Scenario-Driven Carbon Peak Pathways for Transportation in Sichuan Province, China: An Integrated LMDI-STIRPAT Framework

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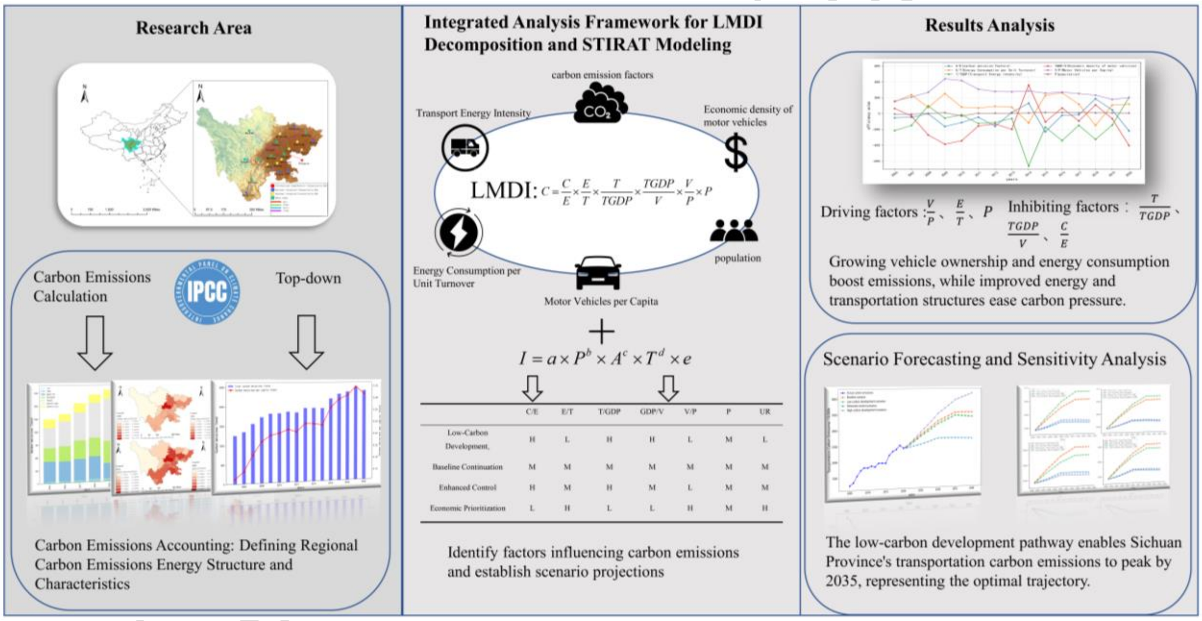
Graphical Abstract



	C/E	E/T	T/GDP	GDP/V	V/P	P	UR
Low-Carbon Development	H	L	H	H	L	M	L
Baseline Continuation	M	M	M	M	M	M	M
Enhanced Control	H	M	H	M	L	M	M
Economic Prioritization	L	H	L	L	H	M	H

Abstract

Transportation is a major contributor to carbon emissions, and achieving carbon peaking in this sector is essential for China's Dual Carbon goals. This study investigates transportation carbon emission dynamics and future pathways in Sichuan Province, a representative western inland region with complex geographical and transport characteristics. A top-down carbon accounting approach was applied to estimate emissions during 2005–2020, while LMDI decomposition and an extended STIRPAT-based scenario framework were employed to analyze historical emission contributions and future trajectories under four scenarios. The results show that transportation carbon emissions increased from 12.47 million tons in 2005 to 24.02 million tons in 2020, with emission growth mainly associated with vehicle expansion and energy consumption, while improvements in energy structure and transport efficiency partially offset this trend. Scenario analysis shows that emissions peak around 2035 under both the Low-Carbon Development and Enhanced Control scenario, with the Low-Carbon Development scenario achieving a substantially lower peak level and stronger mitigation effect compared with other scenarios. The findings highlight the importance of region-specific strategies, including transport electrification, green urbanization, cleaner energy substitution, and low-carbon logistics development, for supporting transportation decarbonization in Sichuan and similar western inland regions.

Keywords: Carbon emission; LMDI; Carbon neutrality Pathways; Scenario Analysis; STIRPAT model; Transportation;

1 Introduction

On September 22, 2020, China officially announced its "Dual Carbon" goals, which aim to achieve carbon peaking by 2030 and carbon neutrality by 2060 (Y. Wang et al. 2021). Within this context, the transportation sector has emerged as an increasingly significant source of carbon emissions due to its high energy consumption, substantial reliance on fossil fuels, and close association with economic development and mobility demand. From 2005 to 2020, carbon emissions from China's transportation sector increased by 683 million tons, reaching 1,023 million tons (L. Li et al. 2024). As China continues to advance green and low-carbon development, mitigating transportation-related carbon emissions has become a critical component of national climate governance and regional sustainable development. In Sichuan Province, policy support for green transformation has also been strengthened in recent years. For instance, the provincial government has promoted the circular economy and further enhanced emission-reduction efforts in the transportation sector (People's Government of Sichuan Province 2016).

Existing studies have provided valuable insights into the decomposition of transport carbon emissions and scenario-based projections. However, transportation carbon emission dynamics can vary considerably across regions due to differences in economic development levels, urbanization patterns, transport structures, and geographical conditions (N. Wang et al. 2022). Compared with eastern coastal provinces and major metropolitan areas, western inland regions often encounter greater challenges arising from complex terrain, uneven infrastructure development, and rapidly increasing transport demand. In this context, Sichuan Province, as one of China's major western provinces, has been designated as a "national strategic hinterland" by the (State Council 2024) , while also facing the dual challenges of transport expansion and low-carbon transition. Therefore, Sichuan provides a representative case for examining how regional development characteristics and policy interventions shape transportation carbon emission trajectories.

To answer these questions, this study applies a complementary analytical framework combining carbon accounting, LMDI decomposition, and an extended STIRPAT-based scenario approach to investigate transportation carbon emission dynamics in Sichuan Province. LMDI is used to identify historical emission contributions, while the extended STIRPAT model is applied to construct future emission scenarios. This study applies these approaches to a western inland province with distinctive transport and development characteristics. By considering Sichuan's transport conditions, urbanization characteristics, and energy transition potential, this study provides insights into regional carbon-peaking pathways and differentiated decarbonization strategies.

2 Literature review

2.1 Breakdown of the factors that cause carbon emissions

Research on transportation carbon emissions has primarily focused on two aspects: identifying historical driving factors and projecting future emission trajectories. Decomposition methods have been widely adopted because they enable the quantification and separation of individual factors' contributions to changes in emissions. Among these methods, the Logarithmic Mean Divisia Index (LMDI) has become one of the most widely used approaches due to its residual-free decomposition property and strong interpretability. (Ang 2005) established the methodological foundation for the practical application of the LMDI method, and subsequent studies have extensively applied it to carbon emission analysis across multiple sectors. In the transport sector, (Guan et al. 2025) applied the LMDI model to investigate the impacts of energy intensity, population size, transport structure, and carbon emission intensity on carbon emissions in the Yangtze River Economic Belt. (Y. Li et al. 2019) employed provincial-level data from China and further demonstrated significant heterogeneity in carbon emissions across provinces, indicating that national-level analyses may overlook substantial regional differences. Furthermore, without considering spatial variations, it remains difficult to fully understand the structural and socio-economic determinants of transportation carbon emissions in China (Feng et al. 2020).

However, compared with regression-based or machine learning approaches, the LMDI method is more suitable for identifying the historical contributions of individual driving factors but has limited capability in directly simulating future policy scenarios (Zhao et al. 2017). Although LMDI performs well in attribution analysis, its forward-looking application generally requires integration with additional forecasting frameworks. This methodological distinction is important because existing studies can generally be classified into two categories: those focusing on historical emission decomposition and those emphasizing future forecasting accuracy or scenario simulation. Therefore, when the research objective is to explain the evolution of transport-related carbon emissions and identify the key factors driving these changes, LMDI remains an appropriate and effective analytical tool.

2.2 Research on Carbon Emissions Projections and Scenario Analysis

Regarding carbon emission forecasting, existing studies have employed various methods, including time series models, grey forecasting models, machine learning algorithms, and scenario analysis based on the STIRPAT framework. Time series models and grey forecasting models are particularly effective when the objective is to infer future emission trends based on historical observations (Q. Li et al. 2023; Yuhong Zhao et al. 2023). In highly nonlinear contexts, machine learning models can improve predictive performance (Ye et al. 2024). However, these approaches often provide limited insights into the specific roles of socioeconomic and technological driving factors. By contrast, the STIRPAT framework, originally proposed by (York et al. 2003), extends the IPAT identity into an empirically estimable stochastic model and enables the flexible incorporation of population, affluence, technology, and other explanatory variables into empirical analyses. Therefore, STIRPAT is particularly suitable for studies that aim not only to project future emissions but also to associate projected outcomes with policy-relevant driving factors.

Existing studies indicate that STIRPAT-based methods are of practical value in regional carbon emission research in China. (S. Wang et al. 2019) combined an extended STIRPAT model with ridge regression and scenario analysis to examine Guangdong Province, demonstrating that scenario modeling is effective for assessing emission reduction potential in rapidly developing regions. At a broader systemic level, (L. Wang et al. 2021) proposed a hybrid STIRPAT–system dynamics framework for investigating transport decarbonization pathways in China, emphasizing the importance of transport structure and technological optimization. At the urban level, (L. Yang et al. 2020) analyzed urban transport carbon dioxide emissions under different policy and technological scenarios, showing that transport policies, land-use patterns, and public transport conditions jointly influence emission levels. Zhu et al. (2024) and (Yu Zhao et al. 2023) also employed combinations of STIRPAT and scenario analysis to explore carbon peaking pathways in China's transport sector and Liaoning Province's construction industry, respectively. These studies demonstrate that STIRPAT-based models are particularly suitable when the research objective is to link future emission pathways with interpretable structural, technological, and policy-related variables, rather than relying solely on black-box prediction models.

Overall, previous studies have demonstrated the effectiveness of LMDI decomposition and STIRPAT-based scenario analysis in carbon emission research. However, existing research has mainly applied these approaches to national-scale assessments, eastern provinces, or highly urbanized regions, while their applicability in structurally heterogeneous regions remains insufficiently explored. Moreover, the linkage between historical emission attribution and future scenario simulation requires further investigation in regional low-carbon transitions. Therefore, this study applies these complementary approaches to Sichuan Province to provide a region-specific perspective on transportation carbon-peaking pathways under different development scenarios.

3 Research Methodology and Data Sources

3.1 LMDI model

The Logarithmic Mean Divisia Index (LMDI) is a widely used decomposition method developed from the Divisia index framework. Its basic principle is to decompose changes in an aggregate indicator into the contributions of multiple driving factors in either additive or multiplicative forms, thereby quantifying the independent effect of each factor. Based on the characteristics of Sichuan's transportation sector and the findings of previous studies (Jiang et al. 2022; Sun et al. 2022), Carbon emission factors($\frac{C}{E}$), Energy Consumption per Unit Turnover($\frac{E}{T}$), Transport Energy Intensity($\frac{T}{TGDP}$), Economic density of motor vehicles($\frac{TGDP}{V}$), Motor Vehicles per Capita($\frac{V}{P}$), and Population(P) were selected as six key driving factors to construct the LMDI model for Sichuan Province. The model is presented in Equation (1), and detailed definitions of the variables are provided in Table 1.

Table 1. Variable definitions

Factors	Unit	Data sources	Significance
$\frac{C}{E}$	$t-CO_2/tce$	*Sichuan Statistical Yearbook* (https://tjj.sc.gov.cn/scstjj/c112132/pic_list.shtml)	The carbon emission intensity for measuring energy consumption is an important factor affecting carbon emissions.
$\frac{E}{T}$	$tce/(t\cdot km)$		Assess the energy efficiency of transport systems.
$\frac{T}{TGDP}$	$t{\cdot}km/CNY$		Indicates the dependence of economic activities on transportation
$\frac{TGDP}{V}$	CNY/veh		Quantify the economic contribution of motor vehicles.
$\frac{V}{P}$	$veh/person$		Reflecting residential transport mode preferences.

P	*person*	Constitutes a fundamental driver of transportation demand, energy consumption, and carbon emissions.

Data on passenger and freight turnover and the number of motor vehicles were obtained from the Transport, Post and Telecommunications section of the Sichuan Statistical Yearbook. Standard coal consumption in the transportation sector was sourced from the Energy section, while GDP of the transportation sector was obtained from the National Accounts section. Population data were collected from the Population section.

$$C = \frac{C}{E} \times \frac{E}{T} \times \frac{T}{TGDP} \times \frac{TGDP}{V} \times \frac{V}{P} \times P \qquad (1)$$

where C denotes transportation carbon emissions, E represents energy consumption in tons of coal equivalent, T is the total converted turnover (passenger-km converted to freight-km equivalents), $TGDP$ signifies the transport sector GDP, V indicates motor vehicle stock, and P corresponds to permanent population.

Simplifying the first equation as :

$$C = CE \times EE \times TI \times VE \times VP \times P \qquad (2)$$

The additive form is

$$C_t - C_0 = \Delta C = \Delta CE + \Delta EE + \Delta TI + \Delta VE + \Delta VP + \Delta P \qquad (3)$$

The breakdown is as follows:

$$\Delta C_H = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \times \ln \frac{CE_i^t}{CE_i^0} \qquad (4)$$

$$\Delta C_I = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \times \ln \frac{EE_i^t}{EE_i^0} \qquad (5)$$

$$\Delta C_J = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \times \ln \frac{TI_i^t}{TI_i^0} \quad (6)$$

$$\Delta C_K = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \times \ln \frac{VE_i^t}{VE_i^0} \quad (7)$$

$$\Delta C_L = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \times \ln \frac{VP_i^t}{VP_i^0} \quad (8)$$

$$\Delta C_P = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \times \ln \frac{P_i^t}{P_i^0} \quad (9)$$

3.2 STIRPAT model

The STIRPAT model is a widely used analytical framework in environmental science for investigating human impacts on the environment. It has been extensively applied to examine carbon emission drivers, conduct regional comparative analyses, and simulate policy scenarios, thereby providing a quantitative basis for environmental policy formulation and emission reduction targets.

$$I = a \times P^b \times A^c \times T^d \times e \quad (10)$$

where I denotes environmental impact, P represents population size, A signifies affluence, T indicates technology level, a is the scaling constant, b,c and d are elasticity coefficients for population, affluence, and technology, respectively, and e constitutes the error term.

To enhance the mathematical operability, elasticity interpretability, and data adaptability of the STIRPAT model, we apply a logarithmic transformation to both sides of the equation, yielding:

$$\ln I = \ln a + b \ln P + c \ln A + d \ln T + \ln e \quad (11)$$

Considering the consistency between historical decomposition analysis and future scenario simulation, the extended STIRPAT model incorporates the emission-related indicators used in the LMDI decomposition framework together with urbanization rate (UR). The inclusion of UR aims to capture broader socioeconomic mechanisms associated with population spatial distribution, travel behavior changes, and transport system development in rapidly urbanizing Sichuan (Xue et al. 2021).

It should be noted that these variables are used to estimate statistical elasticities for scenario construction rather than to establish strict causal relationships. The extended STIRPAT model is expressed as follows:

$$\begin{aligned}\ln C = \ln a + \alpha_1 \ln CE + \alpha_2 \ln EE + \alpha_3 \ln TI + \alpha_4 \ln VE + \alpha_5 \ln VP \\ + \alpha_6 \ln P + \alpha_7 \ln UR\end{aligned} \tag{12}$$

where C denotes transportation carbon emissions in Sichuan, and α_i represents the impact coefficient for energy type i.

3.3 Carbon emission accounting

Current carbon accounting methodologies primarily include the top-down approach, the bottom-up approach, and life cycle assessment (LCA). The top-down approach offers relatively low data collection costs and high computational efficiency; however, it cannot distinguish carbon emissions across different transport modes. The bottom-up approach enables analysis of emission structures and identification of key emission sources, but faces challenges in data availability and acquisition. LCA provides a comprehensive quantification of emissions across all transportation stages but is associated with high data requirements and relatively low computational efficiency (W. Li et al. 2022). Considering the trade-offs among these methods, this study adopts the top-down approach based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories to quantify transportation carbon emissions in Sichuan Province. Provincial-level emissions are further disaggregated to prefecture-level cities using the GDP-ratio method proposed by (Wan et al. 2025), as formalized below:

$$C = \sum_i C_i = \sum_i E_i \times F_i = \sum_i E_i \times ALV_i \times CV_i \times COF_i \times \frac{44}{12} \tag{13}$$

$$UCE = \frac{UGDP}{GDP} \times C \tag{14}$$

where C denotes total CO_2 emissions, with i indexing fossil fuels; C_i denotes CO2 emissions from various fossil fuels. F_i is the carbon emission factor for fossil fuel i. E_i is the consumption of fossil fuel type i. ALV_i is the average low-level heat generation of fossil fuel type i; CV_i is the carbon content per unit calorific value of fuel i; COF_i is the carbon oxidation rate of fuel i; $44/22$ is the carbon-to-CO_2 stoichiometric conversion factor. Additionally, UCE represents urban transport carbon emissions, $UGDP$ denotes Urban Gross Domestic Product, while GDP represents provincial Gross Domestic Product.

It should also be noted that, while the IPCC top-down approach provides an authoritative and consistent framework for long-term carbon accounting, it does not allow for the separation of emissions across different transport modes, such as road, rail, waterway, and air transport. Consequently, this study focuses on the overall evolution, driving factors, and future emission scenarios of transport-related carbon emissions at the provincial level. Within the existing statistical framework of the Sichuan Statistical Yearbook, the top-down approach remains appropriate for ensuring temporal consistency and interannual comparability of provincial-level time-series data. Accordingly, the policy implications of this study should be interpreted at the macro-regional level, rather than as precise estimates of emission reduction potential for individual transport modes.

3.4 Data sources

The Sichuan Statistical Yearbook categorizes transportation, storage, and postal services under a unified energy sector. Given the relatively minor contributions of storage and postal services, these components are aggregated into the transportation category (Shun-ping et al., 2010). To ensure the comparability of the 2005–2020 time-series data, energy categories reported in different editions of the Sichuan Statistical Yearbook were harmonized into a consistent accounting framework. Specifically, for 2005–2010, when transportation energy consumption was reported in a more disaggregated form, fuel-specific carbon emissions were calculated separately using corresponding emission factors and calorific values, whereas for 2011–2020, when the Yearbook reported more aggregated categories such as coal and oil, emissions were calculated directly based on these composite energy categories. This procedure ensures consistency in accounting boundaries while preserving the original statistical structure of each reporting year. Carbon emission factors for coal, oil, and natural gas were derived as weighted averages from multiple institutional studies, while electricity emission factors were obtained from the Provincial Greenhouse Gas Inventory Guideline (Trial), as summarized in Table 2. The final dataset used for time-series analysis contains no missing values; therefore, no interpolation or imputation procedures were required.

Table 2

Organization	Coal	Oil	Electricity
IPCC Guidelines for National Greenhouse Gas Inventories	0.756	0.586	0.801
National Climate Change Task Force, State Science and Technology Commission (SSTC)	0.726	0.583	
The Institute of Energy Economics, Japan	0.756	0.586	
International Energy Agency (IEA)	0.702	0.478	
average value	0.735	0.558	

Average lower heating values were sourced from the *Statistical Survey System for Energy Consumption in Public Institutions* (TJSYS). Carbon content per unit calorific value and oxidation rates were derived from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and the *Provincial Greenhouse Gas Inventory Guideline (Trial)*, as specified in Table 3.

Table 3 Energy Correlation Coefficients

Energy Types	average low-level heat generation (kj / kg)	carbon content per unit calorific value (tc / TJ)	carbon oxidation rate
Crude Oil	42000	20.0	98%
Gasoline	44800	18.9	98%
Kerosene	43070	19.6	98%
Diesel	42650	20.2	98%
Fuel Oil	41816	21.1	98%
Coke	28435	29.4	98%

4 Results and discussion

4.1 Current Situation of Carbon Emissions

As shown in Figure 1, carbon emissions from different energy types in Sichuan's transportation sector generally increased from 2005 to 2020, although their composition changed over time. Emissions associated with oil and natural gas increased significantly, whereas those related to coal and coke gradually declined, indicating a gradual adjustment in the energy structure. Although electricity still accounts for a relatively small share of total transport-related emissions, its growing contribution suggests the increasing role of cleaner energy in the sector. Overall, Sichuan's transportation system has undergone an incipient transition away from traditional high-carbon fuels toward a more diversified energy mix. However, this transition has not yet been sufficient to offset the upward pressure driven by expanding transport demand.

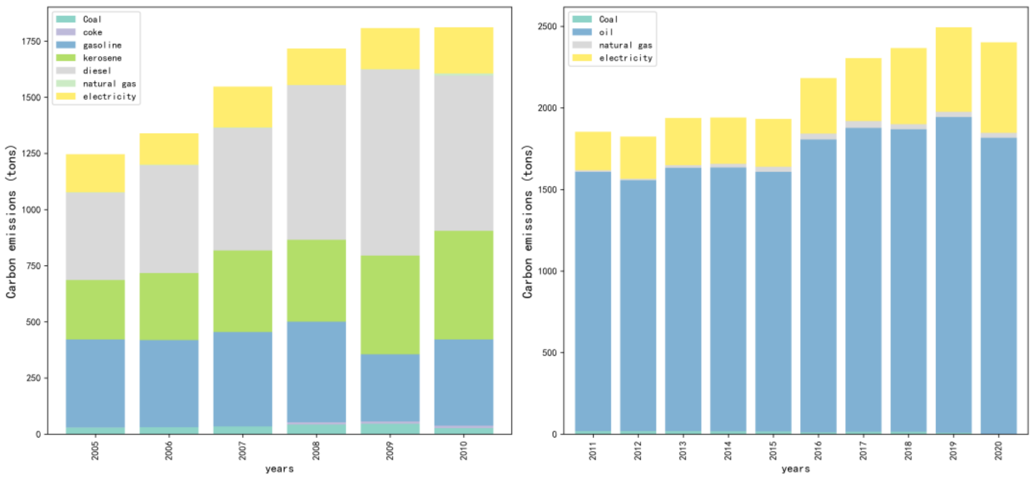


Figure 1 Carbon Emissions by Energy Type in the Transportation Sector of Sichuan Province, 2005-2020

During the 11th Five-Year Plan period (2006–2010), transportation carbon emissions in Sichuan increased steadily from 13.39 million tons to 18.11 million tons, with an average annual increase of 0.94 million tons. This rapid growth was closely associated with accelerated industrialization, urban expansion, and continuous improvements in transportation infrastructure, which jointly stimulated both passenger mobility and freight circulation. During this period, the expansion of transport demand clearly outweighed the mitigating effects of cleaner energy use and efficiency improvements.

During the 12th Five-Year Plan period (2011–2015), transportation carbon emissions fluctuated slightly but continued to rise overall, increasing from 18.53 million tons to 19.31 million tons, with an average annual increase of 0.16 million tons. The slower growth rate suggests that energy conservation and efficiency improvement measures had begun to take effect. The slight declines observed in 2012 and 2015 are likely related to the implementation of stricter energy-saving and emission-reduction policies in Sichuan. Nevertheless, ongoing urbanization, population agglomeration, and rising transport demand continued to drive an overall upward trend in emissions.

During the 13th Five-Year Plan period (2016–2020), transportation carbon emissions further increased from 21.83 million tons to 24.02 million tons, with an average annual increase of 0.44 million tons. Although the COVID-19 pandemic caused a temporary decline in 2020, the overall trajectory remained upward. This stage was characterized by the combined influence of economic growth, increasing private vehicle ownership, and expanding logistics activities. As Sichuan strengthened its role as a transport hub in western China, both passenger travel and freight transport intensified, thereby sustaining upward pressure on transportation carbon emissions.

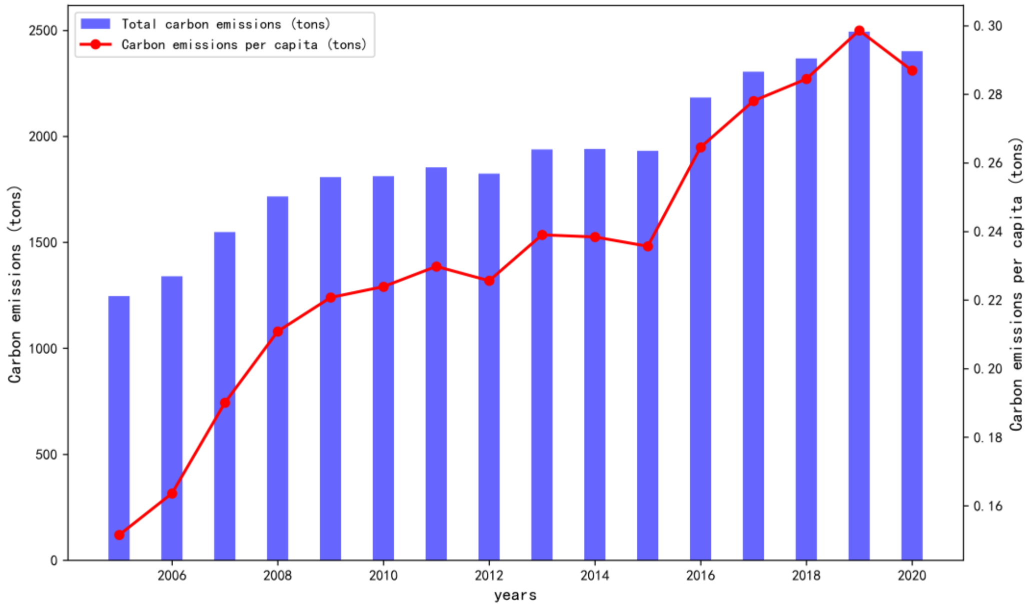


Figure 2 Carbon Emissions and Per Capita Emissions in the Transportation Sector of Sichuan Province, 2005-2020

As shown in Figure 2, carbon emissions per capita in Sichuan increased from 0.15 $t\,/\,person$ in 2005 to 0.29 $t\,/\,person$ in 2020, representing an increase of approximately 90%. This trend indicates that the growth of transport emissions cannot be explained solely by population change but is also closely related to motorization, changing travel behavior, and the structure of the transport system. In particular, the rapid increase in Motor Vehicles per Capita and the continued dominance of road transport contributed substantially to the rise in carbon emissions per capita.

From a structural perspective, the sustained increase in per capita emissions reflects a mismatch between rapidly growing mobility demand and a relatively slower pace of low-carbon transition. Although Sichuan has made progress in promoting rail transit, public transportation, and new energy vehicles, the province still relies heavily on highway transport because it serves as a major transport and logistics hub in western China, particularly for freight movement, while conventional fuel vehicles continue to account for a large share of transport activity. Under such conditions, improvements in the energy structure and clean transport technologies have not yet been sufficient to fully offset the emission growth induced by transport expansion. Overall, the continued increase in both total and per capita transportation carbon emissions suggests that Sichuan remains at a stage where demand growth and motorization expansion outpace the decarbonization effects of structural and technological adjustment.

4.2 Spatiotemporal Analysis of Carbon Emissions

Figure 3 illustrates significant spatiotemporal variations in transportation carbon emissions across Sichuan Province during 2005–2020. Carbon emissions for each city were calculated using Equation (14) and visualized using ArcMap. Chengdu consistently exhibited the highest emission level, with its transportation carbon emissions increasing from 3.62 million tons to 7.65 million tons, approximately 6.3 times higher than those of Yibin in 2020. Spatially, high-emission areas were mainly concentrated in Chengdu and several surrounding cities, including Mianyang and Deyang, which may be associated with higher levels of economic activity, denser transport networks, and more intensive passenger and freight flows. Along the Yangtze River corridor, the rapid increase in emissions observed in Yibin and Luzhou may also be partly related to the expansion of regional logistics activities and waterway transportation. In contrast, Panzhihua exhibited relatively slower emission growth, which may reflect changes in its industrial structure and associated transport demand. In western Sichuan, transportation carbon emissions remained relatively low, likely due to the combined effects of sparse population distribution, ecological protection constraints, and limited accessibility of transport infrastructure.

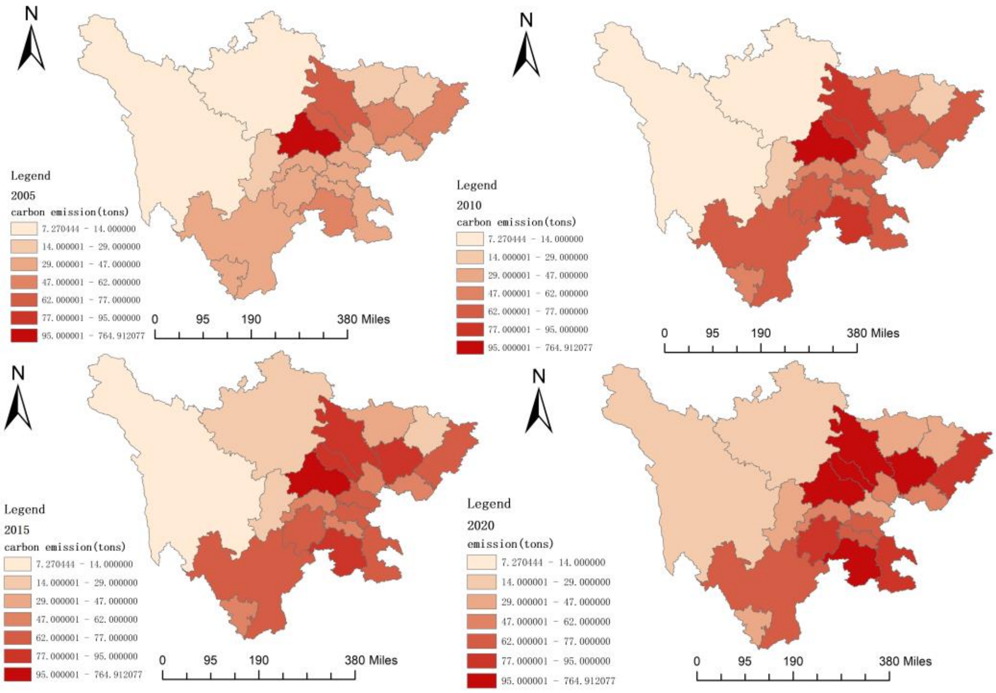


Figure 3 Spatiotemporal Distribution Map of Carbon Emissions in Sichuan Province

To further assess whether the observed spatial differences were associated with statistically significant spatial autocorrelation, this study employed a 0–1 spatial weight matrix to calculate Global Moran's I for transportation carbon emissions in Sichuan Province during 2005–2020. As shown in Table 4, the Moran's I value were not statistically significant in any year, indicating that transportation carbon emissions in Sichuan Province did not exhibit significant global spatial autocorrelation at the prefecture level during the study period. Therefore, the spatial distribution patterns presented in Figure 3 should be interpreted as reflecting regional heterogeneity rather than statistically significant province-wide spatial clustering.

Table 4 Results of Moran's I Index

Year	2005	2006	2007	2008	2009	2010	2011	2012
I	-0.004	-0.016	-0.017	-0.017	-0.013	-0.015	-0.007	-0.005
p	0.395	0.395	0.398	0.398	0.386	0.391	0.386	0.391
Year	2013	2014	2015	2016	2017	2018	2019	2020
I	-0.007	-0.012	-0.011	-0.041	-0.054	-0.065	-0.1	-0.101
p	0.367	0.381	0.379	0.473	0.488	0.452	0.347	0.343

4.3 LMDI analysis

Figure 4 illustrates the decomposition trends of each factor, while Table 5 presents the detailed decomposition results. The results indicate that Motor Vehicles per Capita was the dominant driver of transportation carbon emission growth during 2006–2020, contributing to a cumulative increase of 40.23 million metric tons. Its annual contribution remained consistently high, with relatively limited fluctuations.

Energy Consumption per Unit Turnover was the second largest contributor to emission growth, with a cumulative contribution of 16.00 million metric tons. However, this factor exhibited frequent interannual fluctuations, suggesting that improvements in energy efficiency within Sichuan's transportation sector were not stable throughout the study period.

n contrast, Carbon emission factors, Economic density of motor vehicles, and Transport Energy Intensity played important roles in reducing transportation carbon emissions, with cumulative mitigation effects of 6.96, 15.84, and 22.34 million metric tons, respectively. Among these factors, Carbon emission factors showed a consistent declining trend, indicating gradual improvements in fuel structure optimization. Transport Energy Intensity exhibited considerable interannual fluctuations but generally reflected improvements in transport efficiency. Population had a relatively limited impact, contributing only 0.2 million metric tons cumulatively, with negligible annual variation.

Overall, these decomposition results suggest that transportation carbon emission growth in Sichuan was primarily driven by motorization expansion and increasing transport energy demand, whereas the mitigating effects of energy structure optimization and transport efficiency improvements remained relatively limited. This pattern reflects Sichuan's current development stage, where economic growth, freight activity, and private vehicle expansion continue to exceed the emission reduction effects achieved through cleaner energy adoption and transport restructuring.

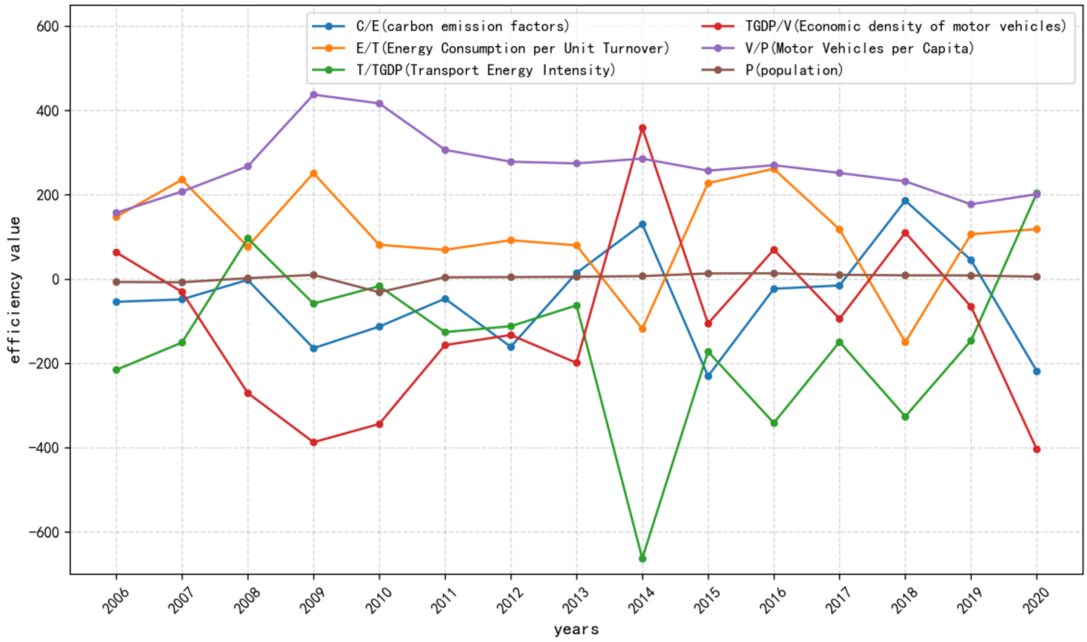


Figure 4. Annual Variation Trends of Decomposition Effects

Table 5. Annual Decomposition Results of Driving Effects Using the LMDI Approach

years	C/E	E/T	T/TGDP	TGDP/V	V/P	P
2006	-53.88	147.76	-215.25	63.46	157.33	-6.77
2007	-47.95	236.03	-150.44	-30.23	207.80	-7.41
2008	-1.86	77.03	96.72	-270.03	267.52	2.20
2009	-163.79	251.61	-57.99	-386.90	437.77	10.14
2010	-112.65	81.45	-16.50	-343.58	416.91	-31.13
2011	-46.31	69.48	-125.71	-156.58	306.66	4.31
2012	-160.56	92.32	-111.69	-132.47	278.60	4.78
2013	14.62	80.11	-62.21	-198.60	274.54	5.57
2014	130.62	-117.86	-662.54	358.89	285.85	7.16
2015	-230.16	227.85	-171.72	-105.35	257.26	13.51
2016	-22.92	261.69	-341.36	69.86	270.25	13.74
2017	-15.00	117.73	-148.89	-94.10	251.90	10.31
2018	186.28	-149.64	-325.90	110.38	232.03	9.00
2019	44.99	106.58	-145.68	-65.42	177.54	8.75
2020	-218.29	118.53	204.19	-403.87	201.56	5.85
Contribution (10000tons)	-696.86	1600.65	-2234.97	-1584.53	4023.53	20.03

4.4 Least Squares Method

Ordinary Least Squares (OLS) is a widely used estimation method in statistics and regression analysis for linear regression models. It estimates regression coefficients by minimizing the sum of squared errors (SSE) between predicted and observed values. In this study, SPSS was used to conduct OLS regression analysis for Equation (10), and the resulting Variance Inflation Factor (VIF) values are reported in Table 6.

Table 6. Variance Inflation Factor (VIF) Values for Considered Determinants

Factor	C/E	E/T	T/TGDP	TGDP/V	V/P	P	UR
VIF	42.453	57.101	60.994	52.678	438.435	12.461	882.387

As shown in Table 6, all explanatory variables exhibit Variance Inflation Factor (VIF) values greater than 10, indicating severe multicollinearity , which compromises estimation accuracy and model robustness (Shrestha 2020).

Among the commonly used approaches for addressing multicollinearity, including principal component regression (PCR), partial least squares (PLS), and ridge regression, this study adopted ridge regression for two main reasons. First, this study aims not only to improve estimation stability but also to maintain the interpretability of the original explanatory variables within the extended STIRPAT framework. Unlike PCR and PLS, which transform original variables into latent components, ridge regression preserves the original variables and therefore enables direct interpretation of the estimated coefficients. Second, the selected explanatory variables have clear theoretical relevance to transportation carbon emissions, and transforming them into latent factors may reduce the policy relevance and practical interpretability of the results (Rao et al. 2023).

4.5 Ridge Regression

Ridge regression is a regularization method designed to address multicollinearity. By imposing a penalty on the regression coefficients, it reduces model instability when explanatory variables are highly correlated, thereby improving robustness and reliability at the cost of a slight loss in estimation efficiency (Chen et al. 2009). As shown in Figure 5, the ridge trace indicates that the regression coefficients gradually stabilize as the ridge parameter K increases. Under the selected value of K = 0.063, the model achieves an R^2 of 0.962, indicating strong explanatory power. Detailed estimation results are reported in Table 7.

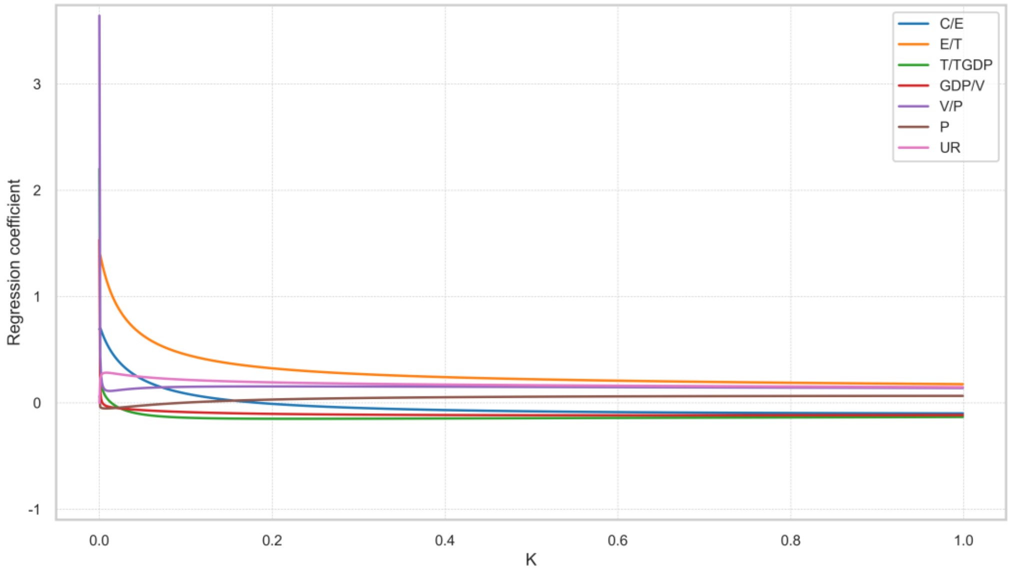


Figure 5 Ridge Trace Plot

To further validate the selected value of K, leave-one-out cross-validation (LOOCV) was employed because relying solely on the ridge trace for parameter selection has limitations. The results are shown in Figure 6.

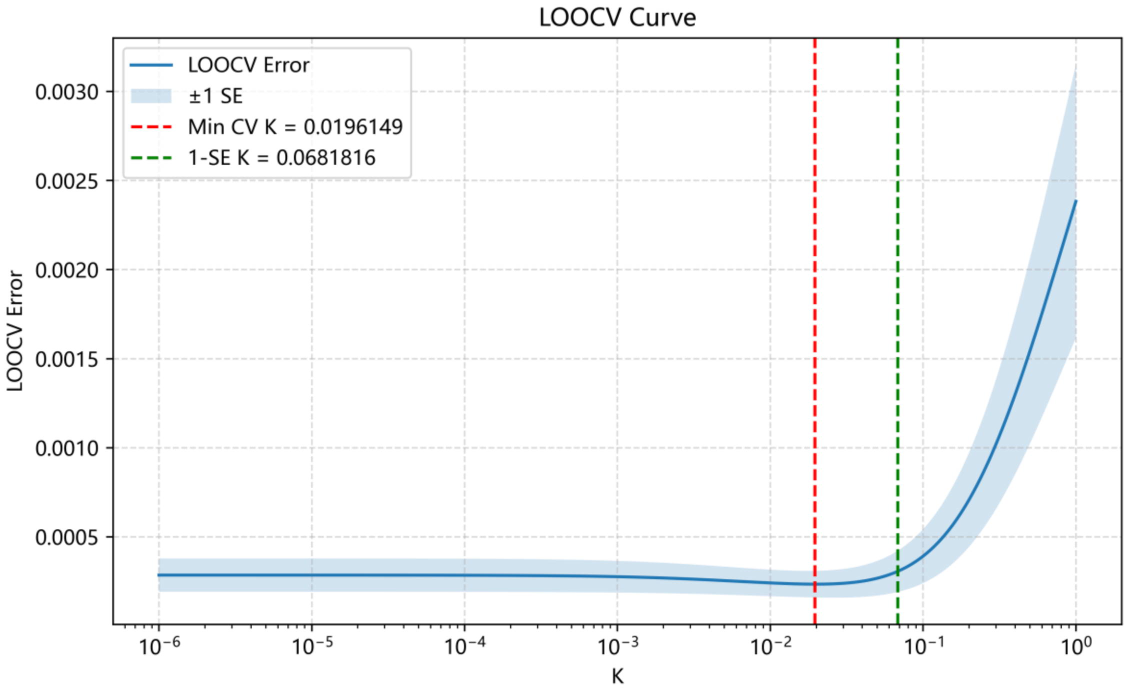


Figure 6 LOOCV validation

The LOOCV results show that the prediction error reaches its minimum when K = 0.0196. However, the error curve remains relatively flat around this minimum, indicating that a range of K values in this neighborhood exhibit similar predictive performance. In accordance with the 1-SE rule, a more parsimonious and stable value of K = 0.0682 is selected. Notably, this value is close to 0.063, further supporting the robustness of the originally selected value of K. Therefore, this paper selects a k-value of 0.063.

Table 7. Ridge Regression Analysis Results

	Non-standardized coefficient		Standardized coefficient	t	significance	R^2	F
	B	standard error	Beta				
ln a	10.873	13.163	-	0.826	0.433		
ln CE	0.25	0.17	0.173	1.469	0.180		
ln EE	0.414	0.084	0.571	4.936	0.001^{***}		
ln TI	-0.055	0.041	-0.121	-1.343	0.216	0.962	29.199
ln VE	-0.048	0.065	-0.074	-0.744	0.478		(0.000***)
ln VP	0.039	0.014	0.144	2.916	0.019^{**}		
ln P	-0.267	1.5	-0.017	-0.178	0.863		

$\ln UR$	0.27	0.066	0.235	4.06	0.004***

Note***、**、*denote statistical significance at the 1%, 5%, and 10% levels, respectively. Adjusted R^2 = 0.929.

The STIRPAT model is obtained as follows:

$$\begin{aligned}\ln C = 10.837 + 0.25\ln CE + 0.414\ln EE - 0.055\ln TI \\ -0.048\ln VE + 0.039\ln VP - 0.267\ln P + 0.27\ln UR\end{aligned} \quad (15)$$

Equation (15) presents the estimated elasticities of the seven selected factors with respect to transportation carbon emissions. Among these factors, carbon emission factors, Energy Consumption per Unit Turnover, Motor Vehicles per Capita, and urbanization rate show positive estimated elasticities. Specifically, Energy Consumption per Unit Turnover exhibits the largest positive elasticity, indicating that a 1% increase in this factor is associated with an approximately 0.414% increase in transportation carbon emissions under the modeled conditions. Similarly, a 1% increase in carbon emission factors, Motor Vehicles per Capita, and urbanization rate corresponds to increases in estimated emissions of 0.250%, 0.039%, and 0.270%, respectively.

In contrast, transport energy intensity, Economic density of motor vehicles, and Population show negative estimated elasticities in the model. Among these factors, population has the largest negative coefficient, with a 1% increase in population associated with an estimated 0.267% reduction in transportation carbon emissions. This result differs from the LMDI decomposition findings, suggesting that the statistical relationship captured by the extended STIRPAT model reflects broader socioeconomic and transport development characteristics rather than a direct causal effect. In Sichuan Province, population growth may be increasingly associated with urban agglomeration, improved public transport services, and more compact land-use patterns. Under such conditions, population concentration may contribute to higher transport efficiency, shorter average travel distances, and a shift from high-carbon private transportation toward public transport (W. Yang et al. 2019) , partially offsetting the potential emission pressures associated with population expansion.

Overall, the STIRPAT results are broadly consistent with the LMDI decomposition in identifying the key driving and mitigating mechanisms of transportation carbon emissions. This consistency supports the complementarity of the two approaches and provides a robust empirical basis for formulating more targeted transportation decarbonization policies in Sichuan Province.

5 Scenario Projections for Sichuan Province

5.1 Scenario setting

Building upon Sichuan's development patterns from 2005 to 2020, this study constructs four scenarios—Low-Carbon Development, Baseline, Enhanced Control, and High-Carbon Development—to project transportation carbon emissions through 2040. The determination of annual growth rates for the seven key factors is based on three considerations: historical trends of relevant indicators in Sichuan Province, quantitative targets or directional requirements outlined in national and provincial policy documents, and the internal logic underlying the four development scenarios.

The relevant policy documents include the *14th Five-Year Plan for Comprehensive Transportation Development of Sichuan Province, the 14th Five-Year Plan for the Modern Comprehensive Transportation System, the 14th Five-Year Plan for National Economic and Social Development of Sichuan Province and the Long-Term Goals for 2035*, as well as other sectoral policies related to transportation, logistics, urbanization, energy transition, and green development (Sichuan Provincial Department of Transportation 2025; Sichuan Provincial People's Government 2024; State Council 2022; State Council General Office 2022).

Three growth rate settings—low, medium, and high—are defined. These terms refer to relative change rates of each variable rather than normative judgments. For variables with negative growth rates, such as Carbon emission factors and Transport Energy intensity, higher values represent larger reductions in magnitude. The analysis covers four periods: 2021–2025, 2026–2030, 2031–2035, and 2036–2040. The detailed parameter settings are provided in Tables 8 and 9.

Table 8: Growth Rates of Various Factors under Different Growth Rate Scenarios over Time

Paradigm	Years	C/E (%)	E/T (%)	T/GDP (%)	GDP/V (%)	V/P (%)	P（%）	UR (%)
Low	2021-2025	-1.3	3	-5	-3	5	0.15	1
	2026-2030	-1.1	2	-4	-2	5	0.15	0.5
	2031-2035	-0.8	-1	-3	-1	4	0.1	0.2
	2036-2040	-0.6	-1	-2	-1	3	0.1	0
medium	2021-2025	-1.5	6	-7	-5	7	0.1	1.5
	2026-2030	-1	5	-6	-4	7	0.018	1
	2031-2035	-0.5	3	-5	-3	6	0.015	0.6
	2036-2040	-0.3	-1	-4	-2	5	0.013	0
High	2021-2025	-1.8	8	-9	-7	10	0.15	2
	2026-2030	-1.7	7	-8	-6	9	0.12	2
	2031-2035	-1.6	4	-7	-5	8	0.1	1.7
	2036-2040	-1.5	1	-6	-4	7	0.07	1.5

Table 9: Specific Settings for Different Factors under Various Development Scenarios

	C/E	E/T	T/GDP	GDP/V	V/P	P	UR
Low-Carbon Development,	H	L	H	H	L	M	L
Baseline	M	M	M	M	M	M	M
Enhanced Control	H	M	H	M	L	M	M
High-Carbon Development	L	H	L	L	H	M	H

Note High=H, Medium=M, Low=L

5.1.1 Carbon emission factors ($\frac{C}{E}$)

The Carbon emission factor ($\frac{C}{E}$) has shown a gradual downward trend, falling from 1.48 $t-CO_2/tce$ in 2010 to 1.26 $t-CO_2/tce$ in 2020, with an average annual decline of 1.61%. This reflects progress in Sichuan Province's transport sector in restructuring its energy mix toward cleaner sources. The *14th Five-Year Plan for the Development of a Modern Integrated Transport System explicitly* emphasizes the need to maintain the declining trend in carbon emission intensity observed during the 13th Five-Year Plan period. Accordingly, the Baseline scenario assumes an initial annual reduction rate of 1.5% for this indicator, with a gradually decelerating trend over time, while the low-growth and high-growth scenarios incorporate corresponding adjustments under different temporal trajectories.

5.1.2 Energy Consumption per Unit Turnover ($\frac{E}{T}$)

Energy Consumption per Unit Turnover ($\frac{E}{T}$) has exhibited cyclical fluctuations in recent years, reflecting ongoing efforts to improve transport energy efficiency. The *Implementation Plan of Sichuan Province for Continuous Air Quality Improvement* mandates strict control of coal consumption, with provincial raw coal consumption capped at 70 million tons by 2025. In addition, the *Action Plan for Modern Logistics Industry Cluster Development and the Action Plan for Promoting High-Quality Multimodal Transport* set a target of reducing the ratio of total social logistics costs to GDP to approximately 13.7% by 2027 while increasing the share of railway freight turnover to 32%. Accordingly, the Baseline scenario assumes an initial annual growth rate of 6%, followed by gradual deceleration and a long-term decline in the growth rate, while the low-growth and high-growth scenarios incorporate corresponding adjustments under different temporal trajectories.

5.1.3 Transport Energy Intensity ($\frac{T}{TGDP}$)

From 2005 to 2020, Sichuan's Transport Energy Intensity ($\frac{T}{TGDP}$) declined from 0.02 tce/CNY to 0.006 tce/CNY, corresponding to an average annual reduction rate of 7.7%. This trend reflects continuous improvements in transport efficiency and a gradual decoupling of economic growth from transport energy consumption. Accordingly, the Baseline scenario assumes an initial annual reduction rate of 7%, followed by a gradual deceleration over time, while the low-growth and high-growth scenarios incorporate corresponding adjustments under different temporal trajectories.

5.1.4 Economic density of motor vehicles ($\frac{TGDP}{V}$)

Economic density of motor vehicles ($\frac{TGDP}{V}$) declined from 24,201 CNY/veh in 2005 to 10,520 CNY/veh in 2020, corresponding to an average annual decline rate of 5.3%. This indicates a persistent downward trend in the economic density of motor vehicles, which is expected to continue in the future. Accordingly, the Baseline scenario assumes an initial annual reduction rate of 5%, while the low-growth and high-growth scenarios incorporate corresponding adjustments under different temporal trajectories.

5.1.5 Motor Vehicles per Capita ($\frac{V}{P}$)

Over the period 2015–2020, Sichuan's Motor Vehicles per Capita ($\frac{V}{P}$) increased from 0.094 to 0.152 $veh/person$, corresponding to an average annual growth rate of 10.5%. The *China Association of Automobile Manufacturers Annual Report* identifies Sichuan as a key automotive market in western China, projecting 5%-6% annual growth in vehicle ownership over the next five years. Accordingly, the Baseline scenario assumes an initial annual growth rate of 7%, while the low-growth and high-growth scenarios incorporate corresponding adjustments under different temporal trajectories.

5.1.6 Population (P)

Population (P) increased from 82.12 million in 2005 to 83.71 million in 2020, corresponding to an average annual growth rate of 0.128%. The *Sichuan Long-term Population Development Plan* sets a target of stabilizing the permanent population at approximately 84.7 million by 2030 through the effective implementation of the three-child policy, with a total fertility rate of approximately 1.6. Accordingly, the baseline scenario assumes an initial annual growth rate of 0.1%, while the low-growth and high-growth scenarios incorporate corresponding adjustments under different temporal trajectories.

5.1.7 Urbanization rate (*UR*)

Since the 13th Five-Year Plan period, Sichuan Province has experienced significant progress in urbanization. The urbanization rate increased from 48.3% to 57.8%. During the 14th Five-Year Plan period, urbanization entered a new stage characterized by stable growth, accelerated population mobility, structural optimization, and continuous improvements in development quality. The *Implementation Plan for Sichuan's New Urbanization During the 14th Five-Year Plan Period* projects that the urbanization rate of the permanent resident population will exceed 60% by 2025. Accordingly, the Baseline scenario assumes an initial annual growth rate of 1.5%, while the low-growth and high-growth scenarios incorporate corresponding adjustments under different temporal trajectories.

To evaluate the reasonableness of the scenario growth-rate settings, the latest available data for 2022 were used to calculate the actual growth rates, with 2019 selected as the base year because transport-related indicators were substantially affected by the COVID-19 pandemic in 2020. The comparison results are presented in Table 10. The estimated growth rates are generally close to the observed values, indicating that the scenario parameter settings are broadly consistent with actual development trends.

Table 10 Actual and target growth rates

	C/E ($t\text{-}CO_2/tce$)	E/T (tce/(t.km))	T/TGDP (t.km/CNY)	TGDP/V (CNY/veh)	V/P (veh/person)	P (person)	UR (%)
2005	1.8708	0.0091	0.0204	24201.3605	0.0179	8212	33
2006	1.7943	0.0103	0.0173	25421.9128	0.0202	8169	34.3
2007	1.7354	0.0121	0.0156	24893.1016	0.0234	8127	35.6
2008	1.7334	0.0127	0.0165	21090.1383	0.0275	8138	37.4
2009	1.5795	0.0146	0.0160	16930.4498	0.0353	8185	38.7
2010	1.4839	0.0153	0.0159	13994.6913	0.0445	8045	40.18
2011	1.4467	0.0159	0.0148	12845.3924	0.0526	8064	41.85
2012	1.3258	0.0167	0.0139	11952.5253	0.0612	8085	43.35
2013	1.3361	0.0174	0.0135	10754.7433	0.0708	8109	44.96
2014	1.4292	0.0164	0.0096	12941.0356	0.0821	8139	46.51
2015	1.2690	0.0184	0.0088	12255.6929	0.0938	8196	48.27

2016	1.2549	0.0209	0.0074	12679.5104	0.1069	8251	50
2017	1.2466	0.0221	0.0069	12158.7014	0.1197	8289	51.78
2018	1.3501	0.0207	0.0060	12746.9989	0.1321	8321	53.5
2019	1.3753	0.0216	0.0057	12408.4124	0.1422	8351	55.36
2020	1.2579	0.0227	0.0062	10520.9720	0.1524	8371	56.73
2021	1.3693	0.0255	0.0049	11104.7757	0.1651	8372	57.82
2022	1.3696	0.0270	0.0046	10884.8738	0.1742	8374	58.35
Actual（2019-2022）	-1.4%	6.1%	-7%	-4.4%	6.9%	0.09%	1.76%
medium（2021-2025）	-1.5%	6%	-7%	-5%	7%	0.1%	1.5%

The Baseline scenario assumes that transportation carbon emissions are managed under the existing policy framework of Sichuan Province without major additional interventions. This scenario reflects the continuation of current policies and their implications for future emission trajectories.

The Enhanced Control scenario emphasizes stronger policy support and technological innovation to promote the sustainable development of the transportation sector while maintaining economic growth (Wu et al. 2018).

The Low-Carbon Development scenario prioritizes the coordinated advancement of economic development and emission reduction through cleaner energy use, transport structure optimization, technological progress, and efficiency improvements (Ji et al. 2024).

The High-Carbon Development scenario assumes a development pathway characterized by relatively weak emission-control measures. Although this scenario may generate short-term economic benefits, including accelerated infrastructure development and increased employment opportunities, it is accompanied by substantially higher carbon emissions and greater resource consumption (Y. Zhang et al. 2025).

By constructing these alternative scenarios, this study compares the potential trajectories of transportation carbon emissions under different policy and development pathways, thereby providing a basis for evaluating future carbon-peaking prospects and formulating transportation decarbonization policies in Sichuan Province.

5.2 Situational Analysis

Substituting the seven defined parameter categories into Equation (15) yields projections of transportation carbon emissions and their trajectories under various scenarios for Sichuan Province, as illustrated in Figure 7. Comparative analysis reveals that future transportation emission trends in Sichuan are substantially influenced by policy and technological factors. Under the Baseline scenario, which maintains current policies, transportation carbon emissions are projected to increase continuously, from 24.44 million tons in 2021 to 35.62 million tons in 2040. Notably, growth decelerates gradually after 2035, demonstrating the delayed efficacy of existing policies. This trajectory is primarily driven by the ongoing expansion of the transportation sector, characterized by rising transport demand, shifts in energy structure, and widespread adoption of transportation technologies.

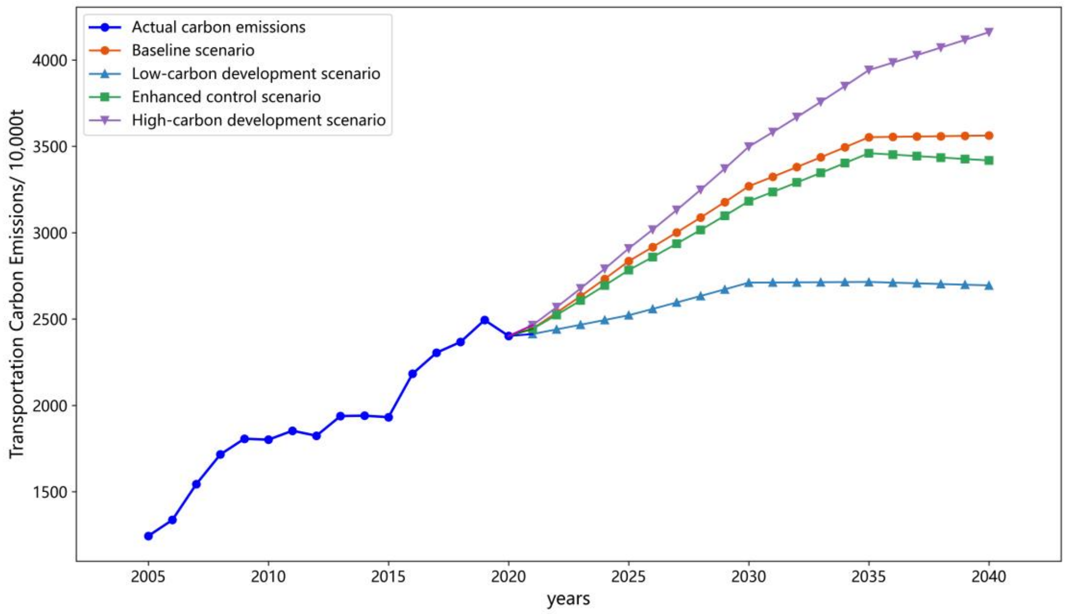


Figure 7 Projected Transportation Carbon Emissions in Sichuan Province, 2021–2040

Among the four scenarios, the High-Carbon Development scenario assumes sustained high economic growth in Sichuan Province throughout the projection period, accompanied by continued expansion of the transportation sector. Under this scenario, transportation carbon emissions are projected to increase rapidly, reaching 41.60 million tons by 2040. These results suggest that, in the absence of stronger emission-reduction measures and technological progress, transportation carbon emissions would continue to rise substantially, thereby increasing the difficulty of achieving regional carbon reduction and broader climate targets.

Under the Enhanced Control scenario, the emission trajectory largely follows that of the Baseline scenario, with transportation carbon emissions peaking at 34.60 million tons in 2035. This scenario assumes stronger government intervention through enhanced transportation emission management and policy incentives for carbon emission reduction. However, as shown in Figure 7, these measures produce only limited mitigation effects, indicating that more effective strategies are required to further improve carbon reduction performance.

Building upon the Enhanced Control scenario, the Low-Carbon Development scenario further promotes cleaner energy use, higher transport efficiency, and structural optimization in urbanization and transport development. Through this integrated pathway, the growth of transportation carbon emissions is more effectively restrained, with emissions projected to peak at 27.14 million tons in 2035. Moreover, the projected emission levels under this scenario remain substantially lower than those under both the Baseline scenario and the Enhanced Control scenario, indicating that coordinated improvements in energy transition, transport structure, and development efficiency provide a more effective pathway for reducing transportation carbon emissions in Sichuan Province.

5.3 Sensitivity analysis

Sensitivity analysis further reveals clear differences between the Baseline scenario and the Low-

Carbon Development scenario. As shown in Figure 8, under the Baseline scenario, transportation carbon emissions continue to increase or remain at a relatively high level under ±10% and ±20% perturbations in the assumed growth rates, without exhibiting a clear carbon-peaking point before 2040. These results suggest that, under the current policy intensity and development trajectory, the Baseline scenario is unlikely to achieve an early carbon peak in the transportation sector.

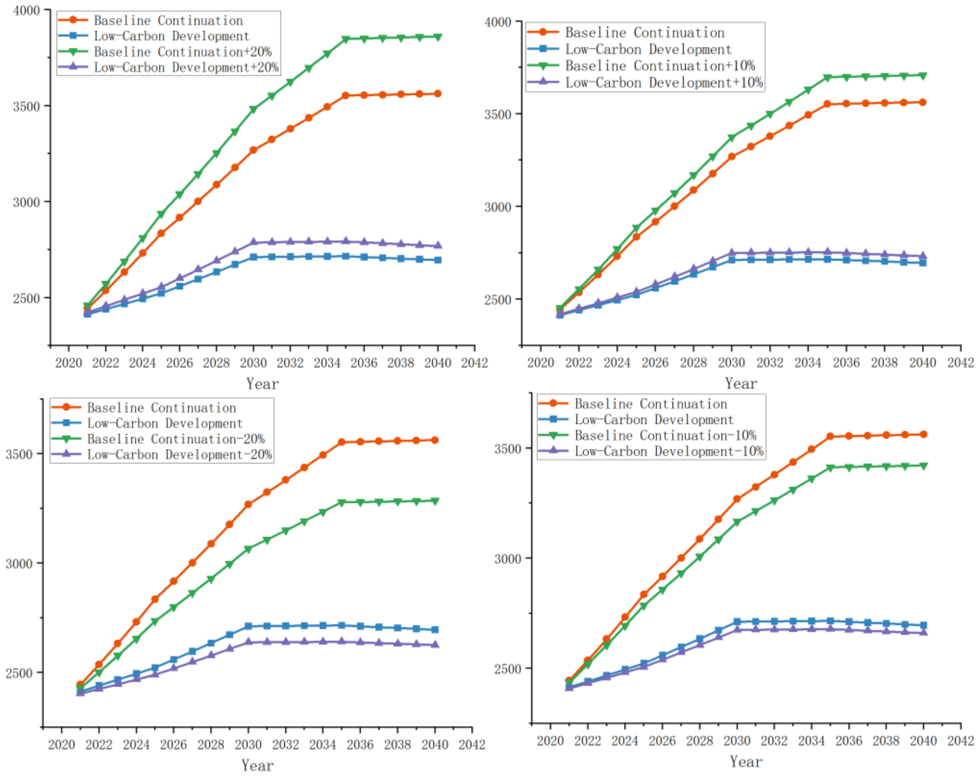


Figure 8 Sensitivity Analysis Results

By contrast, under the Low-Carbon Development scenario, transportation carbon emissions consistently peak around 2035, while the peak magnitude varies only moderately across different perturbation levels. This indicates that the peaking outcome under the Low-Carbon Development scenario is relatively robust to reasonable variations in the assumed parameter values.

Overall, the sensitivity analysis shows that although the projected emission levels are affected by parameter perturbations, the main comparative conclusion remains robust: compared with the other scenarios, the Low-Carbon Development scenario results in an earlier carbon peak and lower cumulative emissions. These findings provide additional support for the credibility of the scenario design and the robustness of the resulting policy implications.

6 Discussion

The findings of this study are generally consistent with existing literature, which identifies motor vehicle ownership and energy consumption as the primary drivers of transport-related carbon emissions in China and other developing economies (Shiraki et al. 2020; Tian et al. 2025). However, beyond confirming these general patterns, this study further refines the understanding of their relative importance in a western inland context. In particular, the LMDI results suggest that the contribution of transport demand expansion is more structurally dominant in Sichuan than in several eastern coastal provinces, where energy efficiency improvements and modal shifts have played a relatively larger role in recent years (Chunping et al. 2018).

A noteworthy finding is that population exhibits a negative estimated coefficient in the STIRPAT model, differing from the results reported in many previous studies. Similar findings have occasionally been observed in highly urbanized regions, where population concentration is associated with improved transport efficiency and lower carbon emissions per capita (W. Yang, et al. 2019). In contrast, in less compact urban systems, population growth tends to increase transport demand and emissions. Therefore, the negative coefficient observed in Sichuan may reflect a transitional urban structure characterized by increasing urban density, improved public transport coverage, and gradual optimization of spatial planning. This suggests that the impact of population is not uniform but highly dependent on regional urbanization patterns and transport system maturity.

Compared with studies focusing on eastern China or the Yangtze River Delta, where multimodal transport systems and cleaner energy structures are more mature, Sichuan exhibits a more complex emission mechanism shaped by geographical constraints and uneven transport infrastructure development. Previous studies have emphasized energy transition and technological improvement as the dominant pathways for mitigating transportation carbon emissions (Cheng et al. 2021; J. Zhang et al. 2022), the present study suggests that, in mountainous and inland regions, structural constraints in transport networks may partially offset the benefits of efficiency improvements. At the same time, the coexistence of abundant hydropower resources and emerging new energy industries distinguishes Sichuan from other western provinces, highlighting the importance of regionally differentiated decarbonization strategies.

Several limitations of this study should also be acknowledged. The scenario analysis is constructed based on historical trends and policy assumptions; however, it relies on the assumption that the relationships between driving factors and transport carbon emissions remain stable over time, which may not hold under future technological, structural, or policy changes. In addition, the estimated elasticities from the STIRPAT model are assumed to be time-invariant, although they may vary in response to evolving socio-economic conditions. The simplification of complex real-world dynamics into predefined scenario parameters may also introduce uncertainty by omitting nonlinear interactions and feedback effects among variables. Therefore, the scenario results should be interpreted as conditional and comparative projections rather than precise forecasts of future emissions.

7 Conclusions and Recommendations

7.1 Conclusions

This study applies a top-down carbon accounting framework to examine transportation carbon emissions in Sichuan Province over the period 2005–2020. By integrating the LMDI decomposition method with the STIRPAT model, it identifies the key driving factors of transportation carbon emissions and projects future emission trajectories under different development scenarios. The main conclusions are as follows:

(1) Transportation carbon emissions in Sichuan Province increased substantially from 12.47 million tons in 2005 to 24.02 million tons in 2020, with an average annual growth rate of 4.5%. Meanwhile, the transportation energy structure gradually shifted toward cleaner energy sources, characterized by an increasing share of electricity consumption and declining reliance on coal and coke. These findings indicate that accelerating the transition from conventional fossil fuels to cleaner energy sources remains essential for reducing transportation carbon emissions.

(2) Analysis of the factors of transportation carbon emissions shows that Carbon emission factors, Energy Consumption per Unit Turnover, Motor Vehicles per Capita, and the urbanization rate exert positive effects on carbon emissions, whereas Transport Energy Intensity, Economic density of motor vehicles, and Population exert negative effects. These findings suggest that improving transport efficiency, optimizing the economic performance of motor vehicles, and steering urbanization toward a low-carbon trajectory are key strategies for mitigating transportation carbon emissions.

(3) Scenario analysis demonstrates that achieving transportation carbon peeking through a low-carbon development pathway is feasible. Under the Low-Carbon Development scenario, Sichuan's transportation sector is projected to reach its carbon peak around 2035, with substantially lower emissions compared with the other scenarios. These findings provide scientific support for formulating region-specific transportation decarbonization strategies in Sichuan Province.

7.2 recommendations

Based on these findings, the following policy recommendations are proposed to support carbon emission reduction in Sichuan's transportation sector:

(1) Sichuan Province should promote green urbanization by strengthening the coordination between urban development and transport planning. Priority should be given to the Chengdu metropolitan area and other major urban corridors, where rapid urban expansion and increasing mobility demand have contributed to higher transportation carbon emissions. Compact urban development, transit-oriented development (TOD), and improved integration of residential, employment, and transport planning should be encouraged to reduce travel distances and dependence on private vehicles. For mountainous and topographically constrained cities, differentiated transport strategies should be implemented to improve accessibility while avoiding excessive expansion of transport infrastructure.

(2) Given Sichuan's abundant hydropower resources and Yibin's advantages in the power-battery industry, the province should further promote transport electrification and cleaner energy utilization. Policy efforts should focus on accelerating the electrification of urban buses, taxis, and logistics vehicles, while expanding charging and battery-swapping infrastructure in expressway service areas, logistics hubs, and intercity transport corridors. In addition, the application of clean electricity and photovoltaic systems in logistics parks, ports, airports, and freight terminals should be encouraged to better utilize Sichuan's clean energy advantages for transportation decarbonization.

(3) Considering Sichuan's mountainous terrain and the relatively high carbon intensity of road freight transport, greater efforts should be devoted to promoting the modal shift of bulk freight and medium- to long-distance freight from road transport to rail and waterway transport, particularly

along major logistics corridors and the Yangtze River transport network. Meanwhile, multimodal transport, digital logistics management, and optimized freight organization should be further developed to reduce empty-load rates and improve overall transport efficiency. Differentiated low-carbon freight strategies should also be formulated for major logistics hubs, including Chengdu, Yibin, and Luzhou, according to their regional transport functions.

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Author Contributions Statement

Luo Jian: investigation, methods, software, validation, writing-original draft. Yang Denghui: conceptualisation, data collation, formal analysis. Mao Changjiang: investigation, software, validation and editing.

Competing interests policy

The authors declare no competing interests.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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