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Rising carbon emissions from expanding highway tunnels and reduction pathways in China



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Highway tunnels are expanding rapidly in China, driving rising operational carbon emissions, yet systematic assessment methods remain limited. Here, we develop a provincial-scale carbon intensity model using empirical data from Sichuan Province, integrating regional electricity emission factors and geological characteristics. The model estimated emission intensities across 30 provinces, yielding a national average of 16,805 tCO₂-eq per km, and validation against 88 tunnel cases from five provinces shows prediction error of less than 5%. We further propose a low-carbon cross-section design strategy and evaluate three policy-technology interaction scenarios: baseline, high-reduction, and low-reduction. The high-reduction scenario could lower emissions by more than 18% relative to the baseline, whereas the low-reduction scenario leads to limited effectiveness. Establishing a nationwide tunnel emission model is essential for infrastructure planning, policy design, and accelerating low-carbon transitions in China and other rapidly developing economies.

Global warming has become one of the most severe environmental challenges facing contemporary society, with excessive carbon emissions at its core^{1–5}. As one of the world's largest energy consumers and greenhouse gas emitters, China emitted 12 gigatonnes (Gt) of carbon dioxide equivalents (CO₂-eq) in 2023, representing 32% of global emissions⁶. Among these, the transportation sector is a significant source of carbon emissions in China, accounting for 15% of the nation's total carbon emissions^{7,8}. As a crucial component of the integrated transportation network, highway tunnels are a key contributor to energy consumption and carbon emissions within the transportation sector.

Over the past few decades, China underwent rapid urbanization and a surge in transportation infrastructure development⁹. Between 2018 and 2023, the number of highway tunnels increased nationally from 17,738 to 27,297, and the total tunnel mileage expanded from 17,236.1 km to 30,231.8 km, with average annual growth rates of 10.8% and 15.1%, respectively⁸. As transportation infrastructure continues to expand, particularly in the development of transportation networks in complex geographical environments and mountainous regions, the demand for highway tunnel construction - which plays a critical role in overcoming challenging geological conditions - is expected to persist^{10–12}. Compared to other transportation infrastructure, such as roads and bridges, highway tunnels exhibit significantly higher carbon emission intensity per unit of mileage^{13–15}. The resource consumption and carbon emissions

during their construction are particularly notable. The substantial carbon emissions generated during the construction of highway tunnels present a significant challenge to achieving China's carbon peak and carbon neutrality goals^{16,17}.

The issue of tunnel carbon emissions has emerged as a significant topic in the field of global transportation infrastructure, particularly in major tunnel construction countries such as Europe, the United States, and China. International research has generally focused on the carbon emission assessment throughout the entire tunnel construction process, with particular emphasis on quantifying the carbon footprint during construction, operation, and maintenance stages^{3,15,17}. In Europe and the United States, low-carbon design and operational management of infrastructure have been integrated into the core agenda of sustainable urban development¹⁸. For example, studies in countries such as Spain and Norway demonstrated that the use of low-carbon concrete and energy efficiency optimization technologies could significantly reduce carbon emissions intensity during the construction phase^{19,20}. Some studies in the United States have focused on integrating big data analytics to optimize energy efficiency and reduce carbon emissions^{21,22}. Moreover, countries such as the United Kingdom have gradually developed policy frameworks related to carbon emissions, promoting the application of low-carbon technologies through economic incentives such as carbon trading and carbon tax subsidies, thereby driving the green transformation of the infrastructure^{23,24}.

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In recent years, global research on carbon emissions has been shifting towards regional systematic analysis, especially through the application of Life Cycle Assessment (LCA) methods, which comprehensively consider the carbon emission characteristics and carbon reduction effects at different stages and across different regions^{1,2,25,26}. This trend is particularly prominent in Europe, where some countries implemented low-carbon planning in transportation infrastructure and adopted a combination of carbon trading markets and environmental regulations to promote the widespread application of low-carbon construction technologies²⁷.

In contrast, China's research on tunnel carbon emissions began relatively late and mostly focused on carbon emission accounting for individual tunnels and preliminary discussions on localized reduction measures^{28,29}. Although the issue of tunnel carbon emissions in China has gained increasing attention in recent years, existing studies have neither conducted systematic national-scale assessments nor sufficiently considered the carbon emission differences across regions and geologies³⁰. Particularly, given that China's energy structure is still heavily reliant on coal-fired power, the carbon emissions intensity in tunnel construction is generally high, and the application of low-carbon technologies remains in its early stages, which makes the challenge of reducing tunnel carbon emissions even more pronounced.

In this context, this study integrated tunnel construction data from multiple regions in China to develop a model for estimating the carbon emission intensity of highway tunnels at the provincial level. It also proposed a carbon reduction pathway based on low-carbon optimization

design of tunnel cross-sections. Through a multi-scenario analysis, the study further assessed the impact of policy support and technological advancements on the carbon reduction potential of tunnels in China. Compared to existing global research, this study not only provided an estimation of the carbon emission intensity and total emissions specific to China's highway tunnels but also incorporated the country's unique policy environment and technological development. It presented a regionally differentiated carbon reduction strategy, offering theoretical support for tunnel carbon emission management and reduction policy formulation in China and other developing countries.

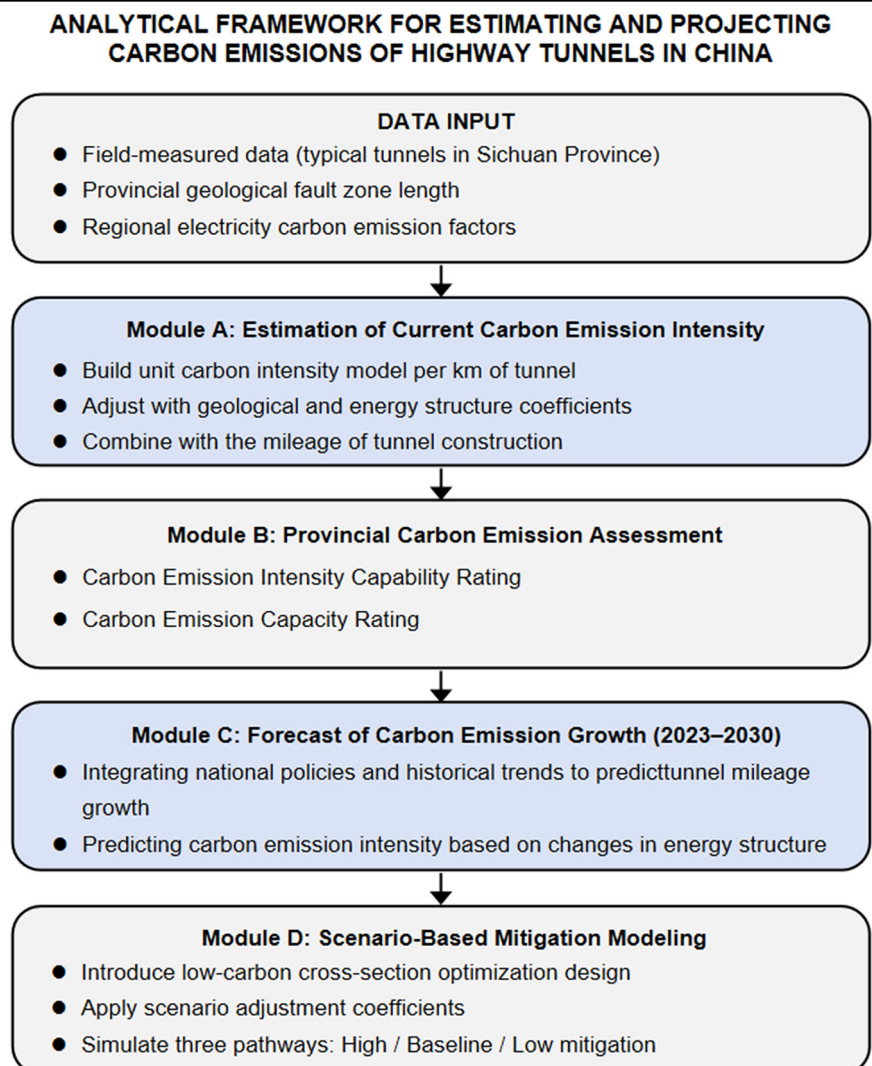
Figure 1 outlines the methodological framework of the study, including the estimation of current tunnel carbon emission intensities, provincial-level extrapolation, construction growth forecasting, and scenario-based mitigation modeling. It helps clarify the logic and sequence of the analytical process applied in this research.

Methods

Estimation of carbon emission intensity for highway tunnels

Due to significant regional differences in data collection, data accessibility, statistical standards, and data availability, accurate calculation of the carbon emission intensity of highway tunnels at the provincial level is challenging. Therefore, the selection of a representative province as a baseline for the study and the application of a scientific methodology to extrapolate carbon emission intensities for other provinces are a rational and necessary research strategy.

Fig. 1 | Analytical framework for estimating and projecting carbon emissions of highway tunnels in China. The framework illustrates the modeling steps, data input, and prediction methods used for analysis.



When developing the carbon emission intensity estimation model, we selected the electricity carbon emission factor and fault zone length as key variables influencing the regional disparities in emission intensity across provinces. The electricity carbon emission factor is closely related to energy consumption and regional differences in energy production structures, significantly affecting carbon emission intensity. Fault zone length, on the other hand, is directly associated with tunnel construction difficulty and energy consumption, and compared to other factors such as rock quality, fault zone length is easier to quantify, making it an ideal parameter for the model.

Sichuan Province was selected as the calibration baseline for the model due to its representative energy structure and geological conditions. The carbon emission intensity calculation model is shown in Eq. (1).

$$F_i = F_{Sichuan} \times \left(w_1 \cdot \frac{f_i}{f_{Sichuan}} + w_2 \cdot \frac{l_i}{l_{Sichuan}} \right) \quad (1)$$

Where F_i is the carbon emission intensity of highway tunnels in the i -th province, $F_{Sichuan}$ is the carbon emission intensity of highway tunnels in Sichuan Province; w_1 and w_2 are the weight parameters for the ratio of electricity carbon emission factor and fault zone length ratio; f_i is the electricity carbon emission factor of the i -th province, $f_{Sichuan}$ is the electricity carbon emission factor of Sichuan Province; l_i is the fault zone length of the i -th province, $l_{Sichuan}$ is the fault zone length of Sichuan Province.

The weight parameters w_1 and w_2 were optimized through Monte Carlo simulations. During the simulations, w_1 was varied over the range [0, 1], and w_2 was set as $1 - w_1$. A total of 10,000 iterations were conducted, using Mean Squared Error (MSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE) as evaluation metrics to assess the error across different weight combinations. The optimal weight combination was selected based on the following criteria:

The first weight set ($w_1 = 0.623$, $w_2 = 0.377$) was identified by minimizing the MSE, effectively controlling large deviations and reducing the impact of data fluctuations, thereby enhancing the model's robustness.

The second weight set ($w_1 = 0.599$, $w_2 = 0.401$) achieved the best composite ranking based on the composite ranking across the three error metrics (ranking the three error metrics, summing the rankings, and selecting the combination with the lowest total rank). This combination achieved a balance between the different error metrics, improving the model's overall stability and accuracy.

Ultimately, the optimal weight combination of $w_1 = 0.599$ and $w_2 = 0.401$ was selected for the model. This choice provided a better balance of errors, ensuring the accuracy and reliability of estimating highway tunnel carbon emission intensity across provinces. By substituting w_1 and w_2 into Eq. (1), the carbon emission intensity of highway tunnels for each province in China was estimated.

Prediction of newly constructed highway tunnel mileage

To predict the future construction trends of highway tunnels in China, this study investigated various machine learning algorithms for forecasting the future tunnel construction mileage across different provinces. The models evaluated included Random Forest, Support Vector Machines (SVM), and Extreme Learning Machines (ELM). We assessed Model performance using metrics such as Mean Squared Error (MSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE). However, the simulation results indicated significant errors between the predicted and observed values. This was primarily attributed to the weak correlation between commonly used features (such as GDP, population, urbanization rate, and percentage of mountainous areas) and the highway tunnel construction mileage, which limited the ability of these models to effectively capture the underlying patterns of highway development.

Following a comprehensive analysis, we leveraged the construction data of expressways to predict the future development trends of highway tunnels. This approach was based on the strong correlation observed between expressways and highway tunnels in terms of construction scale,

technical requirements, and investment, as tunnel construction is often an integral part of expressway projects. Furthermore, the planning and construction goals of expressways outlined for each province in the "14th Five-Year Plan of China for the Development of the Transportation Industry" provide authoritative and forward-looking data that can serve as a reliable reference for future highway tunnel construction.

To this end, we collected and compiled official data on highway tunnel construction mileage across all provinces from 2013 to 2023 (see Supplementary Table 5). The data were sourced from provincial transportation bulletins, transportation yearbooks, and local statistical publications. We denote the annual average new construction ratio of highway tunnels as p_2 and the corresponding ratio for expressways as p_1 (data sourced from the "14th Five-Year Plan of China for the Development of the Transportation Industry" for each province).

For provinces with known p_2 (e.g., Hunan and Jiangxi), we directly used the actual data from Supplementary Table 6. The ratio p_2/p_1 for these provinces reflected the historical relationship between tunnel and expressway construction during the study period. The analysis revealed that while there was some fluctuation in these ratios, the values for most provinces tended to fall within a reasonable range (see Supplementary Table 6, with values generally clustered between 1 and 2).

For provinces with missing p_2 , we imputed the missing values by applying the average ratio of known provinces within the same region. For instance, the average ratio for Anhui and Fujian in East China is 1.39, and this value was applied to the missing data for Shanghai, Jiangsu, and Zhejiang. This approach is based on a reasonable assumption about the distribution of the existing data: when no substantial regional variations are present, missing values can be imputed using the mean of neighboring regions.

Finally, using the annual construction data of newly built highway tunnels in each province, we estimated the future trends in highway tunnel construction across China's provinces.

Prediction of carbon emission intensity of highway tunnels

As a carbon-intensive industry, the carbon emission intensity of highway tunnel construction is significantly influenced by the power supply. The carbon emission intensity of highway tunnel construction (I_{tunnel}) can be decomposed into electricity-related carbon emission intensity (I_e) and non-electricity-related carbon emission intensity (I_{ne}), with the following relationship: $I_{tunnel} = I_e + I_{ne}$.

It was assumed that the non-electricity-related carbon emission intensity (I_{ne}) remained unchanged over time. As the share of clean energy in electricity generation gradually increased, only the electricity-related carbon emission intensity (I_e) during tunnel construction would decrease. Therefore, the carbon emission intensity of highway tunnel construction (I_{tunnel}) would change in line with the variation in electricity-related carbon emission intensity (I_e).

Based on this assumption, this study quantified the impact of an increased share of clean energy in electricity generation on the carbon emission intensity of highway tunnels using the following Eq. (2).

$$I_{target} = I_{current} \times (1 - \eta \times \Delta Fe\%) \quad (2)$$

Where I_{target} represents the carbon emission intensity of highway tunnel construction after the increase in the share of clean energy in electricity generation (in tCO₂-eq per km); $I_{current}$ represents the current carbon emission intensity of highway tunnel construction (in tCO₂-eq per km); η is the proportion of electricity carbon emissions in the total carbon emissions from highway tunnel construction (%); $\Delta Fe\%$ is the relative percentage change in the electricity carbon emission factor (%).

Further explanation of the calculation methods for the variables is provided below. First, $I_{current}$ reflects the carbon emission intensity of highway tunnels across various provinces in China. η represents the proportion of electricity-related carbon emissions during the construction of highway tunnels. Its calculation methodology is consistent with that of

highway tunnel carbon emission intensity. The η values for all provinces are shown in Supplementary Table 9. $\Delta Fe\%$ is calculated using the following Eq. (3).

$$\Delta Fe\% = \frac{F_{\text{target}} - F_{\text{current}}}{F_{\text{current}}} \times 100\% = \frac{F_{\text{fossil}} \times (1 - P_{\text{clean,target}}) - F_{\text{current}}}{F_{\text{current}}} \times 100\% \quad (3)$$

Where F_{target} represents the carbon emission factor of electricity after adjustments to the energy structure; F_{current} represents the current carbon emission factor of electricity under the existing energy structure; F_{fossil} represents the carbon emission factor of electricity generated entirely from fossil fuels; $P_{\text{clean,target}}$ represents the proportion of electricity generated from clean energy sources.

In this study, we assumed that clean energy generation leads to zero carbon emissions. This assumption⁷ is based on the focus of the research on the impact of energy structure adjustment on direct carbon emissions during the power generation stage, and does not cover indirect carbon emissions generated by clean energy power generation equipment during manufacturing, maintenance, scrapping, and other stages. Specifically, to simplify the model, we excluded carbon emissions related to the entire lifecycle of clean energy systems. We acknowledge that these stages do generate carbon emissions, but their scale is relatively small compared to the direct emissions from fossil fuel power generation. Besides, accurate estimation of these lifecycle emissions within the scope of this study is challenging due to data limitations and variability between technology and regions.

In addition, to further narrow the research scope, we also assumed that the carbon emission factor F_{fossil} of fossil fuels remains constant during the study period, without considering the changes in power generation efficiency brought about by technological progress. This assumption enables us to clearly evaluate the trend of the impact of the increasing proportion of clean energy on the overall carbon emission intensity of the power system, without being affected by other variables.

Since the calculation of the electricity carbon emission factor only considers the impact of fossil fuel-based power generation, F_{current} can be expressed as Eq. (4):

$$F_{\text{current}} = F_{\text{fossil}} \times P_{\text{fossil,current}} \quad (4)$$

Where $P_{\text{fossil,current}}$ represents the current proportion of fossil fuel-based power generation. The following relationship holds: $P_{\text{fossil,current}} + P_{\text{clean,current}} = 1$

Thus, the fossil fuel carbon emission factor can be derived as Eq. (5):

$$F_{\text{fossil}} = \frac{F_{\text{current}}}{1 - P_{\text{clean,current}}} \quad (5)$$

The target electricity carbon emission factor, F_{target} can be expressed as Eq. (6):

$$F_{\text{target}} = F_{\text{current}} \times (1 - P_{\text{clean,target}}) \quad (6)$$

where $P_{\text{clean,target}}$ is the target proportion of clean energy generation, ranging from 0 to 1, and can be directly obtained from power statistics. By combining Eq. (5) with varying $P_{\text{clean,target}}$, the electricity carbon emission factor for different clean energy development scenarios can be estimated for each province in China.

By using the above equations, I_{target} and $\Delta Fe\%$ can be calculated. The details are shown in Supplementary Table 9 and Table 10.

Carbon emission reduction method of highway tunnels

In our earlier work, we proposed a tunnel cross-section optimization method based on a modular carbon emission calculation model and elemental inventory data. This approach reduces energy consumption during

tunnel construction and optimizes the carbon emission intensity by adjusting the cross-sectional dimensions and material selection. The optimization method was applied in several tunnel projects, demonstrating significant carbon reduction potential.

The carbon reduction benefits are calculated using the following Eq. (7):

$$\Delta C = (M_{\text{baseline}} - M_{\text{optimized}}) \times EF \times L \quad (7)$$

Where ΔC_{design} represents the carbon reduction achieved through the tunnel lining optimization design; M_{baseline} and $M_{\text{optimized}}$ represent the material usage per unit length of tunnel under conventional lining design and optimized lining design, respectively; EF is the material carbon emission factor; L is the construction mileage of the highway tunnel.

To achieve the low-carbon optimization design method for tunnel cross-sections, the following assumptions were made:

- (1) The primary optimization objective of all design schemes is the minimization of carbon emissions during the construction phase, with no consideration given to other optimization factors such as construction costs or schedules, provided that safety constraints are met.
- (2) We assume that the modular carbon emission calculation framework can be effectively applied under various geological conditions, with the associated calculation errors remaining within an acceptable range. This assumption ensures the applicability and comparability of the low-carbon optimization design method across different tunnel design schemes.
- (3) The influence of design variables such as the type of support structure, concrete lining thickness, and anchor parameters on carbon emissions is predictable. To simplify the optimization process, these design variables are limited to a few key parameters, thereby reducing the complexity of the calculations.

This method was applied in a demonstration project along the Yichang–Fuling section of a tunnel system in Hubei Province, China. We selected representative tunnels with Grade III, IV, and V surrounding rock conditions and constructed two sets of comparative design schemes: the original (baseline) and optimized plans. As shown in Supplementary Table 14, the optimized designs utilize structurally equivalent but materially more efficient configurations. The revised designs comply fully with regulatory standards while reducing the material and energy consumption required during construction.

By applying the modular carbon accounting model, we quantified and compared the construction-phase carbon emission intensity ($\text{kgCO}_2\text{-eq per m}$) under both the baseline and optimized designs for each rock mass grade. The results are presented in Supplementary Table 15. The optimized cross-section schemes achieved significant reductions in carbon intensity across all geological conditions: 30.26% for Grade III, 42.00% for Grade IV, and 22.85% for Grade V. Weighted by tunnel length, the overall comprehensive carbon reduction rate reached approximately 35%. These results were validated against on-site project data and were within an acceptable error margin.

The above results demonstrated that the method is suitable for low-carbon optimization in tunnel construction projects. Due to significant variations in geological conditions and energy structures across different provinces, the carbon reduction rate observed in Hubei Province cannot be directly applied to other provinces. Based on the generalization of Hubei's reduction rate, we estimated the carbon reduction potential for highway tunnels in various provinces of China following the application of the cross-section optimization design method. The details are shown in the Results.

Data sources

The data used in this study consist of the highway tunnel construction mileage, electricity carbon emission factors, and fault zone lengths across various provinces in China. These data form the basis for investigating the carbon emission characteristics and regional differences of highway tunnels

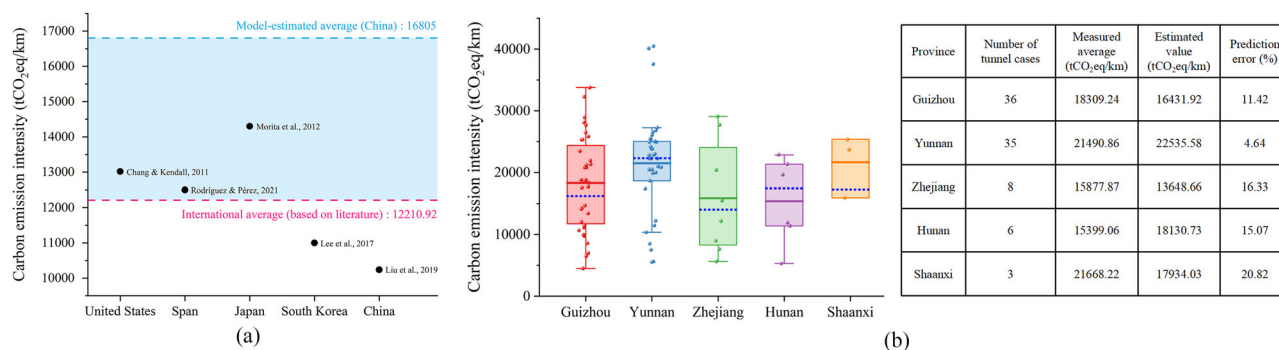


Fig. 2 | Validation of model-estimated carbon emission intensity for tunnels. **a** Comparison of the average carbon emission intensity estimated in China with international averages reported in representative studies. **b** Comparison between

estimated and measured provincial-level carbon emission intensities across five representative provinces in China.

in different provinces. Specifically, the highway tunnel construction mileage serves as the basis for calculating the carbon emissions from highway tunnels, while the electricity carbon emission factor and fault zone length reflect the impact of provincial power production methods and geological conditions on the carbon emission intensity of highway tunnels. The specific sources for these data are detailed in Supplementary Tables 1, 2, and 3.

Results

Current carbon emission status of highway tunnels in China

This study, based on the carbon emission intensity data of highway tunnels in Sichuan Province from previous work^{29,31–33}, quantified the carbon emission intensity of highway tunnels in China, considering the differences in energy structure and geological conditions across provinces.

To further validate the effectiveness of the estimated results in this study, we systematically compared the calculated carbon emission intensities of highway tunnels with data from recent international studies^{13,20,34–36} (Fig. 2a). The average carbon emission intensity of China's highway tunnels, as calculated in this study, was 16,805 tCO₂-eq per km, which was slightly higher than the values reported in most international literature. This difference likely arose from variations in construction standards, tunnel sizes, and energy consumption levels among regions. However, overall, the estimated results from this study were of the same order of magnitude as the carbon emission intensities in international studies and were within a reasonable margin of error.

To further assess the accuracy and applicability of the estimation model, we collected actual data from several inter-provincial highway tunnels in China and quantified the average carbon emission intensities for tunnels in these provinces, comparing them with the results derived from our model (see Fig. 2b). The results showed a good consistency between the model's estimates and the actual data, with an average error of 5.77%. This suggested that the estimation model in this study was highly accurate and reliable in most cases.

However, it is worth noting that the error rate for Shaanxi Province exceeded 20%. This deviation was primarily due to the limited sample size of tunnel construction cases in Shaanxi, as we only focused on a few complex geological cases in the Qinling area, leading to a higher-than-expected carbon emission intensity for this region. To enhance the representativeness of the model, future work should expand the sample size and include more tunnel cases from various geological types.

For the other four provinces, we collected multiple tunnel design cases, and the calculated carbon emission intensities showed a smaller discrepancy compared to the model's estimates. Notably, in the case of Yunnan Province, after collecting data from 35 tunnels and calculating the actual carbon emission intensities, the error rate was found to be only 4.64%, which indicated high reliability of the estimated results.

In conclusion, by comparing the results of this study with those from the domestic and international literature, it was evident that although some discrepancies existed, the overall results were consistent with the carbon

emission intensity data from other studies, proving that the estimation model had strong applicability and reliability. Future research should further refine the model, particularly in the context of regional differences and changes in energy structure, to enhance its adaptability and accuracy.

Using high-resolution satellite imagery, we manually labeled and measured geographic information for each highway tunnel, resulting in the creation of the China highway tunnel construction mileage database (Supplementary Table 3), with an accuracy of 95%. Based on these foundational data, we analyzed the construction mileage and carbon emission characteristics of highway tunnels across Chinese provinces as of the end of 2023, as shown in Fig. 3.

The results indicated that provinces with longer tunnel construction mileage generally had higher carbon emissions (Supplementary Table 4). These provinces (such as Yunnan, Guizhou, and Sichuan) are typically located in mountainous areas where large-scale tunnel construction is required to meet transportation needs. In contrast, some provinces and municipalities (such as Beijing and Jiangsu) have relatively shorter tunnel construction mileage and lower carbon emissions due to their smaller land areas and relatively flat terrain (Figs. 3a and 4c). However, Fig. 3b showed that the differences in tunnel carbon emission intensity between provinces were relatively small. This was because, when calculating the carbon emission intensity of highway tunnels in China, we comprehensively considered the influence of each province's energy structure (which increases carbon emission intensity) and geological conditions (which reduce carbon emission intensity), leading to similar carbon emission intensity results across provinces.

Carbon emission characteristics rating of highway tunnels in China

To further explore the regional differences in tunnel carbon emissions across various regions, this study conducted both quantitative and qualitative analyses at the provincial level. The carbon emission intensity and total emissions of highway tunnels in each province of China were used as research indicators. Figure 4 showed the quartile ranking results of the carbon emission characteristic capacity ratings across different provinces.

Total carbon emissions typically follow a top-down management perspective, where the government is more concerned with examining, from a macro level, whether the local highway tunnel carbon emissions stock and overall growth trend exceed the prescribed limits. Based on this, the government set corresponding emission reduction targets and strategies (Fig. 4a). On the other hand, carbon emission intensity reduction follows a bottom-up management perspective, where construction enterprises focused more on how to safely complete the highway tunnel construction while minimizing pollution and energy consumption to meet transportation needs (Fig. 4b). For instance, Xinjiang Province had the highest carbon emission intensity for highway tunnels, far exceeding other provinces, which could impose significant environmental pressures on enterprises planning and constructing highway tunnels. However, the total carbon

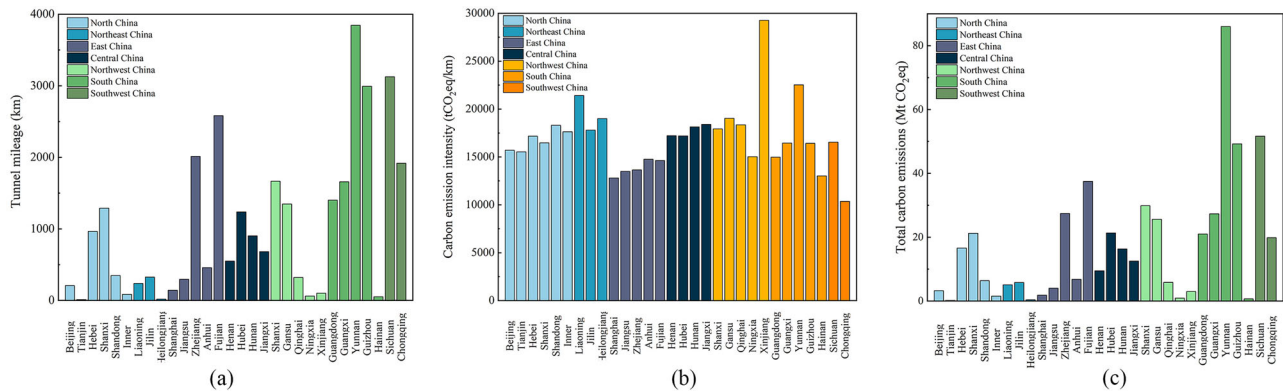


Fig. 3 | Highway tunnel construction mileage and carbon emission characteristics in China in 2023. a Highway tunnel construction mileage. **b** Carbon emission intensity of highway tunnel construction. **c** Total carbon emissions from highway tunnels.

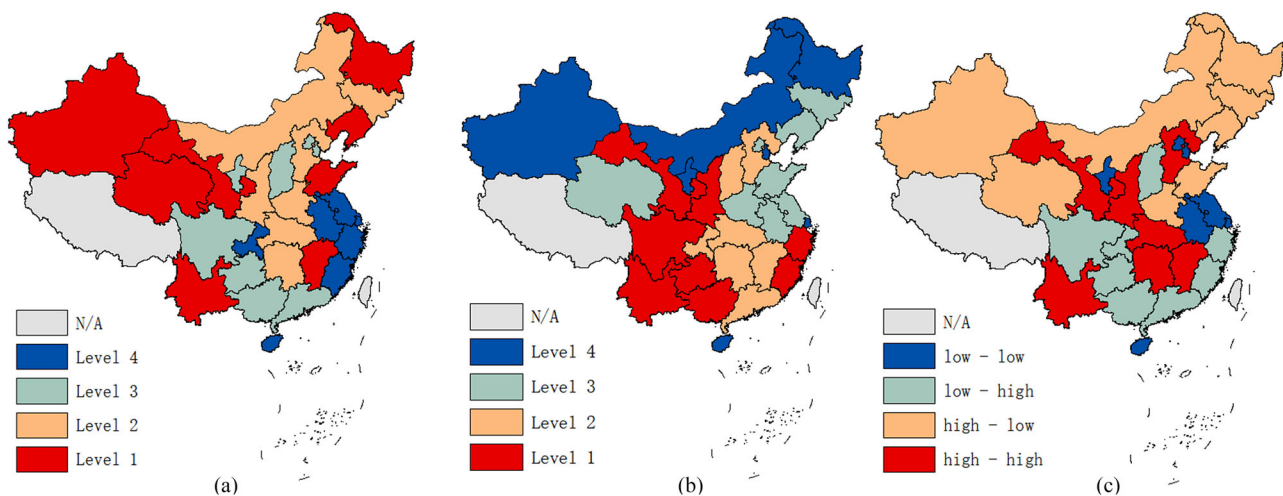


Fig. 4 | Regional analysis of highway tunnel carbon emission characteristics in China. a Provincial capacity rating based on highway tunnel carbon emission intensity. **b** Provincial capacity rating based on total carbon emissions from highway tunnels (Level 4 to 1 indicates increasing capacity). **c** Comprehensive rating of tunnel

carbon emission intensity and total emissions, where the “Low-Low” mode indicates that the province ranks in the bottom 50% nationally for both carbon emission intensity and total carbon emissions.

emissions from highway tunnel construction in Xinjiang remained relatively low compared to other regions, making it a typical case of “high carbon emission intensity - low carbon emission total.” Due to the significantly lower tunnel construction mileage and demand in Xinjiang compared to provinces such as Sichuan and Yunnan, the province received less attention from a macro perspective when formulating national carbon emission reduction measures and pathways for highway tunnels. In contrast, provinces like Yunnan and Hunan, with both high emission intensity and total emissions, were under greater pressure to reduce carbon emissions, as they rank within the top 50% of carbon emissions in China (Fig. 4c).

Forecast of carbon emission growth of highway tunnels in China

With the expansion of China’s transportation network, the construction mileage of highway tunnels continued to increase, which is a key factor driving the changes in tunnel carbon emissions. This study developed a predictive model for highway tunnel construction mileage and created a database for highway tunnels in China. (Supplementary Tables 7 and 8).

In the face of increasing global pressure to address climate change, the transition to clean energy has become a critical pathway to achieving carbon reduction goals. The carbon emissions from highway tunnels primarily arise from the production and transportation of construction materials, as well as the use of construction equipment, with most of the energy demand met by electricity. As the share of clean energy increases, reliance on fossil fuels will gradually decrease, which helps to reduce the carbon emissions factor of

electricity. This, in turn, reduces carbon emissions from electricity consumption during tunnel construction and lowers carbon emission intensity. This study considered the clean energy generation structure as a key variable for forecasting future changes in carbon emission intensity and predicted the growth trends of highway tunnel carbon emission intensity and total emissions from 2023 to 2030 (Supplementary Tables 12 and 13). The visualization of tunnel mileage and carbon emission growth is shown in Fig. 5.

The growth of highway tunnel mileage in different provinces of China showed significant regional differences (Fig. 5a). The southern and southwestern regions (e.g., Guangxi and Sichuan) were projected to experience rapid tunnel growth in the coming years, while the northern, northeastern, and eastern regions would have relatively lower tunnel demand. This phenomenon was closely related to local transportation needs and geographical conditions. Meanwhile, the overall carbon emission intensity of highway tunnels was on a downward trend (Fig. 5b) in China, particularly in the North China region, where the increase in clean energy share significantly reduced the carbon emission factor, driving the decrease in carbon emission intensity. However, in some areas, such as Hubei Province, the carbon emission intensity had slightly increased, which might be related to the delayed energy transition or a short-term increase in tunnel construction activities.

Although the carbon emission intensity has shown an overall decreasing trend, the expansion of infrastructure would lead to a continuous

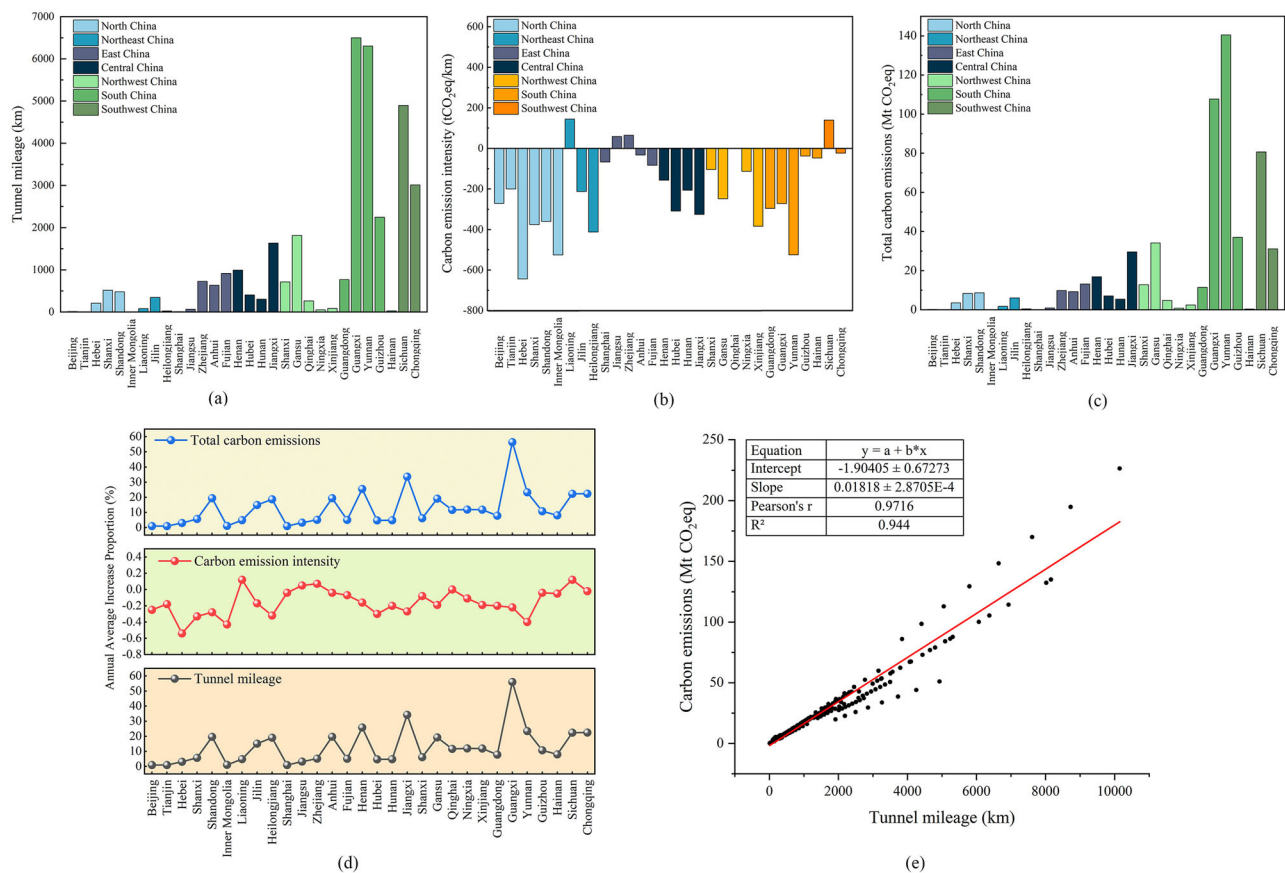


Fig. 5 | Analysis of highway tunnel mileage, carbon emission intensity, and total emissions growth for each province in China from 2023 to 2030. a Highway tunnel mileage. **b** Highway tunnel carbon emission intensity. **c** Highway tunnel total

carbon emissions. **d** Annual average growth rates of highway tunnel mileage, carbon emission intensity, and total emissions. **e** Correlation analysis of tunnel mileage and carbon emissions.

increase in the total carbon emissions (Fig. 5c). Moreover, the average growth rates of tunnel mileage and total carbon emissions showed similar fluctuating patterns (Fig. 5d). Notably, in regions with dense and rapidly growing tunnel construction (e.g., Yunnan and Guangxi), the growth in total carbon emissions was also more pronounced. The change in tunnel carbon emission intensity is minimal (changing by no more than 1% annually), primarily because the carbon emission factor of electricity is already at a low level. Without considering the energy-saving effects from other technological advancements, the increase in the share of clean energy generation had resulted in limited further reductions in carbon emission intensity.

To further clarify the relationship between tunnel mileage and carbon emissions, a linear regression analysis was conducted using the tunnel mileage and carbon emission data from Chinese provinces and municipalities between 2023 and 2030. The results are shown in Fig. 5e. The horizontal axis represents tunnel mileage, and the vertical axis represents tunnel carbon emissions. The Pearson correlation coefficient between the two variables reached 0.9716, indicating a very strong linear correlation. For every 1 km increase in tunnel mileage, carbon emissions increased by 0.673 MtCO₂-eq. This conclusion provided a basis for the dynamic quantitative analysis of highway tunnel carbon emissions in relation to construction mileage in China.

Scenario analysis of the carbon emission reduction path of the highway tunnel in China

Due to the large number of highway tunnels and significant geological differences across China, accurately calculating the carbon reduction potential for all provinces was challenging. Based on previous research findings^{29,31–33}, this study estimated the potential carbon reduction ratios for

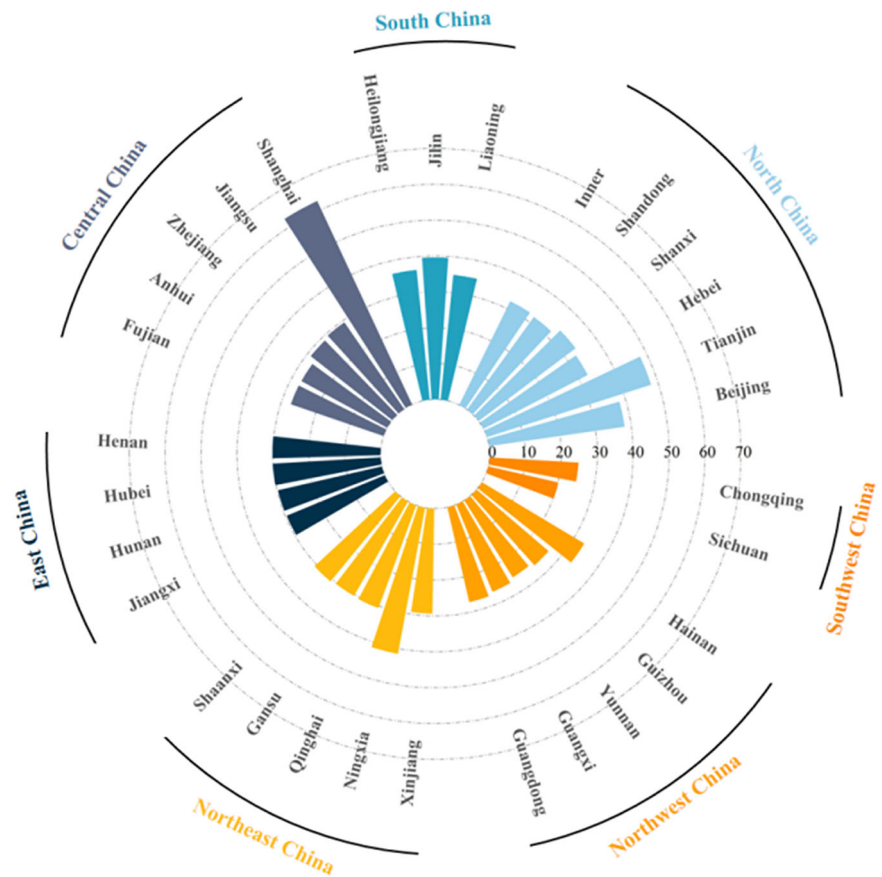
tunnel cross-section optimization across different provinces in China, considering variations in geological conditions and energy structures. The results are shown in Fig. 6. After implementing the low-carbon optimization design for tunnel cross-sections, the achievable carbon reduction ratios ranged from 20.04% (Sichuan) to 62.58% (Shanghai), demonstrating a clear regional variation.

Highway tunnels, as a significant source of carbon emissions in transportation infrastructure, had their reduction potential influenced by various factors, including technological applications, policy interventions, and regional conditions. This study developed a multi-scenario analysis model to quantify the carbon reduction potential of highway tunnels in each province of China from 2023 to 2030 under different development pathways, providing a basis for formulating differentiated reduction policies.

Building upon the previously proposed low-carbon optimization design method for tunnel cross-sections, this study developed three typical scenarios: the baseline scenario (considering the application of a single low-carbon optimization design method), the high-reduction scenario (where policy support and technological advancement work in synergy), and the low-reduction scenario (where policy and technology are constrained). To reflect the amplifying or inhibiting effects of external policy environments and technological developments on the baseline reduction potential, we introduced the scenario adjustment coefficient (SAC), which adjusts the carbon reduction effects across various scenarios. It is important to note that this study assumed that the impact mechanisms of policy support and technological progress on carbon reduction were relatively independent, and their combined effects were represented by a multiplicative relationship.

Technological Improvement (T). Technological factors were identified as key drivers in the continuous reduction of carbon intensity in tunnel

Fig. 6 | Carbon emission reduction potential of highway tunnel sections optimized by all provinces in China. Potential carbon emission reductions from optimizing tunnel cross-sections in different provinces of China. The radial bar displays the percentage of emission reduction potential.



construction, encompassing various aspects such as the substitution of low-carbon materials, energy efficiency optimization, and the application of intelligent construction management^{37,38}. Existing studies showed that the use of low-carbon building materials (e.g., blast furnace slag concrete, prefabricated structures) could reduce carbon emissions by more than 15% during the construction phase^{39,40}. Moreover, enhancing the resource recovery and recycling rates of construction waste and excavated soil further increased the potential for carbon reduction^{41,42}.

Policy Support (P). Policy interventions, through legal, financial, and market mechanisms, played a crucial role in shaping carbon emission pathways, determining the feasibility of low-carbon technologies, and influencing the scale of emission reductions⁴³. The establishment of specialized environmental courts and judicial review mechanisms for ecological protection provided institutional support for green development^{44,45}. Additionally, the advancement of carbon trading systems and carbon tax policies helps internalize carbon costs into investment decisions, thereby incentivizing companies to proactively reduce emissions⁴⁶. Empirical studies indicated that a variety of environmental regulatory policies could significantly contribute to synergistic emission reductions, with carbon intensity decreasing annually by approximately 7.4%⁴⁷.

Based on the quantitative basis of policy support and technological progress mentioned earlier, the specific settings of the three scenario models were shown in Table 1.

Based on the aforementioned scenario models, this study conducted a simulated analysis of the carbon emission trends for newly constructed highway tunnels in China under different scenarios, with the results detailed in Table 2. The simulation results indicated that, in the baseline scenario, where only the low-carbon optimization design method for tunnel cross-sections proposed in this study is implemented, the total carbon emissions

from newly constructed highway tunnels in China by 2030 were expected to be 948.8 million tonnes (Mt). This represented a reduction of approximately 154.6 Mt compared to the carbon emission forecast without any reduction measures (11.03 Gt), resulting in a 14.01% reduction. In the high reduction scenario, due to the combined effect of policy support and technological advancement, the carbon reduction effect was further enhanced compared to the baseline scenario. By 2030, the total carbon emissions from newly constructed tunnels in China were projected to decrease to 916.3 Mt, achieving a reduction rate of 16.95%. In contrast, the low reduction scenario demonstrated the inhibitory effects of weak policy enforcement and slow technological progress. In this scenario, the total carbon emissions by 2030 were projected to be 963.8 Mt, achieving a carbon reduction of only 139.6 Mt, with a reduction rate of 12.65%. Compared to the high reduction and baseline scenarios, this represented a difference of approximately 4.30 and 1.37 percentage points, respectively, demonstrating the significant weakening of the reduction pathway under unfavorable external conditions.

Overall, the predictive results from the three scenarios indicated that although the low-carbon optimization design for tunnel cross-sections has clear carbon reduction potential, its actual effectiveness depended to some extent on the level and stability of policy guidance and technological innovation. The synergistic mechanisms in the high reduction scenario not only enhanced the reduction magnitude but also provided a feasible pathway for the green transformation of future highway tunnel construction. In contrast, in the low reduction scenario, uncertainties in policy and technology might weaken or even offset the expected outcomes of the baseline reduction measures, which should raise significant concerns for policymakers and industry regulators.

According to data provided by the Global Carbon Project, China's total carbon emissions increased from 9.7 Gt in 2016 to 12 Gt in 2024, with an annual growth rate of 2.96%. Based on this growth rate assumption, it was estimated that by 2030, China's total carbon emissions will increase by

Table 1 | Scenario assumptions and SAC

Scenario	Scenario assumption	Key factor	SAC (%)	Notes
Baseline scenario	The project is implemented in strict accordance with current industry standards, utilizing only the low-carbon optimization design method for tunnel cross-sections proposed in this study for emission reduction, without incorporating additional policy incentives or technological advancements.	No additional policy or technological interventions.	1	As the basis for subsequent scenario comparison and analysis. The predicted changes in carbon emission intensity and total emissions for China's highway tunnels from 2023 to 2030 are provided in Supplementary Tables 16 and 17.
High-reduction scenario	Building upon the baseline scenario, external positive interventions at the policy and technological levels are further introduced. It is assumed that policy support can enhance emission reduction benefits by approximately 8%, while technological advancements can lead to a reduction of approximately 12%.	Policy support (an 8% increase), technological progress (a 12% increase).	1.21 (1.21 times the baseline scenario)	The combined effect of both factors is adjusted using the product method.
Low-reduction scenario	This scenario reflects an unfavorable development pathway characterized by insufficient policy support and delayed technological progress. Both policy and technological factors are assumed to exert a 5% inhibitory effect on emission reduction benefits.	Policy and technology each exert a 5% inhibitory effect.	0.90 (90% of the baseline scenario)	Based on the product relationship, this scenario reflects the limitations of policy and technological progress.

Table 2 | Future changes in the carbon emission reduction potential of new highway tunnels under different scenarios

Scenario	Total carbon emissions from highway tunnels in 2023 (100 Mt)	Total carbon emissions from highway tunnels in 2030 (100 Mt) (without considering emission reduction measures)	SCA	Total carbon emissions from highway tunnels in 2030 (100 Mt) (after emission reduction)	Carbon reduction (100 Mt)	Emission reduction rate (%)
Baseline scenario	5.184	11.034	1.21	9.163	1.871	16.95
High-reduction scenario			1.00	9.488	1.546	14.01
Low-reduction scenario			0.90	9.638	1.396	12.65

approximately 2.3 Gt, reaching 14.3 Gt. This data indicated that, as economic development and energy consumption structures continue to evolve, total carbon emissions would rise further, presenting significant challenges to achieving carbon reduction targets.

Against this backdrop, the implementation of low-carbon optimization design methods for newly constructed highway tunnels was expected to achieve a carbon reduction of 154.6 Mt by 2030. This reduction accounted for approximately 1.08% of China's total carbon emissions in 2030 and was expected to represent 6.74% of the emissions growth from 2023 to 2030. This proportion highlighted the significant role highway tunnel carbon reduction plays in mitigating the overall growth of China's carbon emissions. Moreover, as part of the transportation sector, the carbon reduction effect of highway tunnels would be further enhanced with the development of low-carbon environmental policies and green transportation technologies. When combined with other emission reduction measures in the transportation sector, the carbon reduction benefits of highway tunnels would contribute more significantly to the overall carbon reduction strategy.

Integrated assessment of carbon emissions from tunnel expansion in China

We conducted a comprehensive evaluation of China's additional tunnel mileage, incremental carbon emissions, and total carbon reduction (based solely on the low-carbon optimization design method for tunnel sections) between 2023 and 2030 (see Fig. 7).

In southern and southwestern regions such as Yunnan, Guizhou, Sichuan, and Chongqing, strong demand for transportation infrastructure—combined with mountainous terrain and complex topography—led to a sharp increase in tunnel mileage, consequently driving up carbon emissions. These areas became major contributors to the ongoing rise in nationwide tunnel-related emissions. Notably, Yunnan Province alone contributed 35.7 Mt CO₂-eq to the increase in China's emissions, nearly equivalent to the combined contribution of 24 other provinces and municipalities (excluding Guangxi, Sichuan, Guizhou, Chongqing, and Jiangxi). At the same time, these regions also possessed relatively high potential for emission reductions if appropriate reduction measures were applied. In contrast, northern and eastern regions exhibited lower demand for tunnel construction, and thus exerted a comparatively smaller impact on the carbon emission growth in China.

Overall, regional disparities in carbon emissions reflect substantial differences in tunnel construction scale, geological conditions, and technological capabilities across provinces. These variations required region-specific reduction strategies. In high-emission provinces with complex

tunnel construction conditions—such as Sichuan and Yunnan—priority should be given to optimizing construction processes, improving the reuse rate of waste materials, and increasing the proportion of low-carbon materials, thereby reducing emissions during the construction phase. In contrast, regions with less complex tunnel construction could focus on deepening carbon trading market reforms in the building sector and promoting the research and application of advanced low-carbon technologies. Successful experiences in these regions could be scaled up to facilitate the broader low-carbon transformation of the tunnel construction sector.

In addition, local governments played a crucial role in advancing the application of low-carbon technologies and formulating green policies. For example, the governments of Beijing and Shanghai actively promoted green building practices and the adoption of low-carbon technologies in tunnel projects, including the use of environmentally friendly materials and advanced construction methods. These efforts yielded notable success in controlling carbon emissions. By contrast, regions with weaker policy support had made less progress in emission reduction. Therefore, continued promotion of locally driven policies is essential for achieving regional and national carbon reduction goals.

Overall, with continuous technological advancements and sustained policy support, carbon emissions in China's highway tunnel sector were expected to be effectively controlled, contributing significantly to the carbon peaking and carbon neutrality goals.

Discussion

In recent years, research on carbon emissions has expanded to include multiple research fields and multi-scale modeling approaches^{1,2,48}. Some scholars have estimated the total carbon emissions of transportation infrastructure, such as highways and railways, and have explored their growth trends or carbon reduction potential^{13,15,20}. These studies typically employed Life Cycle Assessment (LCA) methods to comprehensively evaluate carbon footprints, providing valuable references for the low-carbon development of similar projects. However, as mentioned in the introduction, most existing research on tunnel carbon emissions focused on the micro level, often using case studies to quantitatively analyze the carbon emissions related to materials, structural types, or construction processes for individual tunnels⁴⁹. While these studies revealed the mechanisms through which key technical parameters affect tunnel carbon emissions, systematic modeling and trend forecasting at the regional or national scale are still lacking.

In contrast, this study achieved both an extension and a breakthrough in research scope and modeling approach. On the one hand, this study

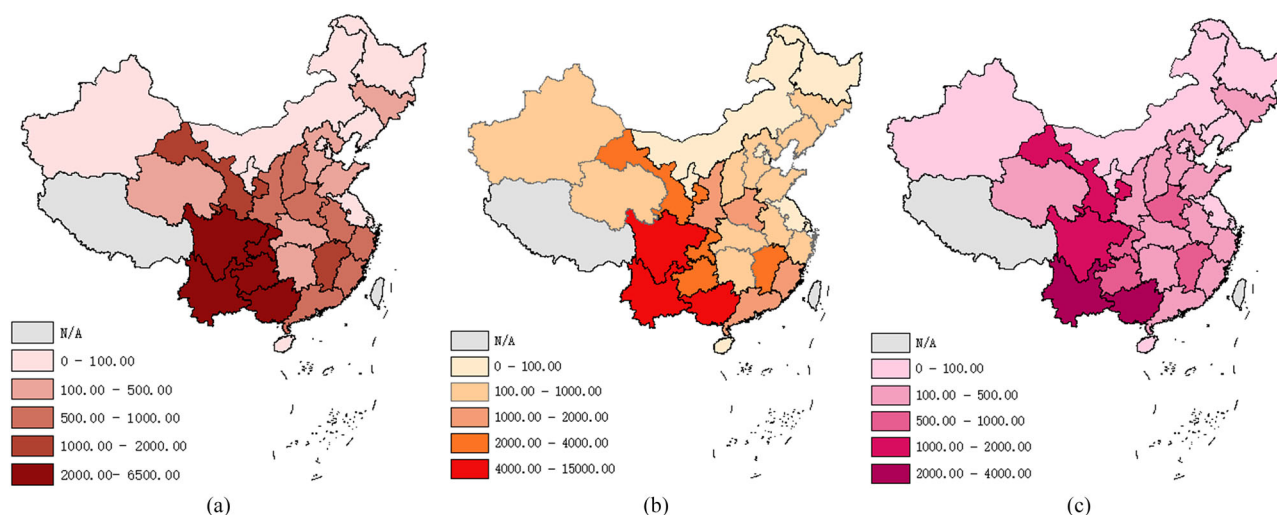


Fig. 7 | Analysis of the growth changes in highway tunnel mileage, carbon emissions, and carbon reduction. **a** New highway tunnel mileage from 2023 to 2030 in China. **b** Total new carbon emissions from highway tunnels. **c** Total carbon

reduction from highway tunnels. The darker the color of the blocks, the stronger the characteristic performance.

constructed a tunnel carbon emission intensity extrapolation model based on field data from Sichuan Province, incorporating electricity carbon emission factors and geological fault zone parameters. It quantified the carbon emission intensity distribution and total emissions for highway tunnels across 30 provinces in China, and validated the model using data from 90 typical tunnels in five provinces. This approach overcame the limitations of single-project analysis and broadened the research on tunnel carbon emissions from the micro to the macro level.

On the other hand, this study proposed a carbon reduction strategy based on low-carbon optimization design for tunnel cross-sections and further constructed three typical scenarios: high reduction, baseline, and low reduction. It introduced the scenario adjustment coefficient to account for the amplifying or inhibiting effects of policy support and technological advancements on the reduction outcomes. This scenario simulation framework, which integrates technology, policy, and regional heterogeneity, enhanced the existing modeling methods for carbon reduction pathways and provided quantitative support for the formulation of green and low-carbon development policies in the tunnel sector.

Overall, by developing a model that can estimate the total carbon emissions of provincial and national level tunnels, this study provided a more comprehensive tool for policy makers and researchers interested in assessing the broader environmental impacts of tunnel construction. In addition, the use of empirical data from different regions enhanced the reliability of our research results and more accurately represented the carbon emission intensity of various regions in China. The model developed in this study could also be applied to future research in other regions, contributing to the global knowledge system of tunnel carbon emissions.

It is important to note that although this study developed a comprehensive tunnel carbon emission model system and conducted multi-scenario analysis of carbon reduction pathways for highway tunnels in China, there are still some limitations. The following is a detailed discussion of the main limitations:

First, the carbon emission intensity data for China's highway tunnels are primarily extrapolated from the measured results in Sichuan Province. Although this method has been validated using data from 90 tunnels across five provinces, with an error tolerance of approximately 5%, differences in material selection, construction techniques, and geological conditions across regions could still affect the model's accuracy^{29,49,50}. To further improve the model's applicability and generalizability, future research should expand the data collection scope to include actual data from more regions and conduct a comprehensive sensitivity analysis. This will enable researchers to better identify and quantify the carbon emission characteristics of different regions, thereby enhancing the robustness and widespread applicability of the model^{51,52}.

Second, while the extrapolation model used in this study processes variable relationships based on proportional relationships, which provides simplicity and applicability, we recognized that this assumption oversimplified the potential nonlinear interactions between different parameters in tunnel engineering^{33,54}. In particular, for large tunnels, high-altitude areas, or special geological conditions, the response relationship between energy consumption and carbon emissions might not conform to a strict linear assumption³⁷. Moreover, factors such as tunnel design optimization, complex geological conditions, and construction organization methods could introduce nonlinear interference^{12,55}. Therefore, future research should consider incorporating multivariate nonlinear regression models or machine learning methods to further reveal the complex interactions between different design parameters, geological factors, and construction methods, thereby enhancing the model's capacity to simulate real-world engineering conditions.

Lastly, the scenario coefficient used in this study is primarily set based on existing literature and experience. While the coefficient reasonably represents the main factors of policy support and technological advancements, it did not fully account for the actual performance of policy enforcement and the speed of technological progress across different regions. For instance, some regions might

have stronger policy support, while others might face difficulties or delays in policy implementation, limiting the effectiveness of carbon reduction. Additionally, the pace of technological progress could vary significantly across regions; some areas might experience faster adoption of low-carbon technologies, while others could be constrained by funding or technical resources. Therefore, the current scenario adjustment coefficient was somewhat subjective and simplified in certain scenarios. Future research could introduce more refined regional adjustment factors or integrate dynamic data to further enhance the reliability and representativeness of the scenario adjustment coefficient.

Data availability

The datasets supporting the findings of this study are included in this article and its supplementary data files.

Code availability

This study did not utilize any custom code or software central to its conclusions.

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Author contributions

Y.G. and S.W. designed the study and wrote the first draft of the manuscript. Z.G. and X.T. collected and were responsible for figure creation and data visualization. Y.G., Y.W., and N.H. performed the simulations and analyses. P.J. and K.S. assisted with the data processing and quality control. C.G. reviewed and provided technical guidance on the manuscript. All authors contributed to the discussions on the methods and writing of the article and reviewed the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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