Environmental Science and Pollution Research (2023) 30:90656–90674
https://doi.org/10.1007/s11356-023-28595-6

RESEARCH ARTICLE

Investigating the impact of transportation system and economic growth on carbon emissions: Application of GMM System for 33 european countries

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Received: 20 January 2023 / Accepted: 30 June 2023 / Published online: 18 July 2023

Abstract

In Europe, there has been a significant shift in the movement of people and things. Nonetheless, despite the fact that transportation is an important component of the supply chain, its environmental consequences pose a severe threat to the ecosystem as a whole. As a result, we intend to explore the relationship between transportation, economy, and CO2 emissions. We used the Static method with Pooled OLS, then tested the Granger causality to validate the use of dynamic approach via the GMM system. The major findings revealed that GDP and trade openness had a considerable impact on CO2 emissions. Although the three modes of transportation have different effects on CO2 emissions, road density has a positive and considerable impact on CO2 emissions. The railway network is inversely connected to CO2 emissions. While the quantity of flight passengers has no substantial effect on emissions. In terms of the impulse response function, there is an initial shock in period 2 for the response of air passengers carried to CO2 emissions, followed by convergence back to zero in period 6, whereas road density has a slight decrease in period 2 with a post shock peak in period 4, followed by convergence back to zero in period 5. The variance decomposition results reveal a little increase until the fifth period for road density, air passengers, and trade openness with coefficients equal to 0.0893, 0.636, and 1.573, respectively, after which these three variables offer decreasing coefficients.

Keywords CO2 emissions · Transportation system · GMM System · Impulse response function · Variance decomposition · Causality test

Abbreviations

CO2	Carbon dioxide
GHG	Greenhouse gases
GLS	Generalized Least Squares
GMM	Generalized Method of Moments
LNAIR	Natural Logarithm of Air passengers carried
LNCO2	Natural Logarithm of CO2 emissions per capita
LNGDP	Natural Logarithm of Gross Domestic Product
LNPOP	Natural Logarithm of Population density
LNRAIL	Natural Logarithm of Railway network length
LNRE	Natural Logarithm of Renewable Energy
LNROAD	Natural Logarithm of Road Density
LNTO	Natural Logarithm of Trade Openness
LNURBAN	Natural Logarithm of Urbanization Rate
OLS	Ordinary Least Squares

Responsible Editor: V.V.S.S. Sarma

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Introduction

The tremendous economic growth worldwide, triggered after World War II known as the postwar economic boom, the unexpected development of industrialization and manufacturing activities, and the expansion of globalization in the second half of the 20th century, imply an intense increase in energy consumption. Nevertheless, this energy use leads to a rise in Greenhouse Gas (GHG) emissions, which consequently causes various issues such as global warming, sea level rise, and so on. In July 2022, wildfires burned more than 51,000 acres in France, and 36,750 people were evacuated. In addition, historic heatwaves affected Europe in 2022, with temperatures reaching 40°C in several regions of Europe in June. Thus, it is necessary to focus on the main causes of this climate change to overcome this issue and achieve carbon neutrality.

Background and significance: Various sectors contribute to the deterioration of environmental quality. Therefore, the impact of CO2 emissions has been investigated differently. Sankaran et al. (2021) and Herman (2016) showed that the manufacturing sector is the main cause of environmental disaster. Yang et al. (2020) assessed the impact of the inflow of remittances on increasing CO2 emissions, while Yang et al. (2022) investigated the link between income inequality, institutional quality, and CO2 emissions rate. Ghazouani et al. (2020) studied the role of carbon tax in mitigating CO2 emissions, while Luo et al. (2017) measured the impact of urban transport on CO2 emissions in Shanghai and Tokyo. Focusing on the transportation sector, we emphasize that, in European countries, transport is the second contributor to greenhouse gas emissions with 27% in 2015 (after power generation with 29%). While it is a source of regional economic growth (Sokolov et al. 2019) and plays a key role in the supply chain of industries, the environmental repercussions of transportation constitute a serious threat to human health, air quality, and the ecosystem as a whole.

Moreover, according to the Eurostat database, in 2015, the energy demand for transport operations amounted to 352.9 Mtoe (Million Tonnes of Oil Equivalent), representing 33% of the total energy consumption in the European Union. The proportion of greenhouse gas emissions from transportation increased from 15% in 1990 to 23% in 2015. While nearly all other sectors reduced their GHG emissions, the transportation sector increased its contribution by 8%. For example, the United Kingdom's annual report on transport and environment (2021) revealed that transportation accounted for 27% of total emissions in the country in 2019. As a result, the transportation sector is a major contributor to atmospheric and noise pollution, as well as land use. Therefore, it is highly required to consider the transportation sector when implementing environmental strategies.

Problem definition: The previous statistics have provided insights to orchestrate the research questions addressed in this paper. These questions include: What is the impact of transportation on the environment? Are road, rail, and air transport equally responsible for CO2 emissions? Is there a difference in the transportation-related CO2 emissions between developed and developing nations, and how does the economic growth level influence this variation?

Despite the existence of many papers addressing the link between the transportation sector and environmental issues, few studies have examined two or three modes of transportation simultaneously. To fill this gap, we will focus on road transport, air transport, and railways to examine how they affect carbon emissions. Furthermore, we aim to assess how developed and developing countries deal with environmental issues. While several articles have addressed environmental issues, few studies have attempted to compare two sets of countries regarding the relationship between transport and sustainability.

Motivation and Objectives: Given its fundamental role in facilitating daily life, it is important to ensure that the transport sector is aligned with the pillars of sustainability. Therefore, studying the sector's impact on carbon emissions is essential to assess its potential in mitigating climate change. The purpose of this study is to assess the relationship between pollution levels and different modes of transportation to understand the environmental impact of transport and identify measures that can help mitigate CO2 emissions in European countries. Additionally, our goal is to compare the contribution of each mode of transport (road, air, and rail) to CO2 emissions and to include the level of development of countries to understand how it affects environmental quality. We will proceed by applying this exercise to 33 European countries, dividing the set into two subsets: the first will cover ten developing countries, while the second will cover 13 developed countries, spanning 19 years from 2000 to 2018. We will estimate this relationship using a static approach, referring to OLS and GLS estimators, and then apply a dynamic approach using the Generalized Method of Moments System (GMM-System) developed by Arellano and Bond (1991). It is worth noting that the GMM technique can address the shortcomings of OLS techniques by taking into consideration issues such as sample data heterogeneity, co-integration between variables, and endogeneity.

Therefore, we will estimate our models on three samples. The first computes the models for the entire sample, the second for developed countries, and the third for developing countries. Our goal is to understand if the link between transportation and CO2 emissions is the same for the entire region or if it varies by country, and to analyze the effect of transportation on environmental quality using various approaches (static and dynamic). Additionally, impulse responses will be applied to show how a variable initially responds to a shock in the other variable and whether the effect of the shock persists or dies out quickly. Furthermore, variance decomposition analysis will be used to identify variations in one variable that can be explained by changes in another variable in the same VAR system.

The remainder of this paper is structured as follows: the second section will be devoted to the literature review, section 3 will tackle the methodology and the models' specification, next, in the fourth section, we will present the data set and variables selected for our estimation, the section 5 will report the empirical results and the economic interpretations, section 6 is dedicated to discuss the results, the last section concludes and gives some policy implications.

Literature review

The impact of GHG emissions on societies, humans, and the environment is studied differently. Even for the same countries, each study treats it according to a specific and different approach. For instance, Arouri et al. (2012) analyzed the nexus between energy, economic development, and CO2 emissions through the application of the Environmental Kuznets Curve (EKC) in the Middle East and North Africa (MENA) region, also, we find Al-Rawashdeh et al. (2014) which applied a quadratic equation to measure the impact of SO2 and CO2 levels on economic growth for 22 countries in the MENA region. Farhani and Shahbaz (2014) assessed the impact of renewable and nonrenewable energy on electricity consumption in CO2 emission, Abdallh and Abugamos (2017) investigated the relationship between urbanization and environmental quality. Globally, there is a divergence in the investigation of the determinants of environmental quality, as well as the utilization of different time-series data. The abundance of available data, particularly long time-series data, has contributed to a wealth of research literature in environmental economics. A significant portion of this literature has focused on exploring the relationship between energy consumption and environmental quality. For example, Alharthi et al. (2021) examined the use of both renewable and non-renewable energy in MENA countries, while Ben Cheikh and Ben Zaied (2021) employed a nonlinear model to study the link between energy and CO2. Jahanger et al. (2022a) investigated the long-term connection between energy and carbon emissions, and Jahanger et al. (2023a) analyzed the impact of non-nuclear energy on the environment,

Regarding the transportation, Dedík et al. (2020), Hassan and Nosheen (2019), and Chang and Kendall (2011) examined the relationship between railway passenger transport and its environmental impact. Liimatainen et al. (2014), Liu et al. (2018), and Boonpanya and Masui (2021) focused on the environmental consequences of freight transport. The environmental impact of air transport was investigated by several researches such as Erdogan et al. (2020), Forsyth (2011), and Sgouridis et al. (2011).

Numerous studies have also explored the relationship between trade openness, globalization, and environmental concerns. Farhani and Ozturk (2015) conducted research in Tunisia, Al-Mulali et al. (2015) focused on Europe, and Kasman and Duman (2015) examined new EU member and candidate countries. Technology has been a focal point in several studies, such as Akashi and Hanaoka (2012), Awan et al. (2022), and Jahanger et al. (2023c).

Alharthi et al. (2021) investigated the impact of renewable and non-renewable energy consumption, urbanization, and GDP on CO2 emissions in the MENA region using the novel quantile regression. The main finding revealed the existence of a significant impact of renewable energy on the reduction of CO2 emissions. Meanwhile, non-renewable energy contributes significantly to the increase in CO2 emissions.

In the same context of MENA countries, Ben Cheikh and Ben Zaied (2021) applied a non linear threshold regression model to check the impact of energy consumption and economic indicators on CO2 emissions. The main results show an inverted U-shaped pattern regarding the impact of energy consumption on CO2 emissions, that is to say, emissions decrease after a given level of economic development. Thus, carbon emissions respond nonlinearly to GDP and energy.

Sun et al. (2022) examined the relationship between urbanization, economic development, renewable energy, and CO2 emissions in the MENA region from 1991 to 2019. The authors argue for the existence of the Environmental Kuznets Curve (ECK) hypothesis in the long run. Also, urbanization and economic growth are significantly related to the emission of greenhouse gases.

Focusing on the nexus between economic development and CO2 emission, it can be argued that the impact of economic characteristics on carbon dioxide emission is still ambiguous and depends on the sample of countries selected. Oh et al. (2010) argued that economic growth was the main factor responsible for increasing CO2 emissions in South Korea, Al-mulali et al. (2012) found a positive impact of energy, GDP, and urbanization on carbon emissions in seven regions, Similarly, the results of Shahbaz et al. (2013) revealed the positive impact of GDP on CO2 emissions in Malaysia. Zhang and Da (2015) noted the existence of a positive nexus between GDP and CO2 in the Chinese economy. Regarding the EKC hypothesis investigation, we can notice that the validity of this hypothesis has not been verified for all countries tested. In sum, it is possible to argue that the majority of developed countries validate the existence of the EKC hypothesis, compared to developing ones, which cannot verify this hypothesis. For instance, Ajmi et al. (2015) have verified this hypothesis for G-7 countries (except for Japan and Italy). In the French economy, Ang (2007) confirmed this hypothesis. A similar finding was revealed in Kasman and Duman's (Kasman and Duman 2015) study of EU countries. Otherwise, Farhani and Ozturk (2015) rejected the hypothesis of EKC for the Tunisian economy.

In Turkey, the EKC hypothesis has not been verified in the studies of Soytas and Sari (2009), as well as Ozturk and Acaravci (2010), a similar finding has been revealed in the paper of Pao et al. (2011) in Russia. Further, Chandran and Tang (2013) confirmed the absence of the EKC hypothesis for ASEAN-5 economies.

Regarding the transport sector, Liimatainen et al. (2014) investigated the link between carbon emissions and road freight transport intensity in Nordic countries in 2010. The main results revealed that Sweden has the highest carbon dioxide emissions level from road freight transport compared to Denmark, which has the lowest CO2 emissions level. Rizet et al. (2014) measured the carbon intensity for the transportation sector. They found that maritime and rail transport modes have the highest levels of carbon efficiency, with respectively 20 and 18 gCO2/tonneKm, followed by road transportation with 111 gCO2/tonneKm, air transportation has the highest level of carbon intensity with an average value of 493 gCO2/ tonneKm.

Hassan and Nosheen (2019) aimed to investigate the presence of the Railway Kuznets Curve. The authors applied the GMM approach to high-income countries from 1990 to 2017. The main results show the presence of a U-shaped Kuznets curve, bidirectional relation of nitrous and methane emissions, and a uni-directional link of CO2 to the railway. The authors argued that investment in renewable energy and adopting fuel-saving travelers could improve environmental quality.

Boonpanya and Masui (2021) conducted a study using a computable general equilibrium model in Thailand to explore the relationship between freight transport and the environment. The main findings of the study suggest that Thailand's Nationally Determined Contribution scenario will lead to a 2.1% and 3.5% decrease in GDP and consumption, respectively, compared to the reference scenario that does not limit greenhouse gas pollution by 2030. Additionally, the study found that the cost of energy-intensive goods will increase in the industry and household sectors under GHG emissions limitation. While the decrease in energy-intensive production may result in a loss to the economy, the mitigation options in freight transport will help to offset the production loss by increasing activities in low-carbon energy-intensive sectors.

Arvin et al. (2015) investigated the relationship between transport intensity, urbanization, economy, and carbon dioxide emissions. The sample covers the G-20 countries (G-20 developed countries, G-20 developing countries, and G-20 total) for 1961-2012. They applied a panel vector auto-regressive model to assess the causality between variables. The main results show the existence of a network of a causal connection between these key variables in the short run (bi-directional relationship), economic growth (measured by the Growth rate of per capita income) trends to converge to its long-run equilibrium path in response to change in other covariates.

Pradhan (2019) aimed to explore the relationships among transportation infrastructure, financial penetration, and economic growth in the G-20 countries from 1961 to 2016. The primary focus was to investigate the presence of temporal causality between these variables. To accomplish this, the panel vector error-correction model (VECM) was employed to assess both the long-run and short-run connections between the variables. The statistical significance of the coefficients, at a 1% level, indicates that changes in both transportation infrastructure and financial penetration have a significant impact on per capita economic growth, leading it to converge towards its long-term equilibrium path. However, the results in the short run varied and were contingent upon the specific measures of financial penetration and transportation infrastructure utilized in the analysis.

In their study, Pradhan et al. (2021) examined the connections between urbanization, transportation, ICT, and economic growth in G-20 countries from 1961 to 2016 using the panel VEC model. The variables considered were ICT infrastructure, transport infrastructure, the degree of urbanization, and per-capita economic growth. To construct composite indices for ICT and transport, the authors employed principal component analysis. Noteworthy findings emerged from the study: there are temporal causal relationships among urbanization, transport, ICT, and economic growth in both the short and long term; there is cointegration between the variables. To ensure the reliability of their findings, the authors employed the Generalized Impulse Response Function and variance decomposition. The results strongly affirm the existence of causal relationships between the variables. Consequently, due to this inherent interconnection, urbanization strategies should be closely tied to the transportation sector. Similarly, the integration of ICT in transportation is likely to lead to the implementation of intelligent transportation systems.

Awan et al. (2022) examined the linkage between carbon dioxide emissions from the transportation sector, innovation, urbanization, and economic growth in 33 high-income countries from 1996 to 2014. The authors utilized the Environmental Kuznets Curve (EKC) hypothesis and a novel quantile methodology. The results indicate that an N-shaped EKC curve is valid for the transport sector. However, the findings from the quantile regression reveal that urbanization has a positive effect on carbon dioxide emissions, and innovation has a negative effect, mitigating transport-based carbon dioxide emissions.

The analysis conducted by Jahanger et al. (2023a) focuses on the impact of nuclear energy within the framework of the Environmental Kuznets Curve (EKC), while also considering human capital and military expenditures in the top 10 nuclear energy countries. The authors utilized a novel approach, the Dynamic Common Correlated Effects Approach, to conduct their empirical analysis. According to the results, an N-shaped EKC exists in the top nuclear countries, emphasizing the need for these countries to prioritize environmental improvement policies. Moreover, the findings suggest that nuclear energy has a positive impact on environmental quality, underscoring the significance of nuclear energy in mitigating environmental degradation.

Yang et al. (2023a) analyzed to investigate the consequence of low-carbon city pilots' intervention on the intensity of electric energy consumption. The study employed the time-varying difference-in-difference technique to analyze data covering the period from 2007 to 2014. The findings show that low-carbon city pilots' intervention leads to a significant reduction in the electricity consumption intensity of firms. Specifically, the findings show that a one percentage point increase in low-carbon city pilots results in a 3.14% reduction in industrial electricity consumption.

Jahanger et al. (2022c) discover the impact of natural resource consumption, foreign direct investment (FDI) inflows, economic growth, and renewable energy consumption on environmental degradation in the context of the NAFTA nations from 1990 to 2018. Causality analysis was employed to examine the relationship between the variables. The results of causality analysis indicate that economic growth, renewable energy consumption, and FDI inflows have a causal influence on the CO2 emission levels of the NAFTA countries without feedback. However, there is no causal relationship between natural resource consumption and CO2 emissions.

For the case of BRICS countries, Jahanger et al. (2023b) analyzed the dynamic association between natural resources, renewable and non-renewable energy use, greenhouse gas emissions, and human capital from 1990 to 2018. This study employed different panel stationarity approaches, panel cointegration approaches, and panel quantile regression to examine the long-run elasticity of the parameters. The empirical outcomes indicate that economic growth and natural resources have a positive impact on greenhouse gas emissions, while non-renewable energy resources boost greenhouse gas emissions. On the other hand, human capital contributes to reducing greenhouse gas emissions, and interaction between human capital and non-renewable energy leads to a beneficial reduction in greenhouse gas emissions in the environment in the panel of BRICS nations.

Jahanger et al. (2022a) utilized the QARDL method to analyze the effects of globalization, economic growth, and renewable energy on carbon dioxide emissions in Mexico over the period from 1990Q1 to 2018Q4. The authors found that renewable energy has a negative impact on environmental degradation, while globalization has a positive effect. The Spectral Causal analysis further revealed that only GDP and GDP squared Granger cause CO2 emissions in the long run. On the other hand, both renewable energy and globalization significantly Granger cause CO2 emissions in the short, medium, and long run, indicating that any policy shock in either independent variable will lead to an increase in carbon emissions.

Jahanger et al. (2023c) investigated the interrelationships between economic growth, renewable energy, technology, the manufacturing sector, and energy efficiency with respect to greenhouse gas emissions in the top ten manufacturing countries. The study uses a novel Method of Moment Quantile Regression (MMQR) approach covering the period from 1990 to 2020. The empirical findings suggest that the manufacturing sector and technology contribute to an increase in GHG emissions, while energy efficiency and renewable energy have a negative relationship with GHG emissions. Furthermore, the study shows that the interactive effect between the manufacturing sector and energy efficiency leads to a beneficial reduction in greenhouse gas emissions in the environment among the top ten manufacturing countries.

Jiang et al. (2022) utilized an extended form of the input-output model, structural decomposition model and energy utilization technique to investigate the structural pollution reduction in China's power and heating sector from 2007 to 2015. The study examined the structural factors that affect CO2 emissions of power and heating energy, including energy intensity, input, and energy composition. The findings suggest that these factors played a critical role in reducing CO2e in China's power and heating sector, and this emission reduction effect showed an increasing trend. The input composition influence was identified as the key factor in reducing pollution in electric heating energy, followed by the energy intensity influence. On the other hand, the energy structure influence was found to be the weakest factor in reducing CO2 emissions.

Jahanger et al. (2023b) examine the impact of democracy, autocracy, and globalization on carbon dioxide (CO2) emissions in 69 developing countries from 1990 to 2018. The empirical findings of FMOLS and DOLS suggest that autocracy, globalization, and financial development have an adverse impact on the environment, whereas democracy and the use of renewable energy have a positive effect. Moreover, the study reveals that the interaction between autocracy and globalization, as well as democracy and globalization, has a negative and significant influence on environmental pollution in the long run.

Methodology

Our analysis starts by conducting a static estimation of the impact of transport, as well as other covariates, on CO2 emissions using Ordinary Least Squares (OLS). We will then test the robustness of OLS through the Breusch and Pagan test for heteroscedasticity and the Wooldridge test for autocorrelation. If these problems are present, we will apply Generalized Least Squares (GLS). Next, we will proceed to the GMM estimation and check for endogeneity before using it. GMM estimation not only accounts for the heterogeneity of countries but also solves the problem of endogeneity of variables, which often arises in studying dynamic issues, such as the relationship between economic growth and environmental quality.

Estimation models

The System GMM is used to combine for each period t the equation in first differences with that in levels. In the first difference equation, the variables are instrumented by their level values lagged by at least one period, while in the level equation, the variables are instrumented by their first differences. The system of equations obtained will be estimated simultaneously through the method of generalized moments. Blundell and Bond (1998) tested this method using Monte Carlo simulations. They showed that the GMM-System estimator is more efficient than that of GMM differences (Arellano and Bond 1991) which only uses the moment conditions of the difference equation.

We used the system generalized method to assess the influence of transportation systems on CO2 emissions. The equation (eq.(1)) for our model is as follows:

$$CO2_{it} = \beta_0 + \alpha CO2_{it-1} + \beta_1 urban_{it} + \alpha_2 gdp_{it} + \alpha_3 road_{it} + \alpha_4 rail_{it} + \alpha_5 airway_{it} + \alpha_6 pop_{it} + \alpha_7 trade_{it} + \alpha_8 re_{it} + \varepsilon_{it} \quad (1)$$

$$\varepsilon_{it} = \mu_i + v_{it}$$

Impulse response function and variance decomposition

The impulse responses function shows how a variable responds to a standard deviation shock in the other variable initially and whether the effect of the shock persists or dies out quickly using the VAR (vector autoregressions) system. The function $IRF(h,\delta) = \partial_{y_{t+h}} / \partial_{\epsilon_t}$ reveals how a shock $\epsilon_t = \delta$ at time t impacts a variable at time $t+h$.

Meanwhile, variance decomposition analysis is applied to measure the variation in an endogenous variable that can be explained by the changes in another variable. It decomposes variation into the component shocks to the endogenous variables in the VAR. The variance decomposition provides information about the relative importance of each random innovation to the variables in the VAR system.

Data and variables

Variables selection

The following table (Table 1) presents the statistics of variables fixed for our estimations for the entire sample. Albania has the lowest CO2 emissions levels per capita and road density with values equal to 1.026 and 12. On the contrary, Luxembourg has the highest value of CO2 with 25.669, and Malta has the maximal value of road density. Slovakia has the lowest number of passengers carried on air transport while Ireland in 2018 has the maximal value. Malta has the lowest total route-km on the railway network, While Germany has the highest railway network with 36642 km.

The data used in this study was gathered from the World Bank Database. The sample consists of 33 European countries, it is divided into two subsamples for our modeling purposes. The first subsample includes developed countries such as the Czech Republic, Hungary, Lithuania, Luxembourg, Latvia, Germany, Belgium, Estonia, Ireland, Greece, Spain, France, Italy, Netherlands, Austria, Finland, Slovenia, Slovakia, Sweden, Switzerland, United Kingdom, and Turkey. The second subsample includes developing countries such as Albania, Armenia, Belarus, Malta, Serbia, Ukraine, Bulgaria, Croatia, Poland, and Romania. The entire sample is also included in the estimation, resulting in three estimates in total.

Our variable selection was guided by both a thorough literature review and the need to include variables that are directly relevant to the transport sector, such as urbanization, trade openness, and economic growth. Urbanization, for

Table 1 Descriptive statistics of variables

Variable	Unit of measurement	Obs	Mean	Std. Dev	Min	Max
CO2 emission per capita	metric tons per capita	627	6,991	3,645	1,026	25,669
Urbanization rate	% of total population	627	70,918	12,125	41,741	98,001
GDP	current US$	627	5,10E+11	8.22e+11	1.91e+09	3.96e+12
Road density	Kilometre per square kilometre	627	138,936	159,024	12	967,5
Railway network	total route-km	627	7807,549	8426,752	11,1	36642
Passengers carried on air transport	Total of passengers	597	1,96E+07	3,17E+07	7925	1,68E+08
Population density	people per sq. km of land area	627	158,219	227,222	12,2958	1514,469
Trade openness	% of GDP	627	82,134	36,896	27,2923	182,085
Renewable energy consumption	% of total final energy consumption	627	27,011	13,605	10	71,111

example, has been identified as a natural result of economic growth in many cities, leading to an increase in transport demand and related issues such as urban congestion, atmospheric pollution, and high levels of energy consumption. Given the strong association between urbanization and transport, especially road transport, it was necessary to include this variable in our analysis.

In order to test the significance of the variable of renewable energy on the reduction of CO2 emissions, we have chosen to use renewable energy. As a result of the tremendous growth of energy consumption in various nations, new policies are required to control energy consumption. Scholars have emphasized the role of renewable energy in mitigating climate change: it will stabilize the level of Greenhouse Gas emissions at 450 ppm CO2-equivalent concentration by 2100 (Akashi and Hanaoka 2012; Krey and Clarke 2011; Luderer et al. 2013). Therefore, energy transition should be a more valuable approach, particularly in countries with a significant potential for renewable sources, such as solar and wind power. For instance, in 2008, the Indian National Plan on Climate Change decide to focus on solar energy technologies as one of its national missions. Its goal is to produce 15% of the total electricity from renewable sources by 2020 (Mittal et al. 2016). Spain's national climate neutrality goal of 2050 asks for renewable to offer 100% of electricity and 97% of the overall energy mix. The energy policy is focused on significant renewable energy deployment, electrification, and renewable hydrogen. As of December 14, 2020, the German government decided to change its energy law to provide a legal foundation for the long-term expansion of renewable energy and help the nation realize its objective of producing 65% of its electricity from clean sources by 2030. The law aims to contribute to achieving carbon-neutral electricity supply and consumption by 2050. To that purpose, the law stipulates the rate at which renewable sources such as wind and photovoltaics will be grown in the coming years. (IEA 2023).

The variables-related transport are selected since transport is one of the three major sectors affecting CO2 emissions (power and industry). Thus, understanding the variables influencing the growth of CO2 emissions from the transportation sector is crucial given its growing importance as a source of emissions in most nations and its importance in the development of climate change mitigation strategies. Modal shifting from less emission-intensive modes (in terms of CO2 emissions per passenger/freight kilometer), such as railway and water transportation, to more emission-intensive modes, such as air transport and private road vehicles, could be one-factor driving transport sector CO2 emissions growth (Timilsina and Shrestha 2009). Accordingly, we aim in this research to focus mainly on road transport, air transport, and railway of their importance in the modal split in transport.

Regarding the road transport, the tremendous growth of urban areas followed by an increase in car ownership involved an increase in energy consumption and pollution problems. Road cars accounted for 72% of all domestic and international transportation greenhouse gas emissions in 2019 (Peyravi et al. 2022). Also, a new passenger vehicle in Europe produced 122 grams of CO2 per kilometer in 2019. This figure is subject to change depending on the car's fuel efficiency, mileage, and energy consumption. These statistics will drop as the decarbonization process in road transport is faster than in other modes of transportation mainly because of the new strategies of switching conventional vehicles to electric cars, the production of new vehicles which are more fuel efficient than the older ones, etc. nevertheless, the estimated rise of traffic demand can mitigate the effect of new measures, thus, to overcome this issue, it is required to introduce new policies that their purpose is to minimize the emission of pollution indicators. EU negotiators reached an agreement (It is the first agreement in the "Fit for 55" package) with states on the Commission's original proposal to achieve zero-emission road mobility by 2035 (a fleet-wide EU objective to cut CO2 emissions from new cars and light commercial vehicles by 100% compared to 2021).

The railway system serves as an alternative to road transportation for short distances and air travel for long distances, and is widely regarded as a cleaner mode of transportation than other alternatives. Despite this, it is currently under scrutiny in many countries, with network lengths decreasing particularly in developing nations. Nonetheless, it remains a promising solution for public transport.

The demand for air travel has grown significantly in recent years, resulting in a corresponding increase in the trips' number and energy consumption. In 2021, aviation accounted for over 2% of worldwide energy-related CO2 emissions, and its growth rate outpaced that of road, rail, and shipping in recent decades. As countries gradually lifted Covid-19 restrictions, aircraft emissions in 2021 rose to approximately 720 Mt, nearly one-third of the reduction observed in 2020 compared to 2019 levels (IEA 2023).

Trade openness represents one of the main indexes of economic prosperity. It is the result of the evolution of industrial and manufacturing activities. However, according to Grossman and Krueger (1991), trade openness impacts significantly the quality of the environment. Taking the example of the United States and China as the first-ranking countries in this index, however, these two countries are also the two first-ranking CO2 emissions.

Regarding the GDP, several scholars have shown interest in analyzing annual data for multiple countries using a range of econometric methods and various indicators to investigate the causal relationship between CO2 emissions, energy consumption, and economic growth (Sebri and Ben-Salha 2014, Destek et al. 2016, Al-Mulali et al. 2015, Park et al. 2018, Hdom and Fuinhas 2020). Some authors such as Mahmood et al. (2019) pointed out that in the first stage of development, economic growth affects negatively the environment because of the focus on the scale effect of economic activities, while in the last stage, this effect will be reversed since a part of policies will invest in advanced technologies to use the energy efficiently and mitigate the GHG emissions. This phenomenon is illustrated by the Environmental Kuznets Curve widely applied.

Country selection

When it comes to the selection of countries, the chosen nations were selected based on a range of factors. These factors include the availability of essential statistical data, the incorporation of a diverse and captivating assortment of developed and emerging economies, and a scarcity of previous research on this specific subject within these nations. According to the International Energy Agency, China, the USA, India, Russia, and Japan, are the most pollutant countries. Thus, although none of the European countries is one of the top five emitters of greenhouse gases, it is noteworthy that some countries do rank high, especially those with high industrial activities, the European Environment Agency mentioned that Germany is responsible on 22% of GHG emission in the entire European Union followed by United Kingdom, Italy, Poland, and France in 2019. Regarding the part of each sector, transport is the most pollutant activity, followed by energy and agriculture.

The expected results of the study are likely to be mixed, given that the selected countries vary in terms of their level of economic growth across the European region. For instance, Sweden, which is a developed European nation that has made significant progress in reducing its greenhouse gas (GHG) emissions, may yield different results than other countries.

In comparison to the European Union (EU) average, Sweden's per capita emissions are below 50%, while Ukraine, a developing European nation, exhibits significantly higher per capita emissions than the EU average. Therefore, our choice of European countries is justified by the fact that transportation is ultimately related to GHG emissions in this region, even in developed economies. The difference in emissions between developed and developing European countries underscores the need to assess the determinants of CO2 emissions and promote global cooperation to reduce GHG emissions and mitigate the impacts of climate change.

Stationarity check

Cross section dependence tests

Before estimating our model, we must assess the stationarity of the data. To achieve this, we begin with the Cross-Section Dependence test (hereafter CSD). Cross-sectional dependence refers to the interdependence of observations in a panel dataset across different cross-sectional units, meaning that the residuals in one unit are correlated with those in other units. The CSD test rejects the hypothesis of independent and identically distributed (IID) errors. Therefore, it is necessary to test for cross-sectional dependence and account for it in panel data analysis.

In our case, we used the Breusch-Pagan Lagrange Multiplier (Breusch and Pagan 1980) test, Pesaran (2004) CD statistic, Pesaran (2004) CD test, and Baltagi et al. (2012) bias-corrected scaled LM test. The results of CSD tests will conduct us to the selection of unit root tests. If there is not cross-section dependence, we can use the unit root tests first generation such as Phillips Perron, Augmented Dickey-Fuller, Im Pesaran, and Shin, nevertheless, if this problem exists, it will be preferable to apply the unit roots second generation such as and Mallala and Wu.

Table 2 reports the results of cross-section dependence. It shows the rejection of the null hypothesis at a 1% significance level and proves the existence of cross-sectional dependence (CD). This outcome means that we will perform the Second Generation Panel Unit Root Tests to study the data Stationarity. In this case, we will use two tests namely Maddala and Wu's (Maddala and Wu 1999) Panel Unit Root test and Pesaran's (Pesaran 2007) Panel Unit Root test (CIPS).

Panel unit root tests

As aforementioned, the main advantage of second-generation panel unit root tests is to overcome the cross-section dependence issue. Similarly to the first-generation tests, the null hypothesis and the alternative hypothesis are expressed as:

H0: Panels contain unit roots
H1: Panels are stationary.

All variables are adopted as their natural logarithm for processing the heteroscedasticity problem. The following table (Table 3) lists the results of unit root tests for the entire sample, suggesting that all the time series are the significant first difference at the 1% threshold (except for population density in the CIPS test). Thus, all variables are stationary in at least one specification of both tests.

Results of estimations

As mentioned earlier, we begin our estimation process with static estimation using the OLS method. Table 4 presents the results of the OLS method for the three samples. We observe

Table 2 Cross-sectional dependence test results

	Description	Breusch-Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD
LNCO2PC	Ln CO2 emission per capita	4816.135***	131.9582***	131.0416***	32.14971***
LNURBAN	Ln Urbanization rate	7919.974***	227.4723***	226.5556***	39.67054***
LNGDP	Ln GDP	8981.049***	260.1246***	259.2079***	94.52009***
LNROAD	Ln Population density	4115.457***	110.3964***	109.4797***	28.18820***
LNRAIL	Ln Railway network	3699.340***	97.59123***	96.67456***	34.12387***
LNAIR	Ln Passengers carried on air transport	3701.155***	97.64708***	96.73041***	34.75870***
LNPOPDENSITY	Ln Road density	7768.383***	222.8074***	221.8907***	-0.888308
LNTRADE	Ln Trade openness	3454.666***	90.06191***	89.14525***	26.09186***
LNRE	Ln Renewable energy consumption	6147.380***	172.9245***	172.0078***	66.34377***

that the model's goodness of fit is satisfactory, with R-squared values ranging from 69.9% to 77.9%. Moreover, the absence of correlation between the error term (u_i) and the explanatory variables is evident from the main observations (corr(u_i, X) = 0). The Fischer test confirms the overall significance of the models, as indicated by a Prob > chi2 value of 0.0000.

The main results reveal that the urbanization rate has the greatest impact on CO2 emissions, it is statistically significant at the 1% threshold for both the full sample and the sample of developing countries. Similarly, GDP affects positively and significantly emissions, the same conclusion is drawn for trade openness. Nevertheless, renewable energy has the biggest influence on reducing CO2 emissions, which is significant for all three samples, and population density also decreases emissions. With coefficients equal to -0,029 and -0,149, respectively, and significant indications at 5% and 10% thresholds, road density and railway total length have a negative and substantial impact on CO2 emissions.

Diagnostic tests

After estimating the OLS technique, it is strongly advised to check for econometric issues particulary, heteroscedasticity and first order error correlation.

Breusch Pagan test of heteroscedasticity

This test makes it possible to test the presence of heteroscedasticity. It seeks to determine the type of the error term variance; in case the variance is constant, then the variables are homoscedastic. Otherwise, if it varies ($V(\varepsilon_t)\neq\sigma^2$), then, there is heteroscedasticity. Indeed, the Breusch-Pagan test fixes the following two hypotheses:

H0 (null hypothesis): Homoscedasticity (constant variance).
H1 (alternative hypothesis): Heteroscedasticity (nonconstant variance).

Table 3 Unit roots test

	Maddala and Wu (1999)				Pesaran CIPS (Pesaran 2007)			
	At levels		First difference		At levels		First difference	
	Specification without trend	Specification with trend	Specification without trend	Specification with trend	Specification without trend	Specification with trend	Specification without trend	Specification with trend
LNCO2PC	43.491	107.565***	645.955***	520.109***	1.605	-2.430***	-14.612***	-11.404***
LNURBAN	432.879***	193.176***	404.486***	318.857***	7.116	8.199	1.979	-6.228***
LNGDP	151.012***	22.160	215.424***	227.127***	-1.298*	-0.311	-9.262***	-5.939***
LNROAD	102.974***	88.221**	518.443***	412.929***	1.096	0.972	-11.780***	-10.041***
LNRAIL	253.779***	192.729***	824.676***	688.544***	0.047	-3.008***	-15.314***	-12.183***
LNAIR	64.128	60.704	414.597***	322.948***	-0.602	1.333	-9.909***	-7.385***
LNPOP	216.500***	158.881***	164.736***	182.548***	5.098	4.007	-0.909	0.875
LNTO	88.805**	91.681**	490.632***	355.791***	-0.325	2.042	-8.343***	-5.739***
LNRE	27.586	76.995	451.089***	351.824***	-1.679**	-1.406*	-12.794***	-10.348***

Table 4 OLS estimation

Variable	Full sample	Developed countries	Developing countries
LNURBAN	0,539*** (0,116)	0,284 (0,177)	0,597*** (0,183)
LNGDP	0,126*** (0,009)	0,116*** (0,011)	0,167*** (0,016)
LNROAD	-0,029* (0,015)	-0,029 (0,043)	-0,034* (0,019)
LNRAIL	-0,149*** (0,038)	-0,062 (0,050)	-0,108* (0,066)
LNAIR	-0,011*** (0,004)	0,004 (0,004)	-0,062*** (0,011)
LNPOP	-0,561*** (0,056)	-0,652*** (0,063)	-0,385** (0,154)
LNTO	0,053** (0,023)	0,026 (0,024)	0,128** (0,053)
LNRE	-0,788*** (0,023)	-0,729*** (0,025)	-0,921*** (0,058)
constant	2,672*** (0,580)	3,472*** (0,763)	0,892 (1,515)
Obs.	627	437	190
R^2-adj	0,7181	0,7799	0,6991
Wald Chi2	1462,79	1358,97	373,95
Prob > Chi2	0,000	0,000	0,000

Empirically, if the probability (p-value) associated with the test is less than 5%, the test reveals the presence of heteroscedasticity indicating that the data used have constant variance.

Wooldridge test for autocorrelation

Regarding the problem of autocorrelation of errors, it is explained by the existence of interconnected errors. This phenomenon shows the risk that the error term may be influenced by another from the antecedent period. The Wooldridge test was applied to verify the absence of autocorrelation of errors.

The test hypotheses are as follows:

H0: Absence of first-order error correlation ($\boldsymbol{\rho}=\mathbf{0}$): Absence of autocorrelation

H1: Correlation of first-order errors ($\varepsilon_t=\boldsymbol{\rho}\varepsilon_{t-1}+\boldsymbol{t}$):): Presence of autocorrelation.

The null hypothesis of constant variance has been rejected

By carrying out the Breusch-Pagan test on panel data, the table above (Table 5) provides a p-value (Prob>chi2= 0.0000) of less than 5% for the three samples. Therefore the null hypothesis of Homoscedasticity (H0) has been rejected and shows the existence of Heteroscedasticity in the three samples. The results of the Wooldridge test, which rules out the presence of auto-correlation in the autoregressive form (AR1), show that the p-value (Prob > F = 0.0000) is less than 0.05. In this case, we reject the null hypothesis (H0: Absence of autocorrelation of errors).

From the results of the two tests of heteroscedasticity and auto-correlation, we can say that the errors are heteroscedastic as well as auto-correlated. In this case, the coefficient estimators from the ordinary least squares method do not have the right properties (non-minimum variance estimators as well as the existence of autocorrelation). To correct these two problems, we will apply the GLS (Generalized Least Squares) regression method to overcome these problems.

The GLS estimator's various models are significant, both globally and individually. In this regard, the GLS estimator is regarded as the best estimator for static applications in our modeling (Table 6).

Causality tests:

Before performing GMM estimation, we will examine the endogeneity problem, which refers to the presence of reverse causality from the dependent variable to the independent variable. We use two tests to accomplish this: the Juodis et al. (2021) Granger non-causality test and the Dumitrescu and Hurlin (2012) Granger non-causality test. In the JKS non-causality test (Table 7), the majority of variables exhibit a significant coefficient, indicating that they reject the null hypothesis of non-causality and are hence endogenous.

Dumitrescu and Hurlin's (2012) Granger non-causality test was applied. The following table (Table 8) shows that the dependent variable Granger causes all independent variables independently, implying that all independent variables are endogenous. Thus, GMM was adopted, and all independent variables were assumed to be endogenous.

Table 5 Diagnostic tests results

	Full sample		Developed countries		Developing countries	
Breusch and Pagan LM test	chibar2(01) 4501.38	Prob > chibar2 0.0000	chibar2(01) 3182.73	Prob > chibar2 0.0000	chibar2(01) 444.66	Prob > chibar2 0.0000
Wooldridge test for autocorrelation	F F(1, 32) = 39.930	Prob>F 0.0000	F F(1, 22) = 17.378	Prob>F 0.0004	F F(1, 9) = 37.250	Prob>F 0.0002

Table 6 Estimation results by GLS

Variable	Full sample	Developed countries	Developing countries
LNURBAN	0,237**	0.815***	-0,202
	(0,118)	(0.121)	(0,360)
LNGDP	0,278***	0.195***	0,085*
	(0,024)	(0.027)	(0,045)
LNROAD	0,079***	-0.176***	0,282***
	(0,028)	(0.040)	(0,038)
LNRAIL	-0,178***	-0.282***	0,103**
	(0,022)	(0.025)	(0,051)
LNAIR	-0,031***	-0.014	0,015
	(0,012)	(0.025)	(0,031)
LNPOP	-0,357***	-0.117***	-0,035
	(0,031)	(0.038)	(0,093)
LNTO	0,350***	0.244***	0,856***
	(0,046)	(0.050)	(0,124)
LNRE	-0,560***	-0.520***	-0,008
	(0,050)	(0.055)	(0,124)
Constant	-2,851***	-2.065***	-5,346***
	(0,590)	(0.636)	(1,587)

Table 7 Juodis et al. (2021) Granger non-causality Test

	Full sample	Developed countries	Developing countries
L.LNURBAN	-1.067***	-1.1338***	-0.889***
	(0.174)	(0.217)	(0.3028)
L.LNGDP	-0.0129	-0.03056***	-0.0063
	(0.00759)	(0.009)	(0.0135)
L.LNROAD	-0.00848	-0.1559***	0.0186
	(0.0137)	(0.0438)	(0.0178)
L.LNRAIL	-0.263***	-0.3237***	-0.371***
	(0.0618)	(0.0651)	(0.136)
L. LNAIR	-0.00496	0.00413	-0.0344***
	(0.00393)	(0.0039)	(0.00963)
L.LNPOP	-0.300**	-0.675***	1.14***
	(0.0951)	(0.0899)	(0.258)
L.LNTO	-0.0108	-0.0516**	0.0528**
	(0.0241)	(0.0262)	(0.049)
L.LNRE	-0.157***	-0.929**	0.386***
	(0.0330)	(0.0384)	(0.062)

Results and discussion

Main findings

The main findings indicate that the instruments used are valid for all the models (full sample, developed countries, and developing countries) since the Sargan/Hansen statistic of over-identification restrictions is not significant at any threshold (with a high enough p-value). Additionally, the AR(2) statistic of the Arellano-Bond test of first-order in-level or second-order in-difference autocorrelation does not reject the null hypothesis of no autocorrelation. This confirms the robustness of our results and the validity of the GMM-system model.

According to the estimation results in Table 9, the lag of CO2 emission has a significant negative effect in only the sample of developed countries. These findings are consistent with those of Gök and Sodhi (2021), who support the assumption of self-improvement of environmental quality, that is, past levels of environmental quality are considered an important determinant of present levels of environmental quality due to strategic complementarity.

In terms of economic growth, a 1% rise in GDP results in an increase in CO2 emissions of 0.065% and 0.179%, respectively, in models (1) and (2). In this respect, these countries' economic progress is a source of environmental damage. The increase in CO2 emissions is a consequence of their strategy, which prioritizes investment and industrial structure over climate change mitigation. Similarly, trade openness harms CO2 emissions at the 1% threshold for all three models, highlighting the possible impact of international trade evolution on environmental quality.

Our findings are congruent with those of the literature; the relationship between economic development and the environment has been extensively researched, and the findings of various studies differ. According to Ahmad et al. (2013), industrialization and population expansion have a favorable impact on CO2 emissions in South Asian countries. In the long run, Shahbaz et al. (2014) discovered that CO2 emissions in Bangladesh are a function of economic development (as measured by GDP). Mallick and Tandi (2015) showed a positive and long-term link between economic development and carbon emissions in South Asia, rejecting the Environmental Kuznets Curve hypothesis. Dogan and Seker (2016) emphasized that economic development indirectly adds to carbon emissions because trade openness progression leads to higher GDP per capita, more energy use, and, thus, higher GHG emissions. Balogh and Jámbor (2017) confirmed the EKC hypothesis since the GDP per capita is positively related to carbon emissions and that squared per capita GDP is negatively correlated with CO2. They emphasized that the increase in the share of trade to GDP produces more environmental pollution, that is to say, the higher part of industry in the total economy produces more CO2. In Gupta 2019, Gupta highlighted the close relationship between economic development and CO2 emissions. He argued that GDP per capita and population are the main contributors to CO2 emissions. The author emphasized the need to focus on promoting energy efficiency as a means

Table 8 Dumitrescu and Hurlin (2012) Granger non causality test

	Full sample		Developed countries		Developing countries	
Independent variable	Z-bar	Z-bar Tilde	Z-bar	Z-bar Tilde	Z-bar	Z-bar Tilde
LNURBAN	22.54***	16.840***	22.110***	16.585***	7.424***	5.439***
LNGDP	16.910***	12.510***	15.036***	11.150***	7.913***	5.815***
LNROAD	13.447***	9.850***	14.753***	10.933***	2.0548**	1.314
LNRAIL	8.177***	5.802***	8.607***	6.211***	1.802*	1.119
LNAIR	7.268***	5.1033***	7.807***	5.597***	1.3619	0.782
LNPOP	25.999***	19.493***	27.061***	20.388***	6.191***	4.492***
LNTO	14.183***	10.416***	17.247***	12.848***	-0.391	-0.564
LNRE	23.439***	17.526***	23.376***	17.557***	7.1273***	5.211***

Table 9 Estimation results of GMM SYS

	Full sample	Developed countries	Developing countries
L1. LNCO2PC	0,089 (0,079)	-0,357** (0,140)	0,466*** (0,136)
LNURBAN	1,067** (0,441)	-3,968 (5,174)	3,423** (1,523)
LNGDP	0,065** (0,033)	0,179* (0,094)	-0,025 (0,034)
LNROAD	0,638*** (0,103)	1,105*** (0,412)	0,032 (0,056)
LNRAIL	-0,355*** (0,070)	1,249 (0,786)	-0,628*** (0,184)
LNAIR	0,028 (0,033)	-0,045 (0,060)	-0,014 (0,072)
LNPOP	-1,086*** (0,102)	-1,413*** (0,361)	-1,305*** (0,416)
LNTO	0,225*** (0,049)	0,255*** (0,094)	0,276*** (0,106)
LNRE	-0,909*** (0,082)	-0,745** (0,318)	-1,016*** (0,235)
Constant	2,005 (1,400)	7,570 (13,194)	0,225 (2,377)
Prob>F	0,000	0,000	0,000
Observations	627	437	190
Countries	33	23	10
Instruments	35	20	22
AR(2)	0,276	0,376	0,998
Sargan	0,116	0,706	0,109

of reducing CO2 emissions. In 2022, Sun et al. demonstrated a long-term positive relationship between GDP and carbon emissions in the MENA region.

Additionally, the use of renewable energy has been found to effectively reduce CO2 emissions, as demonstrated by values of -0.909%, -0.745%, and -1.016% for models (1), (2), and (3), respectively. This finding is supported by several authors, including Iwata et al. (2010), Dogan and Seker (2016), Balogh and Jámbor (2017), and others. Balogh and Jámbor (2017), for example, reported that renewable energy, including nuclear energy, can significantly minimize CO2 emissions. Similarly, Sun et al. (2022) found a negative correlation between renewable energy and greenhouse gas emissions, highlighting that renewable energy sources such as solar, wind, and hydroelectric power can provide alternative energy options with minimal carbon emissions. Additionally, renewable energy sources can be utilized for long periods without worrying about depletion, further underscoring their potential as a sustainable energy solution.

Dogan and Seker (2016) emphasized that renewable energy consumption will be increased to 27% by 2030, and thus, carbon emissions will be decreased by between 20% and 40%. Thus, it is required to financially support researches and universities from different disciplines to work towards providing renewable energy at cheaper costs.

The level of CO2 emissions is significantly impacted by the rate of urbanization, as observed in both the overall sample and the sample of emerging countries. Urbanization refers to the process of populations shifting from rural areas to urban cities and agglomerations. In recent years, the rate of urbanization has become increasingly important as the economy has transitioned from an industrial to a service sector. However, this phenomenon leads to an increase in energy usage, resulting in higher levels of greenhouse gas (GHG) emissions. Two theories can explain this effect of urbanization rate: the first is the ecological modernization theory, which emphasizes that environmental issues increase as a country undergoes development. The second theory is the urban environmental transition theory, which suggests that increased affluence in cities often leads to a surge in production and commercial activities, leading to issues such as polluted air and water due to massive industrial pollution.

The impact of the three transport covariates on CO2 emissions is not uniform. In terms of road density, this variable has a positive and significant effect on CO2 emissions, with coefficients of 0.638% and 1.105% for models (1) and (2), respectively. The quality of road infrastructure plays a crucial role in determining the fluidity of urban traffic and the commercial speed of vehicles. To address the challenge of high road density, a specific solution that can be implemented is the deployment of Public Transport systems. This system decomposes road infrastructure into two parts: one reserved for private vehicles and the other dedicated to public bus transit. This approach can significantly increase the commercial speed of buses and improve overall traffic conditions, thereby mitigating the impact of high road density on CO2 emissions.

In Tunisia, AbdAllah et al. (2013) discovered a long-run link between road transport-related energy consumption, road infrastructure, transport value-added, and carbon emissions from transport. They, on the other hand, rejected the idea of an inverted U-shaped EKC connection for Tunisian transport CO2 emissions. Hou et al. (2022) found a positive link between transport output vehicle ownership and environmental pressure, they found that private cars are responsible for 41–52% of CO2 emissions. Zhu and Du (2019) propose reducing the environmental impact of economic expansion by expanding rail and water transportation and enhancing fuel quality. According to Kharbach and Chfadi (2017), vehicle ownership and population are the main drivers of carbon emissions in road transport in Morocco. Among the factors explaining this result, the authors emphasized vehicle age, which is more than 10 years for 40% of all vehicles in 2011, and thus they have an energy average consumption of 8.57 l/100km compared to an average of 7.148 9 l/100km in the EU.

The negative correlation between CO2 emissions and the network length of railway lines can be explained by the fact that an extended network results in a higher number of passengers, which in turn leads to higher production levels. Long-distance railway lines are typically more environmentally efficient compared to other modes of transport. As the railway network improves, passengers tend to shift away from road transport and towards railway transport as it is faster and more comfortable. Yang et al. (2019) demonstrated the significant impact of high-speed railways on reducing carbon emissions in China. However, while the utilization phase of HSR projects has the potential to mitigate CO2 emissions, several studies have shown that the production and construction phases are highly polluting. For example, Chang and Kendall (2011) emphasized that the production of construction materials accounts for 80% of HSR's carbon emissions. In contrast, the number of passengers carried on air transport has a negligible effect on emissions, as air transport accounts for a small fraction of overall transportation.

Impulse response function

In addition to GMM approaches, we will use the impulse response function to explore the dynamic behavior of the models. It shows how a one-time shock to one of the innovations affects the current and future values of the endogenous variables. The impulse response allows us to determine a variable's response to a shock as well as the forecast variance. The table below (Table 10) shows the impulse response statistics for the next ten years.

All the series are transformed into the first difference of the natural logarithm to analyze the relationship between various variables and CO2 emissions. The results indicate that in the 1-3 period, there is an initial shock in the response of trade openness to CO2 emission per capita, which then converges back to zero in the 5th period. Similarly, for the response of air passengers carried to CO2 emissions, there is an initial shock in period 2, followed by convergence back to zero in period 6. The initial shock for the response of GDP to CO2 emission per capita occurs in the first period, which quickly dies out as the impact returns to almost zero in period 4. In contrast, the population density shows an increase and divergent response from the average value, while road density has a slight decrease in period 2, followed by a post-shock peak in period 4, and then convergence back to zero in period 5.

Variance decomposition

The table below (Table 11) presents the results of the variance decomposition analysis for the next ten years. It shows that 100% of the variability in CO2 per capita is explained by its innovation. The self-shock in CO2 per capita decreases from 99.886% to 92.233%. Additionally, the response of CO2 to the explanatory variables is positive, with coefficients of 0.11% for air passengers carried, 0.02% for GDP, 0.06% for road density, and 0.13% for urbanization rate. Road density, air passengers, and trade openness exhibit a slight increase until the 5th period with coefficients of 0.0893%, 0.636%, and 1.573% (in the 5th period), respectively. However, these three variables show decreasing coefficients after the 5th period.

CUSUM test

The aim of this test is to show if the parameters are stable or not.

Null Hypothesis : parameters are stables (desirables)

Alternative hypothesis: parameters are not stable (not desirables).

The blue line varies between and within redline (Fig. 1), thus, we accept null hypothesis of parameters stability.

Discussion

The comparison between modes of transport shows that road transport has the most significant impact on carbon emissions, it has a positive sign among the three samples.

Table 10 Impulse response statistics

Period	DLNCO2PC	DLNAIR	DLNGDP	DLNPOP	DLNRAIL	DLNRE	DLNROAD	DLNTO	DLNURBAN
1	0.060965	0.000000	0.045014	-0.000218	-7.10E-05	-0.025438	0.001318	0.020932	1.53E-05
2	-0.005359	-0.023722	0.034784	0.000125	0.000753	-0.004814	-0.000644	-0.005465	4.13E-05
3	-0.002885	0.054243	0.007182	0.000267	0.000531	0.004137	-0.000528	-0.008736	9.40E-05
4	0.001428	-0.000555	0.000914	0.000203	0.000285	0.000859	0.001131	-0.004299	7.92E-05
5	-9.15E-05	-0.006164	-0.000685	0.000163	-2.50E-05	-0.000541	0.000279	0.001027	6.15E-05
6	-0.000580	0.000866	-0.001195	0.000142	-0.000128	-0.000187	8.17E-05	0.000543	5.73E-05
7	-7.65E-05	0.000262	-0.000673	0.000133	7.81E-05	0.000108	-9.93E-05	-0.000228	5.43E-05
8	-6.73E-05	-0.000413	-0.000183	0.000128	0.000110	6.15E-05	-0.000124	-0.000114	5.04E-05
9	-0.000175	6.80E-05	-0.000209	0.000122	4.72E-05	2.62E-05	-6.35E-05	-5.95E-05	4.71E-05
10	-0.000141	0.000114	-0.000289	0.000115	3.95E-05	3.32E-05	-4.18E-05	-0.000115	4.40E-05

Table 11 Variance decomposition statistics

Period	S.E.	DLNCO2PC	DLNGDP	DLNPOP	DLNRAIL	DLNRE	DLNROAD	DLNTO	DLNURBAN	DLNAIR
1	0.061000	100.0000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
2	0.062882	94.87443	0.008098	0.213929	0.854213	1.850281	0.082032	1.490289	0.135103	0.491621
3	0.063176	94.20854	0.025725	0.433495	0.853370	2.166890	0.088537	1.548569	0.159369	0.515509
4	0.063356	93.73146	0.030504	0.739336	0.855039	2.200115	0.089512	1.552698	0.165511	0.635829
5	0.063461	93.42204	0.043165	1.021498	0.852396	2.193428	0.089313	1.573499	0.168612	0.636045
6	0.063548	93.17484	0.044163	1.273379	0.852910	2.190216	0.089161	1.569266	0.170951	0.635115
7	0.063625	92.94826	0.044352	1.505322	0.852891	2.184898	0.088960	1.567087	0.173186	0.635048
8	0.063695	92.74592	0.044411	1.715354	0.852303	2.180175	0.088812	1.563754	0.175573	0.633701
9	0.063758	92.56126	0.044753	1.906338	0.851881	2.175865	0.088697	1.560816	0.177955	0.632434
10	0.063817	92.39261	0.044796	2.080928	0.851582	2.171912	0.088578	1.557965	0.180254	0.631376

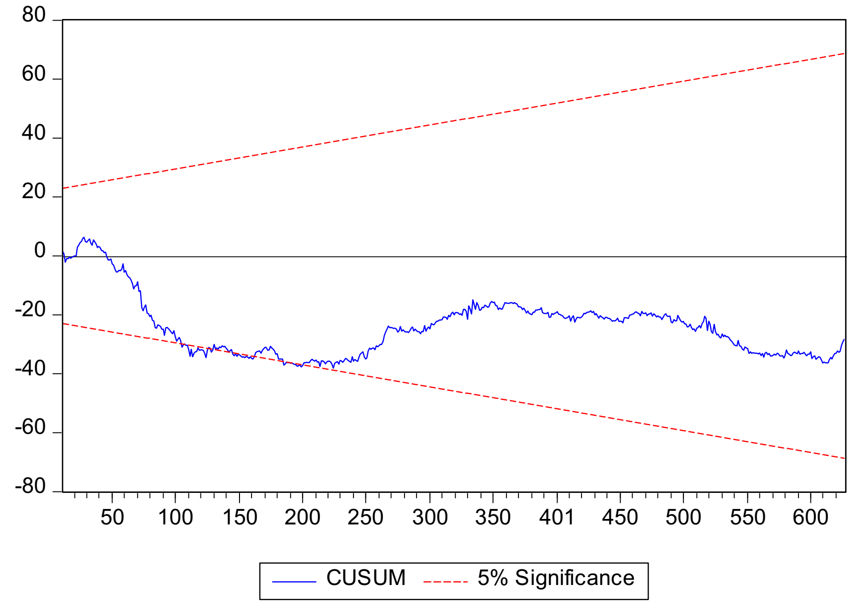
Although regulatory measures have been implemented, the carbon dioxide emissions resulting from road transport in Europe have demonstrated a persistent increase (Helgeson and Peter 2020). The European Environment Agency (EEA) reports that road transportation accounts for approximately 21% of total greenhouse gas emissions in the European Union (EU), making it the primary contributor to the region's emissions. Specifically, CO2 emissions resulting from road transport have increased by 20% since 1990, with 765 million tonnes of CO2 emitted in the EU in 2019, marking a substantial rise compared to 1990 figures. These statistics underscore the urgent need for impactful measures to curb emissions from road transport to mitigate the impacts of climate change.

González et al. (2019) underlined that overall fuel efficiency is an important factor that helps to reduce CO2 emissions in the passenger car sector. Moreover, the findings of Helgeson and Peter (2020) indicate that in decarbonizing the road transport sector, electricity and power-to-x fuels will each play a crucial role, constituting 37% and 27% of total fuel consumption, respectively, by the year 2050.

Boosting the percentage of both passenger and freight journeys taken by trains is crucial for reducing carbon emissions in the transportation sector since rail transportation is among the most environmentally friendly modes of travel. However, according to Dedík et al. (2020), the number of public passenger transport, particularly by rail, is decreasing while individual car transportation is increasing, which is more favored by citizens than mass passenger transport. Furthermore, railway transportation is facing various issues, such as financial concerns, low infrastructure quality, rolling stock non-availability, long distances of stops from village centers, and weak frequency. Thus, the issue of passenger transport is not just about traveling between two locations but traveling with good conditions since public transport cannot meet the passenger's needs in terms of quality, frequency, punctuality, and security. It is easier for passengers to take individual cars, regardless of their negative impact on the environment. Consequently, these insights demonstrate the need for public authorities to work towards achieving a quality of railway transport comparable to individual cars.

The aviation industry is the second greatest source of GHG emissions, accounting for about 2-4% of global anthropogenic emissions (Air Transport Action Group 2019). In 2014, Schafer and Waitz (2014) highlighted that due to the

Fig. 1 CUSUM test of parameters stability



airline industry's rapid growth, environmental degradation and noise are unavoidable unintended consequences. Similarly, in 2007, Chapman stressed that the impact of the airline industry on the environment extends beyond CO2 emissions and includes its effects on the upper atmosphere, which worsen the atmosphere's composition. Nevertheless, During periods of economic downturn and financial hardship, air transportation companies frequently face the risk of survival, particularly when faced with environmental limitations. Therefore, it is necessary to implement stricter regulations and policies for environmental conservation to regulate the correlation between transportation and carbon dioxide emissions (Ouyang et al. 2019) but with taking into consideration economic and financial constraints. Accordingly, the adoption of green airline practices (GAPs) by the aviation industry involves the active participation of stakeholders in managing and reducing the industry's environmental impact by decoupling emissions growth from industry growth, reducing aircraft noise, and implementing technological innovations to enhance travelers' safety and experiences, Amankwah-Amoah (2020).

In our analysis, we found a positive effect of economic growth and trade openness on CO2 emissions. As noted by Spaargaren and Mol (2011), strategies for sustainable consumption and production vary across regions and nations, influenced by factors such as socioeconomic conditions and cultural norms. Concerning environmental issues, it is clear that developing countries prioritize economic development and addressing basic needs over environmental performance (Fang et al. 2007). Unfortunately, these efforts are often hampered by inadequate resources, leading to under-consumption for millions of people (Clark 2007). This stands in contrast to developed nations, where environmental protection is a key priority. These actions are sometimes described as a "backward mindset," with a tendency to "develop first, clean up later" (Rock and Angel 2007). Moreover, some authors propose the pollution paradise hypothesis (Dean 2002), which posits that developing nations relax environmental control requirements to attract foreign investment and promote economic growth, making them the "pollution paradise" of developed nations. Therefore, it is crucial for developing countries to initiate large-scale environmental programs.

Conclusion and policy implications:

Conclusion

Fighting against climate change begins by understanding the environmental problem sources. Indeed, from a global point of view, the modern lifestyle radically affects the modes of production and consumption through a tremendous use of the earth's resources. Transport, being a vital component of our everyday lives, tremendously aids our way of living; but, because of its principal energy method, which is a fossil fuel, transportation is considered the second biggest contributor to air pollution.

The UK Department of Transport's statistics reveal that in 2018, 34% of Nitrogen Oxide (NOx) emissions and 13% of Particulate Matter (PM2.5) emissions were generated by transport. Consequently, our study aims to evaluate the impact of transportation systems on environmental quality across a set of European nations. The econometric findings demonstrate that transportation has a substantial influence on environmental degradation, even in high-income countries. Moreover, trade openness leads to a significant increase in emission pollution for all three samples. However, as highlighted by previous research, while maintaining trade openness and GDP growth at a sustainable level by taking into account environmental protection regulations, the utilization of renewable energy has a significant impact on reducing CO2 emissions.

The relationship between the environment, transportation, and economic growth varies among the countries selected for this study. The strong connection between transportation and environmental performance underscores the need to pursue more sustainable transportation practices, such as investing capital in transport infrastructure, improving transport capacity, and promoting eco-mobility. Additionally, modifying urban form, such as increasing density, land use mix, connectivity, and accessibility, in conjunction with programs that encourage changes in consumer behavior, such as implementing transport pricing, could reduce transport-related greenhouse gas emissions in countries and slow the growth of CO2 emissions.

Policy implications

This paper provides policy implications for reducing environmental pollution in the transportation sector. First, it is important to recognize that conventional transport modes, such as private cars and buses, may not automatically reduce pollution Instead, sustainable mobility options, such as investments in public transportation and active transportation infrastructure (e.g., bike and pedestrian areas), can help minimize GHG-intensive modes of transportation. Research by Von Blottnitz and Curran (2007) demonstrated that bio-ethanol is a preferable resource for transport energy use over conventional fuels, but its production can create issues such as human toxicity and acidification. Electric vehicles, powered by low-GHG emissions electricity, have a large potential to reduce land-based transport GHG emissions. Although the cost of electrified vehicles is decreasing and their popularity is increasing, ongoing investments in supporting infrastructure are necessary for them to scale up. Advancements in battery technology may make it easier to electrify heavy-duty trucks and supplement conventional electric rail networks. However, there are concerns about the environmental footprint and material supply risks associated with battery production, particularly regarding essential minerals. To mitigate these risks, supply diversification methods, energy and material efficiency improvements, and circular material flows should be implemented.

Second, in developing countries, industries should utilize natural resources more efficiently. While researchers and scholars have proposed various methodologies for enhancing sustainability performance, limited governmental and management support in implementing such developments can lead to unsustainable and inefficient manufacturing activities (Luthra et al. 2016). The primary objective of sustainability policies is to ensure the efficient use of primary resources, taking into consideration socioeconomic and cultural backgrounds. Thus, new regulations and standards need to be implemented as a set of incentive mechanisms that force manufacturers to consider environmental constraints.

Regarding the transportation system, policymakers should pay particular attention since it directly affects the ecosystem. In this sense, governments should prioritize integrated, socially inclusive, and environmentally friendly transportation options. Authorities can adopt a portfolio of interventions in this regard, such as providing annual cheap public transportation enrollment, introducing a carbon tax, increasing taxes on private modes, and imposing a congestion tax. For example, in more congested areas of a city, the tax on parking and traveling would be higher, which is a small application of the Polluter Pays Principle that emphasizes the fact that those who produce pollution should bear the costs of managing it to prevent damage to the ecosystem and human health.

Third, sustainable behavior should not only be practiced by producers but also by consumers. The primary goal of sustainable consumption is to raise awareness among consumers about the importance of pursuing sustainable purchasing behaviors (Liu et al. 2018). Many actions can be recommended, such as saving energy at home, adopting eco-friendly travel practices, reducing meat consumption, reusing items, and purchasing eco-friendly materials.

Fourth, substantial assistance should be provided to promote the development of environmental protection patents,. Zhang et al. (2019) have emphasized the significance of scientific research funding in advancing green technology developments. Therefore, governments are encouraged to invest in research and development and to incentivize businesses to incorporate clean technologies into their manufacturing processes.

Limits and perspectives

Like every study, this paper is not exempt from limitations that should be considered in future research. The first limitation is that we did not include maritime transportation as an important element in the variation of CO2 emissions; we focused this research on passenger transport rather than freight transport. The second limitation is that we did not focus on the long-term relationship between endogenous and exogenous factors. It is important to test the time influence on the relation between the selected variables. The third limitation is that we focused on the output of transport rather than energy use. It would be preferred to add transport energy use as an exogenous factor affecting CO2 emissions to test which modes of transport are fuel efficient. However, this variable is not available in some countries selected for our study. Therefore, our research perspectives are presented as follows: 1) applying the environmental Kuznets curve to test the impact of the transportation system on different pollution indicators, 2) integrating maritime transportation to understand the link between freight transportation and GHG emissions, and 3) proposing recommendations to overcome the drawbacks of freight transport on the environment.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Imen Ghannouchi, Fedy Ouni, and Foued Aloulou. The first draft of the manuscript was written by Imen Ghannouchi and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Availability of data and materials The data that support the findings of this study are available on request.

Declarations

Ethical approval Ethics approval was not required for this research.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

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

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