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Research Article

Exploring the link between CO_2 emissions, economic growth, urbanization and transportation infrastructure in China: Evidence from the ARDL model

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Abstract. As the challenge of global climate change becomes increasingly severe, carbon emissions have become a key constraint on sustainable development. This study aims to explore the impact of economic growth, urbanization, and transportation infrastructure on carbon emissions in China. Using time-series data from 1977 to 2022, the study employs the Autoregressive Distributed Lag (ARDL) model to analyze the short-term and long-term dynamic relationships between these variables, and the Vector Error Correction Model (VECM) to assess the causal relationships. The ARDL regression results show that, in the short run, economic growth has an immediate significant positive effect on carbon emissions, while urbanization exhibits mixed lagged effects—initially increasing and later reducing emissions. Transportation infrastructure has no immediate impact but shows a significant emission-reducing effect through its lagged terms. In the long run, economic growth exhibits an insignificant negative impact on emissions, urbanization has an insignificant positive effect, and the expansion of transportation infrastructure is positively associated with increased carbon emissions. Granger causality analysis reveals that carbon emissions and urbanization exhibit a bidirectional causal relationship in the short run. In the long run, carbon emissions are mutually causal with economic growth, and are also unidirectionally influenced by transportation infrastructure. This study emphasizes the importance of developing an integrated policy framework to balance economic growth, urbanization, and transportation infrastructure with environmental sustainability.

Keywords: Economic growth; Urbanization; Carbon emission; ARDL model; Causality

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1. Introduction

Carbon emissions have emerged as a major obstacle to sustainable development in the face of global climate change. As the world's largest developing country, China has undergone rapid economic growth and industrialization, leading to immense carbon emission pressures (Li *et al.*, 2018). According to the International Energy Agency (IEA), China accounts for nearly one-third of global carbon emissions (IEA,2021). In response, the Chinese government has introduced ambitious carbon peaking and neutrality goals, yet achieving these targets requires a deeper understanding of the driving factors behind carbon emissions.

The relationship between economic growth and carbon emissions has long been discussed (Mardani *et al.*, 2019; Antonakakis *et al.*, 2017). Traditional views suggest economic expansion leads to rising energy consumption and direct carbon emissions, but recent advancements in technology have enabled some countries to decouple growth from emissions through industrial restructuring, energy efficiency improvements, and technological innovation (Ozturk and Acaravci, 2010; Lotfalipour *et al.*, 2010; Chang *et al.*, 2023; Akram *et al.*, 2022). Moreover, the formulation of sound macroeconomic policies can contribute to reducing ecological impacts by aligning economic objectives with environmental sustainability.

In China, economic growth has been primarily driven by urbanization, accompanied by rapid infrastructure expansion (Wang *et al.*, 2018; He and Sim, 2015; Tong and Yu, 2018). Urbanization and transportation infrastructure both contribute to increased carbon emissions by driving up energy demand and enhancing transportation accessibility. As urbanization concentrates populations and industries in urban areas, transportation infrastructure expands to accommodate growing transportation needs, leading increasing carbon emissions for more residential energy consumption as well as higher energy use from transportation.

Despite these significant influences, most existing studies examine these factors in isolation, with limited research on their combined effects. Given the unique characteristics of China's economic transition, a systematic analysis of these macro-economic factors is essential. The research results can provide a deeper understanding of the interplay between economic transition and low-carbon development, and valuable insights that inform tailored low-carbon strategies. Moreover, our findings can also serve as a reference for other developing countries seeking to balance economic growth and environmental protection in the urbanization process.

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To investigate these issues, this study employs the Autoregressive Distributed Lag (ARDL) model and the Vector Error Correction Model (VECM) to analyze both short- and long-term dynamics, alongside the Granger causality test to assess causal relationships. The main findings are as follows: (1) Economic growth does not exhibit a statistically significant long-run impact on emissions, and a significant positive association is observed only with the first lag of economic growth in the short run with insignificant subsequent effects; (2) Urbanization and transportation infrastructure also play significant roles—transportation infrastructure contributes to rising emissions in the long run, whereas urbanization has a mixing effect, increasing emissions over time but temporarily mitigating them in the short run; (3) CO_2 emissions and economic growth exhibit bidirectional causality in the long run, while CO_2 and urbanization are interlinked in the short run. A unidirectional long-run causality is observed from transportation infrastructure to CO_2 emissions.

The structure of this paper is as follows: Section 2 reviews the relevant literature, summarizing key findings and existing research gaps. Section 3 introduces the data sources, variable selection, and empirical models. Section 4 presents the empirical results. Section 5 concludes the study and provides policy recommendations.

2. Literature review

Economic growth, urbanization, and transportation infrastructure are closely interconnected, collectively shaping carbon emissions patterns. As economies expand and urban populations grow, the demand for transportation infrastructure rises, facilitating mobility and economic activities (Turok and McGranahan, 2015; Li *et al.*, 2020). While well-developed transportation networks enhance logistics efficiency and economic productivity, they also contribute to carbon emissions increase, particularly in regions reliant on fossil fuels (Shunping *et al.*, 2009; Yin *et al.*, 2015). Consequently, some studies have explored the dynamic relationship among economic growth, urbanization, transportation infrastructure, and carbon emissions, seeking to understand both the short-term environmental trade-offs and long-term sustainability implications.

2.1 Economic growth and carbon emission

The relationship between economic growth and carbon emissions varies significantly across regions, reflecting differences in development stages, energy structures, and policy frameworks. A widely cited explanation for these variations is the Environmental Kuznets Curve (EKC) hypothesis, which posits that carbon emissions initially increase with economic growth, but eventually decline after surpassing a certain income threshold (Kaika and Zervas, 2013; Robalino-López *et al.*, 2015).

Empirical studies from developing regions provide partial support for this hypothesis. For instance, Tenaw and Beyene (2021) confirmed the existence of an EKC pattern in sub-Saharan Africa. However, the estimated turning point appears at a relatively high level of GDP per capita, suggesting that many countries in that region may continue to experience emissions growth in the near term. Similarly, Arouri *et al.* (2012), in their examination of twelve Middle Eastern and North African (MENA) countries, identified an inverted U-shaped relationship between GDP and CO_2 emissions, though the turning points varied considerably across nations. This implies that while some MENA economies may already be on the path toward decoupling, others will require more targeted interventions to reconcile economic growth with environmental sustainability. This perspective is further supported by Nguyen (2020), who, focusing on the Central Asian context, found that while energy consumption contributes to economic activity, carbon emissions exert a negative effect on GDP, highlighting the economic cost of environmental degradation.

In more advanced economies, the evidence is more mixed. Studies of OECD and European countries underscore the heterogeneity of the income–emissions relationship. Bengochea-Morancho *et al.* (2001) highlighted substantial disparities among European Union member states, cautioning against a one-size-fits-all emissions reduction policy. Similarly, Bella *et al.* (2014) observed divergent patterns across OECD nations: in some high-income countries, carbon emissions and electricity consumption begin to decline after reaching a certain income level—consistent with the EKC hypothesis—whereas in others, emissions remain positively associated with GDP due to a continued reliance on fossil fuels. Supporting this view, Ntanos *et al.* (2018) found that renewable energy consumption is more strongly correlated with economic growth in higher-GDP European economies, indicating that a cleaner energy mix can facilitate the decoupling of growth from emissions.

Beyond these regional comparisons, studies from global cross-country analyses provide further insights into the complexity of the growth–emissions nexus. Ntanos *et al.* (2019) demonstrated that the income–emissions relationship not only differs across income levels but also varies by emission source, with stronger associations found in the transport and electricity sectors than in residential or industrial sectors. Acheampong (2018), analyzing 116 countries, concluded that economic growth does not universally lead to higher emissions. For example, in the Caribbean–Latin America region, growth was found to have a negative causal impact on emissions, highlighting the importance of region-specific development patterns.

2.2 Urbanization and carbon emission

Urbanization has accelerated around the world, especially in developing regions like Africa and Asia. The United Nations estimates that by 2050, around 64% of the population in these regions will reside in urban areas (Shahbaz *et al.*, 2016). However, the resulting increase in population mobility, industrial expansion, and transportation further intensifies emission problems. In developing countries, the emission challenges brought about by urbanization are particularly pronounced, as rapid growth often outpaces the implementation of sustainable infrastructure and green technologies. Cao *et al.* (2016) found a direct correlation between urbanization and CO2 emissions, particularly in rapidly growing economies. Liu and Bae (2018) observed that urban population growth in China is strongly associated with increased carbon emissions, highlighting the need for sustainable urban planning. Similarly, Xie *et al.* (2017) noted that transportation infrastructure significantly contributes to emissions in China, underscoring the importance of green transportation policies.

The relationship between urbanization and carbon emissions is complex, which may be linked to the varying urbanization patterns. Cross-regional studies provide further insights into these variations. Martínez-Zarzoso and Maruotti (2011) identified an inverted-U pattern in developing countries, where emissions initially rise with urbanization but decline after surpassing a certain threshold. Al-Mulali *et al.* (2013) further highlight that the urbanization-emissions link differs significantly across countries depending on income levels and energy consumption habits. However, in developing countries like Pakistan, urbanization has been found to consistently increase carbon emissions in both the short and long term (Ali *et al.*, 2019). Similarly, Mignamissi and Djeufack (2021) examined 48 African countries and reported that urbanization's environmental impact depends on resource wealth and institutional quality. These findings emphasize the necessity of region-specific strategies to manage urbanization-induced emissions. Wang and Zhao (2017) found that while urbanization can reduce per capita emissions in highly developed areas through improved efficiency, it often leads to higher emissions in less urbanized regions due to rising vehicle ownership and energy consumption.

2.3 Transportation infrastructure and carbon emission

Transportation infrastructure plays a dual role in shaping carbon emissions, with its impact contingent on factors such as infrastructure type, usage patterns, and economic context. Studies generally associate infrastructure expansion with rising CO_2 emissions. For instance, an analysis of OECD countries over nearly 150 years found that a 1% increase in transportation infrastructure correlates with a 0.4% rise in emissions, particularly in periods of economic growth and urbanization (Churchill *et al.*, 2021). Similarly, research in Shanghai showed that road development increased transport-related emissions while influencing population density (Meng and Han, 2016). These findings echo broader concerns in the literature that expanded infrastructure, while facilitating economic development and mobility, often intensifies fossil fuel consumption and vehicle usage.

Mohmand *et al.* (2020) confirmed this positive relationship, showing that transportation infrastructure development, especially in the early stages of economic growth, tends to increase carbon emissions. Saidi and Hammami (2017) further identified freight transportation as a major source of CO_2 emissions, emphasizing the environmental cost of expanding transport networks. In addition, Schipper *et al.* (2011) highlighted how transportation intensity, coupled with urbanization, contributes substantially to rising emissions, underscoring the need for green infrastructure investment. The bidirectional relationship between transportation infrastructure and economic growth identified by Pradhan and Bagchi (2013) suggests that without integrated sustainability policies, infrastructure-led development may exacerbate environmental pressures. Collectively, these studies illustrate that transportation infrastructure, though vital for economic advancement, can be a significant driver of carbon emissions if not managed within a low-carbon development framework.

However, well-planned transportation infrastructure can enhance efficiency, mitigating environmental impacts. Jain and Tiwari (2016) demonstrated that investments in public transit and bicycle networks in Indian cities could significantly lower fuel consumption and emissions. Arvin *et al.* (2015) further emphasized that population density and energy use patterns mediate the infrastructure-emissions relationship, underscoring the need for context-specific solutions. Pradhan and Bagchi (2013) also highlighted that integrating infrastructure expansion with energy-efficient policies can balance economic benefits with environmental sustainability.

Based on the contradictory findings mentioned above, previous research has empirically analyzed the effect of transportation infrastructure on carbon emissions from both short-term and long-term perspectives. In the short run, expanded infrastructure often leads to increased mobility, which in turn raises fossil fuel consumption, resulting in higher carbon emissions. Mohmand *et al.* (2020) confirmed this positive correlation, noting that economic growth and transportation development initially drive emissions upward. In the long run, however, sustainability-focused policies and technological advancements can mitigate these effects. Dai *et al.* (2018) proposed that as economies shift towards the adoption of renewable energy, the relationship between transportation infrastructure and emissions becomes less pronounced. Evidence from Algeria indicates that energy consumption initially fuels emissions, yet policy-driven shifts toward renewable energy can alter this trajectory (Bouznit *et al.*, 2016). Meng and Han (2016) suggest policymakers must recognize these temporal dynamics when designing transportation strategies. Investing in green infrastructure, promoting energy-efficient mobility options, and enhancing urban compactness can help align transportation development with climate goals.

The existing literature underscores a strong interconnection among economic growth, urbanization, transportation infrastructure, and carbon emissions. While earlier studies have extensively examined the relationship and causality between economic growth and CO2 emissions, the specific mechanisms through which transportation infrastructure and urbanization influence carbon emissions remain underexplored. In addition, the relationship between economic growth and CO2 emission has produced mixed findings, with variations across regions and development stages. Moreover, empirical studies that simultaneously assess the long-term and short-term effects of transportation infrastructure, urbanization, and economic growth on carbon emissions remain limited. Addressing these gaps, this study focuses on the dynamic interactions among these variables, incorporating advanced econometric methods such as cointegration and causality analysis to provide deeper insights into their interdependencies.

3. Materials and methods

3.1 Data Sources

The main aim of this research is to inspect the influence of economic growth, urbanization and traffic infrastructure on carbon emission in China with time series data from 1977 to 2022. Data for the variables were collected from the World

Table 1
Variables definition.

Variable name	Abbreviation	Measurement Proxies	Unit	Source
Carbon emission	CO2	Carbon dioxide emissions	Million Metric Tons	WDI
Economic growth	GDP	Gross domestic product	Million US$ constant 2015	WDI
Urbanization	URBAN	Population in urban agglomerations of more than 1 million	Million	WDI
Transportation Infrastructure	TRAN	The actual length of highway	Kilometres	NBSC

Development Indicator (WDI) and National Bureau of Statistics of China (NBSC). The missing values were imputed using interpolation methods to ensure the integrity and validity of the dataset for subsequent analysis. The variables, abbreviations, and their corresponding measurements are listed in Table 1.

It should be noted that, different from previous studies (Alam *et al.*, 2021; Rehman and Sohag, 2023), we use actual length of highway that have been completed and accepted or put into use as a proxy to measure transportation infrastructure. The data includes the actual mileage of public roads that can accommodate automobiles between cities, between urban and rural areas, and within rural villages. Additionally, the mileage of roads passing through urban streets, the length of highway bridges, the length of tunnels, and the width of ferry crossings are also included.

The choice of highway length as a proxy for transportation infrastructure is based on below considerations. On one hand, highways play a crucial role in facilitating economic activities by connecting urban and rural areas, promoting regional integration, and supporting industrial and commercial development. As a key component of transportation networks, highway infrastructure reflects the scale and accessibility of a country's transportation system. Compared to other indicators such as railway length or public transit capacity, highway length offers a more comprehensive measure of road network expansion, capturing both intercity and intra-regional connectivity. Given that road transportation is the dominant mode of freight and passenger movement in China, we believe this data provides a more accurate representation of the transportation infrastructure expansion driven by urbanization. On the other hand, using highway length aligns with the study's focus on the environmental impact of transportation expansion. Unlike railways or public transit systems, which are often associated with lower carbon footprints, highways predominantly accommodate fossil fuel-powered vehicles, making their expansion more directly linked to changes in emissions levels. Also, data availability and consistency also support the use of highway length as a suitable measure.

3.2 Model specification

Drawing from existing literature, this research delves into the dynamic effects of economic growth, urbanization, and transportation infrastructure on carbon emissions in China. The econometric model is expressed as follows:

$$CO2 = \boldsymbol{f}(\boldsymbol{GDP}, \boldsymbol{URBAN}, \boldsymbol{TRAN}) \quad (1)$$

To mitigate the effects of heteroscedasticity, we transform all variables into their natural logarithmic form. Consequently, Eq. (1) is expressed in the following time series format:

$$lnCO2_t = \beta_0 + \beta_1 lnGDP_t + \beta_2 lnURBAN_t + \beta_3 lnTRAN_t + \varepsilon_t \quad (2)$$

In Eq. (2), the subscript t = 1, . . ., T represents the time period, with the parameter β_0 being the intercept. ε_t denotes the error term and β_1, β_2, and β_3 are the estimated parameters for the corresponding dependent variables.

3.3 Econometric methodology

This study uses the ARDL approach, supplemented by an unrestricted VECM, to analyze long-term relationships. Initially introduced by Pesaran and Shin (1998) and later refined by Pesaran *et al.* (2001), the ARDL method offers distinct advantages over traditional cointegration techniques. Unlike other methods, it is applicable regardless of whether the variables are integrated at I(0), I(1), or a combination of both. Additionally, it demonstrates robust small-sample estimation properties, making it especially suitable for empirical research with limited data availability (Pesaran *et al.*, 2001; Shahbaz *et al.*, 2013; Natsiopoulos and Tzeremes, 2024). In line with prior research, the ARDL model is specified as follows:

$$\Delta lnCO2_t = \alpha_0 + \sum_{i=1}^{q} \alpha_{1i} \Delta lnCO2_{t-i} + \sum_{i=1}^{q} \alpha_{2i} \Delta lnGDP_{t-i} + \sum_{i=1}^{q} \alpha_{3i} \Delta lnURBAN_{t-i} + \sum_{i=1}^{q} \alpha_{4i} \Delta lnTRAN_{t-i} + \beta_1 lnCO2_{t-1} + \beta_2 lnGDP_{t-1} + \beta_3 lnURBAN_{t-1} + \beta_2 lnTRAN_{t-1} + \varepsilon_t \quad (3)$$

where α_0 represents the constant, ε is the error term. The first part of the equation captures the error correction dynamics, while the second part reflects the long-term relationship. This study applies ARDL bound test to examine the long-term and short-term association between CO2 and three dependent variables. The ARDL bounds test, introduced by Pesaran, Shin, and Smith (PSS), is used to examine the existence of a long-run cointegrating relationship among the study variables. This test determines whether the variables exhibit a long-term relationship by estimating both the short-run coefficient (α) and the long-run coefficient (β). The null hypothesis (H0) posits no cointegration among the variables, while the alternative hypothesis (H1) indicates the presence of a long-run relationship. The decision is based on the computed F-statistic: if it exceeds the upper critical bound, H0 is rejected, signaling cointegration. If the F-statistic falls below the lower critical bound, H0 is not rejected, suggesting no long-run relationship. If the F-statistic falls between the upper and lower bounds, the results are inconclusive. The short-run dynamics and the error correction term can be derived by using the following ARDL model:

$$\Delta lnCO2_t = \gamma_0 + \sum_{i=1}^{q} \gamma_{1i} \Delta lnCO2_{t-i} + \sum_{i=1}^{q} \gamma_{2i} \Delta lnGDP_{t-i} + \sum_{i=1}^{q} \gamma_{3i} \Delta lnURBAN_{t-i} + \sum_{i=1}^{q} \gamma_{4i} \Delta lnTRAN_{t-i} + \delta ECM_{t-1} + \varepsilon_t \quad (4)$$

The speed of adjustment parameter (δ), also referred to as the error correction term (ECM) in Eq. (4), indicates the rate at which the system returns to its long-term equilibrium following a short-term deviation. To ensure the model's robustness, we conduct a series of diagnostic tests, including tests for serial correlation, normality, functional form, and heteroscedasticity. To further assess the stability of the regression coefficients, Pesaran (1998) suggest employing the stability tests introduced by Brown *et al.* (1975), specifically the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) tests. These tests update the CUSUM and CUSUMSQ statistics recursively and plot them against identified breakpoints at the 5% significance level. If the plotted statistics remain within the critical bounds, the null hypothesis—that all coefficients in the regression are stable—cannot be rejected, thus confirming the model's stability over time.

4. Empirical Results

4.1 Descriptive statistics

Table 2 presents the descriptive statistics and correlation analysis for the variables, with all variables expressed in non-logarithmic form. In terms of the mean values, carbon emissions (CO2) average 5,595 million metric tons, GDP averages 4,890,293 million US dollars, urbanization level (URBAN) has a mean of 482 million people, and transportation infrastructure

Table 2
Descriptive statistics.

Descriptive statistics	lnCO2	lnGDP	lnURBAN	lnTRAN
mean	5595	4890293	482	2419491
p50	3587	2661723	444	1515750
max	12717	1.63E07	897	5354800
min	1383	327321	165	855600
sd	3916	4946848	230	1656622
skewness	0.571	0.974	0.308	0.547
kurtosis	1.718	2.602	1.787	1.569
Jarque-Bera	5.561	7.572	3.549	6.214
Probability	0.059	0.023	0.17	0.044
N	46	46	46	46
Correlation matrix				
CO2	1			
GDP	0.977	1		
URBAN	0.981	0.961	1	
TRAN	0.991	0.965	0.965	1

(TRAN) averages 2,419,491 kilometers. Over the sample period, CO2 emissions range from a minimum of 1,383 million to a maximum of 12,717 million metric tons, indicating significant variation in carbon emissions. The GDP values fluctuate between a minimum of 327,321 million and a maximum of 16,300,000 million US dollars (constant 2015), reflecting dynamic economic development. The urbanization level spans from 165 million to 897 million people, capturing the steady growth in China's urbanization. Similarly, transportation infrastructure ranges from 855,600 to 5.35 million kilometers, demonstrating the continuous expansion of China's transportation network.

Regarding data distribution, all variables exhibit positive skewness, with GDP (0.974) having the highest asymmetry, followed by carbon emission (0.571), transportation infrastructure (0.547), and urbanization level (0.308). Additionally, the kurtosis values for all variables are below 3, suggesting relatively flat distributions. The Jarque-Bera test results indicate that the p-values for carbon emissions (0.059) and urbanization (0.17) exceed 0.05, suggesting no significant deviation from normality. However, the p-values for GDP (0.023) and transportation infrastructure (0.044) are below 0.05, indicating slight deviations from normality.

The correlation analysis reveals a strong positive correlation between CO_2 emissions and GDP (0.977), urbanization level (0.981), and transportation infrastructure (0.991), suggesting that economic growth, urbanization, and infrastructure expansion are closely associated with increased carbon emissions. Similarly, GDP is highly correlated with urbanization (0.961) and transportation infrastructure (0.965), underscoring their interdependence in China's economic development. Furthermore, urbanization and transportation infrastructure exhibit a strong correlation of 0.965, reflecting the parallel advancement of urban expansion and transport network development.

4.2 Unit root test

Before conducting econometric regression analysis, we need to test the stationarity of all variables to ensure they meet the prerequisite assumptions of the ARDL bounds test, namely that none of the variables exhibit an I(2) process. Otherwise, the estimation results would be invalid (Pesaran *et al.*, 2001). Therefore, this study applies two widely used unit root tests—the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests—with a trend term to examine the stationarity properties of the variables.

Table 3 shows the results of the unit root tests. Based on the ADF and PP test results, all variables do not reject the null hypothesis of a unit root at the level form, indicating that they are non-stationary in levels. For example, carbon emissions, GDP, and transportation infrastructure do not pass the 5% significance level in either the ADF or PP tests (p-value > 0.05), suggesting that these variables contain unit roots and follow an I(1) process. However, after first-order differencing, all variables pass the unit root test at a significant level (p-value < 0.05),

Table 3
Unit root analysis.

Variables	Augmented Dickey-Fuller (ADF)				Phillips-Perron (PP)			
	Level		First Difference		Level		First Difference	
	t-stats	p-value	t-stats	p-value	t-stats	p-value	t-stats	p-value
lnCO2	-1.539	0.815	-3.704**	0.022	-2.005	0.599	-3.763**	0.019
lnGDP	1.179	1.000	-3.379**	0.054	0.151	0.995	-3.411**	0.050
lnURBAN	5.061	1.000	-5.801***	0.000	4.654	1.000	-5.629***	0.000
lnTRAN	-1.92	0.644	-6.413***	0.000	-1.951	0.628	-6.413***	0.000

Note: ***, ** and * represent significance at 1%, 5% and 10% level respectively.

Table 4
ARDL bound test results.

Model	Lower bound	Upper bound	
ARDL (3,4,4,4)	I(0)	I(1)	F-stat: 15.699
10% signifcance	2.72	3.77	K=3
5% signifcance	3.23	4.35	
1% signifcance	4.29	5.61	

indicating that they become stationary after first differencing, confirming their I(1) nature. Overall, the unit root test results satisfy the preconditions for applying the ARDL bounds test for cointegration analysis, as the ARDL method allows for the coexistence of I(0) and I(1) variables (Pesaran and Shin, 1999).

4.3 ARDL bound test

To establish the empirical foundation for the ARDL model, it is essential to determine whether a long-term cointegration relationship exists among the variables. To this end, this study uses the Akaike Information Criterion (AIC) to determine the optimal lag for independent variables, and accordingly, the model to be estimated is set to (3, 4, 4, 4). Based on this specification, we compute F-statistic and compare with the finite-sample critical values provided by Narayan (2005) to determine cointegration.

As shown in Table 4, the F-statistic (15.699) exceeds the upper bound of the critical values at the 1% significance level (5.61), providing strong evidence of cointegration among the variables. This result suggests a robust long-term relationship between economic growth, urbanization, transportation infrastructure development, and carbon emissions.

4.4 ARDL estimation

After confirming the cointegration relationship, we further estimate the long-term and short-term effects, as reported in Table 5. In the long-run estimation, the coefficient of economic growth (lnGDP) is -0.009, but it is statistically insignificant, indicating no robust evidence that economic growth influences carbon emissions in the long run. This result may reflect the complexity of China's growth trajectory, where structural shifts toward cleaner industries coexist with continued reliance on carbon-intensive sectors (Liu *et al.*, 2016; Luukkanen *et al.*, 2015).

The coefficient of urbanization (lnURBAN) is 0.960, which is also statistically insignificant, suggesting that the long-run effect of urbanization on carbon emissions remains inconclusive. Nonetheless, the coefficient of urbanization remains positive, suggesting a potential promotive effect on carbon emissions. This finding aligns with previous studies arguing that urbanization tends to increase emissions (Tan *et al.*, 2016; Borck and Pflüger, 2019). The insignificance of the long-run relationship between urbanization and carbon emissions may be attributed to two key factors. First, recent phases of China's urbanization have shifted from a focus on quantitative expansion toward improvements in urbanization quality—such as enhanced infrastructure efficiency, more balanced public service provision, and optimized urban planning (Zhou *et al.*, 2015; Cheng and Hu, 2023). This transition may weaken the traditional positive association between urban growth and carbon emissions. Second, the urbanization process in China

Table 5
ARDL Long-run and Short-run estimation results.

Variables	Coef.	Std. Err.	t-stat	P-value
LR				
lnGDP	-0.009	0.355	-0.020	0.980
lnURBAN	0.960	0.733	1.310	0.203
lnTRAN	0.468***	0.070	6.670	0.000
SR				
_cons	-2.365***	0.440	-5.370	0.000
D(lnCO2(-1))	0.356***	0.105	3.380	0.003
D(lnCO2(-2))	0.590***	0.141	4.180	0.000
D(lnGDP)	0.729***	0.200	3.650	0.001
D(lnGDP(-1))	-0.183	0.205	-0.890	0.382
D(lnGDP(-2))	-0.016	0.201	-0.080	0.939
D(lnGDP(-3))	0.278	0.164	1.690	0.105
D(lnURBAN)	-0.760	1.722	-0.440	0.663
D(lnURBAN(-1))	1.064	2.301	0.460	0.648
D(lnURBAN(-2))	5.151**	2.049	2.510	0.019
D(lnURBAN(-3))	-3.758***	1.147	-3.280	0.003
D(lnTRAN)	-0.005	0.036	-0.130	0.898
D(lnTRAN(-1))	-0.236***	0.047	-5.070	0.000
D(lnTRAN(-2))	-0.200***	0.041	-4.910	0.000
D(lnTRAN(-3))	-0.148***	0.040	-3.750	0.001
ECT	-0.552***	0.083	-6.650	0.000
Diagnostic tests				
R-squared	0.893			
Adj R-squared	0.810			
F-statistic	15.699			
DW	2.576			
Jarque–Bera	1.31 (0.519)			
BPG	0.00 (0.975)			
LM	6.556 (0.010)			
Reset	1.15 (0.353)			

Note: ***, ** and * represent significance at 1%, 5% and 10% level respectively. The dependent variable is lnCO2. The model specification for lnCO_2, lnGDP, lnURBAN, and lnTRAN is (3, 4, 4, 4), indicating that these variables are included with 3, 4, 4, and 4 lags.

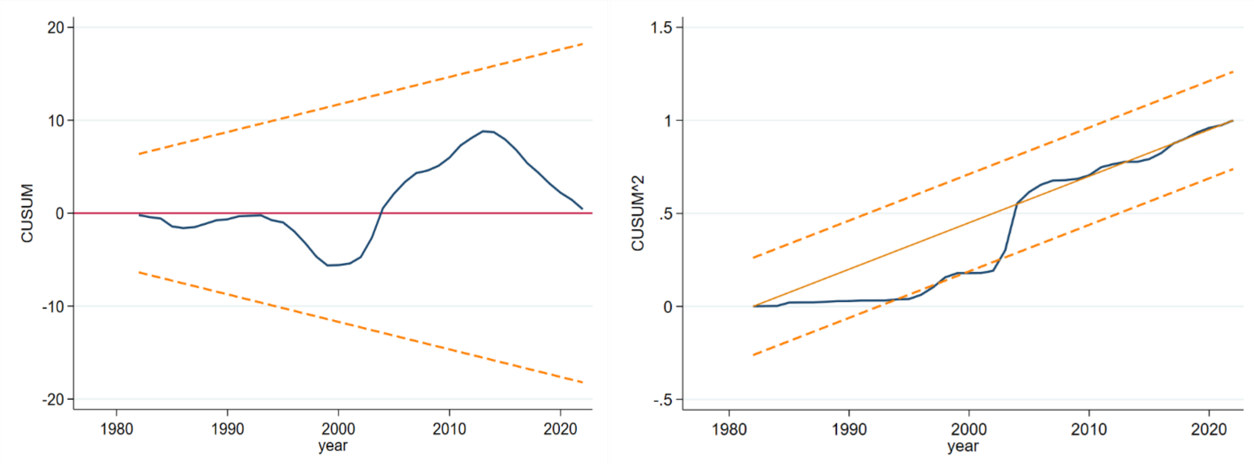

Fig. 1 CUSUM and CUSUM of square.

exhibits substantial regional heterogeneity. Such disparities may dilute the overall statistical significance of the urbanization–emissions nexus at the national level (Li *et al.*, 2022; Xu *et al.*, 2023).

The estimated long-term coefficient for transportation infrastructure development (lnTRAN) is 0.468, which is statistically significant at the 1% level. This suggests that the expansion of transportation networks is associated with higher carbon emissions over time. This result aligns with previous research, which highlights the environmental consequences of extensive transportation development (Li *et al.*, 2013; Talbi, 2017; Li *et al.*, 2024). One possible explanation is that improved transportation infrastructure facilitates greater vehicle ownership and usage, leading to higher fossil fuel consumption and, consequently, increased carbon emissions. Additionally, expanded transportation networks may stimulate economic activities and urban sprawl, further driving up transportation-related energy consumption.

In the short-term estimation, the lagged terms of carbon emissions (D(lnCO2(-1)) and D(lnCO2(-2))) have coefficients of 0.356 and 0.590, both statistically significant at the 1% level. This suggests that carbon emissions tend to follow a path-dependent trajectory, where past levels strongly influence present emissions, potentially due to structural energy reliance and sustained industrial activity (Li, 2022; Marra *et al.*, 2024).

The short-term coefficient of economic growth (D(lnGDP)) is estimated at 0.729 and is statistically significant at the 1% level. However, its first and second lag terms and do not reach statistical significance, suggesting that while GDP fluctuations impact carbon emissions in the short term, these effects may not persist beyond the initial period. This aligns with existing literature suggesting that economic activity influences emissions instantaneously rather than over an immediate cycle (Aydoğan and Vardar, 2020; Fosten, 2019).

Likewise, the short-term coefficient of urbanization (D(lnURBAN)) is estimated at -0.760 but does not reach statistical significance. However, its second and third lag terms and exhibit significant effects. The coefficient for D(lnURBAN(-2)) is 5.151, suggesting that past urbanization may contribute to higher emissions after a lagged period, potentially due to increased energy demand and urban expansion. Conversely, the coefficient for D(lnURBAN(-3)) is -3.758, indicating that urbanization may later contribute to emission reductions, possibly as a result of improved energy efficiency and public transportation infrastructure. These complex dynamic warrants further investigation.

The short-term coefficient for transportation infrastructure development (D(lnTRAN)) is estimated at -0.005 but is not statistically significant. However, its first, second, and third lag terms are all negative and statistically significant. D(lnTRAN(-1)) has a coefficient of -0.236, D(lnTRAN(-2)) has a coefficient of -0.200, and D(lnTRAN(-3)) has a coefficient of -0.148. These findings indicate a potential mitigating effect of transportation infrastructure expansion on carbon emissions in the short run. One plausible interpretation is that improved road infrastructure enhances traffic efficiency and reduces congestion, leading to lower fuel consumption and emissions in the short term. By facilitating smoother transportation networks, better road conditions may contribute to improved fuel economy and reduced idle emissions, thereby temporarily curbing carbon output (Parry, 2002; Stopher, 2004). However, in the long run, the expansion of transportation infrastructure may stimulate greater urban sprawl, increase private vehicle ownership, and reinforce automobile dependence—especially in rapidly urbanizing regions. These effects may ultimately offset the initial efficiency gains and contribute to higher carbon emissions over time.

The estimated coefficient of the error correction term (ECT) is -0.552, which is statistically significant at the 1% level, suggesting that short-term deviations from the long-run equilibrium are gradually corrected over time. Specifically, the adjustment speed is approximately 55.2% per period, meaning that the system requires approximately 1.8 years (calculated as 1/0.552) to fully return to its long-term equilibrium following a short-term shock. The negative and significant ECT coefficient confirms the presence of a stable long-term relationship among the variables.

Diagnostic tests show that the model's R^2 is 0.893, and the adjusted R^2 is 0.810, indicating a high explanatory power. The Durbin-Watson statistic is 2.576, suggesting no severe autocorrelation issues. The results of the Jarque-Bera test indicate that the residuals do not significantly deviate from normality. The Breusch-Pagan-Godfrey (BPG) test reveals the absence of heteroscedasticity in the model, suggesting that the variance of the residuals remains constant across observations. However, the LM test indicates the presence of serial correlation, suggesting that adjustments such as Newey-West standard errors may be necessary. The RESET test further affirms that there are no significant specification errors in the model, providing evidence that the chosen functional form is appropriate for the data.

Table 6
VECM regression results.

Dependent variables	Short-term causality				Long-term coefficient
	lnCO2	lnGDP	lnURBAN	lnTRAN	ECT
lnCO2	-	0.111	0.028**	0.934 **	-0.077***
		(0.266)	(0.023)	(0.026)	(0.000)
lnGDP	-0.020	-	-0.015	-0.561	-0.028**
	(0.921)		(0.415)	(0.375)	(0.032)
lnURBAN	3.919***	2.176***	-	3.286	0.009***
	(0.000)	(0.001)		0.225	(0.000)
lnTRAN	-0.031	-0.001	0.007	-	-0.074
	(0.552)	(0.990)	(0.177)		(0.173)

Note: ***, ** and * represent significance at 1%, 5% and 10% level respectively. The values in parentheses are the p-values.

Table 7
Granger causality relationship.

Variables	Short-run Granger causality	Long-run Granger causality
lnCO2	lnCO2 →lnURBAN, lnTRAN	lnCO2 → lnGDP
lnGDP		lnGDP → lnCO2, lnURBAN
lnURBAN	lnURBAN → lnCO2, lnGDP	lnURBAN → lnCO2, lnGDP
lnTRAN		lnTRAN → lnCO2, lnGDP

To evaluate the stability of the model's coefficients throughout the study period, this research employed the CUSUM and CUSUMSQ tests, with the results presented in Figure 1. The CUSUM statistics are found to stay within the critical bounds at the 5% significance level. However, the CUSUM square test indicates a temporary breach of the upper confidence boundary around 2004, and the test statistic gradually reverts towards the confidence band, implying that the disturbance might be transitory rather than persistent. Despite the partial reversion, we acknowledge the potential parameter instability and perform robustness checks to ensure the validity of our empirical findings.

4.5 VECM Granger causality analysis

The long-term interrelationships between the variables suggest the potential for either unidirectional or bidirectional causality, as posited by Engle and Granger (1987). To explore these causal links further, the study utilizes the Vector Error Correction Model (VECM) approach, with the findings summarized in Table 6.

In the first equation, where carbon emissions (lnCO2) serve as the dependent variable, both urbanization (lnURBAN) and transportation infrastructure (lnTRAN) exhibit a positive and statistically significant coefficient at the 5% level. The error correction term (ECT) is negative and statistically significant at the 1% level, reinforcing the existence of a long-term equilibrium relationship among the variables. In the GDP equation, no variables were found to be statistically significant. However, the error correction term is negative and significant at the 5% level, confirming the presence of a long-run relationship between GDP and the explanatory variables. In the third equation, where urbanization is treated as the dependent variable, it exhibits a highly significant positive relationship with both carbon emissions and transportation infrastructure. In the final equation, no significant relationships are identified with transportation infrastructure as the dependent variable.

Based on the findings in Table 6, the short-run and long-run causality relationship can be concluded as below. In the short term, we found a bidirectional causality between urbanization and carbon emission. A unidirectional causal effect can be observed from carbon emissions to transportation infrastructure, and from urbanization to economic growth. In the long-term, the results indicate bidirectional causality between economic growth and carbon emissions. Similarly, urbanization shows bidirectional causality with economic growth. In terms of unidirectional relationships, urbanization exert a causal effect on carbon emission. Additionally, transportation infrastructure has a one-way causal impact on both carbon emissions and economic growth. Summary of the above causality relationships are presented in Table 7.

4.6 Robustness check

To further validate the long-term estimation derived from the ARDL model, this study employs the Dynamic Ordinary Least Squares (DOLS) technique as an alternative estimation method. This serves as a robustness check to ensure the consistency of the long-run relationships among the variables. DOLS is particularly useful in addressing small-sample bias and potential endogeneity by incorporating leads and lags of first-differenced variables, thereby improving the efficiency of cointegrating estimates (Alcántara and Padilla, 2009). The robustness check results are presented in Table 8.

The findings indicate that the estimated coefficients of the key explanatory variables remain largely consistent with those obtained from the ARDL model in terms of sign, magnitude, and statistical significance, reinforcing the reliability of the long-run estimates. Specifically, the coefficient for transportation infrastructure development (lnTRAN) remains positive and statistically significant at the 1% level in both models (0.468 in ARDL and 0.35 in DOLS), suggesting a robust positive association between transportation infrastructure expansion and carbon emissions.

Similarly, the impact of economic growth (lnGDP) on carbon emissions is found to be statistically insignificant in the ARDL model but negative and significant in the DOLS estimation. Regarding urbanization (lnURBAN), the ARDL estimation suggests an insignificant long-term impact, while the DOLS approach finds a statistically significant positive effect.

Overall, the consistency in the sign and significance of the key variable lnTRAN across both models confirms the robustness of the primary findings. Additionally, the coefficients of lnGDP and lnURBAN remain consistent in sign with those in the baseline regression, further supporting the robustness of the results.

5. Conclusion

This study analyzes the long- and short-term impacts of economic growth, urbanization, and transportation infrastructure on carbon emissions in China over the period 1977–2022. The results indicate a complex and dynamic interplay among these factors. Economic growth exerts a weak negative impact on carbon emissions in the long run, suggesting a potential decoupling trend, while its short-run effect remains significantly positive. Urbanization demonstrates a nonlinear relationship with emissions, marked by an initial increase followed by a decline. Transportation infrastructure shows contrasting effects across time horizons—contributing to emission reductions in the short term but leading to increased emissions over the long run. These findings highlight the need for integrated and time-sensitive policy interventions that balance development goals with environmental sustainability.

Based on the findings, this empirical study offers several policy recommendations for policymakers aiming to promote sustainable economic growth. First, given that economic growth still contributes positively to carbon emissions in the short run, it is essential to pay closer attention to the environmental burden of rapid economic expansion. This calls for stronger policy guidance to steer growth toward a greener transition. For example, governments can adopt proactive fiscal policies—such as subsidies, tax deductions, and green financing tools—to support enterprises that invest in renewable energy, carbon capture technologies, or transition toward service- and knowledge-based production models. These measures can help decouple economic growth from environmental degradation and lay the foundation for a more sustainable development path.

Second, the U-shaped relationship between urbanization and emissions suggests that urbanization can exert a long-term emission-reducing effect if managed properly. This underscores the importance of improving the quality of urban development rather than merely pursuing expansion in scale. Policymakers should promote sustainable urbanization by encouraging compact city layouts, green building standards, and efficient land use planning. Investments should prioritize public transportation networks, renewable-powered infrastructure, and digital technologies that enable smart-city governance. In addition, environmental performance indicators could be integrated into urban development assessments to ensure that carbon reduction is embedded in the urbanization process.

Third, to address the long-term emission increase caused by transportation infrastructure, a shift in transport investment priorities is needed. Specifically, future infrastructure development should emphasize electrified railways, urban metro systems, and intermodal logistics hubs powered by clean energy. In the short term, policymakers should expand subsidies for electric vehicles, build out regional charging networks, and promote green freight programs such as replacing diesel trucks with electric or hydrogen alternatives in logistics corridors.

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