



Asymmetric link between PPP investment and transport CO₂ emissions in india: A QARDL perspective

Ashok Kumar¹ · Sushila Soriya¹

Received: 20 May 2025 / Accepted: 8 December 2025
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Abstract

The transport sector is the third most polluting sector in India. So, transforming it into a more efficient and environmentally sustainable sector is essential., where Public Private Partnerships (PPPs) could play a crucial role. To address modification at the policy level in India, the current study examined how transport carbon emissions are influenced by PPP investment along with urbanization, economic growth, FDI, trade openness and environmental technology innovations. The Quantile Autoregressive Distributed Lag Model (QARDL) has been used for the period 1998Q1-2022Q4. The key results highlights that PPP investment in long run is insignificant in most of the quantiles but significant and negative in the quantiles ranging from 0.6 to 0.9 in short run reflecting the impact of PPP investment in higher quantiles. The Environmental Kuznets Curve (EKC) hypothesis has also been established in the data, whereas urbanization associated with the reduced transport sector emission in 0.2 to 0.9 quantiles. The study also found environmental technology innovation associated with reduced transport emissions. Trade openness found insignificant in long run but significant and adverse effect on the environment in the short run. FDI have adverse effect on transport emission in the long run in all quantiles (0.1–0.9). Finally, policy proposals have been made for transport sector to reduce transport CO₂ emissions in India.

Keywords PPP · Public-private partnership · Transport sector · CO₂ emission · QARDL

JEL code R42 · C22 · Q53

✉ Ashok Kumar
ashok231782@cuh.ac.in

¹ Central University of Haryana, Mahendragarh, Haryana, India

Introduction

One of the major issues confronting the entire planet is environmental degradation. As a result, there are major risks to human survival from global warming, and greenhouse gas emissions, primarily air pollution in developing countries. According to the IEA, 2022, the electricity and heat-producing sector contributes 52.7% of emissions followed by the industry and transport sector which contributes 24.1% and 12.9% respectively in total CO₂ emissions in India. The road sector itself accounts for 90% of total transport sector CO₂ emissions (ICCT, 2022). According to the World Bank, India has progressively become more urbanized in the past few decades, and it is estimated that by 2036 nearly 600 million population will be living in cities, which leads to an increase in the demand for more infrastructure in India. The result of better economic performance and development also contributed to increased urbanization directly impacts the environment (Martínez-Zarzoso and Maruotti 2011; Jedwab and Vollrath 2015). Despite having an adverse impact on the environment, the transport sector has a favorable influence on the growth of economy (Lavee et al. 2011; Nenavath 2023). It implies that the country needs to find some alternatives for the environmentally sustainable development of the infrastructure, especially in the transport sector. However, industrialization and urbanization progress in India demand rapid growth in transportation leading to have repercussion on the environment. Lin and Omoju (2017) and Zhang, (2015) found that there is an adverse effect of urbanization, increase in population, and income levels on transport-related environment degradation in the form of increased CO₂ emission. In 2018, transportation, urban planning, and green innovations were recognized as crucial areas for building a sustainable future by the Geneva Roundtable on Sustainable Development (UNDP 2018). The Paris Climate Change Summit aimed to reduce greenhouse gas emission that leads to climate change using nationally determined contributions (NDC) (UNCCC 2016). The Global Sustainable Development Goal Report, 2023 stressed the need for the transformation of the energy and transport sector by using renewable energy to reduce emissions (UNESCAP 2023). In India, larger proportion of the government budget went for the social welfare schemes which leads to remain low budget for infrastructure development. Even the great economic depression 2008 and COVID19 has exacerbated the financial condition of the country. The involvement of the private firm could be crucial through Public Private Partnership (hereafter PPP) as it provides the required capital as well as technological support which is important to achieve environmental sustainability. According to the World Bank (2024), government is also focusing on more private participation in the transport among all other areas like energy, water and ICT sectors. It reflects the crucial role of PPP in transforming transport sector into more sustainable and high-quality infrastructure with the use of modern technology and innovations.

Various policies promoting the privatization, investment incentives and trade and investment liberalization have attracted FDI, with the aim to boost the economic growth, improve employment opportunity and enhance transfer of technology (Ayadi 2009; Ayadi et al. 2010). These FDI flows especially in manufacturing sector and trade openness increases the freight demand which led to increased carbon emissions through transport. The trade openness is the other important aspect that influence the

environment quality of the country. Le et al. (2016) found long run link between the trade openness and environment quality. They argued that trade openness degrades the quality of environment. It shows that FDI and trade openness enhances the utilization of transport sector, which affects the environment. On the other side, increase in human economic activities in rural or urban area have negative impact on ecosystem and degrades the environment.. Zhang et al. (2017) highlighted that the urbanization can have the both negative or positive effect on the environment. Increase in urbanization leads to increase economic activity, which demands for more transportation indicating that with the strategic and planned way urbanization can be proved sustainable in the developing country.

With the economic growth in the developing country, innovation becomes very crucial to reduce the environmental degradation through innovative technologies. The study of Hodson et al. (2018) highlighted that innovation significantly reduces the carbon emissions through improving energy efficiency. In case of China, by integrating the better production material pricing estimates into national development plan, they can achieve the better quality and sustainable growth. They are also intended to maximize industrial capacity, promote infrastructure investment, and ease of transition into greener and cleaner process (Shao et al. 2022; Xu 2017; Jin and Xu 2025). It reflects that sustainability with high quality can be achieved during the development phase. Innovation especially related to environmentally friendly technologies, helps countries to adopt the sustainable energy sources and production which improves the environmental quality (Álvarez-Herránz et al. 2017). All these shows that the increase in demand of transport sector should be fulfilled without affecting the environment. It will required huge investment, where private participation through PPPs can become fruitful for the country's perspective.

While addressing how India's current policies need to be realigned to improve the environmental quality, this study emphasizes the need for policy-level contribution in reducing the transport-induced CO₂ emission in India through PPP investment. To comply with the sustainable development goals in India, there is a need to assess the impact of PPP investment in transport by incorporating economic growth, FDI, trade openness, urbanization and environmental innovations on CO₂ emission from 1998Q1- 2022Q4. As multiple levels of the policy might have different impacts on every target policy parameter, therefore, it becomes vital to assess the association in the short and long run. This study has used Quantile Autoregressive Distributed Lag (QARDL) approach given by Cho et al. (2015). QARDL permits the estimation of the long-term relationship between variables and allows for any short-term asymmetric changes (Mensi et al. 2019).

After the introduction, literature review will be presented in Sect. 2. Further, collection of data and methodology will be explained in Sect. 3, i.e., the interpretation of the results and discussions explained in Sect. 4. Sections 5 and 6 presents policy implications and conclusions of this study respectively.

Literature review

Modern technology in highly globalized countries may enhance transportation, making it easier for individuals to travel around the globe in the long run. But it contributes to environmental deterioration, as a result of globalization and the speed at which international trade is occurring. Therefore, having an efficient transportation infrastructure can contribute to reducing carbon emissions. It is vital to monitor how transportation affects the quality of the environment for this reason. Therefore, this study explored various past studies that focus on private participation in mitigating CO₂ emissions for environmental sustainability.

The study of Willoughby (2013) highlighted the effectiveness of the PPP to develop urban transport infrastructure. They found the significant positive influence of PPP investment on the urban transport sector to curb air pollution, improve the work and services, and lower the road accidents through technological innovation and with better managerial skills. Wang et al. (2024) investigated the efficacy of the green PPP model to control carbon emissions and found that the carbon reduction effect varies on the features of green PPP projects and the cities in which they are working in China. Similarly, Yuan et al. (2018) have explored that socially responsible PPP projects can mitigate environmental impact and involvement of the PPP sector will improve the creditworthiness and sustainability of the transport sector. In contrast, the study of Georgatzis et al. (2020) analyzed the factors that influence CO₂ emission from the transportation sector in 12 European Union countries. They highlighted that infrastructure investment does not influence the CO₂ emissions from transport sector in this country.

The study of Xue et al. (2017) highlighted that private capital investment in public transport led to significant fuel consumption and a reduction in the CO₂ emission from the transport sector compared to the traditional method with no private investment. Similarly, Dai et al. (2023) scrutinized the secondary data from 1970 to 2019 and found that the consumption of green energy in the transport sector decreased CO₂ emission, whereas economic growth negatively affects the CO₂ emission of the transport sector in the US. Additionally, Omri et al. (2024) highlighted that a positive shock to renewable energy helps in reducing the ecological footprints and CO₂ emission in France. The consumption of biofuels in transport has shown positive impact for reducing carbon emission in Spain (Sanz et al. 2014). In the developing countries, Raza et al. (2021) assessed the association between PPP investment in energy and CO₂ emission and found that there was a non-linear relation. However, the Nonlinear Granger Causality Test indicated that PPP investment did not significantly impact CO₂ emissions in developing countries. Investment in energy sector along with the technology innovation proved to be favorable in the various studies. Technological innovation provides cleaner and more efficient alternatives for the machinery to run without contributing much emissions. Cruz and Katz-Gerro (2016) explored that private sector investment in the transport can enhance the environmental condition using technological innovation and by changing the behavior of consumers as well as employees. It also focused on promoting an energy-efficient transport system, testing fewer polluting fuels, and monitoring vehicles for future innovations. The study of Khan et al. (2020) highlighted the favorable link between consumption-based carbon

emission and PPP investment in energy sector along with technological innovation. On the other side, while focusing on FDI, economic growth with emissions Raghutla et al. (2024) highlighted the influence of PPP investment and FDI on CO₂ emissions and found that economic growth and clean energy consumption contribute to better environmental quality, whereas PPP investment, FDI, and technological innovations have a negative impact on carbon emissions.

Urbanization is the other aspect which affects the emissions in the country (Ali et al. 2017). Ummalla et al. (2023) highlighted in their study that PPP investment in energy helps in reducing carbon emissions in the short and long run whereas urbanization and FDI also have a negative impact on carbon emissions. While focusing on the transport sector, Ahmed et al. (2020) examined that urbanization has a mitigating impact on transport emissions, and the coefficient of urbanization was found significant and negatively correlated with transport emissions. Road transport was also found a key factor in transport emissions in India. In contrast, Lin and Omoju (2017) found the adverse impact of urbanization on the environment due to increasing CO₂ emission from the transport sector. It was also learned that participation of private companies in the transport sector and technological advancement can help to reduce CO₂ emissions in Asia.

Although previous studies have focused on the various factors influencing the environment sustainability by highlighting the role of urbanization, renewable energy and infrastructure investment. Prior studies have focused on the aggregate infrastructure and its impact on the environment by mainly focusing on the energy transition. The role of technology innovation is also significant for environment sustainability. There are very few studies provide evidence on the role of PPP investment especially in the transport sector. While very few studies have examined the impact of FDI and trade openness on transport carbon emissions, as these factors improves the demand for transport significantly. Very few studies have focused on the role of PPP investment especially in transport sector while testing the Environmental Kuznets Curve (EKC) hypotheses. Most of the studies have focused on the aggregate emissions without directly focusing on the transport, which has significant contribution in emissions. PPPs can provide the much-needed advance technology and innovations to improve efficiency and adoption of cleaner technology to support the Environmental Kuznets Curve (EKC) downward turning point. Hence, this study focused on the role of PPP investment in the transport sector on transport emissions by incorporating the economic growth, FDI, trade openness, urbanization and technological innovations by testing the EKC hypotheses.

Materials and methods

Data

The study aims to examine how PPP investment affects the CO₂ emissions released by the transport sector in India. The time for the study is 1998Q1 to 2022Q4. The reason behind taking this time period is that there were major changes that happened between these years in India in the field of PPP development like the establishment of

Table 1 Name and source of variables

Sr. No.	Variables	Specifications	Source
1	Transport sector CO ₂ emissions (TSE)	Transport sector CO ₂ emissions (in metric tons of CO ₂ emissions)	WDI
2	PPP investment in transport sector (PPPT)	Transport sector PPP investment (In constant US dollars)	WDI
3	Foreign Direct Investment (FDI)	Foreign Direct Investment, Net inflows, % of GDP	WDI
4	Urbanization (URB)	Urban population (in % of total population)	WDI
5	Economic growth (EG)	GDP per capita (In Constant 2015 US dollars)	WDI
6	Trade openness (TO)	Trade (% of GDP)	WDI
7	Environmental technology innovation (ETI)	Patent on environmental technologies	OECD

Note: WDI- World development indicators, OECD- Organization for Economic Co-operation and Development

Table 2 Result of descriptive statistics

Variable	Mean	Median	Min.	Max.	Std. Dev.	Jarque- Bera	P value
TSE	3.773	3.875	3.073	4.427	0.457	10.460***	0.005
PPPT	20.245	20.527	16.672	22.503	1.427	6.356**	0.041
GDP	5.716	5.733	5.121	6.283	0.349	7.409**	0.024
URB	2.048	2.045	1.915	2.198	0.083	6.052**	0.048
TO	2.306	2.369	1.770	2.650	0.257	10.167***	0.006
FDI	-1.057	-1.057	-2.184	-0.068	0.506	4.236	0.120
ETI	0.726	0.819	0.280	1.114	0.275	9.844***	0.007

Note: At the 1%, 5%, and 10% levels, significance is indicated by the symbols ***, **, and *, respectively.

Source: Author's own Estimation

India Infrastructure Finance Corporation Limited, 11th five-year plan for 2007–2012. SDG 17 in 2015 helped to boost the role of PPP in sustainable development. Transport carbon emission is the dependent variable in this study. The study has utilized the GDP per capita (in constant 2015 US dollars) and urban population (in % of total population) have been used as the proxies for economic growth and urbanization respectively. This study has also utilized patent on environment technologies as the proxy for environmental innovation variable. All the variables are transformed into their natural logarithmic form before estimation and details regarding the variables are mentioned in the Table 1. Finally, to convert the annual data into quarterly, this study has used the quadratic match sum method (Godil et al. 2020; Arain et al. 2020; Sharif et al. 2019; Shahbaz et al. 2018).

Descriptive statistics

The descriptive statistics for each variable are displayed in Table 2. The descriptive statistics for TSE show that the values are clustered close to the mean value which indicates that the variable has a relatively stable and consistent pattern across the data. Similarly, the descriptive statistics of variables PPPT, EG, FDI, TO, URB, and ETI show low variability in their mean and hence there are no large fluctuations and

extreme outliers in the variable. To check the normality of the data Jarque Bera test has been applied and the results show that all the variables are significant except FDI. Since quantile ARDL does not rely on the normality of the variable, this study has utilized this method (Godil et al. 2020; Batool et al. 2019; Raza et al. 2017; Sharif et al. 2017). QARDL is preferred over the ARDL approach (Pesaran et al. 2001) as QARDL provides the long run and short effects in different quantiles, while ARDL measure only the mean association and assumes homogeneity. It will help in identifying the heterogeneous, nonlinear and asymmetric effects at different quantiles.

Methodology

Developing a robust policy measure requires assessing how policy factors affect target policy variables over the whole data spectrum. The conventional least square-based panel models, which evaluate the influence at the variable's median, may undermine the study's policy-oriented objective. Even throughout the whole data spectrum, there may be asymmetrical influence of the policy parameters on the target policy variable. In time series analysis, frameworks like ARIMA, VAR, and VECM have been widely used to study the macroeconomic factors (Jin and Xu 2025; Xu 2017). They are limited in assessing the asymmetry effects. Thus, to enhance policy-level contribution from this study, the study utilized the QARDL approach.

QARDL model given by Cho et al. (2015) has been utilized to examine the nonlinear association between the dependent variable (CO₂ emission from the transport sector) and independent variables (PPPT, URB, EG, FDI, TO, ETI) for India. Prospective imbalances between PPP investment, urbanization, FDI, trade openness, environment technology innovation and economic growth, with CO₂ emission by the transport sector can be examined using QARDL, an enhanced version of the ARDL model. The following is the ARDL elementary form:

$$\begin{aligned} TSE_t = & \mu + \sum_i^m \beta_1 TSE_{t-i} + \sum_i^n \beta_2 PPPT_{t-i} + \sum_i^o \beta_3 FDI_{t-i} \\ & + \sum_i^p \beta_4 URB_{t-i} + \sum_i^q \beta_5 EG_{t-i} + \sum_i^r \beta_6 EG^2_{t-i} \\ & + \sum_i^s \beta_7 TO_{t-i} + \sum_i^t \beta_8 ETI_{t-i} + \epsilon_t \end{aligned} \quad (1)$$

Above Eq. (1), ϵ_t shows that white noise error explained by least field produced through $(TSE_t, PPPT_t, FDI_t, URB_t, EG_t, EG^2_t, TO_t, ETI_t, TSE_{t-1}, PPPT_{t-1}, \dots)$, and m, n, o, p, q, r, s, t shows the orders of lag drawn through Akaike Information Criterion (AIC).

Cho et al. (2015) extended the model described in Eq. (1) in terms of Quantile mentioned below as the QARDL technique-

$$\begin{aligned}
Q_{TSE_t} = & \mu(\tau) + \sum_i^m \beta_1(\tau) TSE_{t-i} + \sum_i^n \beta_2(\tau) PPPT_{t-i} \\
& + \sum_i^o \beta_3(\tau) FDI_{t-i} + \sum_i^p \beta_4(\tau) URB_{t-i} \\
& + \sum_i^q \beta_5(\tau) EG_{t-i} + \sum_i^r \beta_6(\tau) EG^2_{t-i} \\
& + \sum_i^s \beta_7(\tau) TO_{t-i} + \sum_i^t \beta_8(\tau) ETI_{t-i} + \epsilon(\tau)_t
\end{aligned} \quad (2)$$

Equation (2) shows, $\epsilon_t(\tau) = TSE_t - Q_{TSE_t} - \left(\frac{\tau}{\epsilon_{t-1}}\right)$ Kim and White (2003) and $0 < \tau < 1$ shows the quantile. To carry out the analysis of the data, the study uses the quantile from 0.10, 0.20,0.90. Because of the probability of sequential correlation, the QARDL model explained above is converted as;

$$\begin{aligned}
Q_{\Delta TSE_t} = & \mu(\tau) + \rho(TSE_{t-i} + \phi_{PPPT}(\tau) PPPT_{t-i} + \phi_{FDI}(\tau) FDI_{t-i} \\
& + \phi_{URB}(\tau) URB_{t-i} + \phi_{EG}(\tau) EG_{t-i} + \phi_{EG^2}(\tau) EG^2_{t-i} \\
& + \phi_{TO}(\tau) TO_{t-i} + \phi_{ETI}(\tau) ETI_{t-i}) + \sum_{i=0}^{m-1} \phi_i \Delta TSE_{t-i} \\
& + \sum_{i=0}^{n-1} \omega_i \Delta PPPT_{t-i} + \sum_{i=0}^{o-1} \lambda_i \Delta FDI_{t-i} \\
& + \sum_{i=0}^{p-1} \theta_i \Delta URB_{t-i} + \sum_{i=0}^{q-1} \psi_i \Delta EG_{t-i} \\
& + \sum_{i=0}^{r-1} \delta_i \Delta EG^2_{t-i} + \sum_{i=0}^{s-1} \kappa_i \Delta TO_{t-i} \\
& + \sum_{i=0}^{t-1} \gamma_i \Delta ETI_{t-i} + \epsilon(\tau)_t
\end{aligned} \quad (3)$$

Moreover, the above-mentioned equation (3) was reformulated to show the QARDL-ECM model by Cho et al. (2015);

$$\begin{aligned}
Q_{\Delta TSE_t} = & \mu(\tau) + \rho(TSE_{t-i} - \beta_{PPPT}(\tau) PPPT_{t-i} - \beta_{FDI}(\tau) FDI_{t-i} \\
& - \beta_{URB}(\tau) URB_{t-i} - \beta_{EG}(\tau) EG_{t-i} - \beta_{EG^2}(\tau) EG^2_{t-i} \\
& - \beta_{TO}(\tau) TO_{t-i} - \beta_{ETI}(\tau) ETI_{t-i}) + \sum_{i=0}^{m-1} \phi_i(\tau) TSE_{t-i} \\
& + \sum_{i=0}^{n-1} \omega_i(\tau) PPPT_{t-i} + \sum_{i=0}^{o-1} \lambda_i(\tau) FDI_{t-i} \\
& + \sum_{i=0}^{p-1} \theta_i(\tau) URB_{t-i} + \sum_{i=0}^{q-1} \psi_i(\tau) EG_{t-i} \\
& + \sum_{i=0}^{r-1} \delta_i(\tau) EG^2_{t-i} + \sum_{i=0}^{s-1} \kappa_i(\tau) TO_{t-i} \\
& + \sum_{i=0}^{t-1} \gamma_i(\tau) ETI_{t-i} + \epsilon(\tau)_t
\end{aligned} \quad (4)$$

By using the delta method in the above equation, the combined short-run influence of the aforementioned transport emissions has been calculated using $\phi_* = \sum_{i=0}^{m-1} \phi_i$. Despite the fact that the combined short-run impact of both contemporaneous and preceding EG on the current stage for transport emanations has been recorded as $\delta_* = \sum_{i=0}^{r-1} \delta_i$ Lastly, the speed of adjustment coefficient in Eq. (4) needs to be substantial and inverted.

The long-term EG, EG², PPPT, FDI, TO, ETI, and URB parameters are computed as $\beta_{PPPT*} = -\frac{\beta_{PPPT}}{\rho}$, $\beta_{URB*} = -\frac{\beta_{URB}}{\rho}$, $\beta_{FDI*} = -\frac{\beta_{FDI}}{\rho}$, $\beta_{EG*} = -\frac{\beta_{EG}}{\rho}$, $-\frac{\beta_{EG^2}}{\rho}$, $\beta_{TO*} = -\frac{\beta_{TO}}{\rho}$, $\beta_{ETI*} = -\frac{\beta_{ETI}}{\rho}$ the coefficient of ρ should be reversed and significant in above Eq. (4).

The present study employs the conventional ARDL (Pesaran et al. 2001) for the robustness check in order to determine the reliability of the results determined through QARDL.

Results and discussions

Unit root test

Before moving towards the QARDL estimation, stationarity test is crucial. It is necessary that all the variables should be integrated at level or at first difference. None of the variables are integrated at order 2. Table 3 presents the unit root test results for which ADF unit root test given by Dickey and Fuller (1979), the PP unit root test by Phillips and Perron (1988), and the KPSS test by Kwiatkowski et al. (1992) test have been used. Results indicate that all the variables are stationary at level or at first difference, which is a pre-requisite for applying the QARDL model.

QARDL findings

Tables 4 and 5 presents the results of long and short run coefficient in QARDL estimation. Statistically, the speed of adjustment error correction term (ECT) is found to be negative and significant in all the quantiles pointing to a long-run equilibrium reversal between TSE, PPPT, EG, EG², FDI, TO, URB and ETI. The findings in Tables 4 and 5 provides certain indications for the prospective policy-level changes in India. The coefficient of PPPT is insignificant in most of the quantiles in long run except 0.4 and 0.5, where coefficient is positive and significant. While in the short run, PPPT found to be negative and significant from 0.6 to 0.9 quantiles. It shows that in short run scenario; PPP investment is reducing the transport carbon emissions. This result is parallel to the findings of Alnour et al. (2024). The theory

Table 3 Unit root test

Method Variables	KPSS		ADF		PP	
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
TSE	1.188***	0.130	-0.488	-3.718***	-0.567	-4.634***
PPPT	0.693**	0.086	-2.906**	-4.755***	-2.296	-8.691***
FDI	0.601**	0.0627	-2.839*	-3.727***	-1.907	-5.371***
TO	0.651**	0.255	-2.038	-3.074**	-1.878	-5.028***
ETI	0.631**	0.351*	-1.514	-3.223**	-1.098	-5.446***
EG	1.217***	0.055	-0.578	-2.902**	-0.539	-5.251***
URB	1.216***	0.970***	6.121	-3.050**	5.737	-1.990

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

Table 4 QARDL Results- long run coefficients (TSE is dependent variable)

Quantiles/Variables	C	PPPT	EG	EG ²	TO	FDI	ETI	URB
0.1	5.647 (0.694)	-0.004 (-0.354)	7.990 (0.750)	-3.957 (-0.729)	0.026 (1.224)	0.020* (1.902)	-0.044 (-1.012)	-0.237 (-0.664)
0.2	1.553 (0.888)	0.001 (1.059)	2.255 (0.924)	-1.090 (-0.889)	0.008 (1.175)	0.012*** (4.632)	- (-3.948)	-0.186** (-2.354)
0.3	2.740* (1.713)	0.001 (0.744)	3.910* (1.735)	-1.926* (-1.701)	0.009 (0.959)	0.013*** (6.038)	- (-4.004)	-0.166** (-1.998)
0.4	3.933** (2.114)	0.002* (1.811)	5.583** (2.143)	- (-2.109)	0.002 (0.246)	0.014*** (5.888)	-0.016** (-3.160)	-0.202** (-2.502)
0.5	3.424** (2.205)	0.002*** (2.840)	4.921** (2.251)	- (-2.209)	0.001 (0.136)	0.013*** (6.684)	-0.014** (-3.212)	-0.183** (-2.618)
0.6	2.842 (1.111)	0.001 (0.413)	3.970 (1.122)	-1.940 (-1.081)	0.008 (0.378)	0.014** (3.298)	-0.017* (-1.758)	-0.286* (-1.653)
0.7	2.852 (1.389)	0.001 (0.855)	3.942 (1.376)	-1.920 (-1.326)	0.006 (0.565)	0.016*** (4.963)	-0.018** (-2.103)	- (-2.953)
0.8	2.247 (1.277)	0.001 (0.733)	3.087 (1.248)	-1.498 (-1.197)	0.005 (0.491)	0.016*** (5.088)	-0.015* (-1.991)	- (-2.963)
0.9	0.352 (0.108)	0.000 (-0.177)	0.513 (0.115)	-0.130 (-0.058)	0.031 (1.524)	0.018** (2.541)	-0.015 (-1.287)	-0.619* (-1.868)

Note: coefficients are followed by the T stats in bracket. *, **, *** indicate significance level at 10%, 5% and 1% respectively

of transition management and literature on sustainability will help to acknowledge the findings of this study. Transition management theory states that there are challenges and barriers that must be addressed to move toward more sustainable systems (Kumar 2021). The detected short-term benefits might be the consequence of PPPs' initial achievements in addressing certain challenges, but sustaining these benefits over time might require persistently addressing new challenges that emerge during the transition stages. According to research on sustainability transitions, transitions involve a few interrelated technological, institutional, economic, and sociocultural changes, making long-term objectives difficult to achieve (Dewulf et al. 2009). To convert the short run effect on environment, PPP investment might require long term planning for India. The EG-TSE long-run relation is found positive and significant in the middle quantile ranging from 0.3 to 0.5 quantiles, indicating that increased CO₂ emissions are a result of growing economic development. The long-run relation of EG²-TSE is significant and negative in the similar quantile indicating the presence of long run Environmental Kuznets Curve hypotheses (EKC). It shows that in initial stage of economic growth, emissions will increase but after a certain threshold it will start declining. In short run as well, EG² is significant and negative indicating that after a threshold income transport emission will start reducing. This finding is aligned with the outcomes of Sharif et al. (2020a, b).

There is a paradoxical effect of urbanization, demonstrating the urbanization helps in reducing the CO₂ emitted through the transport. The long-run relation of URB-

Table 5 QARDL Results- short run coefficients (TSE is dependent variable)

Quantiles/Variables	ECT	D(TSE)	D(PPPT)	D(EG ²)	D(EG ² (-1))	D(TO)	D(FDI)	D(FDI(-1))	D(ETI)	D(URB)	D(URB(-1))
0.1	0.006 *** (4.866)	0.351 *** (2.783)	-0.005 (-1.480)	-3.328 *** (-4.008)	-0.390 *** (-3.391)	0.186 *** (3.764)	0.000 (0.028)	-0.048 *** (-3.144)	0.000 (0.004)	-19.162 (-1.180)	-8.665 (-0.577)
0.2	-0.020 *** (-4.637)	0.276 *** (3.201)	-0.003 (-1.136)	-0.373 (-1.506)	-0.250 *** (-3.221)	0.140 *** (4.460)	0.018 (1.598)	-0.020* (-1.899)	0.018 (0.833)	-5.340 (-0.521)	-6.054 (-0.596)
0.3	-0.012 *** (-4.814)	0.249 *** (2.889)	-0.004 (-1.496)	-1.230 *** (-3.007)	-0.212 *** (-2.767)	0.155 *** (4.988)	0.020* (1.882)	-0.022** (-2.097)	0.011 (0.535)	-3.360 (-0.336)	-6.812 (-0.687)
0.4	-0.011 *** (-4.992)	0.245 *** (2.849)	-0.004 (-1.534)	-2.005 *** (-3.591)	-0.218 *** (-2.783)	0.157 *** (4.988)	0.033 *** (2.949)	-0.024** (-2.309)	0.009 (0.398)	3.770 (0.372)	-11.280 (-1.113)
0.5	-0.019 *** (-5.058)	0.240 *** (2.812)	-0.003 (-1.399)	-1.663 *** (-3.424)	-0.204 ** (-2.580)	0.150 *** (4.793)	0.034 *** (2.978)	-0.021* (-1.963)	0.014 (0.643)	2.732 (0.267)	-10.598 (-1.031)
0.6	-0.018 *** (-5.191)	0.266 *** (3.149)	-0.005 ** (-2.249)	-1.229 *** (-3.181)	-0.226 *** (-3.007)	0.180 *** (5.818)	0.026 *** (2.366)	-0.020* (-1.927)	0.002 (0.074)	7.162 (0.735)	-14.841 (-1.523)
0.7	-0.022 ** (-5.624)	0.258 *** (2.946)	-0.006 ** (-2.481)	-1.193 *** (-3.359)	-0.227 *** (-2.899)	0.191 *** (5.975)	0.033 *** (2.907)	-0.024** (-2.179)	-0.004 (-0.189)	12.040 (1.183)	-18.418* (-1.806)
0.8	-0.022 *** (-5.253)	0.282 *** (3.163)	-0.007 *** (2.674)	-0.757 ** (-2.518)	-0.230 *** (-2.861)	0.186 *** (5.698)	0.036 *** (3.020)	-0.022* (-1.988)	-0.006 (-0.249)	16.184 (1.555)	-21.621** (-2.070)
0.9	-0.088 *** (-5.917)	0.463 *** (4.004)	-0.008 ** (-2.316)	0.503 *** (4.722)	-0.406 *** (-3.882)	0.194 *** (4.451)	0.005 (0.363)	-0.034** (-2.294)	-0.001 (-0.026)	13.549 (0.980)	-29.365** (-2.119)
CUSUM test			Stable								
CUSUM sum of square			Stable								

Note: coefficients are followed by the T stats in bracket. *, **, *** indicate significance level at 10%, 5% and 1% respectively.

Lag structure: Lag selection: Automatic (deplags = 2, reglags = 2), AIC

Source: Author's own work

TSE is significant and negative in quantiles ranging from 0.2 to 0.9 in the long run. Even in the short run, urbanization is found to be significant and negative in higher quantiles. It indicates that as the urbanization grows, it leads to reduction in transport emission in the country. It reflects that better public transport system, better transport infrastructure, adoption of cleaner source of fuels in vehicles have reduced the transport emissions with the increased urbanization. In the highly urbanized area, transport system runs on the greater efficiency, with more people opting for public transport leads to reduce carbon emissions. The study's finding is aligned with the Wang et al. (2019), and Kongkuah et al. (2022). FDI is found to be significant and positive in all the quantiles (0.1–0.9) in the long run. It indicates that flow of FDI increases the transport carbon emissions in the country. FDI in India are heavily concentrated in sectors like manufacturing, constructions, retail etc. which heavily depends upon the transport sector. FDI enhances the industrial production, constructions and logistics services, all of which are dependent on the transport. Finally, it leads to increased transport carbon emissions in India. This result is similar to the findings of Aslan et al. (2021). The short run coefficient indicates the lagged effect of FDI with significant and negative coefficient in all the quantiles. It reflects the technology transfer like advance machinery; fuel efficient equipment takes time to materialized. The ETI variables found significant and negative in the quantiles ranging from 0.2 to 0.8 in the long run. It indicates that innovation in environment related technologies is significantly contributing in reducing the transport sector emission in the country. improvements in environment related innovation promotes more cleaner production by improving the fuel efficiency. As the advancement in the innovation, transport sector will be shifted towards the cleaner and energy efficient technology to reduce emissions. This finding is similar to the study of Oyebanji et al. (2022). Trade openness found to be insignificant in all the quantiles in long run, while it is found to be positive and significant in the short run. It reflects that increase in trade openness enhances the movements of transport in form of freight movements and logistics activity. Higher demands of transport lead to more fuel consumption, especially in the developing countries where road sector dominates the freight movements. So, higher trade openness increases the transport emission in India. This result is similar with the study of Pata (2019).

Robustness test

This study has utilized the conventional least square based ARDL test to ensure the robustness of this study presented in Table 6. Error correction term is found to be negative and significant in this study reflecting the adjustment towards long term equilibrium. ARDL which uses traditional least square method also reflects that PPP investment is insignificant in the long run and has negative and significant coefficient in the short run. R-square value is 0.81 reflecting that explanatory variables explain 81% of the deviations in the dependent variable this study. The CUSUM and CUSUM sum of square shows the stability of the model. Hence, the robustness test confirms that the estimated results are reliable and stable in long run and short run.

Table 6 Robustness test: ARDL (TSE is dependent variable)

Variables	Coefficient	T stats	Variables	Coefficient	T stats
PPPT	-0.0011	-0.7295	COINTEQ	-0.0241 ***	-7.2605
EG	16.0268**	2.2669	D(PPPT)	-0.0052**	-2.4865
EG²	-7.9550**	-2.2504	D(EG)	6.3780	1.4266
FDI	0.0168***	5.1732	D(EG²)	-2.7048	-1.2113
TO	0.0195*	1.7933	D(FDI)	-0.0163**	-1.9824
URB	-0.3591**	-2.5784	D(TO)	0.2006***	6.9034
ETI	-0.0204**	-2.3359	D(URB)	-11.4475***	-3.9650
R-squared		0.8140			
Adjusted R squared		0.797			
CUSUM		Stable			
CUSUM sum of square		Stable			

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

Lag selection: Automatic (deplags=2, reglags=1),

Selected model: ARDL(2,1,1,1,1,1,0,1) using AIC (256 models evaluated)

Source: Author's own work

Policy implication

The findings of the study provide the key aspects for suggesting the policy level changes in the country. PPP investment proved to be significant in the short run while insignificant in the long run. For this, government should prioritize the low carbon PPP projects like metro services, electric public transport systems in the high emissions area. Policymakers should promote green procurement guidelines for the PPP projects and set the emissions performance targets for ensuring the more environment friendly transport infrastructure development in the country. In trade openness, governments should have to invest in more low carbon transport infrastructure like rail freight corridors, improved port logistics. Shift on cleaner energy and more fuel-efficient vehicles in the logistics can help in reducing the emissions. Policymakers should promote renewable energy source in transport through better infrastructure. Foreign direct investment is another important aspect that contributes in the emissions. The government should ensure that inflow of FDI is aligned with the environmental goals. More advance technology transfer is required through the FDI to lower the carbon emissions. Policymakers have to ensure that FDI should meet the green production standards and all the environmental compliances while entering in the country.

In the case of urbanization, policymakers should focus on expanding the sustainable public transport system. Government should offer the best public transport services at lowest cost, so that people will opt for public transport facility instead of using their own vehicles. Providing better connectivity to the last mile and opting for cleaner energy will significantly reduce the emissions. Economic growth leads to carbon emissions in the developing countries. With the economic development, policymakers must accelerate the transitions towards the low carbon infrastructure. The role of renewable energy is important for economic activity as fossil fuels are one of the major contributors that degrade the environment. On the other side, the industrial sector should also be focused by the policymakers. They should be provided with the

best technology that will effectively help in the production process without harming the environment. Policymakers should focus on providing monetary help to the industry to adopt renewable energy-based technology. Innovations related to environment technology has significantly reduced the emissions. Policymakers should provide more support to these research and development in the country. Policies should support green technology startups, invest in the EV infrastructure to improve the environmentally friendly technology.

Conclusion

This study has examined the impact of PPP investment on transport sector emission by incorporating the economic growth, trade openness, FDI, environment technology innovation and urbanization. This study has utilized Quantile ARDL methodology to assess the variable as it gives the effect across the quantiles. The period of this study is from 1998Q1-2022Q4. This study proved crucial to help in the policy level changes for the country. The study contributes the role of PPP in reducing transport emissions in global knowledge. The insights provide the global understandings towards the PPP investment with economic indicators, urbanization and technology innovations.

The results of this study are in the line of empirical and theoretical frameworks. The PPP investment found to be insignificant in the long run but significant and negative in the short run. It highlights the favorable impact of PPP investment in the short run reflecting that sustainability transition takes long time to be visible in developing country. Economic growth indicated the EKC hypotheses in this study. It reflects that after a threshold level, economic growth helps in reducing the carbon emissions. Urbanization has a paradoxical effect in this study. It highlights the role of using transport sector at greater efficiency in the urban area with better transport infrastructure facility. FDI is found to be positive in this study reflecting the need to policy level changes to convert it into more sustainable FDI. Trade openness found to be insignificant in the long run and positive and significant in the short run. Environment technology innovation found to be negative and significant in long run. It reflects that better innovation related technology will provide better and cleaner alternative to the government and people in the transport sector.

To highlight the study's contribution at the policy level, it should be noted that the study is conducted on a national scale in India. As the state-wise study may prove more effective due to its demographic and geographical conditions and the policy-level intervention might vary accordingly. Although these are the study's shortcomings, future research should concentrate on urban and rural areas independently. The transport sector should be subdivided into aviation, road, port, and railway for the critical analysis of the areas that are not sustainable, which could offer fresh perspectives on the policy-level issue.

Author contributions Both the authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Mr. Ashok Kumar, and Dr. Sushila Soriya. Both the authors read and approved the final manuscript.

Funding The authors have no relevant financial or non-financial interests to disclose.

Data availability The data used in this study are from the publicly available database available from the authors on request.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this research.

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