Sustainable Futures 9 (2025) 100520

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures

Relative improvements between roads and railways and transport carbon dioxide emissions: An environmental Kuznets curve hypothesis test in China

Wang Peng [a], Yu Xiaoyuan [b,*], Nuzul Azam Haron [c]

[a] Airport College, Shandong University of Aeronautics, No. 391, Huanghe Fifth Road, Binzhou 256600, Shandong, China
[b] School of Finance, Tianjin University of Finance and Economics, No. 25, Pearl River Road, Hexi District. Tianjin 300222, China
[c] Department of Civil Engineering, Faculty of Engineering, Jalan Universiti 1, University Putra Malaysia (UPM), Serdang 43400, Malaysia

ARTICLE INFO

Keywords:
ARDL bounds testing
Economic growth
Environmental Kuznets Curve
Transport carbon dioxide emissions
Transport infrastructure

ABSTRACT

The rapid expansion of transport infrastructure during economic development has led to significant increases in carbon emissions, particularly in developing countries. However, the relationship between different transport modes and carbon emissions across development stages remains unclear. This study examines the relationship between the relative improvement of railways to roads (RPR), economic growth, and transport carbon emissions, aiming to verify the Environmental Kuznets Curve (EKC) hypothesis in China's transport sector. Using an ARDL model and bounds testing approach, we analyze Chinese data from 1978 to 2021. The bounds test confirms a long-term cointegration relationship among RPR, GDP per capita, and transport carbon emissions. Both long-term and short-term analyses support the EKC hypothesis, indicating an inverted U-shaped relationship between economic growth and per capita transport carbon emissions. The impact of RPR on per capita transport carbon emissions is significantly positive in both the long and short term. The error correction term shows that approximately 41 % of short-term disequilibrium is corrected within a year, further confirming the long-term relationship between variables. Diagnostic tests and stability analysis ensure the reliability of the model results. The study reveals that the impacts of transport demand, infrastructure investment, and technological progress on carbon emissions vary across different stages of economic development. These findings suggest that developing economies should adopt a dynamic approach to transport infrastructure planning, with early preparation for railway development to avoid carbon emission lock-in effects. For sustainable development, policymakers should align infrastructure investment priorities with economic development stages while promoting cross-regional coordination in transport planning.

1. Introduction

The influence of transportation on CO2 emissions has been thoroughly explored in numerous studies [1–5]. Nearly one-fourth of global CO2 emissions related to energy stem from transportation, and its emission growth rate outpaces other energy sectors [6,7]. Despite the recognized economic benefits of a vibrant transportation sector, these gains come at the cost of environmental degradation.

Undoubtedly, the expansion of road infrastructure networks enhances transportation services, promotes economic development, and boosts GDP growth. This is primarily because transportation facilities create routes for the access, transport, and distribution of goods and services, leading to reduced travel time and fostering industrialization and economic development [8–10]. Land transportation infrastructure is typically categorized into two types: roads and railways, each promoting economic growth through distinct mechanisms. Roads notably influence local economies by encouraging the concentration of human capital and the clustering of industries [11]. Land transportation infrastructure comprises two main types: roads and railways. Their mechanisms for promoting economic growth differ significantly. Roads have a more pronounced impact on economic growth than railways, particularly in the process of urbanization, where the influence of roads continues to strengthen [12]. Investments in roadway infrastructure may potentially generate more substantial economic benefits in comparison to railway investments, primarily due to their impact on industries such as automotive manufacturing, alternative transportation equipment

* Corresponding author.
E-mail address: yuxiaoyuantc@163.com (Y. Xiaoyuan).

https://doi.org/10.1016/j.sftr.2025.100520
Received 29 September 2024; Received in revised form 14 December 2024; Accepted 16 January 2025
Available online 9 March 2025

production, construction, and road transportation services [13,14] Conversely, high-speed railways significantly contribute to economic growth on a broader scale, mainly by driving industrial and commercial development [15,16].Regarding environmental impacts, railways and roads also differ significantly [17]. Specifically, in terms of greenhouse gas emissions, rail transportation emits less than road transportation [2]. The energy intensity for rail freight is 0.1694 MJ per ton-kilometer, while for road freight, it is 1.7 MJ per ton-kilometer. Nevertheless, the rail equipment sector's energy intensity, at 15.05 tons of standard coal equivalent per ten thousand yuan, significantly exceeds that of the automotive manufacturing industry, which stands at 4.86 tons of standard coal equivalent per ten thousand yuan. Therefore, without further literature to support, it is challenging to definitively conclude which mode of transportation has a lower or higher carbon footprint throughout the entire investment and operation process [13].

The Kuznets Curve hypothesis has been extensively used by scholars to investigate a range of issues related to economic growth, with the Environmental Kuznets Curve (EKC) being especially prominent [18,19]. Since the pioneering work of Grossman and Krueger [20], the EKC hypothesis has been empirically examined across numerous countries and regions, employing various environmental indicators and econometric methods [21–24].The EKC hypothesis has also been extensively studied in the transportation sector. Incorporating transportation issues into the EKC analytical framework provides insights into the environmental impacts of transportation and the potential for achieving sustainable development through policy implementation. It also offers a perspective on the environmental impacts of different regions and transportation modes in relation to economic growth [25–30].

Globally, research on the EKC hypothesis in the transportation sector has yielded diverse findings across different countries and regions. In developed economies, Alshehry and Belloumi analyzed Saudi Arabia's transport sector from 1971 to 2011, finding evidence of a unidirectional causality running from economic growth to transport energy consumption [31]. Similarly, Churchill et al. examined OECD countries and found strong support for the EKC hypothesis in the transport sector, though the turning points varied significantly across countries [32]. In developing economies, Saboori et al. investigated Malaysia's road transportation sector from 1980 to 2009, revealing a non-linear relationship between economic growth and transport CO2 emissions that followed an inverted U-shaped pattern [33]. A comprehensive study by Pablo-Romero et al. covering 27 EU countries demonstrated that the relationship between transport energy consumption and economic growth exhibited different patterns across member states, with some showing evidence of decoupling while others maintained a strong positive correlation [34]. Additionally, research by Ahmed et al. focusing on newly industrialized countries revealed that the nexus between transport-related emissions and economic growth was significantly influenced by factors such as energy efficiency improvements and technological innovation [35].

Due to China's swift economic growth and urbanization, its energy-related carbon emissions now represent nearly one-third of the global total, positioning it as the largest contributor to carbon dioxide emissions worldwide [36,37]. The Environmental Kuznets Curve (EKC) concept has garnered significant attention in academic literature, especially regarding CO2 emissions in China. Existing research has explored the complex dynamics of the EKC phenomenon in the context of China's carbon emissions, taking into account a range of influencing factors, including levels of economic development [38,39], urbanization processes [40,41], technological advancement [42], and regional disparities [43]. These studies have provided empirical evidence for the presence of the EKC in relation to CO2 emissions in China from multiple analytical perspectives. On the other hand, studies incorporating the transportation sector into the EKC framework have become increasingly common [44,44–46]. Studies on the Environmental Kuznets Curve (EKC) within China's transportation sector highlight its complexity and regional variations. Guo et al., through an analysis of provincial panel data from 1997 to 2016, identified an inverted U-shaped correlation between per capita GDP and carbon emissions from the transportation sector (TSCE), providing support for the EKC hypothesis [47]. However, the economic factors influencing TSCE varied across different regions, indicating the need for targeted policies to achieve low-carbon development. In contrast, Liu et al. conducted a broader geographical study, including China, Turkey, India, and Japan. Their findings indicated that the effects of per capita GDP, along with its squared and cubic terms, on per capita CO2 emissions aligned with an N-shaped EKC hypothesis, differing from the simple inverted U-shaped relationship. This study also highlighted the impact of transportation infrastructure investments on environmental degradation, noting that investments in road and aviation infrastructure negatively impacted the environment, while investments in railway infrastructure had positive effects [48]. Hou et al. examined China's transportation sector using the Tapio decoupling elasticity model and the EKC model, analyzing data from 2005 to 2020. Their findings revealed that most provinces showed an inverted U-shaped decoupling trend, further validating the EKC hypothesis in China's transportation industry [49]. However, not all research agrees on the EKC's universal applicability in this context. As an illustration, research conducted by Peng, utilizing panel data from 30 provinces spanning 2001 to 2016 and employing exploratory spatial data analysis (ESDA) in conjunction with an augmented STIRPAT model, failed to uncover evidence supporting the Environmental Kuznets Curve (EKC) hypothesis within China's transportation sector during the examined timeframe [50].

While existing literature has extensively examined the Environmental Kuznets Curve (EKC) in the transportation sector, several critical research gaps remain unaddressed. Previous studies on the EKC for transportation in China, despite employing various methods and variables, have yet to fully account for the comprehensive effects of road and railway infrastructure development on transportation carbon emissions. Most studies treat transportation infrastructure as a homogeneous entity or examine road and railway systems separately, overlooking their dynamic interplay during different stages of economic development. During the economic development process, the demand for different transportation modes evolves with development stages - in early phases, low urbanization levels and high demand for human capital concentration drive road expansion, while later stages see increased railway development due to growing industrial and commercial needs [11].

This study makes several novel contributions to address these research gaps. First, we introduce an innovative analytical framework by incorporating the ratio of relative improvements in railways versus roads (RPR) into the EKC model, as proposed by Zheng [11]. This approach captures how the ratio of road to railway supply may exhibit an inverted U-shaped curve with GDP growth and urbanization, potentially leading to corresponding changes in transportation carbon emissions. Second, we examine both the long-term equilibrium relationship and short-term dynamics among RPR, economic growth, and transportation carbon emissions, offering a more comprehensive understanding of these complex interactions. Third, our study provides empirical evidence from China, where rapid economic growth and massive transportation infrastructure investment make it an ideal case for examining these relationships.

Specifically, this study addresses the following research questions:

a. Do the relationships among RPR, economic growth, and transportation carbon emissions conform to the EKC hypothesis?
b. What are the long-term interactions among RPR, economic growth, and transportation carbon emissions?
c. What are the short-term interactions among RPR, economic growth, and transportation carbon emissions?

The remainder of this paper is structured as follows. This research commences with an introductory section and a concise review of existing literature to identify gaps in current knowledge. Section 2 presents a comprehensive literature review and develops the research hypothesis.

The third section delineates the econometric methodology employed. The fourth section presents the empirical findings and provides a comprehensive discussion. The final section concludes the study, emphasizing its significance and implications.

2. Kuznets theory of relative improvements between roads and railways, transport carbon dioxide and GDP: literature review and hypothesis development

2.1. Literature review on Environmental Kuznets Curve (EKC) and transportation

The Environmental Kuznets Curve (EKC) hypothesis, since its emergence in the 1990s, has established itself as a fundamental framework in environmental economics for understanding the nexus between economic development and environmental degradation. While early investigations concentrated on validating the EKC hypothesis through aggregate emissions analysis [51,52], contemporary research has evolved toward more nuanced, sector-specific examinations, with particular emphasis on the transportation sector due to its dual role as an economic driver and significant environmental polluter.

The empirical evidence supporting the EKC hypothesis in the transportation sector has been substantial and multi-faceted. A comprehensive analysis of OECD countries spanning 1990–2019 revealed robust support for the hypothesis, while also highlighting the heterogeneity in turning points across nations at different developmental stages [53]. This heterogeneity has been further illuminated by recent studies of G7 economies (1990–2019), which have expanded the traditional economic-environmental framework by incorporating human development indicators. These studies demonstrate that enhanced human development correlates with reduced pollution emissions, suggesting a more complex interplay than previously understood through purely economic metrics [54]. This finding aligns with prior research emphasizing the significance of institutional quality and social development in environmental outcomes [21,23].

The role of technological advancement and energy transition has emerged as a critical dimension in recent literature. Studies across diverse geographical contexts have demonstrated that renewable energy adoption significantly contributes to air quality improvement and carbon emission reduction [54,55]. In the transportation sector, this transformation is particularly evident in the increasing electrification of public transport systems and the adoption of alternative fuel technologies [56]. Regional analyses have provided valuable insights into the contextual variations of the EKC relationship. Research conducted in Visegrad countries (1990–2018) has not only confirmed the classic EKC pattern but also emphasized the crucial role of energy consumption patterns [57]. Similar patterns, albeit with varying turning points and relationship intensities, have been observed in studies of Asian [58] and Latin American economies [59].

A significant development in recent literature has been the examination of Foreign Direct Investment's (FDI) impact. While earlier debates centered on the dichotomy between the pollution haven hypothesis and pollution halo effect [60], recent evidence increasingly favors the latter, particularly in jurisdictions with robust environmental regulations [54,57]. This suggests that international investment can serve as a catalyst for technological transfer and environmental best practices in the transportation sector [61].

The urban dimension of transportation-related environmental impacts has gained increasing scholarly attention. Research has demonstrated that urbanization patterns significantly influence transportation emissions, with compact urban development generally associated with lower per capita emissions [62,63]. This relationship has been particularly well-documented in metropolitan areas through studies of public transportation investment and emission patterns [64]. Methodological advancements have enabled more sophisticated analyses of these relationships, with panel quantile regression approaches revealing variations in the EKC relationship across different emission levels [65], and spatial econometric methods highlighting the significance of geographic spillover effects in transportation-related emissions [66].

2.2. Theoretical framework and research hypotheses development

There are three theoretical explanations for the Kuznets curve hypothesis concerning transport carbon dioxide emissions, which are influenced by relative improvements between roads and railways: the economic activity scale effect, the transportation structure transition effect, and the emission reduction technology effect.

The economic activity scale effect posits that as income levels rise during early economic development, transportation demand increases [67]. In the initial phase, population tends to be concentrated in specific regions, leading to localized production and commercial activities. Consequently, short-distance travel suffices for most trade and business needs, favoring road transportation due to its flexible accessibility and relatively lower construction costs. This results in rapid growth of road mileage and a sharp increase in transport carbon emissions. As the economy further develops and urbanization accelerates, inter-regional trade and activities diversify, increasing the demand for long-distance transportation of people and goods. This, in turn, drives the need for high-mobility land transport systems such as highways and railways [11]. Investment in large-scale infrastructure like railways increases, leading to rapid growth in railway mileage. Given that railway transport typically has lower carbon emissions per unit of transportation compared to road transport, the decline in the road-to-railway mileage ratio could potentially decelerate the increase in transportation-related carbon emissions.

The effect of the transportation structure shift indicates that in the initial stages of economic development, due to the limitations of life and production, short-distance travel demands dominate, primarily served by high-carbon-emitting road transportation. As the economy develops and urbanization progresses, the demand for long-distance personal travel increases, gradually revealing the scale effects and speed advantages of railways [68]. This leads to a shift in the transportation structure towards low-carbon railway transport, potentially slowing the growth of transport carbon emissions. However, at a highly urbanized stage, the agglomeration effects brought about by railways may widen the gap between central cities and surrounding areas, and increased urban congestion may once again raise the demand for road transportation, potentially causing carbon emissions to rise again.

The emission reduction technology effect refers to the supply-side perspective. At the initial stages of economic development, governments with constrained public infrastructure budgets tend to prioritize economic growth by directing investments toward the more cost-effective construction of roads to promote development [69]. As economic strength increases, governments become capable of investing in large-scale railway construction and allocating more resources to enhance mobility systems. Simultaneously, as the economy reaches a certain level, societal demand for environmental quality increases, and governments become capable of investing in clean energy and low-carbon technologies. This includes developing electric vehicles, improving fuel efficiency, and promoting clean energy sources. The high versatility and powerful transport capacity of railway systems meet the large-scale, high-demand transportation needs for both people and goods, thereby improving productivity and promoting higher levels of economic performance. Moreover, the increasing electrification rate of railways further reduces carbon emissions per unit of transportation [13]. These factors together might result in a deceleration or even a reduction in the growth rate of transportation-related carbon emissions.

Drawing upon the theoretical framework outlined above and synthesizing insights from the extant literature, this study advances three interconnected hypotheses that collectively examine the dynamic relationships between economic development, transportation infrastructure, and environmental outcomes in China:

H1: There exists an inverted U-shaped relationship between economic growth and transport carbon emissions in China, consistent with the Environmental Kuznets Curve hypothesis.
H2: The road-to-railway mileage ratio (RPR) has a significant positive impact on transport carbon emissions in both short-term and long-term periods.
H3: There exists a stable long-run equilibrium relationship among economic growth, transport infrastructure development, and carbon emissions.

3. Econometric methodology

3.1. Data, variables and model

Drawing from recent empirical studies [70,71], we can explore the long-term relationship between improvements in road and railway infrastructure, transport-related CO_2 emissions, and economic growth through a quadratic model. To validate the EKC hypothesis, we define and employ the following equation:

$$TCO_{2t} = \beta_0 + \beta_1 RPR_t + \beta_2 PGDP_t + \beta_3 PGDP2_t + \varepsilon_t \tag{1}$$

In Eq. (1), RPR represents the ratio of road to railway mileage, PGDP denotes the per capita Gross Domestic Product (in constant 2005 US dollars), PGDP2 is the square of PGDP, and TCO_2 refers to per capita carbon dioxide emissions (measured in tons per capita).

To strengthen the robustness of our analysis and test the EKC hypothesis, we transform the linear equation into its natural logarithmic equivalent. Compared to linear models, log-linear specifications often yield more consistent and efficient results. Moreover, this transformation helps increase the stationarity of the variance-covariance matrix [72]. Consequently, Eq. (1) is reconstructed as follows:

$$lnTCO_{2t} = \beta_0 + \beta_1 lnRPR_t + \beta_2 lnPGDP_t + \beta_3 lnPGDP2_t + \varepsilon_t \tag{2}$$

In the equation, coefficientsβ_1, β_2 and β_3 denote the impacts of relative improvements between roads and railways, GDP, and its quadratic term on transport CO2 emissions, respectively. The term ε_t is regression error term, while β_0 is the intercept for the model. For the EKC hypothesis to hold in model (2), β_1 and β_2 should be positive, while β_3 should be negative.

This study analyzes the relationship between transport-related CO_2 emissions, economic development, and transportation infrastructure in China using annual data from 1978 to 2021. Our analysis primarily focuses on three key variables derived from authoritative sources. The World Development Indicators (WDI) database of the World Bank provides two essential metrics: transport CO_2 emissions per capita (TCO2), which captures emissions from fuel combustion across various transportation modes including road, rail, domestic aviation, and domestic navigation; and per capita GDP (PGDP), measured in constant 2005 US dollars to account for inflation and enable temporal comparisons. The third crucial variable, the road-to-railway mileage ratio (RPR), is calculated using comprehensive transportation infrastructure data from the China Statistical Yearbook, encompassing both road networks (from highways to substandard roads) and railway systems (both electrified and non-electrified tracks).

To ensure robust analysis and accurate per capita calculations, we incorporate supporting data from additional reliable sources. Population statistics are drawn from the China Statistical Yearbook, while detailed transport infrastructure data from the same source provides deeper insights into the evolution of China's transportation network. We also utilize supplementary economic indicators from the WDI database to provide broader context for our analysis of China's transport-related emissions and economic development patterns.

3.2. Unit root tests

Stationarity is a crucial property in time series analysis. However, many economic variables exhibit non-stationary behavior, where mean and variance change over time. Such variables are known as unit root variables [73].

Employing traditional approaches like Ordinary Least Squares (OLS) with non-stationary data can lead to biased and unreliable estimates. To overcome this issue, our study employs two widely accepted unit root tests: the Augmented Dickey-Fuller (ADF) test [74] and the Phillips-Perron (PP) test [73]. The ADF test expands on the standard ADF test by incorporating additional lagged differenced terms of the dependent variable to mitigate autocorrelation effects. It evaluates the null hypothesis of unit root presence in the time series data against the alternative hypothesis of data stationarity. The test follows the regression equation:

$$\Delta Y_t = \alpha + \beta t + \gamma Y_{t-1} + \delta 1 \Delta Y_{t-1} + \ldots + \delta_{p-1} \Delta Y_{t-p} + 1 + \varepsilon_t \tag{3}$$

Where Y_t is the variable of interest, α is a constant, β represents the coefficient of the time trend, p denotes the lag order of the autoregressive process, and ε_t is the error term.

Conversely, the Phillips-Perron test utilizes nonparametric techniques to address serial correlation in error terms without necessitating the inclusion of lagged difference terms. The PP test is founded on the following regression equation:

$$Yt = \alpha + \rho Y_{t-1} + \varepsilon_t \tag{4}$$

Where Y_t is the variable being tested, α is the intercept, ρ is the coefficient of Y_{t-1}, and ε_t is the error term.

3.3. Cointegration method

The cointegration method is a statistical approach employed in econometrics to identify long-run equilibrium relationships among non-stationary time series variables, with various methodologies developed over time, including the residual-based approach [75], the modified ordinary least squares procedure by [76], and the Vector Error Correction Model (VECM). While VECM is commonly used when all variables are integrated of order one, the ARDL bounds testing approach offers several advantages that make it more suitable for our analysis. First, unlike VECM, ARDL can be applied regardless of whether the regressors are purely I(0), purely I(1), or mutually cointegrated, providing greater flexibility [77]. Second, ARDL performs better in small sample sizes compared to VECM [78]. Third, the ARDL approach allows for the incorporation of sufficient numbers of lags to capture the data generating process in a general-to-specific modeling framework. Additionally, the derived error correction model integrates short-run adjustments with long-run equilibrium without losing long-run information [79]. Following the work of several researchers, including Jebli and Ahmad (2017), Alshehry and Belloumi (2015), and Khan et al. (2020) [70,80,81], this study employs the ARDL bounds testing approach to investigate the long-run relationships among the ratio of road to railway mileage (RPR), per capita Gross Domestic Product (PGDP), and per capita carbon dioxide emissions (TCO2).

The ARDL procedure commences with the determination of the optimal lag structure, a crucial step in capturing the dynamic relationships between variables and enhancing model accuracy. W e employ information-based criteria such as the Akaike Information Criterion (AIC) or Schwarz Information Criterion (SIC) [77]. Following this, we perform a series of diagnostic evaluations to ascertain the model's robustness, including the Breusch-Pagan-Godfrey test to assess heteroskedasticity and the Breusch-Godfrey LM test to detect serial correlation [82–84].

To investigate the presence of long-term equilibrium relationships, we apply the bounds testing approach for cointegration, utilizing the following ARDL framework:

$$\Delta \ln TCO2_t = \alpha_1 + \sum_{i=1}^{p} \beta_i \Delta \ln TCO2_{t-i} + \sum_{i=1}^{p} \gamma_i \Delta \ln RPR_{t-i} + \sum_{i=1}^{p} \delta_i \Delta \ln PGDP_{t-i} + \sum_{i=1}^{p} \theta_i \Delta \ln PGDP2_{t-i} + \lambda_1 \ln TCO2_{t-1} + \lambda_2 \ln RPR_{t-1} + \lambda_3 \ln PGDP_{t-1} + \lambda_4 \ln PGDP2_{t-1} + \varepsilon_t \tag{5}$$

where Δ denotes the first difference operator. We evaluate the null hypothesis of no cointegration against the alternative hypothesis using the F-statistic. The computed F-statistic is then compared with the critical values outlined by Narayan (2005) [85], which are more appropriate for small sample sizes.

Upon confirmation of cointegration, we proceed to estimate both long-run and short-run ARDL models. The long-run ARDL specification is expressed as:

$$\ln TCO2_t = \beta_0 + \sum_{i=1}^{p} \beta_{1i} \ln TCO2_{t-i} + \sum_{i=1}^{q} \gamma \beta_{2i} \ln RPR_{t-i} + \sum_{i=1}^{r} \gamma \beta_{3i} \ln PGDP_{t-i} + \sum_{i=1}^{s} \beta_{4i} \ln PGDP2_{t-i} + \varepsilon_t \tag{6}$$

The short-term dynamics are captured through an error correction model (ECM):

$$\Delta \ln TCO2_t = \delta_0 + \sum_{i=1}^{p} \delta_{1i} \Delta \ln TCO2_{t-i} + \sum_{i=1}^{q} \delta_{2i} \Delta \ln RPR_{t-i} + \sum_{i=1}^{r} \delta_{3i} \Delta \ln PGDP_{t-i} + \sum_{i=1}^{s} \delta_{4i} \Delta \ln PGDP2_{t-i} + \theta ECT_{t-1} + \varepsilon_t \tag{7}$$

where ECT_{t-1} represents the error correction term, and θ denote the rate of convergence towards long-run equilibrium.

To ensure the robustness of our ARDL model, we conduct a series of diagnostic tests, including assessments for normality, heteroskedasticity, and serial correlation. Furthermore, we employ the CUSUM and CUSUMSQ tests to assess the temporal stability of the model's coefficients [86].

4. Empirical results and discussions

Before proceeding with the formal econometric analysis, we first examine the basic characteristics and temporal evolution of our key variables. To provide an initial understanding of the data patterns and relationships, we present both graphical and statistical analyses of the three main variables. Fig. 1 illustrates the evolution of these three time series, with the logarithmic levels suggesting potential trends. This visual representation helps identify possible structural changes and long-term relationships among the variables over the study period (1978–2021). Table 1 presents the descriptive statistics of the key variables. Analysis of these statistics reveals that the average value for the relative performance ratio between roadways and railways (RPR) is calculated at 27.38, the mean per capita GDP (PGDP) is $2920.56, and the mean per capita transport CO2 emissions (TCO2) is 0.281 metric tons. The standard deviations for RPR, PGDP, and TCO2 are 11.25, $3589.48, and 0.209 metric tons per capita, respectively, reflecting the variability in the data.

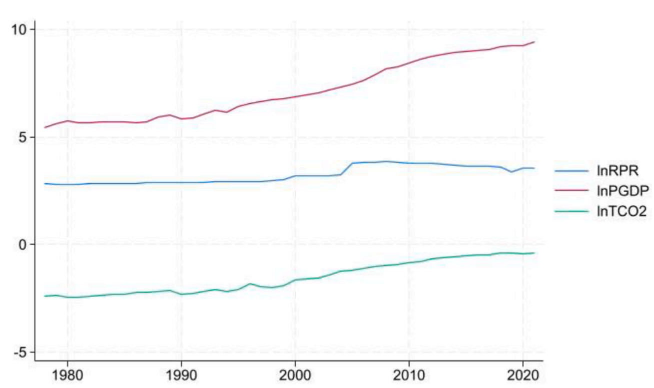

Fig. 1. Plot of natural log levels of relative improvements between roads and railways, per capita gross domestic product, and per capita transport carbon dioxide emissions.

Table 2 displays the outcomes of the ADF and PP tests. These analyses were performed on both the original and first-differenced series, utilizing two model configurations: one with only an intercept, and another incorporating both trend and intercept. The findings from both ADF and PP tests consistently demonstrate that all examined variables - RPR, PGDP, and TCO2 - exhibit non-stationarity in their level forms. This is evidenced by the inability to dismiss the null hypothesis of unit root presence at standard significance thresholds for both test specifications. Conversely, when analyzing the first differences of these variables, both ADF and PP tests emphatically reject the unit root null hypothesis at the 1 % significance level across all variables and model configurations, indicating that stationarity is achieved after first differencing.

However, since conventional unit root tests do not account for potential structural breaks in the series, which might lead to misleading results, we further employ the Zivot-Andrews unit root test. Table 3 presents these results.

The results of the Zivot-Andrews test largely confirm our findings from the conventional unit root tests. Based on these observations, we conclude that our variables are integrated of order one, denoted as I(1). While this finding might suggest the applicability of VECM, we opt for the ARDL approach due to its aforementioned advantages in handling small sample sizes [78] and its flexibility in incorporating dynamic adjustments [77]. Additionally, the ARDL bounds testing approach remains valid even in the presence of structural breaks identified by the Zivot-Andrews test, making it a more robust choice for our analysis [77,79]. The method provides a comprehensive framework for examining both long-run relationships and short-run dynamics among our variables.

In determining the optimal lag structure for our ARDL model, we employed various information criteria. The outcomes of this lag order selection process, considering up to 5 lags, are presented in Table 4. The lag length selection process is crucial for the ARDL bounds testing approach, as it affects the model's ability to capture the dynamic relationships among variables [77]. The results, as illustrated in Table 4, offer a diverse perspective. Both the HQIC and SBIC point towards an optimal lag length of 1, whereas the AIC suggests a preference for 5 lags. The FPE criterion aligns with HQIC and SBIC, also indicating 1 lag as optimal. When faced with such divergent outcomes, researchers often prioritize AIC and SBIC, especially in small sample scenarios, due to their superior performance in these contexts [87]. Considering these

Table 1
Descriptive statistics.

Variables	RPR	PGDP	TCO2
Description	Relative improvements between roads and railways	Per capita gross domestic product (constant 2005 US $)	Per capita Transport carbon dioxide (metric tons)
Max	46.8026	12,617.510	0.6864
Mean	27.3773	2920.559	0.2810
Median	22.1387	916.329	0.1788
Min	16.5245	228.519	0.0861
St. deviation	11.2503	3589.483	0.2090

Table 2
Results of unit root test.

	ADF Test Statistic		PP Test Statistic	
	Intercept	Trend & Intercept	Intercept	Trend & Intercept
Level Variables				
RPR	−0.587	−2.878	−0.563	−2.842
PGDP	0.507	−1.692	0.589	−1.748
TCO2	−1.078	−2.761	−1.032	−2.702
First Difference				
RPR	−4.260***	−4.219***	−6.863***	−6.791***
PGDP	−4.367***	−5.025***	−4.898***	−5.253***
TCO2	−5.973***	−6.052***	−6.442***	−6.540***

Note: 10, 5 and 1 % levels is indicated respectively by *, ** and ***.

Table 3
Results of Zivot-Andrews Unit Root Test.

Variable	Levels		First differences	
lnTR	−3.368 (0)	2005	−7.964 (0)*	2006
lnGDP	−3.127 (0)	2006	−6.372 (0)*	2012
lnTCO2	−3.673 (2)	2002	−7.753 (1)*	1999

Note.
* indicates significance at 1 % level.

Table 4
Lag Length Criteria for Co-integration.

Lag	LogL	LR	FPE	AIC	HQIC	SBIC
0	−11.735	NA	0.000427	0.7557	0.8016	0.8836
1	128.497	280.46	5.1e-07*	−5.9742	−5.7905*	−5.4623*
2	129.532	2.0712	7.80E-07	−5.5658	−5.2444	−4.6700
3	139.013	18.961	7.80E-07	−5.5904	−5.1313	−4.3107
4	143.613	9.1998	1.00E-06	−5.3648	−4.7679	−3.7012
5	166.625	46.025*	5.30E-07	−6.0833*	−5.3487	−4.0359

Note.
* indicates lag order selected by the criterion.

factors, we opt for a lag length of 1, as suggested by the HQIC, SBIC, and FPE criteria. This choice aligns with the principle of parsimony and helps avoid over-parameterization, which is particularly important given our limited sample size [88]. It's worth noting that while this lag length provides a balance between model fit and parsimony, sensitivity analysis with alternative lag structures could be conducted to ensure the robustness of our findings [89].

To assess serial correlation, we implemented the Breusch-Godfrey Serial Correlation LM Test [82,84]. The analysis yielded an F-statistic of 0.06 (p-value: 0.9931) and an ObsR-squared of 0.0139 (p-value: 0.9062). These statistics, being highly insignificant at conventional thresholds, provide strong evidence against rejecting the null hypothesis positing the absence of autocorrelation. For heteroskedasticity evaluation, we applied the Breusch-Pagan/Cook-Weisberg test [83,90], which produced an F-statistic of 0.2776 (p-value: 0.9948) and an ObsR-squared of 0.88 (p-value: 0.3481). These results, also not significant at conventional levels, suggest we cannot dismiss the null hypothesis of homoskedasticity.

The bounds testing procedure yields an F-statistic of 5.971, which exceeds the upper bound critical value at the 5 % significance level (4.865) but falls within the 1 % level bounds (6.719), indicating cointegration at the 5 % significance level. The t-statistic of −3.626, while exceeding the lower bound critical value at the 5 % level (−2.898), only indicates significance at the 10 % level as it falls short of the 5 % upper bound (−3.836). Following the methodological framework of Pesaran et al. (2001) [77] and supported by recent studies such as Narayan and Smyth (2005) [91], this evidence suggests the presence of cointegration relationships, albeit with some qualification.

This interpretation is supported by extensive literature in environmental economics. Narayan and Smyth (2005) [91] argue that in small samples, when the F-statistic exceeds the 5 % upper bound, there is strong evidence to support cointegration, even if it falls short of the 1 % threshold. This approach has been validated by numerous subsequent studies, including Ozturk and Acaravci (2013) [92] and Shahbaz et al. (2017) [93], who found reliable cointegrating relationships under similar statistical conditions. Recent methodological developments by De Vita et al. (2018) [94] and Goh et al. (2017) [95] further support this interpretation, particularly in cases involving environmental variables where structural characteristics may affect the power of the test. They suggest that when the F-statistic exceeds the 5 % upper bound and is supported by t-statistics significant at least at the 10 % level, the evidence for cointegration is robust, especially in small sample applications. Based on these theoretical and empirical foundations, we proceed with the ARDL model specification. The long-run relationship can be expressed as:

$$\ln(\text{TCO2}_2) = \beta_0 + \beta_1 \ln(\text{RPR}) + \beta_2 \ln(\text{PGDP}) + \beta_3 \ln(\text{PGDP}^2) + \varepsilon \tag{8}$$

Where β_0 is the intercept, β_1, β_2, and β_3 are the long-run coefficients, and ε is the error term (Table 5).

The ARDL model estimation results reveal both long-run and short-run dynamics between transport CO2 emissions per capita (TCO2), the turnover ratio (representing relative improvements between roads and railways, RPR), and GDP per capita (PGDP). The outcomes of these analyses are displayed in Tables 6 and 7, respectively.

The long-term estimation outcomes reveal statistically meaningful correlations among the variables, with the exception of the PGDP quadratic term, which shows marginal significance at the 10 % level. The RPR exhibits a statistically significant influence on per capita transport CO2 emissions. Quantitatively, a 1 % rise in RPR corresponds to a 0.40 % increase in per capita transport CO2 emissions (coefficient: 0.4043407, p-value: 0.007). This finding suggests that as road infrastructure improves relative to rail, per capita transportation-related emissions tend to increase. This trend can be attributed to three factors outlined in Section 2: the more frequent exchange of production materials over shorter distances, an increase in individual road travel demands, and the fact that road transport generally produces higher greenhouse gas emissions than rail transport. The association between economic expansion and per capita transport CO2 emissions displays an inverted U-shaped pattern, lending support to the Environmental Kuznets Curve (EKC) hypothesis within the transport sector. The coefficient of lnPGDP is positive (1.453625) and significant (p-value: 0.008), while lnPGDP2 is negative (−0.0648278) and marginally significant (p-value: 0.063). This indicates that transport CO2 emissions per capita initially increase with economic growth but may decrease after reaching a turning point [20].

Short-term dynamics unveil a more intricate interplay among the variables. The error correction term (ECT), being both negative and statistically significant, confirms the presence of a long-run equilibrium relationship among the examined variables [75]. Short-term effects of the turnover ratio on per capita transport CO2 emissions are positive and significant (coefficient: 0.1660288, p-value: 0.014), aligning with long-term findings. The short-term impacts of per capita GDP on per

Table 5
Bounds Test Results.

Test Statistic	Value	Significance	I(0) Bound	I(1) Bound
F-tatistic	5.971	10 %	2.893	4.075
		5 %	3.530	4.865
		1 %	5.039	6.719
t-tatistic	−3.626	10 %	−2.550	−3.442
		5 %	−2.898	−3.836
		1 %	−3.605	−4.626

Table 6
Long-run estimation.

Variable	Coefficient	Std. Error	T-ratio	Prob
lnRPR	0.4043***	0.1401	2.89	0.007
lnPGDP	1.4536***	0.5150	2.82	0.008
lnPGDP2	−0.0648*	0.0337	−1.92	0.063

* Significant at 0.10 level.
*** Significant at 0.01 level.

Table 7
Short-run estimation.

Variable	Coefficient	Std. Error	T-ratio	Prob
D.lnRPR	0.1660**	0.0639	2.60	0.014
D.lnPGDP	0.5867***	0.1543	3.80	0.001
LD.lnPGDP	−0.1348	0.1123	−1.20	0.239
L2D.lnPGDP	0.5474***	0.1150	−4.76	0.000
D.lnPGPP2	−0.0266**	0.0108	−2.46	0.020
Constant	−3.9414***	0.8331	−4.73	0.000
ECT	−0.4106***	0.1132	−3.63	0.001

capita transport CO2 emissions are varied. The immediate effect is positive and significant (coefficient: 0.5866139, p-value: 0.001), while the second lag shows a significant negative impact (coefficient: −0.5473524, p-value: 0.000). This observation suggests that the short-term link between economic expansion and per capita transport emissions is multifaceted and may involve dynamic interactions. The short-term effect of the squared GDP per capita term is negative and significant (coefficient: −0.0266193, p-value: 0.020), supporting the EKC hypothesis in the short term as well.

These discoveries are consistent with earlier research on the interrelationships between economic growth, infrastructure development, and environmental degradation [96]. However, our findings suggest that enhancing railway infrastructure relative to roads could potentially lead to a decrease in per capita emissions, both in the short and long term. This could be due to decreased transportation costs from economies of scale, shifts in travel modes, and reduced use of road vehicles. The evidence for the EKC in the transport sector is consistent with studies such as Erdogan (2020), which identified similar patterns in other countries, and Guo (2022), whose research on China, despite employing different data and methodologies, also supports these findings [26,47]. However, the high turning point suggests that policymakers should not rely solely on economic growth to reduce transport emissions per capita but should also implement targeted policies to promote sustainable transport systems.

The comprehensive diagnostic evaluations and stability analyses conducted provide robust evidence supporting the reliability and validity of the ARDL framework. The model exhibits an R-squared value of 0.9956 and an adjusted R-squared of 0.9946, suggesting that it accounts for 99.56 % of the variance in the dependent variable, thus demonstrating considerable explanatory capacity [77]. The F-statistic of 1024.88, accompanied by a p-value of 0.000, confirms the model's overall statistical significance. Durbin's h-statistic stands at −0.514 with an associated p-value of 0.304, indicating the absence of significant autocorrelation issues within the residuals [86] (Table 8).

To assess the temporal stability of the model parameters, we employed the CUSUM and CUSUM of squares tests [86]. The visual representations of these tests illustrate that the blue line, which denotes the cumulative sum of recursive residuals, consistently remains within the 5 % significance thresholds (represented by the green and red boundaries) throughout the entire sample period. This finding provides robust support for the temporal stability of the estimated parameter coefficients [89] (Fig. 2,Fig. 3).

Table 8
Diagnostics Test.

Statistic	Value	Statistic	Value
R-squared	0.9956	Adjusted R-squared	0.9946
F-statistic	1024.88	Durbin's h-statistic	−0.514
Prob(F-statistic)	0	Prob(h-statistic)	0.304

5. Conclusions and policy implications

This study investigates the relationship between the relative improvement of railways to roads (RPR), economic expansion, and transport carbon emissions within the context of the Environmental Kuznets Curve (EKC) framework. Utilizing the ARDL model and bounds testing approach on Chinese data from 1978 to 2021, we confirm the EKC hypothesis for China's transport sector. Our analysis reveals an inverted U-shaped correlation between economic expansion and per capita transport CO2 emissions in both long-term and short-term perspectives. The road-to-railway mileage ratio (RPR) shows a positive and significant influence on per capita transport CO2 emissions across both time horizons. The error correction term suggests that about 41 % of any divergence from long-run equilibrium is rectified within a year, confirming the presence of a long-term relationship among the variables examined.

This study sheds light on the complex interplay between economic progress, transport infrastructure development, and carbon emissions. Throughout various stages of economic development, fluctuations in transport demand, infrastructure investment, and technological progress differentially impact carbon emissions. Initially, increased transport demand stemming from economic growth is predominantly met by road transport, precipitating rapid increases in carbon emissions. As the economy advances, the demand for long-distance transport rises, spurring investment in large-scale infrastructure such as railways, potentially decelerating emission growth.

As urbanization intensifies, the transport structure gradually transitions from road-dominated to more rail-dependent, potentially mitigating carbon emission growth. However, it is noteworthy that in highly urbanized stages, novel complex factors may emerge, such as the agglomeration effects induced by railways potentially reinvigorating demand for road transport. Moreover, economic development engenders technological advancements and policy shifts. As economic prowess increases, governments acquire the capacity to invest in more environmentally sustainable transport systems and clean technologies. Notably, enhancements in railway systems and increased electrification rates may further diminish carbon emissions per unit of transport.

Based on our empirical findings of the EKC relationship and the role of transport infrastructure composition, we propose several macro-level policy recommendations for sustainable development. Given that economic development stages significantly influence transport carbon emissions, policymakers should adopt a dynamic and forward-looking

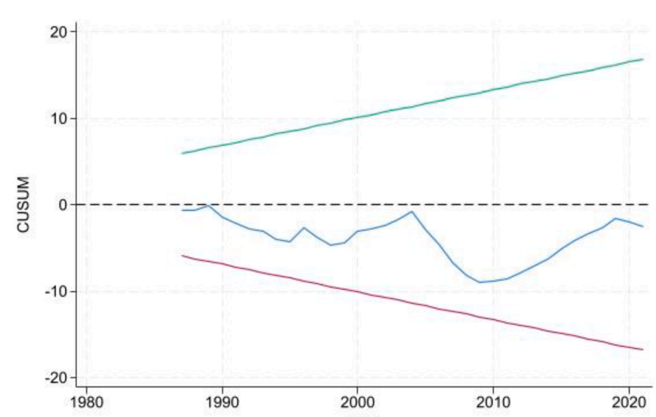

Fig. 2. Plot of Cumulative Sum of Recursive Residuals.

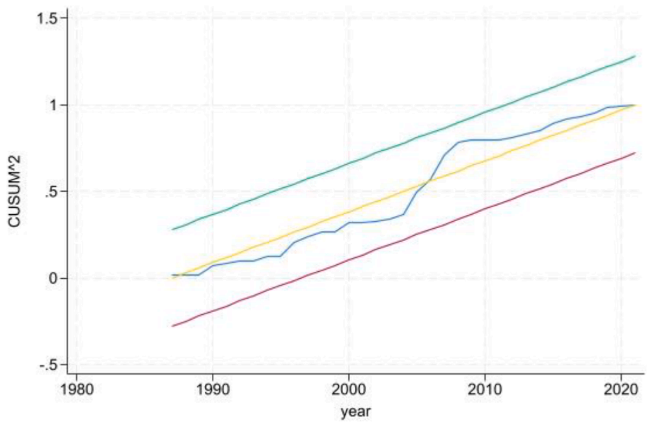

Fig. 3. Plot of Cumulative Sum of Squares of Recursive Residuals.

approach to infrastructure planning. In the early stages of economic development, while road construction may be necessary to meet immediate transport needs, governments should simultaneously lay the foundation for railway development to avoid carbon emission lock-in effects. As economies progress to middle-income stages, a gradual shift in infrastructure investment priority from roads to railways becomes crucial, particularly in densely populated economic corridors where the emission reduction potential of railways can be maximized.

The relationship between economic growth and transport carbon emissions also suggests the importance of coordinated regional development strategies. In more developed regions where the turning point of the EKC curve has been reached, policy focus should be on optimizing existing infrastructure and promoting modal shifts towards low-carbon transport options. For regions still on the rising portion of the EKC curve, policies should aim to flatten the curve by learning from developed regions' experiences and leapfrogging to more sustainable transport systems. This could involve early adoption of advanced railway technologies and integrated transport planning, even at lower income levels.

To facilitate this transition, national-level policy frameworks should be established to guide infrastructure investment decisions across different development stages. These frameworks should include clear targets for the relative development of railways versus roads, aligned with regional economic development levels and urbanization patterns. Financial mechanisms, such as development funds and green bonds, should be structured to support this long-term transformation of transport infrastructure. Additionally, cross-regional cooperation mechanisms should be established to ensure coordinated infrastructure development and prevent inefficient competition in transport investment among regions.

While our study provides valuable insights into these macro-level relationships, several limitations should be acknowledged. A key limitation is the focus on main variables without incorporating control variables such as urbanization rates, energy prices, technological progress, and policy interventions, which could potentially affect the comprehensiveness of our findings. Additionally, the study's single-country focus and limited data availability may affect the generalizability of our conclusions. These limitations suggest important directions for future research. Future studies should incorporate a broader range of macroeconomic and structural variables to provide more robust evidence of the development patterns we identified. Cross-country comparative analyses would be particularly valuable in understanding how different development paths and initial conditions influence the relationship between transport infrastructure choices and carbon emissions.

Furthermore, future research directions should extend to several critical areas. First, exploring non-linear relationships between variables could reveal more complex patterns in the transport-emission nexus across different development stages. Second, investigating the specific mechanisms by which infrastructure improvements influence transport mode choices would provide valuable insights for policy design. Third, examining potential carbon emission rebound phenomena in highly urbanized stages could help anticipate and address future challenges in advanced economies. Fourth, research should focus on the long-term implications of current infrastructure choices on future development possibilities, particularly how path dependency might affect the transition to low-carbon transport systems. Finally, studies should examine how technological progress and innovation in transport systems might alter the traditional relationship between economic growth and carbon emissions, potentially offering new pathways for sustainable development. Such comprehensive research would contribute to a deeper understanding of how countries can better manage their transport infrastructure development to achieve both economic growth and environmental sustainability objectives.

Declaration of generative AI in scientific writing

During the preparation of this manuscript, the authors utilized OpenAI's ChatGPT for the purpose of language refinement and improving the clarity of specific sections. All outputs generated by the tool were carefully reviewed and edited by the authors to ensure accuracy, relevance, and compliance with the journal's standards. The authors take full responsibility for the integrity and originality of the content presented in this manuscript. No generative AI was used to create scientific data, analyses, or substantive content that forms the core of the study.

CRediT authorship contribution statement

Wang Peng: Writing – original draft, Methodology, Data curation, Conceptualization. **Yu Xiaoyuan:** Software, Methodology, Conceptualization. **Nuzul Azam Haron:** Supervision.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

Data availability

Data will be made available on request.

References

[1] S. Solaymani, CO2 emissions patterns in 7 top carbon emitter economies: the case of transport sector, Energy 168 (2019) 989–1001, https://doi.org/10.1016/j.energy.2018.11.145.
[2] H. Du, Z. Chen, B. Peng, F. Southworth, S. Ma, Y. Wang, What drives CO2 emissions from the transport sector? A linkage analysis, Energy 175 (2019) 195–204, https://doi.org/10.1016/j.energy.2019.03.052.
[3] M. Umar, X. Ji, D. Kirikkaleli, A.A. Alola, The imperativeness of environmental quality in the United States transportation sector amidst biomass-fossil energy consumption and growth, J. Clean. Prod. 285 (2021) 124863, https://doi.org/10.1016/j.jclepro.2020.124863.
[4] J. Cubells, C. Miralles-Guasch, O. Marquet, Traffic pollution as a privilege: an intersectional approach to environmental justice and transport emissions, Transport Res. D-Tr E 126 (2024) 104032, https://doi.org/10.1016/j.trd.2023.104032.
[5] Q. Qiao, H. Eskandari, H. Saadatmand, M.A. Sahraei, An interpretable multi-stage forecasting framework for energy consumption and CO2 emissions for the transportation sector, Energy 286 (2024) 129499, https://doi.org/10.1016/j.energy.2023.129499.
[6] A. Ajanovic, The future of electric vehicles: prospects and impediments, WIREs Energy Environ. 4 (2015) 521–536, https://doi.org/10.1002/wene.160.
[7] A. Ajanovic, C. Dahl, L. Schipper, Modelling transport (energy) demand and policies—an introduction, Energ. Policy 41 (2012) iii–xiv.
[8] C.P. Ng, T.H. Law, F.M. Jakarni, S. Kulanthayan, Road infrastructure development and economic growth, IOP Conf. Ser.: Mater. Sci. Eng. 512 (2019) 012045, https://doi.org/10.1088/1757-899X/512/1/012045.
[9] P. Rode, G. Floater, N. Thomopoulos, J. Docherty, P. Schwinger, A. Mahendra, et al., Accessibility in Cities: transport and Urban Form, editors., in: G. Meyer,

S. Shaheen (Eds.), Disrupting Mobility, Springer International Publishing, Cham, 2017, pp. 239–273, https://doi.org/10.1007/978-3-319-51602-8_15.

[10] Y. Gao, Y. Zhang, H. Li, T. Peng, S. Hao, Study on the relationship between comprehensive transportation freight index and GDP in China, Procedia Eng. 137 (2016) 571–580, https://doi.org/10.1016/j.proeng.2016.01.294.

[11] Q.Y. Zheng, T.H. Law, S.V. Wong, C.P. Ng, Relative improvements between roads and railways and economic performance: a panel data analysis, Transp. Policy 153 (2024) 87–96, https://doi.org/10.1016/j.tranpol.2024.05.012.

[12] Y. Weizheng, Research about the impact of transportation infrastructure on economic growth in a transportation power, E3S Web Conf. 253 (2021) 01037, https://doi.org/10.1051/e3sconf/202125301037.

[13] Q. Yang, X. Hu, Y. Wang, Y. Liu, J. Liu, J. Ma, et al., Comparison of the impact of China's railway investment and road investment on the economy and air pollution emissions, J. Clean. Prod. 293 (2021) 126100, https://doi.org/10.1016/j.jclepro.2021.126100.

[14] S. Chakrabarti, Can highway development promote employment growth in India? Transp. Policy 69 (2018) 1–9, https://doi.org/10.1016/j.tranpol.2018.05.009.

[15] W.W. Rostow, The Stages of Economic growth: A non-Communist Manifesto, Cambridge university press, 1990.

[16] M. Jin, K.-C. Lin, W. Shi, P.T. Lee, K.X. Li, Impacts of high-speed railways on economic growth and disparity in China, Transport Res A-Pol 138 (2020) 158–171, https://doi.org/10.1016/j.tra.2020.05.013.

[17] R. Barrientos, F. Ascensão, P. Beja, H.M. Pereira, Borda-de-Água L. Railway ecology vs. road ecology: similarities and differences, Eur. J. Wildlife Res. 65 (2019) 12, https://doi.org/10.1007/s10344-018-1248-0.

[18] D. Acemoglu, J.A. Robinson, The Political Economy of the Kuznets Curve, Rev. Dev. Econ. 6 (2002) 183–203, https://doi.org/10.1111/1467-9361.00149.

[19] D.I. Stern, The environmental Kuznets curve after 25 years, J. Bioecon. 19 (2017) 7–28, https://doi.org/10.1007/s10818-017-9243-1.

[20] Grossman G.M., Krueger A.B. Environmental impacts of a North American free trade agreement 1991.

[21] S. Dasgupta, B. Laplante, H. Wang, D. Wheeler, Confronting the environmental Kuznets curve, J. Econ. Perspect. 16 (2002) 147–168, https://doi.org/10.1257/0895330027157.

[22] M. Ahmad, A. Muslija, E. Satrovic, Does economic prosperity lead to environmental sustainability in developing economies? Environmental Kuznets curve theory, Environ. Sci. Pollut. R. 28 (2021) 22588–22601, https://doi.org/10.1007/s11356-020-12276-9.

[23] S. Dinda, Environmental Kuznets curve hypothesis: a survey, Ecol. Econ. 49 (2004) 431–455, https://doi.org/10.1016/j.ecolecon.2004.02.011.

[24] Q. Wang, F. Ren, R. Li, Exploring the impact of geopolitics on the environmental Kuznets curve research, Sustain. Dev. 32 (2024) 1700–1722, https://doi.org/10.1002/sd.2743.

[25] U.K. Pata, Z. Ahmed, S. Eryilmaz, F. Zeren, Y.G. Gencer, Analyzing the environmental Kuznets curve for transportation modes in European countries, Transport. Res. Part D: Transport Environ. 122 (2023) 103893, https://doi.org/10.1016/j.trd.2023.103893.

[26] S. Erdogan, Analyzing the environmental Kuznets curve hypothesis: the role of disaggregated transport infrastructure investments, Sustain. Cities. Soc. 61 (2020) 102338, https://doi.org/10.1016/j.scs.2020.102338.

[27] M. Guo, S. Chen, J. Zhang, J. Meng, Environment Kuznets curve in transport sector's carbon emission: evidence from China, J. Clean. Prod. 371 (2022) 133504, https://doi.org/10.1016/j.jclepro.2022.133504.

[28] Y. Zhang, X. Chen, Y. Wu, C. Shuai, L. Shen, G. Ye, Peaks of transportation CO_2 emissions of 119 countries for sustainable development: results from carbon Kuznets curve, Sustain. Dev. 28 (2020) 550–571, https://doi.org/10.1002/sd.2008.

[29] S. Erdogan, F.F. Adedoyin, F.V. Bekun, S.A. Sarkodie, Testing the transport-induced environmental Kuznets curve hypothesis: the role of air and railway transport, J. Air. Transp. Manage 89 (2020) 101935, https://doi.org/10.1016/j.jairtraman.2020.101935.

[30] A. Sharif, S. Afshan, S. Chrea, A. Amel, S.A.R. Khan, The role of tourism, transportation and globalization in testing environmental Kuznets curve in Malaysia: new insights from quantile ARDL approach, Environ. Sci. Pollut. R. 27 (2020) 25494–25509, https://doi.org/10.1007/s11356-020-08782-5.

[31] A.S. Alshehry, M. Belloumi, Energy consumption, carbon dioxide emissions and economic growth: the case of Saudi Arabia, Renew. Sustain. Energy Rev. 41 (2015) 237–247, https://doi.org/10.1016/j.rser.2014.08.004.

[32] S.A. Churchill, J. Inekwe, K. Ivanovski, R. Smyth, The environmental Kuznets curve in the OECD: 1870–2014, Energy Econ. 75 (2018) 389–399, https://doi.org/10.1016/j.eneco.2018.09.004.

[33] B. Saboori, M. Sapri, M. Baba bin, Economic growth, energy consumption and CO2 emissions in OECD (Organization for Economic Co-operation and Development)'s transport sector: a fully modified bi-directional relationship approach, Energy 66 (2014) 150–161, https://doi.org/10.1016/j.energy.2013.12.048.

[34] M del P Pablo-Romero, L. Cruz, E. Barata, Testing the transport energy-environmental Kuznets curve hypothesis in the EU27 countries, Energ. Econ. 62 (2017) 257–269, https://doi.org/10.1016/j.eneco.2017.01.003.

[35] Z. Ahmed, Z. Wang, S. Ali, Investigating the non-linear relationship between urbanization and CO2 emissions: an empirical analysis, Air Qual. Atmos. Hlth. 12 (2019) 945–953, https://doi.org/10.1007/s11869-019-00711-x.

[36] X. Ma, C. Wang, B. Dong, G. Gu, R. Chen, Y. Li, et al., Carbon emissions from energy consumption in China: its measurement and driving factors, Sci. Total Environ. 648 (2019) 1411–1420, https://doi.org/10.1016/j.scitotenv.2018.08.183.

[37] J.S. Gregg, R.J. Andres, Marland G. China, Emissions pattern of the world leader in CO_2 emissions from fossil fuel consumption and cement production, Geophys. Res. Lett. 35 (2008), https://doi.org/10.1029/2007GL032887, 2007GL032887.

[38] A. Jalil, S.F. Mahmud, Environment Kuznets curve for CO2 emissions: a cointegration analysis for China, Energy Policy 37 (2009) 5167–5172, https://doi.org/10.1016/j.enpol.2009.07.044.

[39] J.S. Riti, D. Song, Y. Shu, M. Kamah, Decoupling CO2 emission and economic growth in China: is there consistency in estimation results in analyzing environmental Kuznets curve? J. Clean. Prod. 166 (2017) 1448–1461, https://doi.org/10.1016/j.jclepro.2017.08.117.

[40] Z. Wang, F. Yin, Y. Zhang, X. Zhang, An empirical research on the influencing factors of regional CO2 emissions: evidence from Beijing city, China, Appl. Energ. 100 (2012) 277–284, https://doi.org/10.1016/j.apenergy.2012.05.038.

[41] Z. He, S. Xu, W. Shen, R. Long, H. Chen, Impact of urbanization on energy related CO2 emission at different development levels: regional difference in China based on panel estimation, J. Clean. Prod. 140 (2017) 1719–1730, https://doi.org/10.1016/j.jclepro.2016.08.155.

[42] J. Yin, M. Zheng, J. Chen, The effects of environmental regulation and technical progress on CO2 Kuznets curve: an evidence from China, Energ. Policy 77 (2015) 97–108, https://doi.org/10.1016/j.enpol.2014.11.008.

[43] Y.-Q. Kang, T. Zhao, Y.-Y. Yang, Environmental Kuznets curve for CO2 emissions in China: a spatial panel data approach, Ecol. Indic. 63 (2016) 231–239, https://doi.org/10.1016/j.ecolind.2015.12.011.

[44] S. Yazici, Investigating the maritime freight-induced EKC hypothesis: the case of Scandinavian countries, Front. Environ. Sci. 10 (2022) 727830, https://doi.org/10.3389/fenvs.2022.727830.

[45] E. Dursun, Investigating the air transport-induced EKC hypothesis: evidence from NAFTA countries, Int. J. Energy Econ. Policy 12 (2022) 494–500, https://doi.org/10.32479/ijeep.13347.

[46] S.J. Abul, E. Satrovic, Revisiting the environmental impacts of railway transport: does EKC exist in South-Eastern Europe, Pol. J. Environ. Stud. 31 (2022) 539–549, https://doi.org/10.15244/pjoes/141329.

[47] M. Guo, S. Chen, J. Zhang, J. Meng, Environment Kuznets curve in transport sector's carbon emission: evidence from China, J. Clean. Prod. 371 (2022) 133504, https://doi.org/10.1016/j.jclepro.2022.133504.

[48] Y. Liu, A. Ali, Y. Chen, X. She, The effect of transport infrastructure (road, rail, and air) investments on economic growth and environmental pollution and testing the validity of EKC in China, India, Japan, and Russia, Environ. Sci. Pollut. R. 30 (2022) 32585–32599, https://doi.org/10.1007/s11356-022-24448-w.

[49] L. Hou, Y. Wang, L. Hu, Y. Wang, Y. Li, Y. Zheng, Economic growth and carbon emissions analysis based on tapio-ekc coupled integration and scenario simulation: a case study of china's transportation industry, Environ. Dev. Sustain. 26 (2023) 18855–18881, https://doi.org/10.1007/s10668-023-03418-3.

[50] Z. Peng, Q. Wu, M. Li, Spatial characteristics and influencing factorsof carbon emissions from energy consumptionin China's transport sector:an empirical analysis based on provincialpanel data, Pol. J. Environ. Stud. 29 (2019) 217–232, https://doi.org/10.15244/pjoes/102369.

[51] D.I. Stern, The rise and fall of the environmental Kuznets curve, World Dev. 32 (2004) 1419–1439.

[52] G.M. Grossman, A.B. Krueger, Economic growth and the environment, Q. J. Econ. 110 (1995) 353–377, https://doi.org/10.2307/2118443.

[53] A.N. Çatik, A. İlhan, C. Akdeniz, Testing the environmental Kuznets curve hypothesis in the transport sector for OECD countries: a dynamic panel threshold approach, Environ. Sci. Pollut. R. 31 (2023) 6372–6384, https://doi.org/10.1007/s11356-023-31468-7.

[54] N.C. Leitão, The Link between Human Development, Foreign Direct Investment, Renewable Energy, and Carbon Dioxide Emissions in G7 Economies, Energies. (Basel) 17 (2024) 978, https://doi.org/10.3390/en17050978.

[55] X. Liu, S. Zhang, J. Bae, The impact of renewable energy and agriculture on carbon dioxide emissions: investigating the environmental Kuznets curve in four selected ASEAN countries, J. Clean. Prod. 164 (2017) 1239–1247, https://doi.org/10.1016/j.jclepro.2017.07.086.

[56] G.R. Timilsina, A. Shrestha, Transport sector CO2 emissions growth in Asia: underlying factors and policy options, Energy Policy 37 (2009) 4523–4539, https://doi.org/10.1016/j.enpol.2009.06.009.

[57] N.C. Leitão, C.C. Dos Santos Parente, D. Balsalobre-Lorente, J.M Cantos Cantos, Revisiting the effects of energy, population, foreign direct investment, and economic growth in Visegrad countries under the EKC scheme, Environ. Sci. Pollut. R. 30 (2022) 15102–15114, https://doi.org/10.1007/s11356-022-23188-1.

[58] T. Li, Y. Wang, D. Zhao, Environmental Kuznets curve in China: new evidence from dynamic panel analysis, Energy Policy 91 (2016) 138–147, https://doi.org/10.1016/j.enpol.2016.01.002.

[59] M del P Pablo-Romero, A. Sánchez-Braza, Residential energy environmental Kuznets curve in the EU-28, Energy 125 (2017) 44–54, https://doi.org/10.1016/j.energy.2017.02.091.

[60] M.A. Cole, R.J.R. Elliott, J. Zhang, Growth, foreign direct investment, and the environment: evidence from Chinese cities, J. Region. Sci. 51 (2011) 121–138, https://doi.org/10.1111/j.1467-9787.2010.00674.x.

[61] M. Shahbaz, S. Nasreen, F. Abbas, O. Anis, Does foreign direct investment impede environmental quality in high-, middle-, and low-income countries? Energ. Econ. 51 (2015) 275–287, https://doi.org/10.1016/j.eneco.2015.06.014.

[62] Kenworthy J., Newman P. The end of automobile dependence: how cities are moving beyond car-based planning 2015.

[63] E.L. Glaeser, M.E. Kahn, The greenness of cities: carbon dioxide emissions and urban development, J. Urban. Econ. 67 (2010) 404–418, https://doi.org/10.1016/j.jue.2009.11.006.

[64] F. Creutzig, P. Jochem, O.Y. Edelenbosch, L. Mattauch, D.P.V. Vuuren, D. McCollum, et al., Transport: a roadblock to climate change mitigation? Science 350 (2015) 911–912, https://doi.org/10.1126/science.aac8033.

[65] H. Zhu, L. Duan, Y. Guo, K. Yu, The effects of FDI, economic growth and energy consumption on carbon emissions in ASEAN-5: evidence from panel quantile regression, Econ. Model. 58 (2016) 237–248, https://doi.org/10.1016/j.econmod.2016.05.003.

[66] Y. Yu, N. Zhang, J.D. Kim, Impact of urbanization on energy demand: an empirical study of the Yangtze River Economic Belt in China, Energ. Policy 139 (2020) 111354.

[67] J. Dargay, D. Gately, M. Sommer, Vehicle Ownership and Income Growth, Worldwide: 1960-2030, Energy J. 28 (2007) 143–170, https://doi.org/10.5547/ISSN0195-6574-EJ-Vol28-No4-7.

[68] D. Puga, European regional policies in light of recent location theories, J. Econ. Geograph. 2 (2002) 373–406, https://doi.org/10.1093/jeg/2.4.373.

[69] S. Fan, C. Chan-Kang, Regional road development, rural and urban poverty: evidence from China, Transp. Policy 15 (2008) 305–314, https://doi.org/10.1016/j.tranpol.2008.12.012.

[70] A.S. Alshehry, M. Belloumi, Study of the environmental Kuznets curve for transport carbon dioxide emissions in Saudi Arabia, Renew. Sustain. Energy Rev. 75 (2017) 1339–1347, https://doi.org/10.1016/j.rser.2016.11.122.

[71] G. Bölük, M. Mert, The renewable energy, growth and environmental Kuznets curve in Turkey: an ARDL approach, Renew. Sustain. Energy Rev. 52 (2015) 587–595, https://doi.org/10.1016/j.rser.2015.07.138.

[72] T. Chang, W. Fang, L-F. Wen, Energy consumption, employment, output, and temporal causality: evidence from Taiwan based on cointegration and error-correction modelling techniques, Appl. Econ. 33 (2001) 1045–1056, https://doi.org/10.1080/00036840122484.

[73] P.C. Phillips, P. Perron, Testing for a unit root in time series regression, Biometrika 75 (1988) 335–346, https://doi.org/10.1093/biomet/75.2.335.

[74] D.A. Dickey, W.A. Fuller, Distribution of the Estimators for Autoregressive Time Series with a Unit Root, J. Am. Stat. Assoc. 74 (1979) 427–431, https://doi.org/10.1080/01621459.1979.10482531.

[75] R.F. Engle, C.W. Granger, Co-integration and error correction: representation, estimation, and testing, Econometrica: J. Econometr. Soc. (1987) 251–276, https://doi.org/10.2307/1913236.

[76] P.C. Phillips, B.E. Hansen, Statistical inference in instrumental variables regression with I (1) processes, Rev. Econ. Stud. 57 (1990) 99–125, https://doi.org/10.2307/2297545.

[77] M.H. Pesaran, Y. Shin, R.J. Smith, Bounds testing approaches to the analysis of level relationships, J. Appl. Economet. 16 (2001) 289–326, https://doi.org/10.1002/jae.616.

[78] P.K. Narayan, S. Narayan, Estimating income and price elasticities of imports for Fiji in a cointegration framework, Econ. Model. 22 (2005) 423–438, https://doi.org/10.1016/j.econmod.2004.06.004.

[79] E. Nkoro, A.K. Uko, Autoregressive Distributed Lag (ARDL) cointegration technique: application and interpretation, J. Stat. Econometr. Methods 5 (2016) 63–91.

[80] M. Kahia, M. Ben Jebli, M. Belloumi, Analysis of the impact of renewable energy consumption and economic growth on carbon dioxide emissions in 12 MENA countries, Clean Tech. Environ. Policy 21 (2019) 871–885, https://doi.org/10.1007/s10098-019-01676-2.

[81] M.K. Khan, M.I. Khan, M. Rehan, The relationship between energy consumption, economic growth and carbon dioxide emissions in Pakistan, Financ. Innov. 6 (2020) 1, https://doi.org/10.1186/s40854-019-0162-0.

[82] T.S. Breusch, A.R. Pagan, A simple test for heteroscedasticity and random coefficient variation, Econometrica: J. Econometr. Soc. (1979) 1287–1294, https://doi.org/10.2307/1911963.

[83] T.S. Breusch, A.R. Pagan, The Lagrange multiplier test and its applications to model specification in econometrics, Rev. Econ. Stud. 47 (1980) 239–253, https://doi.org/10.2307/2297111.

[84] L.G. Godfrey, Testing against general autoregressive and moving average error models when the regressors include lagged dependent variables, Econometrica: J. Econometr. Soc. (1978) 1293–1301, https://doi.org/10.2307/1913829.

[85] P.K. Narayan, The saving and investment nexus for China: evidence from cointegration tests, Appl. Econ. 37 (2005) 1979–1990, https://doi.org/10.1080/00036840500278103.

[86] R.L. Brown, J. Durbin, J.M. Evans, Techniques for testing the constancy of regression relationships over time, J. R. Stat. Soc. B 37 (1975) 149–163, https://doi.org/10.1111/j.2517-6161.1975.tb01532.x.

[87] H. Lütkepohl, New Introduction to Multiple Time Series Analysis, Springer Science & Business Media, 2005.

[88] C. Brooks, Introductory Econometrics For Finance, Cambridge university press, 2019.

[89] M. Bahmani-Oskooee, R.C.W. Ng, Long-run demand for money in Hong Kong: an application of the ARDL model, Int. J. Bus. Econ. 1 (2002) 147.

[90] R.D. Cook, S. Weisberg, Diagnostics for heteroscedasticity in regression, Biometrika 70 (1983) 1–10, https://doi.org/10.1093/biomet/70.1.1.

[91] P.K. Narayan, R. Smyth, Electricity consumption, employment and real income in Australia evidence from multivariate Granger causality tests, Energy Policy 33 (2005) 1109–1116, https://doi.org/10.1016/j.enpol.2003.11.010.

[92] I. Ozturk, A. Acaravci, The long-run and causal analysis of energy, growth, openness and financial development on carbon emissions in Turkey, Energy Econ. 36 (2013) 262–267, https://doi.org/10.1016/j.eneco.2012.08.025.

[93] M. Shahbaz, T.H. Van Hoang, M.K. Mahalik, D. Roubaud, Energy consumption, financial development and economic growth in India: new evidence from a nonlinear and asymmetric analysis, Energ. Econ. 63 (2017) 199–212.

[94] G. De Vita, S. Katircioglu, L. Altinay, S. Fethi, M. Mercan, Revisiting the environmental Kuznets curve hypothesis in a tourism development context, Environ. Sci. Pollut. R. 22 (2015) 16652–16663, https://doi.org/10.1007/s11356-015-4861-4.

[95] S.K. Goh, R. McNown, Macroeconomic implications of population aging: evidence from Japan, J. Asian Econ. 68 (2020) 101198, https://doi.org/10.1016/j.asieco.2020.101198.

[96] H. Achour, M. Belloumi, Investigating the causal relationship between transport infrastructure, transport energy consumption and economic growth in Tunisia, Renew. Sustain. Energy Rev. 56 (2016) 988–998, https://doi.org/10.1016/j.rser.2015.12.023.