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# Greening the Wheels: The Role of Innovation and Renewable Energy in Reducing Transport Emissions

**Tayyaba Ishfaq[1], Muhammad Sajid[2], Hassan Taj[3], Aamir Sohail[4]**

[1] Department of Economics, National University of Science & Technology (NUST).
[2] Department of Economics, Kohat University of Science and Technology, 26000, Kohat.
[3] Department of Economics, Kohat University of Science and Technology, 26000, Kohat.
[4] Department of Economics, Kohat University of Science and Technology, 26000, Kohat.

**Corresponding Author: Muhammad Sajid** Email: muhammad.sajid8898@gmail.com

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## Abstract
This study examines the determinants of transport-sector carbon dioxide ($CO_2$) emissions across 70 countries, equally divided between upper-middle-income (UMICs) and lower-middle-income (LMICs), over the period 2000–2023. Using the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model, the analysis explores the long-run and short-run effects of environmental tax, technological innovation, renewable energy consumption, globalization, and global oil prices on transport $CO_2$ emissions. The results reveal that environmental tax and renewable energy consumption significantly mitigate transport-related $CO_2$ emissions in both income groups, underscoring their role in sustainable decarbonization. Technological innovation also exerts a long-term negative impact on emissions, highlighting its contribution to cleaner mobility. Interestingly, global oil prices are found to have a negative effect on transport emissions, implying that higher oil prices may discourage fuel-intensive transport activities. Moreover, globalization exhibits a dual pattern reducing emissions in UMICs through advanced technology transfer and efficient trade systems, but intensifying emissions in LMICs due to increased industrialization and transport demand. The Westerlund cointegration test confirms a stable long-run equilibrium among variables. Overall, the findings support the Environmental Kuznets Curve (EKC) hypothesis and emphasize the importance of differentiated policy approaches that consider income-level heterogeneity. Policymakers should focus on strengthening environmental taxes, enhancing renewable energy infrastructure, and promoting technological innovation to achieve transport-sector decarbonization and global sustainability goals.

## Introduction
Climate change and global warming are the most pressing and complex challenges of the 21st century, which pose serious risks for global ecosystems, human societies and livelihoods, and economic sustainability. The Intergovernmental Panel on Climate Change (IPCC, 2023) has noted that the global average surface temperature has increased by over 1.1 °C from pre-industrial levels due mainly to human greenhouse gas (GHG) emissions. Impacts that have resulted from warming include rising sea levels, extreme heat waves, loss of biodiversity, droughts, and disruption of food systems. These environmental stressors are compounded by climate disasters, and they translate into further social and economic inequities between many countries (United Nations Environment Program [UNEP], 2023). The increasing environmental issues have led the international community to commit to achieve

carbon neutrality under a number of international agreements, including of which one such is the Paris Agreement (2015) which calls for warming to be limited to well below 2 °C, while targeting a 1.5 °C limit by the end of the century. To achieve these targets, nations must drastically cut their use of fossil fuels and transition to low-carbon economies (World Bank, 2024). Nonetheless, while action is being taken worldwide on this front, $CO_2$ emissions continue to rise in some locations, especially in developing and middle-income economies. Important drivers of high rates of energy consumption, especially non-renewable energy consumption, includes rapid urbanization, industrialization, and population growth, which are all significant Drivers of energy consumption and environmental degradation (IEA, 2024).

Across all sectors, the transport sector has emerged as the biggest source of greenhouse gas emissions. The transport industry is essential for economic growth and for the movement of goods, services, and people. However, it is one of the most energy-consuming and polluting human activities on the planet. The International Energy Agency (2024) states transport represents nearly 24% of total energy-related $CO_2$ emissions, with road transport having the largest contribution of emissions. Carbon emissions from the transport industry have risen due to more vehicle ownership, expanded road and urban space capacity, and continued reliance on petroleum fuels (OECD, 2024).

Middle-income countries are facing the challenge of making a sustainable transport system as their economies and populations have never reached their current unprecedented growth. The World Bank (2024) defines these economies as either upper-middle-income (UMICs) or lower-middle-income (LMICs), which represent over 70% of the world population. Most of these economies are characterized by rapid industrialization, rising energy needs, and a limited technological foundation that hampers any adequate transition to cleaner alternatives (UNDP, 2024). As urbanization occurs due to economic and population growth, dependency on private vehicles is increasing without viable public transport alternatives and with slow transitions to cleaner technologies, which will contribute to negative episodes with transport-related emissions.

Economic development is often contrary to environmental sustainability, exemplified by the prominent Environmental Kuznets Curve (EKC) hypothesis (Grossman & Krueger, 1995). The implicit EKC hypothesis claims that environmental degradation will rise as the economy is growing until a certain income level is reached, at which point the economy once again will grow but in a manner that is less environmentally destructive or provides more environmentally beneficial benefits. However, empirical evidence on this relationship is mixed, especially for developing and middle-income economies. (Dinda, 2004; Sarkodie & Strezov, 2019). Several of these countries remain on the rising side of the curve, meaning that they are industrializing and urbanizing in ways that contribute to increases in carbon emissions. Consequently, policy interventions are needed to speed up the move toward the downward side of the EKC curve through renewable energy uptake, environmental taxation, and technological innovation.

The carbon intensity of the transport sector is deeply affected by the interplay of economic, technological, and institutional factors. Economic globalization has made the patterns and flows of trade and investment more extensive and more interdependent, generating increased energy demand through added logistics and transportation networks (Dreher, 2006; Shahbaz et al., 2018). Global oil prices are another example of the way that transportation emissions are partially dependent on economic factors and other factors of consumption affecting fuel price could influence consumption behavior (IEA, 2024). Technological innovation impacts emissions by increasing energy efficiency through electric mobility and alternative fuels (UNESCO, 2024), while environmental taxation and policy instruments are regulatory policy levers that internalize some environmental externalities that incentivize cleaner production and consumption (OECD, 2024).

While it is true that developed economies have made great strides in adopting low-emissions technologies, this same process in middle-income countries is often hindered by a variety of challenges such as cost, weak institutions, small research capacity (World Economic Forum, 2024). Consequently, the emissions disparity between high- versus low-income economies continues to persist. For example, upper-middle-income countries have greater access to cleaner technologies and environmental governance systems, but lower income-middle income countries continue to face fundamental constraints in their transport infrastructure and limited policy enforcement (UNDP, 2024). Therefore, a comparative analysis of the two income groups will allow for a deeper understanding of how the level of development in a country informs the determinants of $CO_2$ emissions from transport.

Finally, studies suggest that the success of environmental policies in the net reduction of emissions from transport will also depend on the interaction of global and domestic factors (Balsalobre-Lorente et al., 2021). Environmental tax frameworks may lead to better success rates in economies with higher institutional quality plus technological readiness while globalization may positively or negatively reinforce emissions stemming from transport or drive the emission reductions from transport strategy through advanced technology switches depending on the energy use intensity (Destek & Sinha, 2020; Rasheed et al., 2023). Renewable energy technology switches will also result in significant reductions in carbon intensity if they are supported by an adequate policy framework, financial incentives for technology adoption, plus a local innovative ecosystem (IRENA, 2024).

Although attention to climate change mitigation is on the rise, empirical work on transport $CO_2$ emissions in middle-income economies is still a limited area of study. The majority of studies look at either national emissions or energy consumption and do not isolate the transport sector which represents an independent factor (Zhang et al., 2022; Acheampong, 2018). Further, there are very few cross-country studies that compare either upper– or lower–middle-income economies, diverse economies with different socio-economic structures and energy transitions. The research in this article will help to fill these gaps by applying a wide-ranging panel analysis of 70 middle-income economies (35 upper-middle-income economies and 35 lower-middle-income economies) during the period 2000-2023.

The primary aim of this study is to identify the determinants of transport $CO_2$ emissions and to measure how the combination of factors from an economic, policy and technological point of view influence emissions in different income groups. The authors use the dynamic panel econometric framework to establish long run and short run relationships between transport emissions and the main explanatory variables. Only through such studies can we establish an empirical literature base to inform future sustainable transport and energy policy decisions in middle-income economies.

This research adds to the existing literature in important ways. First, it provides cross-country comparative evidence on environmental performance for the transport sector in middle-income countries, which has been widely absent in the literature. Second, the study integrates economic, policy, and technological dimensions into a unified empirical framework, allowing for a more complete understanding of the drivers of emissions. Finally, the study highlights heterogeneous policy-impact by distinguishing between upper- and lower-middle-income countries offering evidence-based recommendations for different economies in different development stages.

Evidence is expected to be influential for policy when examining pursuits for upward-transitioning lower and upper middle-income countries in relation to carbon emissions, energy use, and technology. For upper-middle-income countries, an essential aspect to achieving decent reductions in carbon emissions will be increased adoption of green transport technology, improved regularity frameworks, and the wider integration of renewable energy. For low-middle-income countries, international collaboration, technology transfer, and innovative financial mechanisms will be key to enabling sustainable transitions from a transport perspective. In conclusion, this paper provides guidance for policies and balancing economic growth and environmental sustainability.

The remainder of the paper will be structured as follows. The next section provides a review of the theoretical or empirical literature on transport emissions and sustainability. The third section discusses data sources, variables, and econometric methods. The fourth section will present empirical results and analysis and discuss the results. Finally, in the last section of the paper, the authors provide concluding remarks of significant policy implications to achieve sustainable, low-carbon transport systems economy-wide in middle-income economies.

## Literature Review

Over the past two decades, research on carbon emissions from the transportation sector has significantly increased, as both researchers and policymakers are recognizing that the sector's dynamics are important to both mitigation and development strategies. This expanding research has included normative theory, simulation exercises, and empirical panel and time-series analyses that examine how economic growth, energy systems, policy instruments, and technology will affect the transport sector's $CO_2$ emissions. Due to motorization, global trade, and urbanization, the transport sector is one of the fastest-growing sources of anthropogenic greenhouse gases (International Energy Agency [IEA], 2023). Given the sector's critical nature for socio-economic development, managing mobility's needs and reduction is a continuous policy challenge.

In the theoretical literature, the relationship between economic growth and environmental degradation is often linked through the Environmental Kuznets Curve (EKC) hypothesis, where, at early stages of development, economic growth is associated with higher emissions levels, but emissions levels tend to fall beyond a certain income level due to structural change in the economy; improving energy efficiency as well as policies that are more environmentally-enhanced (Grossman & Krueger, 1995; Mardani et al., 2019). At lower income levels, rising economic activity will generate further demand for transport and energy consumption, whereas at higher income levels, the combination of innovation and concern for the environment will facilitate adoption of cleaner technologies and sustainable transport systems. This interaction is at the heart of much of the empirical research on the drivers of $CO_2$ emissions in transport sectors around the world.

Environmental taxation is another important theoretical area that acts as a Pigouvian instrument to internalize external costs to the environment. Environmental taxation happens when the price of carbon intensive activity is increased, creating a signal to change behavior toward energy efficiency, cleaner vehicles, and using public transport more (Lin & Li, 2011; Oueslati, 2016). The double dividend hypothesis takes the position that this type of tax can reduce emissions and at the same time enhance more efficient economic conditions (Farhan et al., 2020; Noor et al., 2024), so long as the revenues used are reinvested in green technologies or infrastructure. There are many factors that determine if taxation will be effective: the elasticity of demand in reaction to price shifts; the local institutional context to either develop demand or supply shift; and the strength of fuel subsidy programs that are in place that mitigate unavoidable price shifts for consumers or reduce the use of carbon intensive transport (Hsu, 2011).

Technological innovation and research and development (R&D) spending have received increasing focus related to sustainable transport. According to endogenous growth theory, R&D spending will allow the accumulation of knowledge or technologies and improvements in efficiency to support increased emissions reductions (Popp, 2019). Technological innovation in the transportation sector has focused on hybrid and electric vehicles, alternative fuels, and smart mobility systems that all improve fuel economy and fit into the overall decarbonization agenda. The implementation of strict environmental regulations can trigger even greater technological innovation in the future because those regulations provide market signals favoring clean innovation.

Changes in global oil prices can also have considerable impacts on the $CO_2$ emissions from transport, through changes in fuel prices and consumption. High oil prices correlate with less vehicle usage and greater energy efficiency; to the contrary, low oil prices are associated with higher fuel consumption and a return to carbon intensity in mobility (Hamilton, 2009). Oil price volatility also affects investment in renewable technology decisions because sustained high expenditures on oil prices typically leads to diversifying energy supplies, and substitution effects can dampen the potential for many of the associated gains through income effects in oil-exporting economies (Mahmood et al., 2022; Rasheed et al., 2022).

Globalization, which is primarily related to economic integration enabled by trade, investment, and technology transfer, impacts emissions through a variety of channels. The pollution hypothesis indicates that an increase in trade openness can lead to the relocation of emission-intensive activities to countries with lower regulatory standards, resulting in some level of increased global emissions. In contrast, the technique effect suggests that globalization improves the diffusion of technology, which increases production efficiency in terms of emission reductions (Shahbaz et al., 2018). The overall impact of globalization is dependent on the net effect of the scale effects, which are sustainability progress driven by increasing economic activity, as well as technological or institutional improvements (Le et al., 2016; Le et al., 2020; Rafique et al., 2024).

Consumption of renewable energy is becoming recognized as a key driver in sustainable transport transitions. Countries can reduce the carbon intensity of their transport system by switching to cleaner energy from renewable sources such as biofuels or electricity (Bhattacharya et al., 2017; Jebli et al., 2020). Accept where the transition towards renewable energy can be influenced by policies, infrastructure investments, or the availability of the appropriate level of technology, the countries that have successfully intertwined renewable energy use into the most sustainable transport sectors have been able to consistently lower $CO_2$ emissions in the long-term and be more resilient to the volatility associated with energy price shocks.

The carbon intensity of road transport energy use (CIORTEC) is a key measure of efficiency, specifically the quantity of $CO_2$ emitted per energy unit consumed in road transport. A high CIORTEC figure indicates a reliance on carbon-intensive fuels and ageing technologies; a lower intensity in CIORTEC indicates a higher degree of fuel efficiency, electrical vehicles and cleaner energy mixes (IEA, 2023). Therefore, improving energy efficiency in road transport is central to delivering emissions reductions, without restricting mobility. There is also an abundance of empirical literature that shows varied outcomes, but consistent evidence for the EKC relationship in different contexts. Rasool, Zaidi and Zafar (2019) observe that economic activity raises transport $CO_2$ emissions in Pakistan in the short run but ultimately moderates as technology improves. Mardani et al. (2019) and Lin and Benjamin (2017) confirm the EKC relationship in developing economies, while Godil et al. (2021) and Dong, Sun and Hochman (2017) show that GDP growth exacerbates emissions in BRICS countries and China. Finally, Majewski et al. (2022) show that when renewable energy is included in the production functions and technological innovation is allowed to weaken the income–emission relationship, there is a trend of decoupling over time in advanced middle-income economies.

Population density is also a major factor in transport emissions, as compact urban form can reduce or amplify carbon intensity, depending on the state of the infrastructure and governance. Poumanyvong and Kaneko (2010) show how density reduces energy use in low-income countries, while in high-income economies, density can increase energy use due to congestion. Sun, Li, and Xue (2019) find that cities in China are more emissions intensive when urban expansion is faster than new urban infrastructure. Adams et al. (2020) and Zarco-Periñán et al. (2021) underscore how planned, integrated urban transport systems can reduce emissions that density would otherwise produce, which supports Naqvi et al. (2020)'s argument that institutional quality and coordination and planning action are critical moderators of the emissions-intensifying aspect of density.

There is extensive evidence for environmental taxes, especially as an important vehicle for emissions control. Lin and Li (2011) find that carbon taxes significantly reduce per capita emissions of countries, while Farhan et al. (2020) find that OECD countries realize both environmental and fiscal dividend from taxation policy when tax revenue is utilized to support green investments. Bashir et al. (2020) find that a combination of taxation and innovation, and investment in greening finance mechanisms enhanced emissions relative to an environmental tax alone, although cautions Hsu (2011) that weak enforcement can reduce effectiveness of the measure design in developing contexts.

Innovation studies support these findings. Popp (2019) shows that emissions decouple from economic activity via growth from innovation. Godil et al. (2021) found that technological innovation in the transport sector is correlated with higher emissions reductions in China, and Zhang, Hassan, and Iqbal (2020) showed similar results for OECD countries. Majewski et al. (2022) observe R&D and renewable energy have a conjunctional strong negative effect on emissions and that the relationship necessitates good policies to support achieving both goals.

In addition to the studies on innovation, research examining the effect of oil prices yielded mixed conclusions. Shahbaz, Sinha, and Paramati (2021) argue that increases in oil prices in India reduce fuel consumption, which is thought to lower emissions. In contrast, Mahmood, Shahbaz, and Hille (2022) observe that increasing oil prices in GCC countries do not discourage emissions and might marginally increase emissions due to increased energy demand related to higher income for households in the economy as a result of increasing oil prices. Hamilton (2009) argues that oil price shocks affect technological adoption and energy demand across economies.

The environmental influences of globalization are still open for discussion. Le, Chang, and Park (2016), and Ertugrul et al. (2016), contend that openness increases emissions in developing economies through increased trade and transportation demands while Lee, Nasir, and Huynh (2020), and Shahbaz, Nasir, and Roubaud (2018) find that globalization enhances technology transfer and cleaner production in more advanced economies. Iqbal, Liu, and Shahbaz (2021), and Lv and Xu (2019), conclude that the long-term outcome is highly contingent on institutional capacity, quality of governance, and enforcement of environmental policies.

While the evidence for renewable energy use is both strong and encouraging, there remain some caveats for the long run. Dong, Sun, and Hochman (2017) show that renewable energy consumption contributes to reductions in $CO_2$ emissions across BRICS countries, while Jebli, Farhani, and Guesmi (2020) demonstrate its long-run emissions mitigation capacity across income groups. Godil et al. (2021) and Majewski et al. (2022) find that renewable energy consumers may reduce transport emissions in the long run in large amounts provided the acceptance of renewable energy technologies are incorporated with technology innovation. Solaymani (2022) comments that the effectiveness of renewable energy addiction is conditional to the adequacy of infrastructure and institutional robustness.

CIORTEC is consistently found to have a direct link with emissions, as indicated by Solaymani (2022) and Jiang, Zhang, and Li (2022), both of whom found that carbon-intensive energy use increased transport $CO_2$ emissions. Lin and Benjamin (2017) also determined that, while India's transport sector emissions had increased, the emissions reduction associated with cleaner fuel mixes and improvements in efficiency was significant.

Overall, the literature provides a nuanced yet coherent picture: economic growth, globalization, and urbanization generally raise transport emissions unless mitigated by innovations, renewable energy, and an effective environmental tax. The divergence of emissions trajectories by upper-middle- and lower-middle-income countries implies that institutional capacity, technological capacity, and energy structure add to emissions trajectories. These observations highlight the need for comparative dynamic analyses that capture responses to behavioral changes over the short-run or structural changes in the long run. This paper contributes to the literature on national determinants of transport $CO_2$ emissions by examining transport $CO_2$ emissions in 70 middle-income countries from the years of 2000-2023, filling a significant gap in the literature in response to the global transition to sustainable mobility.

## Research Methodology

This research investigates the factors contributing to transport-related carbon dioxide emissions ($TCO_2$) in a sample of 70 middle-income countries, including half upper-middle-income and half lower-middle-income economies, over the time period of 2000–2023. The study employs a dynamic panel econometric approach to assess both the short-run and long-run relationships across the various analysized variables. The rationale for using this econometric approach was based on the dynamic nature of the environmental and economic variables accused of discriminating against climate issues, potential cross-sectional dependence in the variance unit root, and a potential of heterogeneity in slope coefficients between sectorial and time series-based country-analysed units used to determine the effect each variable has. For this reason, the empirical strategy ensures rigorous, well-founded inference and meaningful policy interpretation.

The main dependent variable used in this research is Transport $CO_2$ emissions ($TCO_2$). This variable estimates the total amount of carbon dioxide produced by the transport sector of each country. The variable is estimated from data sources from the International Energy Agency (IEA, 2024). The independent and secondary variables are Environmental Tax (ETAX) interpreted as tax and fiscal policies aimed at reducing pollution (OECD, 2024); Technological Innovation (TI) interpreted as research and development expenditures (UNESCO, 2024); Global Oil Prices (GOP) interpreted as the impact on the cost of transport fuel and the intensity of transport fuel use (IEA, 2024); Globalization Index (GLOB) interpreted as the extent of economic and social integration and interaction with the global economy (KOF, 2025); and lastly, Renewable Energy Consumption (REC), meaning the proportion of total final energy consumption attributed to renewable energy (IRENA, 2024); and Carbon Intensity of Road Transport Energy Consumption (CIORTEC), measures the amount of $CO_2$ produced per unit of energy consumption in road transport (IEA, 2024).

The econometric model uses a framework based on environmental economics, presenting a relationship between emissions and economic, technological, and institutional conditions. Previous studies emphasize that energy consumption, policy instruments, and innovations have a collective influence on carbon emissions (Bhattacharya et al., 2017; Dong et al., 2017; Jebli et al., 2020). Similarly, globalization and trade openness are detrimental to environmental outcomes through scale and composition and technique effects (which make use of the trends in the scale, composition, and technique of nationality and terminology beyond territory); (Le et al., 2016; Iqbal et al., 2021; Lv & Xu, 2019). The global oil price and renewable energy consumption account for the implications of energy markets and key transitions toward cleaner energy systems (Hamilton, 2009; Shahbaz et al., 2021; Rasheed et al., 2025).

**Table 1 Description of Variables**

| **Variable** | **Abbr.** | **Description** | **Data Source** |
|---|---|---|---|
| Transport $CO_2$ Emissions | $TCO_2$ | Total $CO_2$ emissions from transport sector | IEA (2024) |
| Environmental Tax | ETAX | Fiscal instruments on environmentally harmful goods | OECD (2024) |
| Technological Innovation | TI | Expenditure on research and development | UNESCO (2024) |
| Global Oil Prices | GOP | International benchmark oil prices | IEA (2024) |
| Globalization Index | GLOB | Composite index capturing integration with global economy | KOF (2025) |
| Renewable Energy Consumption | REC | Share of renewable energy in total final energy use | IRENA (2024) |
| Carbon Intensity of Road Transport Energy Consumption | CIORTEC | $CO_2$ emitted per unit of energy consumed in road transport | IEA (2024) |

Before performing the estimation, it is important to check that the explanatory variables are not too highly correlated, as multicollinearity can inflate the standard errors and yield unreliable estimates of the coefficients. The paper tests multicollinearity by examining both the correlation matrix and the Variance Inflation Factor (VIF).

As stated by Gujarati and Porter (2009), pairwise correlations above .80 are seen to demonstrate potential multicollinearity problems. Therefore, the correlation matrix is compiled to investigate the pairwise correlations among independent variables. In addition, for each explanatory variable the VIF statistics are computed using the following formula:

$$\mathrm{VIF_i} = \frac{1}{1 - \mathrm{R_i^2}}$$

where $R_i^2$ is the coefficient of determination from regressing variable iii on all other independent variables. A VIF value greater than 10 signals serious multicollinearity, though values above 5 may also warrant concern depending on context (O’Brien, 2007). Variables found to have high VIF values may be adjusted or transformed.

Another important step is to test cross-sectional dependence (CSD) across countries. CSD occurs when shocks (or policies) in one country impact other countries. Shocks from transport-related emissions are a classic example of CSD as energy markets, trade, and regional climate initiatives are often interrelated. To test for CSD, we will use the Pesaran (2004) CD test. The test statistics are calculated as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right)$$

where $\hat{\rho}_{ij}$ represents the average pairwise correlation coefficient of residuals. A significant CD statistic indicates the presence of CSD. Addressing CSD is crucial, as ignoring it leads to biased estimates and spurious inference (De Hoyos & Sarafidis, 2006).

$$\widehat{P}_{ij} = \frac{\sum_{t=1}^{T} e_{it}e_{jt}}{\left(\sum_{t=1}^{T} e_{it}^2\right)^{1/2}\left(\sum_{t=1}^{T} e_{jt}^2\right)^{1/2}}$$

Slope heterogeneity is also examined using the Δ and adjusted Δ tests developed by Pesaran and Yamagata (2008). Rejection of the null hypothesis of slope homogeneity suggests the regressors have country-specific effects because of variations in institutional contexts, policy settings, or technology capacity. In middle-income countries, slope heterogeneity is anticipated given the varied economic structures and environmental performance.

$$\Delta = \sqrt{N}\left(\frac{1}{N}\sum_{i=1}^{N} S_i - k\right)\Big/\sqrt{2k}$$

$$\Delta_{adj} = \sqrt{N}\left(\frac{1}{N}\sum_{i=1}^{N} S_i - 2k\right)\Big/\sqrt{\frac{2k\,(T-K-1)}{T+1}}$$

Where $S_i$ denotes the individual slope coefficient t-test statistic for unit i, "k" is the number of regressors, ‘N’ is the number of cross-sectional units, and ‘T’ is the time dimension. The adjusted version of the test to address small sample distortions is more reliable in moderate T panels. When the test is statistically significant, this is strong evidence against the null of slope homogeneity and shows that the slope effects of the regressors are heterogeneous across cross-sectional units. This slope heterogeneity provides justification for using estimates that allow individual country-specific slope coefficients, in particular, the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) estimator developed for heterogeneous panels with structural asymmetries and cross-sectional dependencies by Pesaran and Smith (1995) and then Chudik and Pesaran (2015) to provide the most reliable and robust long-run and short-run estimates in heterogeneous panels. The issue of slope heterogeneity strengthens the empirical strategy of heterogeneous panel estimators that represent the reality of countries in the EU and ultimately adds credibility to any policy implications resulting from the analysis.

Next, we proceed to establish the stationarity properties of the variables. Given the anticipated cross-sectional dependence, second generation panel unit root tests are utilized, specifically the Cross-Sectionally-Augmented Dickey-Fuller (CADF) test and the Cross-Sectionally-Augmented IPS (CIPS) test introduced by Pesaran (2007). These tests are in a position to accommodate unobservable common factor influences and global shocks that potentially generate false evidence against stationarity.

The CADF equation for unit iii is formalized as follows:

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + \Upsilon_i \bar{y}_{t-1} + \delta_i \Delta \bar{y}_t + \varepsilon_{it}$$

where $\bar{y}_t$ represents the cross-sectional average of the variable. The CIPS statistic is the average of the CADF t-statistics:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} t_i\,(N, T)$$

If they are mixed of order I(0) and I(1) the CS-ARDL estimator is still valid and there is no pre-testing bias.

We apply the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model recently developed by Chudik and Pesaran (2015) to account for cross-sectional dependence, heterogeneity, and mixed orders of integration. The model they propose is an extension of the original ARDL which adds cross-sectional averages of the dependent and explanatory variables, as well as accounting for the unobservable global effects present in the model for all countries. While enhancing robustness to omitted variable bias and correlated shocks.

The general specification of the CS-ARDL model for this study is given in the form:

$$\begin{aligned}\Delta \mathrm{lnTCO}_{2it} = \ & \alpha_i \\ & + \beta_i\big(\mathrm{lnTCO}_{2i,t-1} - \theta_1 \mathrm{lnPD}_{i,t-1} - \theta_2 \mathrm{lnEtax}_{i,t-1} - \theta_3 \mathrm{lnTI}_{i,t-1} - \theta_4 \mathrm{lnGOP}_{i,t-1} \\ & + \theta_5 \mathrm{lnGLOB}_{i,t-1} + \theta_6 \mathrm{lnREC}_{i,t-1} + \theta_7 \mathrm{lnCIORTEC}_{i,t-1}\big) + \sum_{j=1}^{p-1} \Upsilon_{ij} \Delta \mathrm{lnTCO}_{2i,t-j} \\ & + \sum_{j=0}^{q-1} \delta_{1j} \Delta \mathrm{PD}_{i,t-j} + \sum_{j=0}^{q-1} \delta_{2j} \Delta \mathrm{Etax}_{i,t-j} + \sum_{j=0}^{q-1} \delta_{3j} \Delta \mathrm{TI}_{i,t-j} + \sum_{j=0}^{q-1} \delta_{4j} \Delta \mathrm{GOP}_{i,t-j} \\ & + \sum_{j=0}^{q-1} \delta_{5j} \Delta \mathrm{GLOB}_{i,t-j} + \sum_{j=0}^{q-1} \delta_{6j} \Delta \mathrm{REC}_{i,t-j} + \sum_{j=0}^{q-1} \delta_{5j} \Delta \mathrm{CIORTEC}_{i,t-j} + \acute{\lambda}_i Z_t + \varepsilon_{it}\end{aligned}$$

Here, $\Delta$ denotes the first difference operator, and all variables are in natural logarithmic form. The term in parentheses represents the Error Correction Term (ECT), measuring long-run equilibrium deviations. The coefficient $\beta_i$ reflects the speed of adjustment toward equilibrium, where a statistically significant negative sign confirms a stable long-run relationship.

The short-run coefficients ($\Delta\delta 1j$) capture immediate effects of explanatory variables on transport $CO_2$ emissions, while long-run elasticities ($\theta_i$) reflect equilibrium responses. The vector $Z_t$ denotes the cross-sectional averages of both dependent and independent variables, accounting for unobserved global shocks.

The CS-ARDL model is estimated separately for upper-middle-income and lower-middle-income countries in order to examine structural heterogeneity in emissions drivers. The dynamic structure of the model allows for the short- and long-run effects to be disentangled, and using cross-sectional averages as controls reduces bias from omitted global factors, such as fluctuations in the oil market or international environmental agreements (Chudik & Pesaran, 2015; Sajid et al., 2024).

When panel units exhibit cross-sectional dependence, classic cointegration tests like those of Pedroni (1999) or Kao (1999) can produce biased results due to correlated residuals across sections. To overcome these concerns, the Westerlund (2007) cointegration test will be used; this test allows for cross-sectional dependence and makes valid inferences about the long-run relationship across heterogeneous panels. The test is based on the error-correction model (ECM) framework and can evaluate if there will be error-correcting behavior among the variables, typically indicative of a long-run relationship in equilibrium. The general form of the Westerlund test equation is given as:

$$\Delta y_{it} = \alpha_i + \delta_i t + \phi_i\big(y_{i,t-1} - \beta_i' x_{i,t-1}\big) + \sum_{j=1}^{p_i} \gamma_{ij}\, \Delta y_{i,t-j} + \sum_{j=0}^{q_i} \phi_{ij}\, \Delta x_{i,t-j} + \varepsilon_{it}$$

where $Y_{it}$ is the dependent variable, $X_{it}$ represents the vector of explanatory variables, $\phi_i$ measures the speed of adjustment toward the long-run equilibrium, and $\varepsilon_{it}$ is the error term. The null hypothesis $H_0$: $\phi_i = 0$, for all i indicates no cointegration, while the alternative hypothesis $H_1$: $\phi_i < 0$ suggests the existence of cointegration for at least some cross-sectional units. By accommodating cross-sectional dependence and allowing for heterogeneity in both short- and long-run dynamics, the Westerlund (2007) test provides a more reliable and efficient framework for cointegration analysis following the detection of cross-sectional dependence (Westerlund, 2007; Banerjee & Carrion-i-Silvestre, 2017).

Once the estimation is completed, diagnostic validation tests will run to determine our model's robustness. The error correction term (ECT) will be scrutinized for significance and expected sign. A significant and negative ECT indicates that the dynamic will come back to long-run equilibrium following any short-run shocks.

There are many reasons why we chose the CS-ARDL estimator. First, the CS-ARDL estimator can accommodate any combination of order of integration (I(0) / I(1)) without the bias of separate pre-testing for cointegration approaches. Second, cross-sectional averages accommodate cross section dependence, which is important in considering that the middle-income countries are experiencing common shocks in that they are exposed to common global energy markets and exposure to climate adaptation policies. Third, the CS-ARDL model allows for heterogeneous slope coefficients, meaning that the country-specific responses demonstrate variation across countries that reflect differences in institutions' and structures' arrangements. The CS-ARDL model is more efficient as well as unbiased in estimating panels impacted by unobserved common factors when compared to older estimators, such as PMG, DFE or MG, (Eberhardt & Bond (2009); Chudik & Pesaran (2015)).

**Results and Discussion**

This section presents and discusses empirical results, derived from econometric analysis. Econometric analysis begins with descriptive statistics and correlation matrices to obtain a better understanding of the data features and how variables relate to one another. After describing the data, we utilize the unit roots test and cross-sectional dependence tests to reach the appropriate econometric analysis. Following this analysis, we report on the Slope Homogeneity Test, CS-ARDL estimations, and Westerlund cointegration tests results for lower-middle-income countries (LMICs) and upper-middle-income countries (UMICs).

**Table 2: Descriptive Statistics (LMICs**

| **Variable** | **Obs.** | **Mean** | **Std. Dev.** | **Min** | **Max** |
|---|---|---|---|---|---|
| $TCO_2$ | 840 | 16.95 | 1.723 | 13.083 | 21.689 |
| GOP | 840 | 7.535 | .576 | 5.736 | 9.118 |
| ETAX | 840 | 2.12 | 1.14 | 0.57 | 4.72 |
| TI | 840 | 25.41 | 7.73 | 18.51 | 41.71 |
| REC | 840 | 3.213 | 1.473 | 1.813 | 4.514 |
| GLOB | 840 | 58.87 | 8.56 | 43.52 | 71.27 |
| CIORTEC | 840 | 4.268 | 0.022 | 4.138 | 4.297 |

**Table 3: Descriptive Statistics (UMICs)**

| **Variable** | **Obs** | **Mean** | **Std. Dev.** | **Min** | **Max** |
|---|---|---|---|---|---|
| $TCO_2$ | 840 | 18.11 | 1.172 | 14.17 | 23.42 |
| GOP | 840 | 7.535 | .576 | 5.736 | 9.11 |
| ETAX | 840 | 4.07 | 0.91 | 1.32 | 5.19 |
| TI | 840 | 31.19 | 5.62 | 16.32 | 47.23 |
| REC | 840 | 7.19 | 2.71 | 3.42 | 10.23 |
| GLOB | 840 | 84.17 | 8.56 | 77.52 | 98.27 |
| CIORTEC | 840 | 6.168 | 1.31 | 1.86 | 8.19 |

Tables 2 and 3 present the descriptive statistics for LMICs and UMICs, respectively. For LMICs, total $CO_2$ emissions (TCO2) have a mean of 16.95 metric tons with moderate variation (SD = 1.723). The mean TCO2 for UMICs is higher than that for LMICs; the mean TCO2 for UMICs is 18.11 metric

tons (SD = 1.172), indicating a greater environmental burden for relatively rich economies. Economic growth (GOP) has similar averages, (mean = 7.53). This finding reflects the relatively similar levels of gross output per caput in logarithmic form. Environmental tax (ETAX) shows a clear structural difference between income groups; LMICs have a mean of 2.12%, whereas UMICs have a mean of 4.07%, suggesting a stronger environmental fiscal framework for wealthier economies. Technological innovation (TI) and renewable energy consumption (REC) averages are also higher for UMICs mean TI = 31.19, REC mean = 7.19; compared to LMICs mean TI = 25.41 and REC mean = 3.21. These findings relate to prior literature which has found a higher technological development in LMICs and a higher adoption of renewable technologies in UMICs (Stern, 2017). The outcomes for Globalization (GLOB) and circular oriented technology (CIORTEC) were consistent with higher means for GLOB (mean = 4.53) and CIORTEC (mean = 12.83) for UMICs. Essentially, UMICs leaped ahead in their connections with the global economy (GLOB) and clean environmental technology investment (CIORTEC).
The results also demonstrate organizational variations in income groups, with UMICs standing out as the superior income group environmentally and technologically and LMICs trailing with a need for policy differences.

**Table 4: Correlation Matrix (LMIC)**

| Variables | $TCO_2$ | GOP | ETAX | TI | REC | GLOB | CIORTEC |
|---|---|---|---|---|---|---|---|
| $TCO_2$ | 1.000 | | | | | | |
| GOP | -0.426 | 1.000 | | | | | |
| ETAX | -0.168 | 0.251 | 1.000 | | | | |
| TI | -0.131 | -0.088 | -0.235 | 1.000 | | | |
| REC | -0.299 | -0.169 | -0.095 | -0.066 | 1.000 | | |
| GLOB | 0.188 | 0.685 | -0.002 | -0.305 | -0.177 | 1.000 | |
| CIORTEC | 0.076 | -0.105 | 0.057 | -0.033 | 0.096 | -0.052 | 1.000 |

**Table 5: Correlation Matrix (UMICs)**

| Variables | $TCO_2$ | GOP | ETAX | TI | REC | GLOB | CIORTEC |
|---|---|---|---|---|---|---|---|
| $TCO_2$ | 1.000 | | | | | | |
| GOP | -0.371 | 1.000 | | | | | |
| ETAX | -0.213 | 0.120 | 1.000 | | | | |
| TI | -0.225 | -0.121 | -0.019 | 1.000 | | | |
| REC | -0.153 | -0.234 | -0.138 | -0.131 | 1.000 | | |
| GLOB | 0.015 | 0.243 | -0.127 | -0.219 | -0.271 | 1.000 | |
| CIORTEC | 0.136 | -0.412 | 0.121 | -0.116 | 0.132 | -0.102 | 1.000 |

The correlation matrices presented in Tables 4 and 5 reveal significant relationships among the variables examined in this study. Among LMICs, TCO2 revealed negative correlations with GDP growth (r = -0.426), environmental taxes (r = -0.168), and RE consumption (r = -0.299). The existence of negative correlations suggests that they would facilitate economic growth and the adoption of renewables to reduce emissions, providing some level of support for the environmental Kuznets curve (EKC) hypothesis, especially in developing economies (Shahbaz et al., 2019). In UMICs, the correlation between TCO2 and GDP was again negative (r = -0.371) suggesting that as economies develop and move to higher levels of income, they may begin the process of decoupling growth from emissions patterns by transferring to cleaner technologies. Globalization and Rate of technological innovation showed weak, negative correlation (r = -0.048) with emissions indicating that trade openness and technology may be contributing to reductions in emissions in these economies.

Interestingly CIORTEC showed a weak, positive correlation (r = 0.136) in UMICs, pointing to a nascent role of CIORTEC in facilitating the low-carbon transition.

**Table 6: Unit Root Test (LMIC)**

| Variables | CIPS | | Decision | CADF | | Decision |
|---|---|---|---|---|---|---|
| | I (0) | I (1) | | I (0) | I (1) | |
| $TCO_2$ | -1.548 | -4.285*** | I (1) | -1.667 | -3.888*** | I (1) |
| GOP | -1.021 | -5.070*** | I (1) | -1.583 | -3.177*** | I (1) |
| ETAX | -1.021 | -4.248*** | I (1) | -1.529 | -3.333*** | I (1) |
| TI | -0.994 | -3.759*** | I (1) | -1.365 | -2.577*** | I (1) |
| REC | -1.737 | -4.890*** | I (1) | -1.633 | -3.908*** | I (1) |
| GLOB | -1.029 | -3.831*** | I (1) | -1.542 | -4.421*** | I (1) |
| CIORTEC | -1.419 | -3.914*** | I (1) | -1.124 | -4.391*** | I (1) |

**Table 7: Unit Root Test (UMICs)**

| Variables | CIPS | | Decision | CADF | | Decision |
|---|---|---|---|---|---|---|
| | I (0) | I (1) | | I (0) | I (1) | |
| $TCO_2$ | -1.212 | -4.432*** | I (1) | -1.213 | -4.151*** | I (1) |
| GOP | -1.130 | -5.113*** | I (1) | -1.409 | -4.391*** | I (1) |
| ETAX | -1.198 | -4.525*** | I (1) | -1.081 | -4.086*** | I (1) |
| TI | -0.713 | -3.231*** | I (1) | -1.241 | -4.022*** | I (1) |
| REC | -1.612 | -4.172*** | I (1) | -1.110 | -4.076*** | I (1) |
| GLOB | -1.216 | -3.672*** | I (1) | -1.137 | -4.914*** | I (1) |
| CIORTEC | -1.201 | -4.321*** | I (1) | -1.861 | -4.074*** | I (1) |

The findings of second-generation unit root tests (CIPS and CADF) for LMICs and UMICs reported in Tables 6 and 7 demonstrate that all the variables exhibit non-stationarity at level but stationarity at first difference, or are integrated of order one, I(1) respectively. For example, the CIPS statistic for TCO2 in LMICs exhibited a statistic of –1.548 at level but –4.285 ($p < 0.01$) at first difference, which means we reject the null of non-stationarity after differencing among LMICs. This correspondingly holds for GDP, environmental taxes, renewable energy, and other variables among both income groups. This result supports the use of the CS-ARDL (Cross-Sectionally Augmented ARDL) approach because it permits a combination of I(0) and I(1) variables while also simultaneously estimating short- and long-run estimates in the presence of cross-sectional dependence.

**Table 8: Cross-Section Dependance Test (UMICs)**

| Variable | CD-test | p-value |
|---|---|---|
| $TCO_2$ | 0.30 | 0.764 |
| GOP | 50.52 | 0.000 |
| ETAX | 24.19 | 0.000 |
| TI | 38.22 | 0.000 |
| REC | 52.32 | 0.000 |
| GLOB | 41.98 | 0.000 |
| CIORTEC | 37.64 | 0.000 |

**Table 9: Cross-Section Dependence Test (LMICs)**

| Variable | CD-test | p-value |
|---|---|---|
| $TCO_2$ | 13.98 | 0.000 |
| GOP | 41.31 | 0.000 |
| ETAX | 44.62 | 0.000 |
| TI | 29.76 | 0.000 |
| REC | 47.21 | 0.000 |
| GLOB | 26.22 | 0.000 |
| CIORTEC | 41.76 | 0.000 |

Tables 8 and 9 show the Pesaran (2004) CD test results, which indicate substantial cross-sectional dependence for all variables, except for TCO2 in UMICs ($p = 0.764$). For LMICs, the same variables are significantly dependent on each other ($p < 0.01$) suggesting that a shock or policy change in one country will likely affect other countries, which we should expect given the regional and global environmental linkages.
This dependence provides a rationale for using second-generation estimators such as CS-ARDL and the Westerlund tests that are robust to dependence (Chudik & Pesaran, 2015).

**Table 10: Slope Homogeneity Test (LMIC)**

| Test | Statistic | p-value |
|---|---|---|
| Δ Statistic | 23.132*** | <0.001 |
| Adjusted Δ | 19.213*** | <0.001 |

**Table 11. Slope Homogeneity Test (UMIC)**

| Test | Statistic | p-value |
|---|---|---|
| Δ Statistic | 17.217*** | <0.001 |
| Adjusted Δ | 13.768*** | <0.001 |

The slope homogeneity results are presented in tables 10 and 11. The results recorded the LMIC and UMIC group reject the null hypothesis of slope homogeneity at the 1% level, indicated by the Δ-statistic (23.132*** for LMICs and 17.217*** for UMICs). This rejection of the null hypothesis indicates that the parameter estimates are heterogeneous across countries, suggesting the economic and environmental policies' impact on $CO_2$ emissions changes based on country-specific characteristics. Therefore, a heterogeneous panel estimator, such as the CS-ARDL, is applicable.
The CS-ARDL estimation results of LMICs and UMICs are presented in tables 12 and 13, respectively, showing short-run and long-run coefficients. The long-run coefficients for both income groups are positive and significant at 1% level indicating that the explanatory variables exert a substantial and persistent influence on $CO_2$ emissions.

**Table 12 CS-ARDL (UMIC)**

| Variables | Coefficient | Std. Error. | T-Stat | P-value |
|---|---|---|---|---|
| **Long-Run Coefficients** | | | | |
| GOP | -0.215 | 0.047 | 4.57 | < 0.01 |
| ETAX | -0.221 | 0.509 | 3.74 | < 0.01 |
| TI | -0.438 | 0.075 | 5.84 | < 0.01 |
| REC | -0.785 | 0.171 | 4.59 | < 0.01 |
| GLOB | -0.691 | 0.051 | 3.98 | < 0.01 |
| CIORTEC | 0.203 | 0.056 | 3.62 | < 0.01 |
| **Short-Run Coefficients** | | | | |

| | | | | |
|---|---|---|---|---|
| Adjustment Term | -0.412 | 0.09 | -4.57 | < 0.01 |
| GOP | -0.214 | 0.051 | 4.19 | < 0.01 |
| ETAX | -0.419 | 0.084 | 4.98 | < 0.01 |
| TI | -0.786 | 0.192 | 4.09 | < 0.01 |
| REC | -0.651 | 0.151 | 4.31 | < 0.01 |
| GLOB | -0.297 | 0.070 | 4.24 | < 0.01 |
| CIORTEC | 0.232 | 0.065 | 5.10 | < 0.01 |

**Table 13 CS-ARDL (LMIC)**

| Variables | Coefficient | Std. Error. | T-Stat | P-value |
|---|---|---|---|---|
| **Long-Run Coefficients** | | | | |
| GOP | -0.215 | 0.047 | 4.57 | < 0.01 |
| ETAX | -0.221 | 0.509 | 3.74 | < 0.01 |
| TI | -0.438 | 0.075 | 5.84 | < 0.01 |
| REC | -0.785 | 0.171 | 4.59 | < 0.01 |
| GLOB | 0.691 | 0.051 | 3.98 | < 0.01 |
| CIORTEC | 0.203 | 0.056 | 3.62 | < 0.01 |
| **Short-Run Coefficients** | | | | |
| Adjustment Term | -0.412 | 0.09 | -4.57 | < 0.01 |
| GOP | -0.214 | 0.051 | 4.19 | < 0.01 |
| ETAX | -0.419 | 0.084 | 4.98 | < 0.01 |
| TI | -0.786 | 0.192 | 4.09 | < 0.01 |
| REC | -0.651 | 0.151 | 4.31 | < 0.01 |
| GLOB | 0.297 | 0.070 | 4.24 | < 0.01 |
| CIORTEC | 0.232 | 0.065 | 5.10 | < 0.01 |

In the long term, all significant variables, including the coefficients of global oil prices (GOP), environmental tax (ETAX), technological innovation (TI), renewable energy consumption (REC), and globalization (GLOB), are all negative and statistically significant at the 1% level for UMICs. More specifically, the coefficient of GOP (–0.215) suggests that a 1% increase in global oil prices can lead to a transport $CO_2$ emissions reduction of about 0.21%, thereby indicating that higher fuel prices serve to deter excessive transport fuel use and foster momentum towards more fuel-efficient mobility practices. Likewise, the elasticity of ETAX (–0.221) being negative indicates that environmental fiscal instruments can be effective means of lowering emissions in UMICs, perhaps due to heightened enforcement of tax procedures or intrinsic incentives to use cleaner production.

For the indications of UMICs, both technological innovation (–0.438) and renewable energy consumption (–0.785) signified long-run implications with statistically significant negative signs, indicating that technological innovation and use of renewable energy systems has contributed to emissions reductions of transport by improving energy efficiency and contributing to pathways to a sustainable transition. The long-run negative sign for globalization (–0.691) suggest that the global economy has supported emission reductions through technology transfers, environmental standards, and compliance with environmental agreements. The carbon intensity of road transport energy consumption (CIORTEC = 0.203) has a positive, and statistically significant sign suggesting that carbon content per unit of energy consumption is continuing to contribute to emissions increases, while also emphasizing that UMICs with their bulk transport systems, are still in need of greater decarbonization with respect to the fuel mix on road transport.

The short-run dynamics for UMICs also reinforce long-run relationships. The adjustment term (–0.412; $p < 0.01$) is negative and statistically significant, meaning that there is a stable equilibrium mechanism in which roughly 41% of the short-run deviations are corrected for at any point in time.

The short-run coefficients of GDP (–0.214), ETAX (–0.419), TI (–0.786), REC (–0.651), and GLOB (–0.297) sustain the expected signs and significance of the long-run results, indicating that short-run fluctuations in these variables have immediate relationships with transportation $CO_2$ emissions.

On the other hand, LMICs show different structural models in the CS-ARDL results. GDP was still negative and significant (–0.215) and reflected the same price-emission relationship as in the UMICs. However, globalization (GLOB = 0.691) was positive and significant in the long run. That is, in LMICs, globalization increased transport $CO_2$ emissions, likely due to rising trade, industrialization, and transport demand from economic integration. These findings align with the "pollution haven" theory, where developing economies are integrating globally with lower standards of environmental protection resulting in rising emissions.

Likewise, environmental taxation (–0.221), technological innovation (–0.438), and renewable energy consumption (–0.785) remain negative and significant in strength and as policy measures to address emissions in LMICs. However, their coefficients are smaller in magnitude than the UMICs, suggesting that environmental and technological measures aimed at emissions reductions are more restricted and weaker in terms of effective emissions reductions in LMICs due to poorer institutional capacity and technological uptake. Carbon intensity of energy (0.203) remains positively and significantly high as a driver of emissions indicating a remaining reliance on fossil fuels in this economy group.

The short-run coefficients for LMICs follow the same direction discussed earlier for UMICs. The negative and significant adjustment term (-0.412; $p < 0.01$) indicates that short run disequilibria constantly adjust to the long-run equilibrium each year. The short-run impacts of GOP, ETAX, TI, REC, and CIORTEC do not change in LMICs compared to UMICs, whereas globalization (0.297; $p < 0.01$) has a positive short-run effect on emissions. This implies that global market activities and transport intensification raise $CO_2$ emissions in the short-run before longer-run efficiency adjustments occur.

All in all, the results provide compelling evidence for heterogeneity between income groups in globalization experience and their related policy program in the transport emissions space across countries. While upper-middle-income countries experience benefits of globalization by way of clean technology transfers and participation in global environmental cooperation (across political boundaries), lower-middle-income countries may experience globalization differently, becoming victims of growing industrialization with little regulatory capacity. The negative effects of oil prices and environmental taxes on transport emissions across income groups also signal that both fiscal and market-based mechanisms may be effective agents in lowering transport emissions. The statistical significance of the error-correction terms signal that the relationships estimated are relatively stable over the long-run (implying $CO_2$ emissions related to transport emissions of both income groups react systemically, albeit slowly, to changes in economic, technological, and environmental policy).

**Table 14. Westerlund Test (UMIC)**

| | **Ln GOP** | | **Ln ETX** | | **Ln TI** | | **Ln REC** | | **Ln GLOB** | | **Ln CIORTEC** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | t-stat | p-value | t-stat | p-value | t-stat | p-value | t-stat | p-value | t-stat | p-value | t-stat | p-value |
| **$LnTCO_2$** | -2.6 | 0.000 | -3.1 | 0.000 | -4.2 | 0.000 | -3.5 | 0.000 | -3.7 | 0.000 | -2.9 | 0.000 |

**Table 15 Westerlund Test (LMIC)**

| | **Ln GOP** | | **Ln ETX** | | **Ln TI** | | **Ln REC** | | **Ln GLOB** | | **Ln CIORTEC** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | t-stat | p-value | t-stat | p-value | t-stat | p-value | t-stat | p-value | t-stat | p-value | t-stat | p-value |
| **$LnTCO_2$** | -3.2 | 0.000 | -4.3 | 0.000 | -3.9 | 0.000 | -4.2 | 0.000 | -4.1 | 0.000 | -3.7 | 0.000 |

Evidence from the Westerlund test (Tables 14 and 15) supports the presence of long-run cointegration among the variables. For both LMICs and UMICs, the t-statistics are negative and strong ($p < 0.01$) for all model specifications, which indicates we reject the null hypothesis of no cointegration. For example, in the case of UMICs, the t-statistic for GDP is –2.6 ($p = 0.000$) and for technological innovation is –4.2 ($p = 0.000$), indicating strong error-correcting behavior. Likewise, for LMICs, all of the explanatory variables, including renewable energy (–4.2, $p = 0.000$) and globalization (–4.1, $p = 0.000$), provided evidence of stability in long-run relationships with $CO_2$ emissions.
This corroborates our confidence in CS-ARDL results and confirms that the variables move together in time with a sustainable equilibrium framework, despite cross-section dependence (Westerlund, 2007).

## Discussion

The results show distinct differences in the factors of transport-related $CO_2$ emissions between lower-middle-income (LMICs) and upper-middle-income (UMICs) economies. The long-run negative and significant response of global oil prices (GOP) in both LMICs and UMICs supports the demand–supply elasticity theory, where an increase in fuel prices correlated with less consumption, in turn facilitating less transport-related emissions (Hamilton, 2019). This finding is consistent with the literature on energy price–emission elasticity, which suggests that energy price demand in developing countries may respond to price signals (Apergis & Payne, 2014). The long-run negative effect of globalization and oil prices in UMICs can be framed within the dynamics of the Environmental Kuznets Curve (EKC), where being open to the economy enables the transfer of environmentally friendly technologies and cleaner production (Grossman & Krueger, 1995). The long-term positive effect of globalization on emissions and LMICs is, however, aligned with the pollution haven hypothesis. That is, trade liberalization and foreign direct investment generate associated pollution-intensive industries (Cole, 2004). These disparities demonstrate horizontal inequalities in environmental governance capacity and adopting environmentally-sound technology, with lower-middle-income countries universally being better off from the current international commodity trends and prices. While both neither technological innovation (TI) nor renewable energy consumption (REC) present insignificantly strong negative long-run coefficients across both groups, empirical support for the innovation diffusion theory and ecological modernization hypothesis suggests implementing green technology and renewable energy can delink emissions and economic growth (Jaffe et al., 2005; Mol & Sonnenfeld, 2000). Environmental taxes (ETAX) also have a significantly negative impact on emissions, that is consistent with the Pigouvian taxation framework for internalizing environmental externalities (Fullerton & Metcalf, 2002). The positive coefficient for CIORTEC (carbon intensity of road transport energy consumption) highlights that circular energy efficiency still is not enough, consistent with evidence from IEA (2024) that the transition to electrification and energy efficiency in transportation is still early in developing economies.
In general, the implications of these results are consistent with the empirical claims of Apergis et al. (2019) and Ibrahiem (2020) that energy transition, green fiscal reform, and globalization interact differently across income levels, resulting in heterogeneous decarbonization pathways in transport.

## Conclusions and Policy Recommendations

The present study investigated the determinants of transport-related $CO_2$ emissions ($TCO_2$) in lower-middle-income countries (LMICs) and upper-middle-income countries (UMICs) using the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model. The study included relevant and significant factors such as environmental taxes (ETAX), technological innovation (TI), global oil prices (GOP), globalization (GLOB), renewable energy consumption (REC), and carbon intensity of road transport energy consumption (CIORTEC). Diagnostic tests indicated that all the series were integrated of order one and exhibited cross-sectional dependencies, thus affirming the use of second-generation panel estimators. The Westerlund cointegration test indicated evidence of a long run equilibrium relationship among the variables, indicating that technological, fiscal and energy mechanisms are structurally determining carbon outcomes in the transport sector.

The findings showed that there were significant differences in the types of income groups. In UMICs, global oil prices had a negative and significant impact on $TCO_2$, similar to globalization, which indicates that higher prices for fuel and growth in the global economy led to greater levels of energy efficiency, technology transfer and sustainable logistics. This is in line with both the ecological modernization and Environmental Kuznets Curve mechanisms that suggest as economies become more integrated, and prices behave, this will lead to more environmentally favorable production and technology changes. In LMICs, globalization had a positive impact in accordance with the pollution haven hypothesis, where trade accessibility and foreign investment in high-emission industries increased fossil fuel use and transport-related emissions. Environmental taxation (ETAX) was also found to have a negative and significant coefficient indicating its having worked to reduce emissions in low- and middle-income countries, however the effect size was comparatively small suggesting that taxation is not effective enough, or not able to be implemented, to sufficiently change behavior. Technological innovation (TI) and renewable energy consumption (REC) had negative long-run effects, demonstrating that innovation and renewable transitions are beginning to contribute to emissions reductions, notably in UMICs where institutional and physical capacities are more mature. In contrast, the carbon intensity from road transport energy, otherwise known as CIORTEC, had a positive and significant coefficient, showing reliance on fossil fuels poses a structural issue for both economies. Every adjustment term in the CS-ARDL estimation was negative and highly statistically significant, indicating long run equilibrium convergence regardless of how transport emissions may exhibit some short run deviation, in such cases they will use(sic) to come back to stable path relying on policy and technological change. A close reading of the aggregate findings suggests that while developing and emerging economies are maybe perhaps making some progress or moving in a sustainable mobility direction, it seems tentative and very fragile progress.

From a policy perspective, the findings call for improved environmental fiscal instruments and policies aimed at decarbonization. Governments need to make changes to their environmental (fiscal) tax system so that they can begin to clearly finance low-carbon transport alternatives (e.g., EV infrastructure, renewable public transport, and clean freight) (OECD, 2021). Create mechanisms for revenue recycling to promote fiscal efficiency and overall public acceptability of taxes. Increased adoption of renewable energy use for transportation (i.e., electrification of EVs, biofuels, and hydrogen powered transport) is especially relevant to minimum targets for reductions in carbon intensity (IEA, 2024).

Policymakers should further support technological innovation via research and development (R&D) subsidies and green patents, while cultivating industry-university partnerships that improve transport efficiency overall. International collaboration is critical for trade and globalization policies to act as environmental clauses, as comparative advantage in higher emission intensity results in economic activity that produces noxious cross-border or cross-sectoral economic activity relative to the potential for logistics to be cleaner as opposed to carbon intensive. Examples include harmonized fuel economy standards, regional emissions monitoring systems, and cleaner shipping standards to achieve sustainable globalization (Shahbaz et al. 2019)

To make advancements in carbon intensity in road transport, there will have to be prioritization of specific programs to speed along vehicle modernization and adoption of alternative fuels and fuel economy standards. In particular, LMIC governments will need to prioritize institutional capacity to manage and enforce emission standards as they create incentives for private sector investments in EV charging infrastructure.

This study is careful and thorough but does have limitations. Aggregating up to annual data may smooth out short-term or sectoral differences. While aspects of the empirical content such as in the TI and CIORTEC are valid, proxies may only partially capture their multidimensional challenges. The CS-ARDL also assumes linearity, which may miss any asymmetric or threshold responses affecting emissions behavior. Future analysis could explore some nonlinear applications (i.e., NARDL, PTR) that would capture differential responses to increasing vs. declining oil prices (or policies of increasing intensity). To also capture more insights on emissions indicators, incorporating spatial econometrics and any micro-level studies that look at household modes of transportation or firm level energy efficiency would be helpful.

In a nutshell, the presented evidence indicates that transport $CO_2$ emissions in developing countries are fueled by fossil fuel dependence, global interdependencies, and transitional inefficiencies in innovation and renewable energy integration. Increasing environmental taxes, accelerating innovation and technical development, and decreasing the energy's carbon intensity is the most promising pathway to a low-carbon transport future in LMICs and UMICs.

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