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Does rail transportation matter for climate outcomes? evidence from public transport systems in Asia

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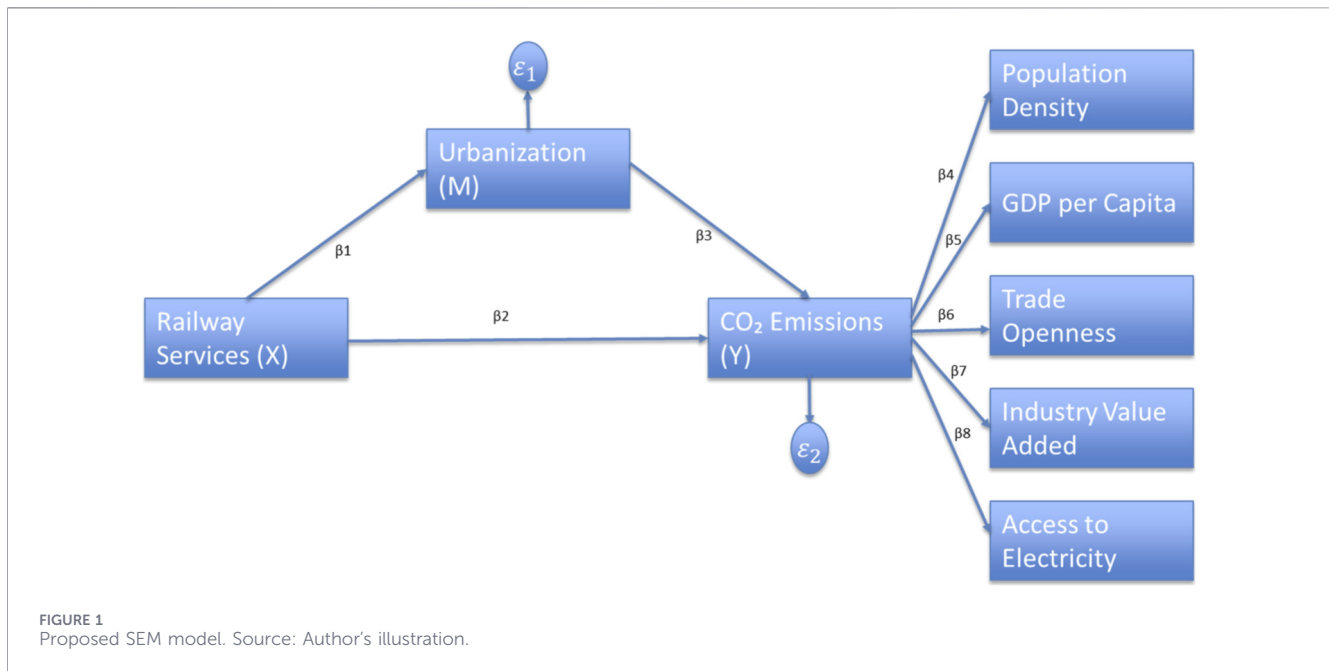
The transport sector has emerged as a significant contributor to carbon dioxide emissions in Asia, driven by rapid economic growth, urbanization, and transportation demand. While the government has focused on the use of public transportation for mitigating carbon emissions, there is a lack of empirical evidence on its environmental impact. This research attempts to understand the impact of rail transportation on carbon dioxide emissions in 16 countries in Asia from 2005 to 2019. Panel data regression techniques, such as pooled OLS, fixed-effects, and random-effects, are employed, in addition to Structural Equation Model to understand the direct and indirect impact of public rail investment on the environment. The result show that the rail transportation has a significant impact on carbon emissions as a 1% increase in railway infrastructure is associated with approximately 0.138% reduction in CO₂ emissions. Urbanization, however, has a positive and significant impact on carbon emissions. In addition, analysis of regional heterogeneity revealed that rail transportation has a significant impact on carbon emissions in Asia, although the impact is low in South Asia.

KEYWORDS

access to electricity, asian, CO₂ emissions, population density, rail transportation, sustainable transport, urbanization

1 Introduction

Carbon dioxide (CO₂) remains the pre-eminent greenhouse gas emitted through human activities, contributing over three-quarters of global greenhouse gas emissions and projected to accelerate at an unprecedented rate. This uptrend, especially due to fossil fuel burning, has contributed to enhanced greenhouse effects and their negative impacts on the environment and health, such as climate change and its associated outcomes of extreme events, poor air quality, and increased morbidity of cardio-respiratory diseases (Kwakwa et al., 2023; Nunez, 2019). In this scenario, it has become a matter of prime importance to determine sector-wise methods of reducing greenhouse gas emissions and in what manner global strategies can keep a pace with economic and urban development. Within the major emitting sectors, transport is singled out as an area where there are intense pressures (Inderwildi and King, 2012). Also, there is heavy reliance on fossil fuels. Reduced visibility due to atmospheric pollution and emissions associated with greenhouse gases, especially in regions where there is rapid urbanization, poses an increasing strain. Asia, as opposed to other regions, is characterized by rapid economic development, urbanization, and increasing motorization.



Such factors, which were less common 2 decades ago, have considerably impacted emissions associated with transport, which pose an increasing strain, especially in vulnerable environments created by urbanization. Within Asia, countries are characterized by notable diversities in economic development, urbanization, energy structure, and transport infrastructure; hence, this region is significant for testing various transport options. Under these circumstances, rail transport has been identified as an important player within the strategy for the decarbonization of transport in the long term. Compared with road traffic and aviation, rail transport networks, particularly electrified networks, are known to be more energy-efficient with lower values for carbon dioxide emissions per passenger kilometer (average values based on the data provided in Zuo et al., 2018; Carbon Independent, 2023). Quantitative assessments indicate that the per kilometer emission value for passenger trains on the medium/long distance range may vary from 19 g per kilometer to 71 g per kilometer depending upon the emission value used for the mechanism as well as various other factors, as against 120 g per kilometer for private cars and 285 g per kilometer for flights (Carbon Independent, 2023).

Apart from the GHG emissions associated directly with its use, a positive systemic contribution of train-based public transportation to the mitigation of GHG emissions in the transport sector exists (Indiaghgp.org, 2023; ORR Data Portal, 2023). By promoting the shift from the use of private cars to the utilization of public transportation and facilitating a large number of users to travel in a train at a time, the overall GHG emissions associated with transportation activities could decline da Fonseca-Soares et al., 2024. Findings from Europe have supported the idea that public transportation systems have the potential to decrease the overall urban emissions of CO₂ by tens of millions of tonnes every year by cutting down the use of cars and encouraging foot mobility (International Association of Public Transport (UITP), 2019). This has also been found to happen in other scenarios in which the overall GHG emissions associated with public transportation

users are lower than exclusive car users (APTA, 2021) (Figure 1). All these have special implications for Asian countries in which the growth of cities is presently transforming the geography of those nations.

Despite the accumulation of research on sustainable transportation, there exist some issues in terms of the environmental efficiency of rail transport in regions that are in the process of rapid development, like those in Asia. Specifically, existing empirical research has focused on investigating the direct association between transport and emissions, with some research conducted on individual countries or developed regions. Although there are some research findings that emphasize the environmental benefits of rail transport, due to its energy efficiency and lower emissions per passenger-kilometer, there is limited empirical evidence on the impact of the expansion of rail transport on emissions in diverse Asian countries. Additionally, there is limited knowledge about how rail transport can affect emissions through mechanisms like urbanization and socioeconomic factors. In light of the above, the research question that this paper aims to address is as follows: under which circumstances and through which channels does the expansion of rail transport in the Asian economies impact CO₂ emissions? The research question is particularly pertinent in the case of the Asian economies because of the substantial impacts of the ongoing urbanization and population growth on their energy consumption and environmental outcomes. Though the literature has already addressed the relationships between transportation infrastructure and urbanization and their impacts on environmental outcomes, few research studies have explored the direct and indirect channels of the impacts of the expansion of rail transport on environmental outcomes.

To bridge the research gap, the present study investigates the relationship between rail transport and CO₂ emissions in 16 Asian countries from 2005 to 2019. The study combines panel data econometric approaches with a structural equation modeling approach to estimate the direct and indirect relationships

between rail transport, urbanization, and CO₂ emissions. The study contributes to the literature in three ways. First, the study contributes to the literature by providing new cross-country empirical findings on the environmental impacts of rail transport in Asian economies. Second, the study examines the indirect effect of rail transport on CO₂ emissions through the role of urbanization. Third, the study combines the findings of the panel data approaches with the structural equation modeling approach to develop a more comprehensive analytical framework. The rest of the paper is structured as follows. [Section 2](#) provides a discussion of the relevant literature in the fields of public transport, railway infrastructure, and carbon emissions. [Section 3](#) introduces the data and methodology that will be used in the paper's empirical analysis. In [Section 4](#), the results will be presented and discussed, while [Section 5](#) concludes and draws lessons for future studies.

2 Literature review

2.1 Public transportation, modal shift, and carbon emissions

A substantial extent of research has proven the significance of transportation in carbon emissions and the particular significance of private vehicle dependency in the increase in emissions in the urban sector. The early empirical research reveals the significance of public transport in decreasing carbon emissions due to the shift from private vehicles. For example, [Barth and Boriboonsomsin \(2009\)](#) provided sufficient support for the idea that the promotion of public transport and the discouragement of private vehicles can lead to a dramatic decrease in carbon emissions due to decreased vehicular kilometers and improvements in energy efficiency. [Litman \(2009\)](#) goes further and asserts that the promotion of public transport use and the discouragement of private vehicles are the most effective methods for abating carbon emissions in the transport sector. Apart from modal substitution, more emphasis has been placed on technological and operational efficiency within public transport networks. [Liu et al. \(2019\)](#), [Ebusco \(2020\)](#) emphasize that electric and hybrid buses have a strong potential for reducing emissions and that environmentally friendly technological advancements have a significant positive effect on public transport regarding environmental issues. Nevertheless, barely can environmental and technological factors be accounted for without behavioral support. Research rooted in behavioral economics underlines that attitudes and economic values affect transport mode use significantly. [Steg et al. \(2008\)](#) strongly support that facilitating environmental attitudes has a significant positive effect on using public transport, and thereby reducing emissions indirectly. Urban structure and land use are further mediating factors in the linkage between public transportation and emissions. [Cervero and Murakami \(2010\)](#) show, in a TOD analysis, that regions enjoying high-quality access to public transportation are characterized by lower VMT and lower carbon emissions. This is an indication that the relationship between transportation infrastructure and emissions includes many indirect factors, and therefore, it is important to consider the influences in the process and not view infrastructure alone as an important factor. Research focused on policy, in particular, further reinforces the effectiveness associated with an integrated approach. For instance,

[Ülengin et al. \(2018\)](#) establish that an approach comprising more than one policy, for instance, fuel tax, parking fees, and public transport subsidies, is better than a standalone policy technique at encouraging the usage of public transport, hence reducing carbon emissions. The significance of the body of research highlighted is the principle that public transport not only serves to mitigate carbon emissions, but it also influences behavioral transformation and planning changes.

2.2 Rail transportation and carbon emissions

From the broader literature on public transportation, the position of rail transport is unique because of its energy efficiency as well as scalability. Compared to other modes of transportation, it has been found that the carbon emissions for the transportation of one passenger per kilometer are lower for railways, specifically for electrified railways. The energy efficiency and performance of railways in terms of greenhouse gas emissions have been examined by [Liimatainen et al. \(2014\)](#) to establish the superiority of railways in terms of performance in heavily used scenarios. Some studies also apply the discussion above as they relate to investment in rail transport within climate and other environment-related policies and frameworks. For instance, in their study involving evidence in the Chinese Province of Shanxi, [Aunan et al., \(2004\)](#) argued that investments in rail transport can lead to co-benefits through the mitigating effects of such investments on emissions as well as local air pollutants. Hoyos et al., in their paper in 2016, analyzed the implications of high-speed rail and found that high-speed rail is more carbon-efficient compared to other modes of transport if well linked into the national transport network. More recent empirical contributions have stressed the role of modal shift from road to rail as instrumental for achieving emissions reductions. [Ramos da Silva et al. \(2023\)](#), based on evidence from Portugal, quantify the emissions savings and cost reductions associated with increased rail usage and further reiterate the shifting of freight and passenger transport toward rail-based systems. Review studies, such as [Kapetanović et al. \(2019\)](#), synthesize this evidence of the role of rail transport in contributing to energy conservation, climate mitigation, and broader environmental sustainability objectives. Comparative analyses between rail and road transport confirm rail transport's relatively low carbon footprint, as recently evidenced by [Skrúčaný et al. \(2018\)](#) for Poland. Despite these achievements, a great amount of the current literature on rail transport is geographically focused on Europe and certain parts of China. Furthermore, the current literature does not give adequate consideration to the indirect emissions relationships between rail transport and urbanization/economic structure/energy access. In addition, the current stream of research on rail transport does not empirically examine the relationships between rail transport investment and emissions levels. In fact, the key works on rail transport have long argued that rail transport enjoys efficiency advantages ([Glaeser, 2009](#); [Scott, 2011](#)).

2.3 Research gap, hypotheses, and methodological motivation

Though the available literature has provided significant insights on the relationship between transportation infrastructure and environmental outcomes, some significant gaps in the available literature have also been identified. First, the available empirical

evidence is mostly based on developed economies, while evidence for Asian economies is limited. Second, while the available literature has mostly focused on the direct relationship between transportation infrastructure and environmental outcomes, the indirect relationship between transportation infrastructure and environmental outcomes has been less explored. Third, the relationship between rail transport and urbanization has not been sufficiently examined. Rail transport is viewed as an environmentally efficient mode of transport because its emissions per passenger or freight are less compared to road transport. Expanding rail transport infrastructure can help reduce the usage of private vehicles and road freight transport, hence lowering energy consumption and emissions. Based on this understanding, the first hypothesis assesses the direct relationship between rail transport intensity and CO₂ emissions.

H1: Rail transport intensity is negatively associated with CO₂ emissions

Apart from these direct impacts, rail transport may have indirect impacts on emissions through urbanization and socioeconomic transformation. Better rail transport infrastructure may shape urbanization processes and promote more condensed cities. These processes may in turn impact energy consumption patterns and hence impact emissions. It is therefore essential to investigate whether or not rail transport impacts emissions through these indirect pathways.

H2: Rail transport impacts CO₂ emissions indirectly through its impact on urbanization and associated socioeconomic processes

Additionally, economic growth and urbanization have been recognized as substantial factors in influencing environmental quality. Rapid urbanization in Asian economies may lead to increased energy consumption, transportation activities, and industrial production, which may cause increased emissions. However, transportation infrastructure in the form of rails may help reduce these environmental pressures.

H3: Urbanization is positively related with CO₂ emissions in Asian economies

In order to test the hypotheses anticipated in the study, the research will use a combination of panel regression analysis and Structural Equation Model (SEM). To test the direct relationships between rail transport intensity and CO₂ emissions (H1 and H3), the research will use various panel regression analysis techniques. On the other hand, the Structural Equation Model will be employed to test the indirect relationships between rail transport and CO₂ emissions through the mediating role of urbanization (H2). This will enable the researcher to have a better and more comprehensive understanding of the direct and indirect relationships between rail transportation and environmental outcomes.

3 Methods and materials

3.1 Data source and variables

For the purpose of this analysis, data were derived from the World Bank for a group of 16 Asian countries: Azerbaijan, China, Georgia, India, Indonesia, Iran, Israel, Japan, Kazakhstan, Kyrgyzstan, Malaysia, Mongolia, South Korea, Tajikistan, Uzbekistan, and Vietnam. They

were deliberately chosen from the 48 in Asia so that there would be full availability of data for all variables under study from 2005 to 2019, and they also span a range of economic classifications (high-, middle-, and low-income), levels of rail infrastructure maturity, and urban development patterns. This heterogeneity provides valid intra- and inter-regional comparisons and enhances the external validity of the findings. While the sample is specific to a region, the composition of the structural conditions adds to the generalizability of methodological findings to other regions of the world. The study utilized the variable $\ln\text{RAIL}$, which is based on passenger rail transport (measured in million passenger-kilometers), for the measurement of the development in rail transport. This was informed by the fact that data on rail transport was consistently available for all the countries included in the sample during the period of study. In addition, we utilized the variable $\ln\text{AE}$ (access to electricity) for measuring the differences that exist in infrastructure in terms of energy levels across different countries. The data was transformed into logarithmic form. This helps in controlling heteroscedasticity, improves normality in data distribution, and enables the estimation of coefficients that are elastic in nature. Since all the variables are in logarithmic form, the estimated coefficients are elasticities that indicate the percentage change in CO₂ emissions due to a one percent change in the respective variables. The variables and definitions are presented in Table 1.

The analysis of the relationship between rail transportation and the emission of CO₂ in the Asian countries is conducted using the panel data analysis method. The use of the panel data analysis method is important because it helps the analysis control for any heterogeneity between the countries and also enhances the efficiency of the analysis.

The general empirical model that is used is as follows:

$$\text{CO}_{2it} = \beta_0 + \beta_1 \text{Rail}_{it} + \beta_2 \text{Urban}_{it} + \beta_3 \text{GDP}_{it} + \beta_4 \text{Energy}_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

Where 'i' denotes country and 't' represents time. CO₂ emissions represent the dependent variable, whereas rail transport intensity, urbanization, economic growth, and energy consumption represent the explanatory variables. μ_i represents the unobserved country-specific effects, and λ_t represents time-specific effects. In order to estimate the model, three different panel data estimators are utilized: Pooled Ordinary Least Squares, Fixed Effects, and Random Effects models. In order to ascertain the model specification for the analysis, the Hausman test is performed to compare the results from the Fixed Effects model and the Random Effects model. A significant value for the test statistic indicates that the Fixed Effects model should be used for the analysis as the random effects assumption is violated. Several diagnostic tests are performed to ensure the robustness of the empirical results. First, panel unit root tests are performed to check for the stationary nature of the variables. If required, the appropriate transformations are done. Second, serial correlation tests for the error terms are performed to ensure that the error terms are not correlated over time. Finally, cross-sectional dependence tests are performed to check for the presence of cross-sectional dependence in the panel data. To ensure that the models are free from heteroscedasticity and serial correlation, the models are estimated with robust standard errors clustered for each country. This helps to ensure the reliability of the results as the coefficients are not biased due to panel data.

TABLE 1 Variable definitions.

Variables	Definition	Measurement units	Source
<i>lnCO2</i>	Carbon dioxide emissions	Thousands of tonnes	World Bank
<i>lnRAIL</i>	Railway passengers	Million passengers times km's	World Bank
<i>lnURBAN</i>	Percent urban population	Percentage of Urban population	World Bank
<i>lnPD</i>	Population density	People per square km	World Bank
<i>lnPCG</i>	GDP <i>per capita</i>	Constant 2010, dollars	World Bank
<i>lnTO</i>	Trade openness	Exports plus imports as percent of GDP	World Bank
<i>lnSI</i>	Value added by industry	As percent of GDP	World Bank
<i>lnAE</i>	Access to electricity	Percent of the population	World Bank

Source: Author's compilation

TABLE 2 Descriptive statistics.

Variables	Obs	Mean	Std. Dev	Min	Max
<i>lnCO2</i>	240	5.176	0.873	3.682	7.030
<i>lnRAIL</i>	240	3.831	1.263	1.519	6.158
<i>lnURBAN</i>	240	1.918	0.104	1.733	2.079
<i>lnPD</i>	240	1.975	0.559	0.699	2.727
<i>lnPCG</i>	240	3.682	0.495	2.791	4.598
<i>lnTO</i>	240	1.862	0.206	1.387	2.309
<i>lnSI</i>	240	1.507	0.133	1.222	1.820
<i>lnAE</i>	240	1.986	0.033	1.830	2.000

Source: Author's calculation.

As panel data models (pooled OLS, fixed effects, and random effects) can account for both country-specific and time-specific effects, they are frequently employed in cross-country emission studies (Chamberlain, 1984; Bai, 2009; Bell and Jones, 2015). According to methods employed by Little et al. (2007), Ramos da Silva et al. (2023) and Hoyos et al. (2016) to investigate transport-environment linkages, the SEM approach is especially appropriate in this case since it captures the mediation effect of urbanization. As per need we also employed the same above said methods in the present study. Descriptive statistics of the variables used in the analysis are presented in Table 2. From analysis, it can be deduced that population density and GDP *per capita* have a larger standard deviation which defines the spread of the data in relation to the mean. Minimum and maximum describe the spread of each variable of interest with the 'Access to Electricity' variable describing the level of service that all members of population have.

3.2 Panel regression analysis

To test rail transport's use in attaining optimal CO₂ emission reduction scenarios using empirical analysis, the study applies pooled cross-sectional analysis and panel fixed effects and panel random effects analyses.

In a pooled regression all observations across the cross-sections and over time are used to obtain one set of regression coefficients for the entire sample. It offers a first outlook at the general trend between rail transport and CO₂ emissions which ignores temporal or individual differences.

$$lnCO_{2it} = \beta_0 + \beta_1 lnRAIL_{it} + \beta_2 lnURBAN_{it} + \beta_3 lnPD_{it} + \beta_4 lnPCG_{it} + \beta_5 lnTO_{it} + \beta_6 lnSI_{it} + \beta_7 lnAE_{it} + \epsilon_{it}$$

Where lnCO₂- is the dependent variable or carbon emissions. The various control variables used are including; number of rail passengers (lnRAIL), level of urbanization (lnURBAN), population density (lnPD), *per capita* GPD (lnPCG), Trade openness (lnTO), share of industry (lnSI) and access to electric power (lnAE). where, β₀ stands for control while β₁, β₂, β₃, β₄, β₅, β₆, and β₇ are the coefficients of the independent variables of the model. ε_{it}- This symbol stands for the residual term, which comprises of other factors that could not be measured and variation in the dependent variable.

In this subsequent analysis, fixed effects regression is used to account for characteristics in each country that remain constant over time and might affect the CO₂ emission rates including geographical and infrastructural structures.

$$lnCO_{2it} = \beta_0 + \beta_1 lnRAIL_{it} + \beta_2 lnURBAN_{it} + \beta_3 lnPD_{it} + \beta_4 lnPCG_{it} + \beta_5 lnTO_{it} + \beta_6 lnSI_{it} + \beta_7 lnAE_{it} + \alpha_i + u_{it}$$

In lnCO₂_{it} represents the dependent variable that is carbon emission and independent variables for entity i at time t are lnRAIL_{it}, lnURBAN_{it}, lnPD_{it}, lnPCG_{it}, lnTO_{it}, lnSI_{it}, and; lnAE_{it} while, γ₀, γ₁, γ₂, γ₃, γ₄, γ₅, γ₆ and γ₇ are the coefficients of α_i is the fixed effect for entity i, which addresses the time invariant characteristic for the entity. u_{it} is the random distorting variable at the/entity level for time t, which isolates all the unpredictable tremors that may manifest in the dependent variable once all the entity-specific fixed effects are controlled for.

We also perform a Random-Effects Regression analysis in which entity-specific random effects are included to account for both time-invariant and time-varying heterogeneity across entities: We also perform a Random-Effects Regression analysis in which entity-

specific random effects are included to account for both time-invariant and time-varying heterogeneity across entities:

$$\ln CO_{2it} = \beta_0 + \beta_1 \ln RAIL_{it} + \beta_2 \ln URBAN_{it} + \beta_3 \ln PD_{it} + \beta_4 \ln PCG_{it} + \beta_5 \ln TO_{it} + \beta_6 \ln SI_{it} + \beta_7 \ln AE_{it} + u_i + \varepsilon_{it}$$

With $\ln CO_{2it}$ as dependent variable: carbon emissions for entity i in time t ; $\ln RAIL_{it}$, $\ln URBAN_{it}$, $\ln PD_{it}$, $\ln PCG_{it}$, $\ln TO_{it}$, $\ln SI_{it}$, $\ln AE_{it}$ as the independent variables of entity i at time t , β_0 , β_1 , β_2 , β_3 , β_4 , β_5 , β_6 , β_7 as the coefficients of the corresponding independent. The term μ_i is the arbitrary random effect specific only to the entity i , which reflects the specific deviations for the given entity from the average dependence between the given set of variables. ε_{it} is the residual or the error term for the i th entity at the t th time point, to account for the remainder and addition random effects and shocks that have occurred on the dependent variable.

3.3 Structural equation model (SEM)

Apart from the panel data regression models, this study makes use of Structural Equation Model (SEM). This is important in the analysis of complex relationships, especially in relation to rail transport, urbanization, and CO₂ emissions. This methodology is advantageous in that it allows for the estimation of several relationships at once, as well as the assessment of both direct and indirect effects among variables. The SEM approach includes two main components: the measurement model and the structural model. The measurement model indicates how well a variable is related to a latent construct, if applicable. In this study, the analysis is mainly based on observed variables, thus limiting the measurement component. On the other hand, the structural model indicates how variables are related in a causal manner, especially in relation to rail transport, urbanization, economic activity, and CO₂ emissions. In SEM, maximum likelihood estimation (MLE) is used in estimating the structural model, as it is advantageous in structural modeling in comparison with other approaches. This approach enables the assessment of indirect effects, especially in relation to rail transport and its impact on CO₂ emissions, as well as its impact on urbanization and economic activity. In order to check how well the SEM model fits, several goodness-of-fit measures are considered, which include the Comparative Fit Index (CFI), the Root Mean Square Error of Approximation (RMSEA), and the Standardized Root Mean Square Residual (SRMR). Before the estimation of Structural Equation Model (SEM) for the given variables, one should define the paths between the presented variables and their indicators—a measurement model. According to the information to be used in the analysis, we shall define $\ln CO_2$ as the dependent variable while $\ln RAIL$ as the independent variable of interest. Other variables to be included in the model shall be, $\ln URBAN$, $\ln PD$, $\ln PCG$, $\ln TO$, $\ln SI$, and $\ln AE$ as the control variables. We have assumed the variables in the model to be combined linearly in this formulation.

The SEM can be represented by the following structural and measurement equations: The SEM can be represented by the following structural and measurement equations:

$$\ln CO_2 = \beta_0 + \beta_1 \ln RAIL + \beta_2 \ln URBAN + \beta_3 \ln PD + \beta_4 \ln PCG + \beta_5 \ln TO + \beta_6 \ln SI + \beta_7 \ln AE + \varepsilon_1$$

Measurement Equations:

$$\ln CO_2 = \lambda_1 * \eta_1 + \zeta_1; \ln RAIL = \lambda_2 * \eta_2 + \zeta_2$$

$$\ln URBAN = \lambda_3 * \eta_3 + \zeta_3; \ln PD = \lambda_4 * \eta_4 + \zeta_4$$

$$\ln PCG = \lambda_5 * \eta_5 + \zeta_5; \ln TO = \lambda_6 * \eta_6 + \zeta_6$$

$$\ln SI = \lambda_7 * \eta_7 + \zeta_7; \ln AE = \lambda_8 * \eta_8 + \zeta_8$$

Where, β_0 , β_1 , β_2 , β_3 , β_4 , β_5 , β_6 , and β_7 are structural coefficients—real direct effects of the independent and control variables on the dependent variable, $\ln CO_2$. ε_1 is disturbance term for $\ln CO_2$ which implies the residual variation in the dependent variable. η_1 , η_2 , η_3 , η_4 , η_5 , η_6 , and η_7 are the liabilities of $\ln CO_2$, $\ln RAIL$, $\ln TO$, $\ln URBAN$, $\ln PD$, $\ln PCG$, $\ln SI$, and $\ln AE$, respectively. Here λ_1 , λ_2 , λ_3 , λ_4 , λ_5 , λ_6 , λ_7 , and λ_8 are the factor loadings which indicate how much the observed variable is related to the corresponding factor. ε_1 , ε_2 , ε_3 , ε_4 , ε_5 , ε_6 , ε_7 , and ε_8 are the error terms that depict the variances not accounted for by the equations.

In this way, the SEM enables the computation of the direct and indirect effects of the independent and control variables on $\ln CO_2$ and the interrelationships between the control variables. Furthermore, - when using reflective measurement model - it enables to accommodate measurement error and estimate the factor loadings of the latent variables and their manifest indicators. The analysis of the model is carried out using the STATA software and the fit of the model assessed with test of fit such as the chi square test.

4 Results

The result of Pooled (OLS) cross-section analysis and the Fixed-effects (Within) model analysis is provided in Table 3. The pooled regression analysis shows that all the variables except $\ln PCG$ are significant at 1% level and have a positive sign, implying that a rise in these variables means that $\ln CO_2$ also increases. However, it shows that the GDP *per capita* ($\ln PCG$) increases would decrease the $\ln CO_2$ by 23%. Further the variables $\ln TO$ and $\ln URBAN$ do not seem to have any influence on $\ln CO_2$. Potential reasons for the wrong sign of the Railway passengers ($\ln RAIL$) variable could be due to the fact that the present model does not include cross-section fixed effects and hence, unobserved cross-section heterogeneity could be an issue.

Thus, we undertook the Fixed-effects (Within) and Random-effect panel regression analysis because they help when it comes to implementing the correction for unbiased analysis across multiple groups. Nevertheless, the result of the Hausman test turns out to be significant with a chi-square statistic equal to 54.30 and the p value of "0.000". This result suggests that the unobserved individual effects are correlated with the explanatory variables making the random effects estimator inconsistent. Hence, we go for the fixed effects model for this analysis and the result is provided in the third column of Table 3. The empirical findings reveal that factors like $\ln PCG$ (*per capita* GDP), $\ln TO$ (trade openness), $\ln SI$ (share of industry), and $\ln AE$ (access to energy) have a positive impact on $\ln CO_2$ emissions.

TABLE 3 Pooled (OLS), fixed-effects (within) and random-effects GLS regression.

Variable	Dependent variable (DV)- <i>lnCO2</i>		
	Pooled (OLS)	Fixed-effects (within)	Random-effects (GLS)
<i>lnRAIL</i>	0.659*** (0.000)	-0.138*** (0.0000)	-0.010 (0.741)
<i>lnURBAN</i>	0.661* (0.099)	3.144*** (0.000)	2.710*** (0.000)
<i>lnPD</i>	0.137*** (0.000)	0.550*** (0.001)	0.647*** (0.000)
<i>lnPCG</i>	-0.299*** (0.002)	0.326*** (0.000)	0.299*** (0.001)
<i>lnTO</i>	0.038 (0.701)	0.130*** (0.002)	0.101** (0.042)
<i>lnSI</i>	1.046*** (0.000)	0.461*** (0.000)	0.480*** (0.000)
<i>lnAE</i>	4.523*** (0.000)	0.863*** (0.000)	0.726*** (0.003)
Constant	-8.417*** (0.000)	-5.262 (0.000)	-4.714 (0.000)
<i>R-squared</i>	0.932	0.742	0.714
Number of obs	240	240	240
<i>F-Statistic</i>	-	89*** (0.000)	-
Mean-variance inflation factor (VIF) test	3.95	-	-

Source: Author's calculation, Note: *** indicates 1% level of significance; ** indicates 5% level of significance; * indicates 10% level of significance.

This suggests that as economies grow, trade increases, industries expand, and energy access improves, we see a corresponding rise in environmental degradation. These results align with previous research, including studies by Zhang et al. (2014) and Nathaniel and Khan (2020), which also found similar positive links between economic and industrial metrics and CO₂ emissions in developing and emerging economies. Additionally, the negative correlation between rail usage (*lnRAIL*) and CO₂ emissions highlights the environmental benefits of rail transport. This is consistent with findings from Ramos da Silva et al. (2023) and Skrucany et al. (2018), who pointed out how rail infrastructure can help reduce carbon emissions from transportation. The estimated coefficients largely behave as expected: *lnRAIL* shows a negative sign, indicating that more rail usage leads to lower emissions, as a 1% increase in railway infrastructure leads to approximately 0.138% reduction in CO₂ emissions. The variables *lnURBAN* (urbanization), *lnPD* (population density), *lnPCG*, *lnTO*, *lnSI*, and *lnAE* all show positive signs, underscoring their roles in increasing environmental pressure. The income variable, “*lnPCG*,” has opposite signs in different model specifications: negative in the pooled model but positive in the fixed effects model. This is closely related to the EKC hypothesis, which states that environmental degradation tends to increase first but then decrease after a specific income level is reached. The differences in signs between these two model specifications could be due to differences in levels of development among these countries. Some of these countries may be in the initial stages of the EKC, where economic growth leads to increased environmental degradation, whereas others may be progressing toward a more environmentally friendly development path through technology and regulations. With an R-squared value of 0.742, the model explains about 74.2% of the variation in *lnCO₂* emissions, demonstrating strong explanatory power. However, the within-group variation is quite

small at 2%, suggesting that most of the differences in emissions are due to variations between countries or regions rather than changes over time. Moreover, the F-statistics confirm the model's overall significance at the 1% level, and the high values indicate a good fit, further supporting the robustness of these findings.

4.1 Diagnostic tests

Cross-sectional dependence test (Pesaran's test): The null hypothesis for cross-sectional independence based on Pesaran, testing, yields the test statistic of 0.902 with the value of the p-test equal to 0.366. By so doing, these results suggest that the observations are not cross-sectionally dependent. Hence, it can be concluded that there is no serial correlation of errors for different groups within the panel.

4.2 Robustness analysis

4.2.1 SEM mediation model specification and analysis result

This Structural Equation Model (SEM) study dives into the connections between railway services, urbanization, and CO₂ emissions across 16 Asian countries from 2005 to 2019, using a mediation framework where urbanization acts as a middleman (Table 4). The findings show that railway services (*lnRAIL*) have a significant and positive effect on urbanization (*lnURBAN*), implying that better rail infrastructure boosts urban growth by improving regional connectivity and accessibility. This aligns with the insights of Banister and Berechman (2001), who pointed out that transportation infrastructure, especially railways, is crucial for promoting urban development by easing the movement of people and goods.

TABLE 4 SEM analysis.

Variables	OIM Coef	Std. Err	Z Value
Structural model			
lnURBAN			
lnRAIL	0.023***	0.005	4.4
Cons	1.831	0.021	88.63
lnCO₂ emission equation			
lnURBAN	3.144***	0.391	8.03
lnRAIL	-0.138***	0.026	-5.27
lnPD	0.550***	0.158	3.48
lnPCG	0.326***	0.067	4.85
lnTO	0.130**	0.039	3.36
lnSI	0.461***	0.070	6.54
lnAE	0.863***	0.181	4.77
Cons	-5.00959	0.750652	-6.67
LR test of model vs. saturated: chi2 (20)			
CFI: 0.95			
RMSEA: 0.04			
SRMR: 0.03			

Source: Author's Calculations; Note: *** indicates 1% level of significance; ** indicates 5% level of significance; * indicates 10% level of significance.

Additionally, the model indicates that urbanization has a positive effect on CO₂ emissions, echoing earlier research by Poumanyong and Kaneko (2010), which highlighted that urban growth in developing countries often leads to increased carbon emissions due to rising energy needs, more vehicles on the road, and concentrated industries in urban areas. The positive relationship between urbanization (lnURBAN) and CO₂ emissions (lnCO₂) underscores the concern that rapid urbanization, if not managed sustainably, can worsen environmental issues.

Interestingly, while railway services encourage urbanization, they also show a negative direct impact on household-level CO₂ emissions. This suggests that efficient rail systems could help lower the carbon footprint by providing low-emission transport options. This finding backs up the arguments made by Skrúčaný et al. (2018), who highlighted the environmental benefits of rail transit over road transport, particularly in reducing *per capita* emissions.

Furthermore, the control variables—population density (lnPD), GDP *per capita* (lnPCG), trade openness (lnTO), value added by industry (lnSI), and access to electricity (lnAE)—all show a positive link to CO₂ emissions. This aligns with what Nathaniel and Khan (2020) and Zhang et al. (2014) found, indicating that economic growth, industrial activities, and increased access to modern energy sources are key drivers of higher emissions, particularly in developing Asia. In a summary, the SEM results reveal that railway services play a dual role. They can boost urban development, but they also have the potential to reduce emissions if integrated into a broader strategy focused on

sustainable urban planning and green transportation. These findings highlight the importance of policy approaches that utilize railway infrastructure not just for improving mobility and economic benefits, but also for promoting low-carbon transitions in urban areas.

4.2.2 Regional heterogeneity test

This understanding is about how these variables affect CO₂ emissions in various geographical environments. Table 5 presents the results of a regression analysis investigating the relationship between diverse factors and CO₂ emissions (lnCO₂) across distinct regions: The strategies included promoting the centrality and the western part of Asia, south Asia, Asia's eastern part and South-east Asia with the most important consideration being the acknowledgement of the region's diversity.

Coefficients of the independent variables; lnRAIL, lnURBAN, lnPD, lnPCG, lnTO, lnSI, and lnAE quantify the specific effects of these variables on the regional lnCO₂ emissions. More importantly, the number of asterisks represents the practical hints at the statistical relevance of these impacts. Moreover, in the model, there are significant differences in the degree to which independent variables improve the R-squared values for the analysis of the lnCO₂ emissions variations in the different regions. Also, F-Statistic proves the overall importance of the model in each region thus emphasizing the importance of the regional differences when estimating the complex connection between the

TABLE 5 Regional heterogeneity analysis.

Variable	Dependent variable (DV)- $\ln\text{CO}_2$			
	Central and western Asia	South Asia	East Asia	South east Asia
$\ln\text{RAIL}$	-0.183*** (-2.82)	0.283*** (6.22)	-0.002 (-0.12)	-0.108 (-1.25)
$\ln\text{URBAN}$	6.470*** (2.83)	-2.440 (-1.30)	-0.371 (-0.88)	8.880*** (3.71)
$\ln\text{PD}$	-0.187 (-0.52)	1.665** (2.36)	0.478 (0.71)	-2.388*** (-3.81)
$\ln\text{PCG}$	0.193 (1.11)	0.547*** (5.25)	0.673*** (8.10)	0.222 (0.45)
$\ln\text{TO}$	-0.030 (-0.42)	0.170 *** (3.12)	0.071 (1.34)	0.030 (0.43)
$\ln\text{SI}$	0.647*** (5.71)	0.461*** (6.22)	0.200 (1.50)	0.231 (0.76)
$\ln\text{AE}$	6.414 (1.36)	0.139 (0.93)	0.114 (0.55)	-1.660** (-2.46)
Constant	-21.146** (-2.14)	3.585* (1.74)	2.146 (1.24)	-3.671 (-1.15)
<i>R-squared</i>	0.625	0.989	0.914	0.955
Number of obs	90	30	60	45
<i>F-Statistic</i>	141.93	2.86	413.73	60.40

Source: Author's calculation, Note: *** indicates 1% level of significance; ** indicates 5% level of significance; * indicates 10% level of significance, Parenthesis represents t value.

specified variables and CO₂ emissions. The analysis of regional heterogeneity also emphasizes the differences in the environmental effects of rail transport among Asian subregions. While rail transport is generally favorable for emission reduction in several regions, the study's results suggest that this relationship may not hold in South Asia, where the estimated coefficient is positive. This result may be related to some specific features of transport systems in this region. For instance, some Asian countries, including India, still have a system of railways that are partially based on diesel-type locomotives, whereas the rate of electrification of railways is also lower compared to several East Asian countries. In addition, high rates of urbanization may increase transport needs faster than the development of rail transport infrastructure.

In short, the results from the panel regression analysis as well as the SEM approach point to the fact that rail transportation holds a significant place in determining the environmental outcomes for Asian economies. Although urbanization and economic growth contribute to the increase of CO₂ emissions, the growth of rail transportation seems to alleviate the environmental pressures to a certain extent. The results point to the fact that the promotion of sustainable transportation systems, including rail transportation, is essential for the reduction of carbon emissions as well as the achievement of environmentally sustainable urbanization.

5 Conclusion, policy implications and future research

The study offers important insights into mechanisms by which rail transport can play a role in long-term emission savings and sustainable mobility. Through the integration of panel econometric analysis with SEM, the research goes beyond the determination of correlations to unravel how rail infrastructure acts upon urbanization and thereby CO₂ emissions. This strategy increases our knowledge of causal links, showing that while urbanization is likely to increase emissions, railway

systems-if optimally linked-can counter this trend through low-carbon transport alternatives. Strategic country selection across 16 Asian nations with diverse economic systems and levels of rail maturity guarantees the applicability of results to a multitude of settings, and the analytical framework is easily transferable for use in other regions. Policy considerations bring to the fore the importance of tailoring approaches to regions, harmonizing technological improvements (e.g., electrification and integration of renewable energy), and urban planning that unlocks rail investment's greatest climate advantage. Combined, these strategies make rail transport not just a green option but a key pillar in meeting global climate objectives.

The validity of these results is ensured by several diagnostic tests such as Pesaran's test for the cross-section dependence and Hausman's test opting for the fixed effects model due to the reduction of the unobserved heterogeneity. The heterogeneity of regional analysis makes it crucial to adapt policies related to rail transport to the characteristics of the given region, indicating that railways' effects on CO₂ emissions may differ significantly between subregions of Asia.

These outcomes reaffirm the significance of the rail transport as a green means of transport that will define sustainable development in Asia. The authorities must focus on increasing the development of railway networks to increase its performance and capacity, making rail transport the preferable means of freight and passengers transportation. While integrating the project of rail transport and the planning of cities would provide easy access to rail transport the desired results are achieved by increasing the adoption of rail transport *in lieu* of carbon based modes of transport. Information education on the effects of environmental conservation by embracing rail transport can also go a notch higher.

For these purposes, it will be useful to ask for subsidies for common usage of rail, as well as to finance initiatives on the development of ecological orientations of rail transport. Applying regional and country peculiarities' policies can cover the distinct demand and requirements in various Asian sub-areas to boost the rail transportation's effect on the decrease in CO₂ emissions.

Also, promotion of technological development of railways and application of such measures as electrification and use of renewable power sources will improve rail transport's environmental sustainability. Coordinated cooperation between Asian nations can help to openly exchange the most successful strategies and innovations for the development of rail transport in the region and bring Asia's railway systems up to a high level.

Systematic review of the policies of rail transport is as important to determine whether these policies are appropriate for use and whether they are useful in other situations. These multifaceted approaches ensure that the rail transport sector changes into a backbone of the green Asia and plays the substantial role in the worldwide fight against climate change.

Despite the contribution of the study, some limitations are identified. To begin with, the study is based on secondary data and covers only 16 Asian countries owing to data availability constraints for the selected variables. Additionally, data for 2020–2021 was excluded for the analysis since the COVID-19 pandemic caused a temporary disruption to the normal patterns of transportation activities. Finally, while the panel econometric models and SEM are valuable tools for analysis, it is possible that the complex interrelationship between transportation systems, economic growth, and the environment is not fully captured.

The scope of future research could be expanded in several ways. To give an example, future studies could be carried out by including other variables, such as the use of renewable energy sources, technology development, or policy measures related to sustainable transport. In addition, country-specific or regional analysis could offer valuable information on the impact of differences in institutions, economics, and infrastructures on the environmental consequences of rail transport. Future studies could also be carried out on the impact of developing transport technologies and integrated urban transport systems on sustainable transport.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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