

Onur ŞEYRANLIOĞLU, PhD (corresponding author)

onur.seyranlioglu@giresun.edu.tr
Giresun University, Giresun, Türkiye

Ayşegül HAN, PhD

aysegul.han@inonu.edu.tr
Inonu University, Malatya, Türkiye

Financing Mobility: Environmental Impacts of Transport Infrastructure Investments in OECD Europe

Abstract. *The fact that transport infrastructure investments threaten environmental sustainability, despite the benefits they provide as one of the fundamental drivers of economic integration, constitutes the core problem of this research. In this context, the aim of the study is to analyse the effects of railway, road, and air transport infrastructure investments on environmental degradation in selected OECD European countries, utilising data covering the 1995-2023 period. The research employed the CIPS unit root test, Durbin-Hausman, Pedroni, and Kao cointegration tests, as well as Panel FMOLS and DOLS estimators for long-run coefficient estimations. The empirical findings reveal that infrastructure investments in all three transport modes significantly increase environmental degradation, thereby challenging the conventional view that railway investments represent a purely environmentally friendly alternative. Furthermore, the analysis results confirm the validity of the N-shaped Environmental Kuznets Curve (EKC) hypothesis regarding the relationship between economic growth and environmental pollution. The study demonstrates that when planning transport infrastructure investments, policymakers must move beyond traditional approaches that solely prioritise capacity expansion and economic efficiency and concurrently adopt a multidimensional optimisation strategy where environmental constraints are also integrated into decision-making processes.*

Keywords: *transport infrastructure investment, environmental degradation, EKC hypothesis, OECD Europe countries.*

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1. Introduction

The transport sector, which is an indispensable part of modern human life and one of the most important driving forces of economic development, connects people and communities to products and services, facilitates trade, and makes vital contributions to the formation of markets (Bassi et al., 2022; Malik et al., 2024). The sector is one of the key elements of macroeconomic efficiency in terms of accelerating access to goods and services, expanding international trade, increasing market mobility, creating direct employment, reducing company costs, and ensuring human mobility (Barro, 1990; Skorobogatova & Kuzmina-Merlino, 2017; Berg &

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Ihlström, 2019). In particular, it is argued that improvements in transport infrastructure investments raise the marginal productivity of private capital, thereby increasing economic efficiency and reducing production input costs (Aschauer, 1990). However, while transport systems make such an active contribution to the socio-economic development of countries, they can also contain a paradox that poses serious threats to environmental quality (Chatti, 2021; Çatik et al., 2024).

Despite its critical role in the economic development process and the added value it provides, the transport sector exacerbates the threat of global warming by increasing greenhouse gas emissions due to its fossil fuel-based energy structure and is positioned among the sectors producing the highest carbon emissions worldwide (Fan et al., 2018; Liu et al., 2020; Giannakis et al., 2020; Gyamfi et al., 2022). The transport sector accounts for more than one-third of carbon dioxide (CO₂) emissions originating from end-use sectors. The Net Zero Emissions (NZE) Scenario requires that sector emissions be reduced by approximately one-quarter by 2030, even though transport demand continues to increase. Transport emissions grew at an average annual rate of 1.7% from 1990 to 2022; this rate of increase was higher than all other end-use sectors except industry. To align with the NZE scenario by 2050, the target is to reduce transport sector CO₂ emissions by more than 3% annually until 2030 (IEA, 2025). The steady increase in emission volume resulting from transport activities has propelled sustainable transport strategies to the top of policymakers' agendas. These systems, which provide safe access and eco-friendly mobility to citizens, are a critical component of the sustainable growth model. However, in contrast to its strategic position supporting development, the sector ranks among the most energy-intensive areas (Alshehry & Belloumi, 2017; Wang & Lin, 2019; Ozkan et al., 2019).

Transport infrastructure is situated at the intersection of climate and development requirements, playing a decisive role in the future course of emissions. Infrastructure planning directly influences transport mode preferences and the associated emissions. However, transport infrastructures can create a lock-in effect for high-carbon emissions due to their very long service lives (Guivarch & Hallegatte, 2011; Henao et al., 2015; Tiwari et al., 2016). It is argued that improvements in transport infrastructure make mobility easier and more attractive; this convenience encourages the purchase of more passenger or commercial vehicles, which can lead to higher emissions (Beirão & Cabral, 2007; Börjesson et al., 2015). Similarly, although the expansion of transport infrastructure aims to make traffic more fluid, these investments can make industrial transport more frequent, bringing about negative effects such as pollution. Furthermore, the environmental burden arising during infrastructure construction and the weakening of the natural environment's self-repair capacity can cause the deterioration of air quality for a long period (Durán-Fernández & Santos, 2014; Li et al., 2016; Yang et al., 2018). Although transport infrastructure projects aim to minimise emissions by increasing operational efficiency, they may enter resource competition with environmental control mechanisms due to high investment costs and capital intensity. Moreover, the long duration of infrastructure development processes and traffic congestion

during the construction phase can limit the expected environmental benefits of these investments. Due to these complex dynamics, the relationship between transport infrastructure and environmental degradation continues to be debated in the literature (Guttikunda et al., 2014; Ahmad et al., 2016; Guo et al., 2020).

This dynamic relationship carries great importance within the context of the Environmental Kuznets Curve (EKC) hypothesis, which examines the relationship between economic growth and environmental pollution (Gyamfi et al., 2022). The EKC hypothesis, introduced to the literature by Grossman and Krueger (1991), predicts that environmental degradation increases at the onset of economic growth but decreases after a certain income level is reached. However, it is also debated in the literature that the relationship between transport infrastructure investments and environmental degradation does not always conform to this classic inverted U-shape and that the relationship may be N-shaped. Consequently, different stages of economic development are characterised by unique levels of environmental pollution. In the light of these discussions, the main aim of this study is to analyse the effect of transport infrastructure investments on environmental degradation in a sample of selected OECD (Organisation for Economic Co-operation and Development) member European countries using data from the 1995-2023 period. Transport, which is a strategic component particularly for the European Union (EU) economy, continues to be the main driving force of the principle of the free movement of people, goods, services, and capital that defines the Single Market (Gherghina et al., 2018). International authorities have turned towards defining sustainable growth routes because of transport-induced negative externalities. In this direction, the 2030 Sustainable Development Goals (SDGs), adopted in 2015, show a high level of dependency on the performance of the transport sector. Indeed, fundamental goals such as zero hunger (SDG 2), good health and well-being (SDG 3), affordable and clean energy (SDG 7), industry, innovation and infrastructure (SDG 9), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), and climate action (SDG 13) interact directly or indirectly with the transport sector (Bassi et al., 2022). On the other hand, significant policies continue to be adopted to encourage decarbonisation in different modes of transport. At this point, the current transformation in the EU's transport policies has evolved into a strategic approach aimed at minimising the environmental costs of infrastructure investments. In this context, legal frameworks such as the Green Deal and the Alternative Fuels Infrastructure Regulation direct transport investments towards the construction of smart and sustainable infrastructure that supports low-emission technologies rather than traditional capacity expansion. Furthermore, the expansion of the Emissions Trading System to cover road and maritime transport aims to internalise the negative externalities of transport infrastructure on environmental degradation through carbon pricing. These comprehensive measures taken on a European scale indicate that the critical balance between transport investments and ecological sustainability is being reconstructed through strict regulations and technological modernisation (IEA, 2025).

Within this framework, to contribute to existing debates, this research addresses infrastructure investments by disaggregating them into rail, road, and air transport and tests the relationship between economic growth and environmental degradation within the context of the EKC hypothesis. In this context, the research aims to seek answers to the following fundamental questions: Do rail, road, and air infrastructure investments in selected OECD European countries have an increasing or decreasing effect on CO₂ emissions? Which functional form (linear, quadratic, or cubic) does the relationship between economic growth and environmental degradation exhibit within the framework of the EKC hypothesis?

The organisation of the study is as follows: The second section presents the theoretical background and literature review, while the third section addresses the unique contribution of the research to the literature. The fourth section covers the data set and methodological framework, and the fifth section includes the analysis findings. Finally, the research concludes with the results, discussion, and policy implications.

2. Theoretical Framework and Literature Review

Transport-induced pollution is a phenomenon intertwined with the economic structure, considering the sector's driving force in economic growth, beyond merely being an atmospheric problem. Due to this dynamic relationship, different stages of economic development are characterised by unique levels of environmental pollution (Gyamfi et al., 2022). The EKC hypothesis, which examines the relationship between economic growth and environmental degradation, was first introduced to the literature by Grossman and Krueger. They revealed the dynamic relationship between economic growth and the environment in an N-shaped form through a cubic model established with a sample of 42 countries (Grossman & Krueger, 1991). The EKC hypothesis became central to environmental economics studies following the 1992 World Bank Development Report. Contrary to static assumptions that view the environmental costs of economic activities as independent of technological and social change, this approach emphasises that rising income levels increase environmental sensitivity and protection capacity (Stern, 2004). While the interaction between transport infrastructure and the environment maintains its importance in current literature, researchers have recently focused particularly on the determining role of these infrastructure elements on environmental degradation (Erdogan, 2020; Wang et al., 2023; Liu et al. 2023). The transport sector is among the leading contributors to greenhouse gas emissions due to its fossil fuel dependency; this situation makes the role of infrastructure investments on environmental sustainability a critical research topic (Georgatzi et al., 2020; Malik et al., 2024).

Numerous studies in the literature indicate that investments in transport infrastructure increase environmental pollution. For instance, Xie et al. (2016) revealed that Chinese transport infrastructure investments could degrade the urban environment by using a spatial Durbin model across 281 Chinese cities. Similarly,

in a recent study on Pakistan, Malik et al. (2024) determined that a 1% increase in transport infrastructure increased CO₂ emissions by 0.010%. Using a similar approach in the case of Pakistan, Avotra and Nawaz (2023) demonstrated that positive shocks in transport infrastructure increase environmental degradation. Regarding the distinction between transport modes, it is observed that road and air investments are the primary drivers of environmental destruction. In a significant study in this context, Erdogan (2020) determined in an analysis of 21 OECD countries that investments in road and air infrastructure have a significant and positive effect on environmental degradation. Furthermore, the inverted U-shaped EKC hypothesis was confirmed. Supporting these findings, the study by Wang et al. (2023) revealed the degrading effect of road and aviation infrastructure investments on emissions in the samples of China, Türkiye, India, and Japan. Additionally, the N-shaped EKC hypothesis was confirmed in the study by Wang et al. (2023). Using a similar research model, Liu et al. (2023) examined the samples of China, India, Russia, and Japan; while revealing the degrading effect of road and aviation infrastructure investments on emissions, they also confirmed the inverted U-shaped EKC hypothesis. Furthermore, while Pereira and Pereira (2019) stated that airport investments increased emission intensity in the Portugal sample, Gyamfi et al. (2022) emphasised that air transport degraded environmental quality in developing countries. Focusing on the physical impact of infrastructure, Asher et al. (2020) drew attention to the negative ecological footprint created by the expansion of motorways on forest areas. As a surprising finding, Neves et al. (2017), contrary to many other studies, reported that railway infrastructure investments increased carbon emission levels in 15 OECD countries.

Another strand of the literature argues that investments in specific modes of transport (predominantly rail) reduce environmental degradation. Erdogan (2020) and Wang et al. (2023) demonstrated that, unlike road and air transport, investments in rail infrastructure have a significant and pollution-reducing effect on environmental degradation. Liu et al. (2023) also stated that modern electric rail systems are less polluting and that rail investments support sustainable transport by reducing emissions. Some studies suggest that road investments may also contribute to environmental quality under certain conditions. Using data from the 2003-2015 period in a sample covering 285 cities in China, Sun et al. (2019) revealed that road infrastructure reduced pollution emission intensity and promoted green growth. Similarly, Pereira and Pereira (2019) stated that both road and rail investments in Portugal could help reduce emission intensity. Guo et al. (2020), in research conducted on a sample of 280 Chinese cities, argued that the relationship between transport infrastructure and air quality is not linear; they maintained that transport infrastructure investments are conducive to improving air quality once a certain income or vehicle ownership threshold is exceeded. Furthermore, the studies by Zhao et al. (2022) and Chatti (2021) demonstrated the improving effect of technological innovations in smart transport systems on environmental quality.

A definitive causality or a significant relationship has not always been found in the relationship between transport infrastructure and the environment. The most

prominent study on this subject was conducted by Georgatzi et al. (2020). In their study examining 12 European countries, the researchers revealed that neither road nor rail infrastructure investments had a statistically significant effect on environmental pollution.

The existing literature offers a heterogeneous perspective on the environmental effects of transport infrastructure investments. While the carbon-intensive character of road and air transport deepens environmental destruction, the environment-supporting role of rail investments is predominantly emphasised. However, inconsistencies in empirical findings prove that the relationship between transport investment types and environmental degradation can evolve according to regional, sectoral, and structural factors. In this context, this study aims to resolve this uncertainty in the literature regarding the impact of transport infrastructure investment types on environmental degradation within a sample of OECD European countries and to synthesise sectoral effects on an empirical basis.

3. Research GAP

The existing literature displays a landscape far from a definitive consensus, presenting contradictory findings regarding the environmental effects of transport infrastructure investments. Uncertainty persists regarding the disaggregated effects of infrastructure types and the functional structure of this relationship, particularly in developed and developing economies. This study aims to fill this empirical gap by addressing the investments in question on a modal basis and analysing the relationship beyond classical patterns through the perspective of the EKC hypothesis. The focus of the research on a sample of selected OECD European countries is a strategic choice; for this region hosts the world's most comprehensive decarbonisation policies and technological transformation targets within the axis of the European Green Deal and Sustainable Development Goals. Consequently, this study clarifies the contested ground in the literature and presents a critical projection for policymakers by answering the question of whether high infrastructure expenditures in Europe deepen pollution by creating carbon lock-in or reduce emissions through smart investments.

4. Data Set, Model, and Methodology

The model in Equation (1), established by following the studies of Wang et al. (2023) and Liu et al. (2023), includes in its sample the OECD member European countries of Belgium, Czech Republic, Finland, France, Germany, Hungary, Ireland, Latvia, Lithuania, Poland, Slovakia, Spain, Sweden, Switzerland, and Türkiye, for which full data were accessed in the relevant period. Based on the studies followed in the research, environmental degradation was used as the dependent variable; and rail, road, and air investments representing transport infrastructure investments were used as independent variables. Mean-centered GDP (GDP_c) and its quadratic (GDP_c²) and cubic (GDP_c³) terms were used to test different forms of the EKC

hypothesis. To address the structural multicollinearity inherent in polynomial specifications, the GDP variable was mean-centered before constructing its quadratic and cubic terms. Specifically, the centered GDP variable was obtained by subtracting the sample mean of $\ln GDP$ from each observation, and the squared and cubic terms were subsequently generated from this centered variable. Prior to centering, the VIF values for GDP, GDP^2 , and GDP^3 were extremely high (1087217; 4352456; and 1092082, respectively). After mean-centering, the corresponding VIF values declined substantially to 8.219, 1.226, and 7.087, respectively, all remaining below the conventional threshold of 10. To minimise specification errors in the model, trade openness and foreign direct investment were included as control variables (Pata & Caglar, 2021; Khan et al., 2022; Wang et al., 2023). Data regarding infrastructure investments in the research were obtained from the OECD database. Since infrastructure investments for the transport sector are published in current Euro values on the OECD website, these values were converted into current dollar values using the annual average EUR/USD parity. Subsequently, current dollar values were converted to 2015 constant prices using deflators published by the World Bank. In the research, variables other than the TRD and FDI variables were used in natural logarithmic form.

$$LNCO2_{it} = \beta_0 + \beta_1 LNRAIL_{it} + \beta_2 LNROAD_{it} + \beta_3 LNAIR_{it} + \beta_4 LNGDPC_{it} + \beta_5 LNGDPC2_{it} + \beta_6 LNGDPC3_{it} + \beta_7 TRD_{it} + \beta_8 FDI_{it} + u_{it} \quad (1)$$

Here, β_0 denotes the constant term and u_{it} denotes the error term. Details regarding the variables examined within the scope of the model are presented in Table 1.

Table 1. Variables and data sources

Symbol	Variables	Description	Data source
Dependent variable			
CO ₂	Environmental degradation	Per capita carbon dioxide emission (metric tons per capita)	World Bank
Independent variable			
RAIL	Rail infrastructure investment	Constant 2015 US\$	OECD
ROAD	Road infrastructure investment	Constant 2015 US\$	OECD
AIR	Air infrastructure investment	Constant 2015 US\$	OECD
GDP	Economic growth	Per capita gross domestic product (constant 2015 US\$)	World Bank
FDI	Foreign direct investment	In percentage of GDP	World Bank
TRD	Trade openness	In percent of GDP	World Bank

Source: Authors' processing.

General multicollinearity among the non-polynomial explanatory variables was assessed using variance inflation factors (VIFs). Excluding the polynomial GDP terms, which are addressed separately in relation to structural multicollinearity, the

centered VIF values ranged from 1.069 to 8.465. Although GDP exhibited the highest VIF (8.465), none of the values exceeded the conventional threshold of 10, indicating no evidence of severe general multicollinearity among the explanatory variables.

When addressing the effect of transport infrastructure investments on environmental degradation in OECD member European countries, the validity of the EKC hypothesis can be tested for different variations by considering the parameter estimates specified below (Wang et al., 2023):

$\beta_4 = \beta_5 = \beta_6 = 0$: There is either a linear relationship or no relationship between environmental degradation and economic growth.

$\beta_4 > 0$ and $\beta_5 = \beta_6 = 0$: Environmental degradation and economic growth exhibit a monotonically increasing trend.

$\beta_4 < 0$ and $\beta_5 = \beta_6 = 0$: Environmental degradation and economic growth exhibit a monotonically decreasing trend.

$\beta_4 > 0$, $\beta_5 < 0$ and $\beta_6 = 0$: The EKC hypothesis is valid in the classic inverted U-shape; while environmental degradation increases in the initial stages of economic growth, a decrease is observed after a certain income level.

$\beta_4 < 0$, $\beta_5 > 0$ and $\beta_6 = 0$: The EKC hypothesis is valid in the classic U-shape; environmental degradation is low at low-income levels and shows an increase as income rises.

$\beta_4 > 0$, $\beta_5 < 0$ and $\beta_6 > 0$: The EKC hypothesis exhibits an N-shaped (cubic polynomial) structure; environmental degradation initially rises as income increases, then decreases, and may show an increase again at high income levels.

$\beta_4 < 0$, $\beta_5 > 0$ and $\beta_6 < 0$: The EKC hypothesis exhibits an inverted or opposite N-shaped pattern; environmental degradation first decreases at certain income levels, then increases, and decreases again at high income levels.

In addition to evaluating the individual signs and statistical significance of the polynomial income coefficients, their joint significance was examined using the Wald test. Specifically, the null hypothesis that the coefficients of GDP_c , GDP_c^2 , and GDP_c^3 are jointly equal to zero ($H_0: \beta_{GDP_c} = \beta_{GDP_c^2} = \beta_{GDP_c^3} = 0$) was tested for both the Panel FMOLS and Panel DOLS estimations. Rejection of the null hypothesis indicates that the polynomial income terms are jointly statistically significant.

As part of the descriptive analysis, the normality of the variables was assessed using the Jarque-Bera (JB) test. The null hypothesis of the JB test states that the variable follows a normal distribution, whereas rejection of the null hypothesis indicates a departure from normality.

To provide a clear overview of the empirical strategy and facilitate the interpretation of the sequential econometric procedures, the methodological framework of the study is summarised in Figure 1.

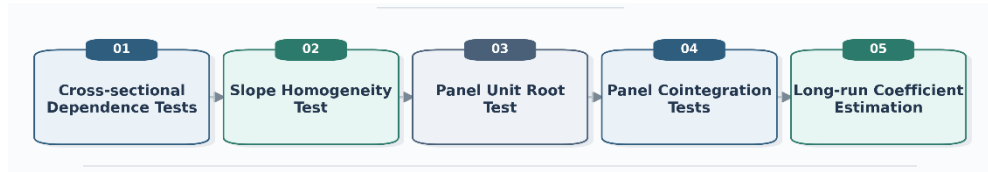


Figure 1. Methodological framework of the empirical analysis

Source: Authors' processing.

As illustrated in Figure 1, the empirical procedure begins with tests for cross-sectional dependence and slope homogeneity, as these properties determine the appropriate panel-data techniques to be employed in the subsequent stages. Cross-sectional dependence was evaluated using the Breusch-Pagan LM, Pesaran scaled LM, bias-corrected scaled LM, and Pesaran CD statistics. Given the dimensions of the panel ($N = 15$ and $T = 29$), the Breusch-Pagan LM statistic was considered the primary diagnostic. Slope homogeneity was examined using the Delta and Adjusted Delta tests developed by Pesaran and Yamagata (2008). Based on the presence of cross-sectional dependence, the second-generation CIPS unit root test was subsequently employed. After establishing the integration properties of the variables, the existence of a long-run relationship was investigated using the Durbin-Hausman, Pedroni, and Kao panel cointegration tests. Finally, the long-run coefficients were estimated using the Panel FMOLS and Panel DOLS estimators.

The Cross-sectionally Augmented IPS (Im, Pesaran, and Shin) (CIPS) test, one of the second-generation tests, is used to investigate the presence of a unit root in panel data. The CIPS statistic is obtained as the average of the Cross-sectionally Augmented Dickey-Fuller (CADF) test statistics calculated for each cross-section:

$$CIPS = N^{-1} \sum_{i=1}^N CADF_i \quad (2)$$

The statistic is compared against a specific critical value to determine whether the series is stationary (Pesaran, 2007).

Following the stationarity test, cointegration analysis is performed to determine whether a long-term relationship exists between the variables. The Durbin-Hausman cointegration test developed by Westerlund (2008) is a panel cointegration method used in cases where cross-sectional dependence and model heterogeneity exist. The test examines long-term relationships at both the group and panel levels and operates under the assumption that autoregressive parameters differ across cross-sections. The H_0 hypothesis indicates that there is no long-term relationship across all cross-sections. Rejection of this hypothesis indicates the presence of cointegration in some or all cross-sections, depending on the test statistic considered (Di Iorio & Fachin, 2008). The fundamental model of the Durbin-Hausman test is presented as follows:

$$\begin{aligned} y_{it} &= \alpha_i + \beta_i x_{it} + z_{it} \\ x_{it} &= \delta x_{it-1} + w_{it} \end{aligned} \quad (3)$$

Here, z_{it} models cross-sectional dependence by accounting for the effect of common factors:

$$\begin{aligned} z_{it} &= \lambda_i' F_t + e_{it} \\ F_{jt} &= p_j F_{jt-1} + u_{jt} \\ e_{it} &= \phi_i e_{it-1} + v_{it} \end{aligned} \quad (\text{For all } j, p_j < 1) \quad (4)$$

Here, F_t and F_{jt} represent the common factor vectors, while λ_i represents the factor loadings. The kernel estimator required for the test is calculated as follows:

$$\widehat{w}_i = \frac{1}{T-1} \sum_{j=M_i}^{M_i} \left(1 - \frac{j}{M_i+1}\right) \sum_{t=j+1}^T \widehat{v}_{it} \widehat{v}_{it-j} \quad (5)$$

The Durbin-Hausman group and panel statistics are calculated using this estimator and the variance estimates ($\widehat{\sigma}_i^2$) as follows (Westerlund, 2008):

$$\begin{aligned} DH_g &= \sum_{i=1}^n \widehat{S}_i (\tilde{\phi}_i - \widehat{\phi}_i)^2 \sum_{t=2}^T \widehat{e}_{it-1}^2 \\ DH_p &= \widehat{S}_n (\tilde{\phi} - \widehat{\phi})^2 \sum_{i=1}^n \sum_{t=2}^T \widehat{e}_{it-1}^2 \end{aligned} \quad (6)$$

Here, $\widehat{S}_i$ and $\widehat{S}_n$ are variance estimates used in the calculation of the test statistics.

In addition to the Durbin-Hausman test, Pedroni (1999) and Kao (1999) cointegration tests were also applied to examine the existence of a long-term relationship within the panel data set.

The test developed by Pedroni (1999) is suitable for models containing multiple explanatory variables and provides both within-panel and group-mean test statistics while accounting for heterogeneity and cross-unit differences. The Pedroni test is based on the following regression model:

$$y_{it} = \alpha_i + \delta_i t + \beta_{1i} x_{1it} + \beta_{2i} x_{2it} + \dots + \beta_{Mi} x_{Mit} + e_{it} \quad (7)$$

Here, y_{it} represents the dependent variable, x_{Mit} ($m = 1, \dots, M$) represents the independent variables, α_i represents the constant term, $\delta_i t$ represents the deterministic trend, and e_{it} represents the error term. The existence of a long-term relationship is evaluated by testing the stationarity of the error terms.

In contrast, the panel cointegration test developed by Kao (1999) assumes a common cointegration vector across panel units and focuses on models with fixed intercepts. The test is conducted based on residuals using the following model:

$$\begin{aligned} y_{it} &= \alpha_i + \beta x_{it} + e_{it} \\ \Delta e_{it} &= \rho e_{it-1} + u_{it} \end{aligned} \quad (8)$$

The existence of cointegration depends on the stationarity of the error terms ($\rho < 0$), which is evaluated using a Dickey-Fuller-type panel (t)-statistic. The null hypothesis (H_0) states that there is no cointegration relationship in the panel, whereas the alternative hypothesis indicates the existence of a long-term relationship with a common cointegration vector.

Following the determination of the long-term panel cointegration relationship, Panel Dynamic Ordinary Least Squares (DOLS) and Fully Modified Ordinary Least Squares (FMOLS) methods are employed to estimate the long-term elasticities in the established model. The FMOLS method is widely preferred in panel data cointegration analyses as it corrects for serial correlation, endogeneity, and simultaneity bias (Balsalobre-Lorente & Leitão, 2020; Rahman & Vu, 2020). Kao and Chiang (2001) emphasise that DOLS reduces bias effectively and has favourable finite-sample properties compared with FMOLS. For these reasons, the DOLS estimation results were prioritised, while the FMOLS results were used for robustness comparison. In addition, the distributional properties of the disturbance terms were assessed by applying the Jarque-Bera (JB) normality test to the residuals obtained from both the Panel FMOLS and Panel DOLS estimations. The null hypothesis of the JB test states that the residuals follow a normal distribution, whereas rejection of the null hypothesis indicates a departure from normality. This diagnostic was employed to determine whether residual non-normality constitutes a concern for the long-run estimations.

5. Results

The empirical results are first presented through descriptive statistics, followed by cross-sectional dependence and slope homogeneity, unit root, cointegration, and long-run coefficient estimation results.

Table 2 presents the descriptive statistics of the data.

Table 2. Descriptive statistics

Variables	Mean	Median	Std. Dev.	Skewness	Kurtosis	Jarque-Bera
CO ₂	4.46	4.14	1.26	-0.04	2.23	10.92***
RAIL	20.13	20.25	1.69	-0.30	2.63	9.25***
ROAD	20.88	20.98	1.63	-0.79	4.60	91.60***
AIR	18.48	18.57	1.76	-0.37	2.92	10.25***
GDP	26.41	26.58	1.39	-0.20	2.45	8.45**
FDI	4.32	1.98	10.54	3.46	28.45	12612.57***
TRD	104.93	92.52	44.31	0.68	2.82	34.49***

Note: The *** and ** symbols indicate the 1% and 5% significance levels respectively.

Source: Authors' processing.

When the skewness statistics of the data are examined, it is observed that variables other than FDI and TRD exhibit slight negative skewness, whereas the TRD variable displays positive skewness. The kurtosis values indicate that the ROAD and FDI variables have higher peaks compared to a normal distribution. The

Jarque-Bera test results were found to be statistically significant for all variables, indicating that the variables deviate from a normal distribution.

The results of the cross-sectional dependence and homogeneity tests are presented in Table 3.

Table 3. Cross-sectional dependence test and delta test results

Variables	Breusch-Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD	Delta	Delta Adj.
CO ₂	1563.57***	100.65	100.38	25.92	10.840	13.393***
RAIL	1041.42***	64.62	64.35	29.08		
ROAD	1016.83***	62.92	62.65	22.64		
AIR	251.63***	10.12	9.85	6.87		
GDPc	2814.94***	187.00	186.74	53.03		
FDI	260.94***	10.76	10.49	7.85		
TRD	2129.64***	139.71	139.45	45.81		

Note: The *** and ** symbols indicate the 1% and 5% significance levels respectively.

Source: Authors' processing.

The results presented in Table 3 reveal the presence of cross-sectional dependence within the model and among the variables. The findings of the Delta test indicate that the variables under consideration do not exhibit a homogeneous structure but rather possess heterogeneous characteristics. For this reason, it was deemed appropriate to utilise panel unit root tests that account for cross-sectional dependence in the subsequent stages. For this purpose, the CIPS test, one of the second-generation unit root tests, was preferred in the study, and the results obtained are presented in Table 4.

Table 4. CIPS unit root test results

Variables	Constant	Trend + Constant
CO ₂	-1.85	-1.327
ΔCO ₂	-3.902***	-3.968***
RAIL	-1.198	-1.581
ΔRAIL	-3.98***	-4.057***
ROAD	-1.217	-1.556
ΔROAD	-3.675***	-3.786***
AIR	-1.817	-1.274
ΔAIR	-3.795***	-3.629***
GDPc	-1.406	-1.068
ΔGDPc	-3.747***	-3.492***
FDI	-2.004	-1.166
ΔFDI	-3.143***	-4.112***
TRD	-1.341	-1.575
ΔTRD	-3.819***	-4.878***

Note: The *** symbol indicates the 1% significance level.

Source: Authors' processing.

Based on the findings from both the intercept and intercept-and-trend models of the CIPS unit root test presented in Table 4, it has been determined that the variables are stationary at the first difference. Following the unit root tests, the existence of a long-term relationship between the variables was investigated using the Durbin-Hausman, Kao, and Pedroni cointegration tests. The results of these tests are presented in Table 5.

Table 5. Cointegration analysis results

Tests	Statistics	p-value
Durbin-Hausman Cointegration Test		
DHg	1.408*	0.080
DHp	1.826**	0.034
Kao Cointegration Test		
ADF	2.138**	0.016
Pedroni Cointegration Test		
Modified Phillips-Perron t	4.524***	0.000
Phillips-Perron t	-3.766***	0.000
ADF t	-2.705***	0.003

Note: The ***, **, and * symbols indicate the 1%, 5%, and 10% significance levels respectively.

Source: Authors' processing.

The findings presented in Table 5 reveal the existence of a long-term cointegration relationship among the variables in the model. Following the confirmation of the existence of cointegration, the long-term coefficient estimates between the variables are presented in detail in Table 6.

Table 6. Long-term coefficient estimation results

Variables	Panel FMOLS		Panel DOLS	
	Coefficient	t-statistic	Coefficient	t-statistic
RAIL	0.033	7.623***	0.113	5.620***
ROAD	0.027	4.216***	0.180	5.574***
AIR	0.016	5.196***	0.034	7.567***
GDP _c	0.637	10.370***	0.300	8.604***
GDP _c ²	-0.282	-7.405***	-0.746	-10.608***
GDP _c ³	0.004	4.423***	0.255	12.605***
FDI	0.002	5.832***	0.006	5.864***
TRD	0.006	6.524***	0.001	6.296***

Note: *** indicates the 1% significance level. The Jarque-Bera test does not reject residual normality for either estimator (Panel FMOLS: JB = 1.949, p = 0.377; Panel DOLS: JB = 2.658, p = 0.265). GDP_c denotes mean-centered lnGDP; GDP_c² and GDP_c³ are its quadratic and cubic terms.

Source: Authors' processing.

The estimator findings presented in Table 6 reveal that transport infrastructure investments have significant and positive effects on environmental degradation. A 1% increase in railway investments raises carbon emissions by 0.033% and 0.113%

according to FMOLS and DOLS estimates, respectively. The effect of investments in road infrastructure is likewise positive. A 1% increase in investments in road infrastructure raised emissions by 0.027% and 0.18% according to FMOLS and DOLS results, respectively. A similar trend is observed in airline investments. A 1% increase in airline infrastructure investments increased emissions by 0.016% and 0.034% according to FMOLS and DOLS results, respectively.

On the other hand, both FMOLS and DOLS estimation results show that the coefficients for GDP_c and GDP_c^3 are positive, while the coefficient for GDP_c^2 is negative. The Wald test also confirms the joint significance of the polynomial income terms, rejecting the null hypothesis that the coefficients of GDP_c , GDP_c^2 , and GDP_c^3 are jointly equal to zero for both estimators (Panel FMOLS: $\chi^2(3) = 37.284$, $p < 0.001$; Panel DOLS: $\chi^2(3) = 47.559$, $p < 0.001$). Therefore, the obtained results confirm the validity of the N-shaped (cubic polynomial) EKC hypothesis for the selected OECD member European countries. In other words, environmental degradation first rises with income growth, then decreases, and finally shows an increase again as it reaches high income levels. Finally, a limited positive effect of foreign direct investments and trade openness on environmental degradation has also been detected.

6. Conclusions, Discussion, and Policy Implications

Although the transport sector is a fundamental pillar of economic integration and global trade, it threatens environmental sustainability due to fossil fuel dependence and carbon-intensive infrastructure processes. In this context, this study analysed the impact of railway, road, and airline investments on environmental degradation and the EKC hypothesis in selected OECD European countries over the 1995-2023 period. Panel data results confirmed a positive relationship between all transport modes and environmental degradation. The findings demonstrated that not only fossil-fuel-intensive road and airline investments but also railway investments, considered relatively greener, significantly increase carbon emissions. While this effect in road and air transport can be explained by increased traffic and carbon lock-in, the impact of rail can be attributed to high energy and resource consumption during construction and operation phases. Furthermore, the study validated the N-shaped EKC hypothesis between economic growth and environmental degradation. Accordingly, pollution initially rises with income growth and declines with environmental sensitivities yet rises again at very high-income levels due to the scale effect and consumption demand. The positive impact of trade openness and foreign direct investments confirms that these economic activities in Europe still generate environmental costs.

The results of this study present strong evidence that the development of transport infrastructure in OECD European countries may not always yield environmental improvements. Firstly, the emission-increasing effect of road and airline infrastructure investments largely aligns with the prevailing views in the literature. As emphasised by Erdogan (2020) and Wang et al. (2023), these modes

are the transport types with the highest dependence on fossil fuels. The positive coefficient of road investments suggests that the expansion and quality improvement of roads may increase cumulative emissions by encouraging greater vehicle ownership and usage rather than alleviating traffic flow. The similar effect observed in airline investments can be explained by the carbon-intensive growth of the aviation sector alongside globalised trade and tourism demand. The most striking finding of the study, which diverges from the consensus in the literature, is the determination that railway infrastructure investments also increase environmental degradation. While many studies in the literature such as Liu et al. (2023) and Wang et al. (2023) define railways as an environmentally friendly mode and argue that they reduce emissions, the findings of this study parallel the results obtained by Neves et al. (2017) for OECD countries indicating that railway investments increase carbon emissions. This situation can be explained from the perspective of carbon lock-in. Large-scale infrastructure projects such as high-speed rail lines create a massive carbon footprint due to the intensive use of cement and steel during the construction phase. Furthermore, the fact that the electricity grid powering the railway network has not yet been fully decarbonised in some of the European countries examined may lead to indirect emission increases during the operational process. In the context of the relationship between economic growth and the environment, the analysis results confirmed the N-shaped EKC hypothesis. This finding differs from the studies of Erdogan (2020) and Liu et al. (2023) which argue that the relationship is an inverted U-shape. However, it demonstrates consistency with Wang et al. (2023), who identified an N-shaped relationship in samples from China, Türkiye, India, and Japan.

The results of this study have revealed that investments in transport infrastructure in selected OECD European countries increase environmental degradation. In particular, the finding that railway infrastructure investments also have a positive effect on carbon emissions, contrary to the consensus in the literature, serves as a critical warning for policymakers. This result indicates that building more infrastructure alone does not ensure environmental sustainability. Therefore, policymakers should structure transport policies not merely on capacity expansion but on technologies that will minimise the life-cycle emissions (construction and maintenance) of the infrastructure. Whilst expanding railway networks, it is imperative to simultaneously decarbonise the energy grid powering these lines. Given the emission-increasing effect of road and airline investments, fiscal instruments capable of breaking the fossil fuel dependence in these modes must be introduced. Since infrastructure investments create a traffic-inducing effect, policymakers should focus on the full integration of carbon taxation and emission trading systems into the transport sector rather than on physical investments. Furthermore, the N-shaped EKC hypothesis confirmed by the study proves that economic growth increases pollution again after a certain threshold. This situation demonstrates that economic growth cannot spontaneously resolve environmental problems in the high-income European countries examined. Consequently, governments must immediately tighten strict environmental regulations and energy efficiency standards without waiting for growth to occur. Finally, the positive effect

of trade openness and foreign direct investments on pollution reveals that international trade agreements and foreign capital inflows must be conditional upon environmental standards.

While this study provides significant empirical evidence regarding the relationship between transport infrastructure and environmental degradation, it is subject to certain limitations. Due to data constraints, the research is limited to the 1995-2023 period and 15 selected OECD European countries. Furthermore, only per capita CO₂ emissions were utilised as the indicator of environmental degradation in the model, whilst the ecological footprint or other greenhouse gases were excluded from the analysis. Future research may test the generalisability of the findings by extending the analysis to economies with varying levels of development or different geographical regions to address these limitations.

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