCH) are decomposed. Among them, the EFFCH is further decomposed into pure technical efficiency (PECH) and scale efficiency (SECH), from which the dynamic changes of carbon unlocking efficiency are obtained. The specific calculation results are shown in Table 4, and the total factor productivity (TFPCH) and the changing trend of its decomposition index are shown in Figure 2.

It can be seen from Table 4 that the average TFPCH index from 2010 to 2021 is 1.054. The total factor productivity of carbon unlocking efficiency increases by 5.4% per year on average. The TFPCH index has shown a growth trend since 2011, and the overall carbon unlocking efficiency change index is in an upward

TABLE 4. Total factor productivity and its decomposition of each province from 2010 to 2021.

Year	EFFCH	TECHCH	PECH	SECH	TFPCH
2010–2011	0.982	1.232	0.900	1.092	1.210
2011–2012	1.082	0.981	0.966	1.120	1.061
2012–2013	0.997	1.108	1.091	0.914	1.104
2013–2014	1.038	1.018	0.975	1.064	1.056
2014–2015	1.043	1.008	0.981	1.064	1.051
2015–2016	1.346	0.754	1.257	1.071	1.014
2016–2017	0.887	1.174	0.840	1.056	1.041
2017–2018	0.966	1.004	0.984	0.982	0.970
2018–2019	1.183	0.904	1.069	1.107	1.070
2019–2020	0.949	1.005	1.009	0.940	0.954
2020–2021	1.021	1.064	0.985	1.037	1.086
Mean	1.039	1.015	1.000	1.039	1.054

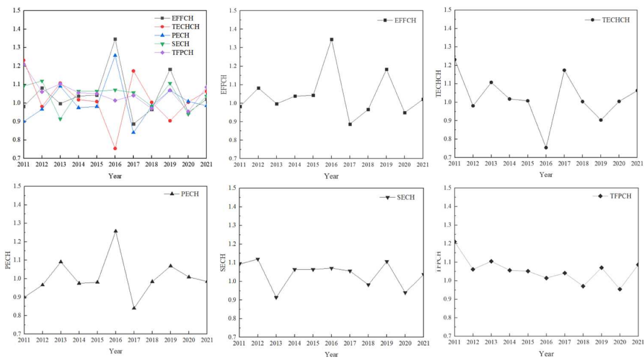

FIGURE 2. Trends in decomposition results of carbon unlocking efficiency.

stage. This indicates that since implementing the low-carbon development policy during the 12th Five-Year Plan period, provinces and cities have actively implemented relevant policies to promote the innovation and progress of carbon emission reduction technologies. The overall efficiency of the national carbon unlocking has been improved. The growth rate of TECHCH in 2010–2011, 2012–2013, 2016–2017, 2017–2018, 2019–2020, 2020–2021 is greater than that of EFFCH. In general, the increase of EFFCH is more significant than the increase of TECHCH, especially the increase of SECH is higher. In particular, the improvement in technical efficiency was greater from 2013 to 2016. From 2016, especially after 2019, the increase in TFPCH is mainly dependent on the improvement of TECHCH, which indicates that the low-carbon development of China's highways has been significantly improved over the past few years, and technological progress has increased. Although technical efficiency has increased, it has done so at a relatively slow pace. Overall there is a need to further enhance the management of low-carbon technologies and improve resource utilization.

Figure 2 shows the total factor productivity and its decomposition indicators show different fluctuations, with large fluctuations in the early period and stabilization after 2016, specifically, from 2010 to 2011 at a relatively high growth level, and from 2011 to 2012 when most indicators showed a significant decline and stabilized.

Table 4 shows the changes in total factor productivity and its decomposition index in the time dimension. The results of the carbon unlocking Malmquist index and its decomposition term measurement for specific companies and their provinces and three regions are shown in Table 5.

TABLE 5. Total factor productivity and its decomposition.

Province	Company	EFFCH	TECHCH	PECH	SECH	TFPCH
Guangdong	Guangdong Provincial Expressway Development Co., Ltd	1.027	1.013	1.031	0.996	1.040
Hunan	Hunan Investment Group Co., Ltd	1.030	1.030	0.970	1.061	1.060
Shanxi	Shanxi Road and Bridge Co., Ltd	1.040	1.039	1.000	1.040	1.080
Guangdong	Dongguan Development (Holdings) Co., Ltd	1.039	1.014	1.041	0.998	1.054
Hunan	Xiandai Investment Co., Ltd	1.019	1.016	0.945	1.078	1.035
Tianjin	China Merchants Expressway Network Technology Holdings Co., Ltd	1.000	1.015	1.000	1.000	1.015
Anhui	Anhui Expressway Co., Ltd	1.073	1.015	0.948	1.132	1.089
Henan	Henan Zhongyuan Expressway Co., Ltd	1.046	1.010	1.039	1.007	1.056
Fujian	Fujian Expressway Development Co., Ltd	1.065	0.994	1.000	1.065	1.058
Hubei	Hubei Chutian Expressway Co., Ltd	1.064	1.016	1.066	0.999	1.081
Chongqing	Chongqing Road and Bridge Co., Ltd	1.093	0.974	1.000	1.093	1.065
Jiangxi	Jiangxi Ganyue Expressway Co., Ltd	1.055	1.018	0.951	1.109	1.074
Shandong	Shandong Hi-speed Co., Ltd	0.975	1.041	1.022	0.954	1.015
Guangxi	Guangxi Wuzhou Communications Co., Ltd	1.070	1.014	1.000	1.070	1.084
Jiangsu	Jiangsu Expressway Co., Ltd	1.027	1.010	1.036	0.991	1.037
Guangdong	Shenzhen Expressway Co., Ltd	1.043	1.016	1.027	1.015	1.060
Sichuan	Sichuan Expressway Co., Ltd	1.015	1.031	0.937	1.082	1.046
Jilin	Jilin Expressway Co., Ltd	1.022	1.007	1.000	1.022	1.029
Eastern Region	–	1.025	1.015	1.022	1.003	1.040
Central Region	–	1.044	1.019	0.990	1.056	1.063
Western Region	–	1.059	1.006	0.979	1.082	1.065
Mean	–	1.039	1.015	1.000	1.039	1.054

As seen from Table 5, the TFPCH of the provinces where listed Chinese expressway companies are located has increased in most cases, with an average growth rate of 5.4%. The change of EFFCH is greater than that of TECHCH, especially the increase of scale SECH is 3.9%. This shows that the growth of EFFCH is the main factor in the growth of TFPCH. Under the joint action of PECH and SECH, the average annual growth rate of technical efficiency is 3.9%. In terms of technological progress, except for Shandong Province the average TECHCH index of the provinces where other highway listed companies are located is greater than 1, and the overall average technological level rises by 3.9%. It can be seen that with the continuous development of highway construction, the management level of enterprises has been synchronized to improve, and the innovation level of low-carbon technology is also improving, which effectively improves the efficiency of carbon unlocking in all provinces.

From the perspective of the three major regions, the efficiency index of carbon unlocking basically shows an increasing trend. The TFPCH in the western region increased by 6.5%, which was the highest growth area, followed by 6.3% in the center and 4.0% in the east. The growth rates in the central, eastern, and western regions were roughly the same. The growth of TFPCH in the three regions is due to the development of EFFCH brought by the rapid progress of the low-carbon management level. This improvement may be due to the fact that since the 12th Five-Year Plan, the Ministry of Transport has comprehensively promoted the construction of pilot demonstration projects for energy conservation and emission reduction environment, which has played a leading role in the green and low-carbon development of highways. The three regions actively implement low-carbon policies, enhance low-carbon innovation capabilities, and promote the efficiency of carbon unlocking.

In general, EFFCH is the main factor of TFPCH growth. Compared with the EFFCH index, the TECHCH index's growth rate is relatively slow. The fastest growth in EFFCH in the western region indicates that the strategy of developing the west has promoted the introduction of advanced technology, which has led to an

TABLE 6. Descriptive statistics of relevant variables.

Influencing factors	Variable code	Variable meaning	Mean	Standard deviation	Min	Max
Economic development level	RGDP	The logarithm of regional per capita GDP	10.88	0.42	11.828	9.914
Industrial structure	IND	The proportion of the output value of the secondary industry in regional GDP	0.459	0.054	0.59	0.321
Science and technology development level	TEC	The logarithm of the number of patent applications	10.056	1.298	12.739	6.996
Openness to the outside world	OPEN	The proportion of import and export trade volume of foreign-invested enterprises in regional GDP	0.157	0.176	0.713	0.011
Urbanization level	URB	The proportion of urban resident population in the total population	0.595	0.104	0.849	0.388

increase in the level of regional independent innovation, and technological upgrading relative to the central and eastern regions. In terms of SECH, the growth of SECH is greater than the growth of PECH in the central and western regions, especially in the western region, where the growth rate reaches 8.2%. It shows that these two regions should increase the innovation and investment of low-carbon technology and promote the low-carbon development of highways in various regions to improve the carbon unlocking efficiency.

4. Analysis of the influencing factors of carbon unlocking efficiency

From the above empirical results, it can be seen that there are differences in the efficiency of carbon unlocking. The difference is not only affected by input and output indicators but also driven by other factors. To comprehensively and deeply analyze the influencing factors and influence degree of carbon unlocking efficiency, this study takes the influencing factors as independent variables, takes the super efficiency of carbon unlocking as the dependent variable, establishes the Tobit regression model, and analyzes the influence of other factors on the efficiency of carbon unlocking.

4.1. Variable description and data sources

The explanatory variable Y_{it} is the value of carbon unlocking super-efficiency considering undesirable output, i and t represent the values of different regions in different periods. Referring to the previous literature research, the level of economic development, industrial structure, the level of scientific and technological development, degree of opening to the outside world, and urbanization level are selected as explanatory variables. The level of economic development (RGDP) was chosen to express the regional gross domestic product per capita; The industrial structure (IND) was selected to represent the share of secondary industry output in regional GDP; The level of scientific and technological development (TEC) was chosen to indicate the number of patent applications; The degree of openness to the outside world (OPEN) is selected to be expressed as the share of import and export trade in regional GDP; The urbanization level (URB) is chosen to be described as the proportion of the urban resident population to the total population. To ensure the accuracy of the regression results, GDP per capita and patent grants are treated in logarithmic terms.

All data are from China Statistical Yearbook, China Urban Statistical Yearbook, and China Industrial Statistical Yearbook. Individual missing data are filled in by mean interpolation.

TABLE 7. Tobit model regression results.

Variables	Coefficient	Standard deviation	Z value	P value
lnRGDP	0.338^{***}	0.046	7.33	<0.001
IND	0.589^{***}	0.136	4.336	<0.001
lnTEC	-0.09^{***}	0.008	−11.129	<0.001
FDI	-0.143^{**}	0.062	−2.296	0.022
URB	0.846^{***}	0.187	4.517	<0.001
Constant	-3.173^{***}	0.37	−8.564	<0.001

Notes. $^{**}p < 0.05$; $^{***}p < 0.01$.

4.2. Model construction and result analysis

Based on the above indicators, this paper constructs the Tobit regression model of carbon unlocking efficiency influencing factors as:

$$y_{it} = c + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \epsilon_{it}.$$

In the formula, y_{it} represents the carbon unlocking efficiency value of different regions in different periods; β_i is parameters to be estimated; ϵ_{it} is a random interference term.

In this paper, we use stata14.0 software to carry out Tobit regression analysis on the influencing factors of carbon unlocking efficiency from 2010 to 2021, and the regression results are shown in the Table 7.

Based on the regression results, the specific analysis is as follows:

(1) The correlation coefficient between the level of economic development and carbon unlocking efficiency is 0.338 and passes the test of significance at 1% level, which means that there is a significant positive correlation between the level of economic development and carbon unlocking efficiency. An increase in the level of economic development will bring about a large investment in technology and capital, bringing about the upgrading of industrial structure and effectively reducing carbon emissions. Regions with higher levels of economic development have better measures to reduce carbon emissions and invest more in environmental governance, resulting in higher levels of carbon unlocking efficiency. With the improvement of the economic development level, the construction and use of highways will lead to the transfer of high-carbon industries in surrounding cities. For some reason, enterprises originally developed in economically developed cities will choose to transfer industries with high carbon emissions to small and medium-sized cities, which will improve the carbon unlocking efficiency of developed cities.

(2) The correlation coefficient between industrial structure and carbon unlocking efficiency is 0.589 and passes the test of significance at 1% level, which means that there is a significant positive correlation between industrial structure and carbon unlocking efficiency. In recent years, China has adhered to the road of new industrialization, continuously optimized the industrial structure, improved energy efficiency, reduced the production and emission of pollutants, and further enhanced the efficiency of carbon unlocking. In addition, the change in industrial structure will impact the scale and mode of economic growth, and the scale and mode of economic growth directly affect the efficiency of carbon unlocking.

(3) The correlation coefficient between the level of technological development and carbon unlocking efficiency is −0.09 and passes the test of significance at 1% level, which means that there is a significant negative correlation between the level of technological development and carbon unlocking efficiency. In general, increased levels of technology favor the efficiency of carbon unlocking. The reason why the findings of this paper are different from the traditional meaning is that although enterprises have been developing low-carbon technologies in recent years, they are generally characterized by high investment, long payback periods, and low rates of return. Due to imperfect safeguard mechanisms, low-carbon technologies have yet to fully apply to highway construction.

(4) The correlation coefficient between the degree of openness to the outside world and carbon unlocking efficiency is −0.143 and passes the significance test at 5% level, which means that there is a significant negative correlation between the degree of openness to the outside world and carbon unlocking efficiency. The scale and structural effects of foreign investment, in general, can increase carbon emissions, but its technological effects can significantly reduce carbon emissions. However, the technical effects are currently more minor than the scale and structural effects. With the construction of expressways, the surrounding small and medium-sized cities have relatively backward development and low economic level. To improve the economic level, they will choose to accept high-carbon industries transferred from other cities, resulting in increased carbon emissions and reduced carbon unlocking efficiency.

(5) The correlation coefficient between the level of urbanization and carbon unlocking efficiency is 0.846 and passes the significance test at 1% level, which means that there is a significant positive correlation between the level of urbanization and carbon unlocking efficiency. The urbanization area is generally a leader in the comprehensive green, low-carbon transformation of the economy and society and the innovation and promotion of green, low-carbon technology. It is a crucial link in promoting carbon emission reduction and improving carbon emission efficiency. Therefore, the improvement of urbanization level is conducive to improving the efficiency of carbon unlocking.

5. Conclusion

The development of highways not only brings social and economic benefits to society but also brings severe pressure of environmental pollution accordingly. To realize the low-carbon transformation of highways and promote the development of low-carbon technology and low-carbon institution, it is also necessary to strengthen the government's attention to low-carbon and low-carbon subsidies to enterprises. Based on the panel data of highway listed companies from 2010 to 2021, this paper combines the unexpected output super-efficiency SBM model with the Malmquist index. With technology, institution, and economy as inputs, economic development level and carbon emissions as expected and undesirable outputs. Static and dynamic analysis of carbon unlocking efficiency in the provinces where 18 listed highway companies are located. Finally, the Tobit regression model is used to analyze the influencing factors of carbon unlocking efficiency. The following conclusions were reached:

From the static analysis of carbon unlocking efficiency, the overall carbon unlocking efficiency maintains an upward trend with a relatively small magnitude. However, the value does not exceed 1, which shows that the carbon unlocking efficiency is still low. Comparing the carbon unlocking efficiency of three major regions, we can find that the eastern is higher than the central and western regions, which indicates that the eastern is not only higher than the central and western regions in terms of economic development but also gives priority to the central and western regions in achieving carbon unlocking. The central region has experienced rapid economic development in recent years, but it has not taken into account the innovation and application of green and low-carbon technologies, so the efficiency of carbon unlocking is low. Although the starting point of the western region is low, the development momentum is good, and the carbon unlocking efficiency is relatively high.

From the dynamic analysis of carbon unlocking efficiency, the change in carbon unlocking efficiency is relatively flat, and most of the carbon unlocking efficiency indexes are greater than 1, indicating that the index of the change of carbon unlocking efficiency is in an upward stage, and relying on technical efficiency can effectively improve the level of carbon emission efficiency. The increase of EFFCH in each region is greater than the increase in TECHCH. Significantly, the rise of SECH is higher. The improvement of carbon unlocking efficiency mainly depends on the progress of TECHCH. From the viewpoint of time, both the carbon unlocking efficiency change index and its decomposition index show fluctuations in different situations. The fluctuations in the early period are relatively large and tend to be stable after 2016. From the overall viewpoint, EFFCH is the main driving force for the growth of carbon unlocking efficiency, and TECHCH grows more slowly compared with EFFCH. From the growth of SECH, the growth of SECH in the central and western regions is greater than the growth of PECH, which indicates that the region should increase the investment of enterprises and the government in low-carbon technologies to promote the low-carbon transformation of highways.

The regional economic level, industrial structure, and urbanization level are significantly positively correlated with the carbon unlocking efficiency. The level of scientific and technological development and opening to the outside world are significantly negatively correlated with the carbon unlocking efficiency.

Given the above analysis, the article proposes the following recommendations for improving carbon unlocking efficiency and highway low-carbon transformation:

(1) Actively promote low-carbon policies and improve relevant laws and regulations. The institution is the code of conduct of the economic and social system and an essential aspect of carbon unlocking lies in the institution's innovation. The government should vigorously promote the development and innovation of the low-carbon system, actively promote and improve the low-carbon tax policy, low-carbon industrial compensation policy, carbon trading allocation policy, etc.
(2) Enhance low-carbon innovation capabilities and encourage corporate technology sharing. Technological innovation and low-carbon technology instead is the critical factor in getting rid of carbon-based technology systems, which is the key to solve the carbon lock-in effect from the root. Low-carbon technology innovation includes carbon-free energy technology. Enterprises should increase low-carbon technology innovation, improve the utilization rate of resources, actively research and develop energy-saving and emission-reducing environmental protection technologies, and promote the use of low-carbon materials. Enterprises can also learn from each other, encourage them to cooperate in low-carbon technology R&D, and add low-carbon technology R&D cooperation and R&D results sharing among each other.
(3) Government low-carbon subsidies play an essential role in supporting enterprises' low-carbon practices. It is suggested that the government should strengthen low-carbon subsidies for enterprises that actively develop low-carbon. At the same time, take supporting measures such as optimizing intellectual property protection and improving the legal environment to maintain the benefits achieved by enterprises through low-carbon innovation. Enterprises should also increase their investment in low-carbon technology research and development accordingly.
(4) Strengthen regional cooperation between provinces and cities to promote high-efficiency carbon unlocking in a coordinated manner. At present, there are still large differences in the carbon unlocking efficiency among Chinese provinces and cities, especially the carbon unlocking efficiency in the central and western regions is low, and there is great room for improvement. Improve the bonus policy of introducing scientific research talents into the central and western regions, increase the frequency of technical exchanges between the eastern, central and western regions. Improve the internal management level of the central and western regions with the advantage of talents and technology in the east, so as to improve the carbon unlocking efficiency and promote low-carbon development of highways.

This article only collects and analyzes data from 18 listed highway companies and their provinces, excluding all provinces in China. Provincial level data is incomplete. Therefore, it may not accurately reflect the actual level of carbon unlocking efficiency. In the future, we can continue to collect relevant data on the highway industry in various provinces and cities, expand the data samples of research subjects, to accurately reflect the carbon unlocking efficiency of highways in each province, and ensure the accuracy of research. The formation of carbon lock-in is a complex process, and its influencing factors include not only technology, institutions, and economy, but also other factors that can be further analyzed.

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Data Availability Statement. The data used in this paper is available online in the figshare. Dataset. https://doi.org/10.6084/m9.figshare.24903588 [40].

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