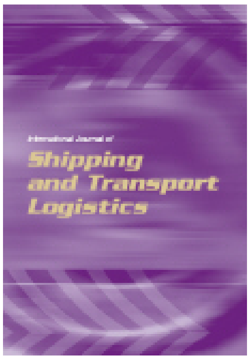

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Can air transportation reach to zero carbon emissions: comparative econometric analysis between transportation modes in the USA

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Can air transportation reach to zero carbon emissions: comparative econometric analysis between transportation modes in the USA

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Abstract: The lack of research examining the impact of all modes of transportation on carbon dioxide (CO_2) emissions evaluated collectively in a single study is a void in the transportation-environment literature. This research fills that need by utilising the ARDL technique to project forward in time and estimate the impact of various transportation modes, including pipelines, on CO_2 emissions in the USA between 1980–2022. In a distinct model that takes into account economic development and energy use, all forms of transportation modes are analysed. The findings of the ARDL suggest that there is a correlation that is interpreted as a statistically significant inverse link between the modes of transportation of air and pipelines and CO_2 emissions. A 1% increase in air transportation and pipeline transportation causing a decrease of CO_2 emissions by 0.03% and 0.06% respectively. Likewise, causalities detected between air transportation and CO_2 emissions, air transportation and energy use, pipeline transportation and CO_2 emissions, pipeline transportation and energy use. Lastly, policy implications suggested such as using renewable energy resources and alternate cleaner resources on all modes of transportation systems to develop sustainable transportation for environment.

Keywords: CO_2 emissions; air transportation; transportation modes; pipeline transportation.

JEL codes: L91, L92, L93, L95, Q53, Q54.

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1 Introduction

Global warming has emerged as a pressing environmental issue in recent decades, one that poses a significant danger to long-term prosperity (Dogan et al., 2022). The existence of greenhouse gases leads to global warming. When it comes to global warming, carbon dioxide emissions are the biggest culprit (Sencer Atasoy, 2017; Awaworyi Churchill et al., 2021). The existence of greenhouse gases adds to global warming. The majority of the rise in the concentration of greenhouse gases in the atmosphere over the past 150 years can be traced back to activities carried out by humans. The majority of the increase in the atmospheric concentration of carbon dioxide that has occurred since the pre-industrial era may be attributed to the burning of fossil fuels. Alterations in land use have also made a substantial contribution, although one of a lesser magnitude (Alley et al., 2007).

The greatest contributor to greenhouse gas emissions in the USA is fossil fuel burning for electricity (27%), and transportation (27%). Greenhouse gas emissions in the US have dropped 7% since 1990. Emissions vary annually based on the economy, fuel prices, and other variables. 2020 US greenhouse gas emissions fell 11% from 2019. Coronavirus

(COVID-19) pandemic-related travel and economic activity reductions caused a significant drop in CO_2 emissions from fossil fuel usage. Due of decreased travel, the COVID-19 pandemic reduced transportation emissions by 13% (EPA, 2022).

Emissions from transportation in the USA amounted to 1.64 billion metric tons of carbon dioxide in 2021, making it the world's biggest source of such emissions. More pollution was produced by it than by all traffic in China, India, and Russia combined (Statista, 2022). When it comes to transportation emissions per capita, the USA likewise ranks at the top again. Even though the US transportation industry is forecast to increase at a fraction of the pace of growth of non-OECD nations, it is still predicted to require one quarter of global transportation energy in 2030 (Greene et al., 2011).

There are many studies related to transportation modes and their environmental effects by processing the modes of transportation separately. Using information for a panel of 17 OECD nations from 1870 to 2014, Awaworyi Churchill et al. (2021) analyse the impact of infrastructure of transportation on carbon dioxide. Consistent with previous research such as Acheampong et al. (2022), Asher et al. (2019), Dai et al. (2023), Emodi et al. (2022), Huang and Guo (2022), Xu et al. (2022), the findings indicate a positive link among transportation infrastructure and carbon dioxide. Environmental goals set by the European Union, such as the recent proposal by the European Commission to reduce emissions by 90% by 2050, are not on track to be met, as evidenced by the positive relationship between road transportation and CO_2 emissions in the countries studied by Marrero et al. (2021). In their study in China, Li et al. (2017) results show positive relationship between air, road and water transportation and CO_2 emissions while negative relationship between rail transportation and CO_2 emissions. In contrast to their results, this paper shows different results in case of CO_2 emissions relationship between transportation modes.

Despite their relevance, research on the dynamic relationships between diverse modes of freight transportation in multiple models and CO_2 emissions over time series data of more than three decades, identifying long-run correlations, capturing direct and indirect effects is lacking. There are a number of different ways in which this study contributes to the existing body of literature:

1 The study investigates the relationship between transportation modes and CO_2 emissions for more than four decades. Through the utilisation of time series data, this study makes an initial attempt to investigate the relationships that exist in the USA between the various forms of freight transportation and CO_2 emissions from the years 1980 to 2022.

2 The utilisation of pipeline transportation is yet another distinction that distinguishes this research from other studies that are comparable to this type of investigation. None of the studies that have been conducted have taken into account the influence that pipeline transportation has on carbon dioxide emissions that are associated with transportation.

3 Further investigation into the relationship between the various modes of freight transportation and the differences in CO_2 emissions is carried out with the use of ARDL techniques which benefits from its ability to handle variables with different integration orders, estimate both short-term and long-term dynamics, and perform well with small sample sizes, making it highly versatile and robust for econometric analysis and forecasting.

The following is an outline of how the next portions of the research are structured: in the next section, Section 2, a condensed literature review on topics related to transportation and CO_2 emissions is provided. Section 3 presents the study's data and methodologies, while Section 4 offers summary and final thoughts.

2 Literature review

Many previous studies have analysed CO_2 links in the context of a single mode of transportation, such as rail or road, rather than considering all modes together. In this part, the empirical findings from studies of the various forms of transportation and environmental degradation are provided.

Hu et al. (2020) investigated the association between aircraft characteristics and CO_2 emissions at several airports in China between 2007 and 2016 using spatial distribution analysis. The results reveal that there are significant geographical distribution discrepancies amongst airports due to economic growth patterns, airport size, and aircraft types, and that the majority of airports have a great potential for reducing CO_2 emissions without sacrificing economic performance. Utilising the Tapio decoupling index, Li et al. (2019) analysed the connection between the growth of China's transportation sector and its CO_2 emissions from a provincial perspective, using data from 30 different provinces. The results indicated that underdeveloped provinces were more likely than industrialised and coastal provinces to have a weak decoupling condition. Income level was the most important element restricting the growth of decoupling in the transport industry. According to the review study of Jiang et al. (2021), high-speed rail (HSR) projects have ramifications for carbon dioxide (CO_2) emissions through their interactions with other modes of transportation, such as airplanes, cars, and slower trains. Studies are conceptually divided into three levels:

1 a comparison of HSR emissions to those of other modes

2 the emission consequence of traffic reallocation caused by HSR

3 a life cycle evaluation (LCA).

They determined that the literature is still at a relatively incipient stage. Kamga and Yazici (2014) elaborates on how the construction of a high speed rail transportation lead to the USA to move closer to environment friendly transport, create a more balanced, and break away from the status quo, various transportation system that improves efficiency and the quality of travel with which it can be accomplished.

Li and Zhang (2020) proposes a unique paradigm for lowering CO_2 emissions from freight operations, taking into consideration both external incentives such as low carbon subsidy policy, and operational services like demand sensitivity, frequency of services on each train trip train routes. The creation of an optimisation model which regards the dependability of the transportation network, the profits made by railway operators, and the amount of carbon dioxide reduced from the atmosphere. Parametric versus non-parametric projections of the impact of transportation substructure on greenhouse gas were compared on OECD countries across roughly 150 years by Awaworyi Churchill et al. (2021). They also analysed the connections between economic development and transportation infrastructure and population expansion. Results suggest an important correlation between CO_2 and transport infrastructure during globalisation's first stage between 1870–1911 and World War II between 1939–1946. Yu et al. (2021) use an enhanced gravity model to analyse CO_2 emissions and the impact of railway speedup on air travel demand from 2013 to 2017 for 546 city pairings. During the research period, passengers have migrated from air travel to rail travel, conclude in a decrease in carbon dioxide emissions, as a result of enhanced train services driven by speed. Hepting et al. (2020) utilised a climate model, offering insights into the extremely long-term climatic consequences under various emission assumptions up to 2,100. The modelling methodology demonstrates that the development of emissions is the consequence of intricate interactions between demand growth and supply decisions, which have a substantial impact on climate impact. Using multiple panel regression analysis, Hájek et al. (2021) explore how specific policy instruments conduce to the reduction of transportation emissions in groups of EU nations. According to the research, increased permission costs contribute to the decrease of emissions. Using panel methodologies, Al-Mulali et al. (2015) assess the effect of international tourist arrivals on transportation-related CO_2 emissions in 48 countries. The findings show that in every country investigated, tourism significantly impacts CO_2 emissions from transportation, with the exception of European countries. Byrnes and Warnken (2006) calculate the total and per capita energy expenditures and GHG emissions related with Australian tour boat operations. According to their findings, the total greenhouse gas emissions from tour boat operations in Australia account for around 0.1% of the country's transportation industry. Yang et al. (2015) analyse the spatial-temporal trends and regional disparities in CO_2 emissions from transportation in China by using a carbon-emission transportation model, for the years of 2000–2012. The data revealed that yearly growth rates for transportation resulted per capita and total CO_2 emissions were 9.29% and 8.69%, respectively. Yang et al. (2019) examined the influencing variables and regional spillover impacts of transportation caused CO_2 emissions by model of spatial panel data using panel data between 2000 and 2015 on China. They discovered that China's transportation-related CO_2 emissions are expected to continue to show an increasing trend in the future. Using robust and sophisticated fixed-effect panel quantile regression models, over the years 1990-2016, several elements that contribute to carbon emissions from international air travel are examined by Habib et al. (2022). The data show that there is a wide range of quantiles in the impact of air passenger trips, air freight transport, and air transport volume on environmental degradation, with the influence being positive and becomes more evident as the trend rises. Zhao et al. (2022) examine the impact of intelligent transportation on carbon dioxide emissions by using spatial econometric models in China between 2002 and 2017. The findings show that there is both a general increase in the use of smart transportation and a significant amount of variation across different regions resulting in a decrease of emissions.

With a strong and novel quantile approach, Awan et al. (2022) analyse the environmental Kuznets curve for transportation between 1996 and 2014 on 33 countries with high-income. An N-shaped EKC curve is supported by the data, suggesting that this form is appropriate for the transportation sector. Using data between 1991 and 2019, Sohail et al. (2021) examines the asymmetric effect of transportation modes such as rail and air on environmental deterioration in Pakistan. As expected, the data show that the number of people using airplanes and trains to travel has contributed to an increase in greenhouse gas emissions. Using multi-variate panel data analysis, Shafique et al. (2021) identify the connections between transportation, economic expansion, and environmental deterioration in the ten Asian countries with the greatest carbon emission between 1995 and 2017. According to the results, there is just one way that transportation contributes to environmental deterioration. Using the ARDL, DOLS, and FMOLS models, Dursun (2022) evaluates the link between economic development, air transportation, CO_2 emissions, energy consumption and in the framework of the EKC hypothesis from 1970 to 2020. The data demonstrate that the transportation sector's heavy reliance on fossil fuels contributes to environmental deterioration. Li et al. (2017) employ a combined VECM and ARDL to discover long-and short-run causality connection between mode-specifically development of transportation and carbon dioxide emissions, such as inland waterway, airline, road, and railway. The results indicate that internal enlargement of roads, airways, and waterways of China result in long-term increases in CO_2 emissions.

Current research indicates that there are several studies on transportation modalities independently. This indicates a need for further research into the interplay between various modes of transportation and the environment. This study perfectly fits to develop transportation and environment literature.

3 Data and methodology

With Granger causality tests and the ARDL method popularised by Pesaran et al. (2001), this study aims to research connections between transportation modes, energy use, carbon dioxide (CO_2) emissions, and economic development. The current paper examines potential long-term impacts of various transportation systems, consumption of energy, and economic growth on CO_2 emissions on USA in a time period of 1980 and 2022.

3.1 Data

The World Bank Development Indicators (World Bank, 2022), the US Energy Information Administration (EIA, 2022), US Department of Transportation (USDOT, 2022) and British Petroleum Statistics are used to compile annual data on the USA for the years 1980 to 2020 (BP, 2022). Data contain GDP constant 2015 US$ (GDP), total energy CO_2 emission (CO_2) measured in million metric tons, air freight transportation (AIR) measured in millions of ton-miles, rail freight transportation (RAIL) measured by the million ton-miles, highway freight transportation (HWT) measured by the million ton-miles, water freight transportation (WT) measured in millions of ton-miles, pipeline freight transportation (PT) measured in millions of ton-miles and primary energy consumption (EC). Data on GDP constant 2015 US$ is from the Word Bank Development Indicators (World Bank, 2022). Data on CO_2 emissions is from US Energy Information Administration (EIA, 2022). Data air, rail, highway, water and pipeline transportation are from US Department of Transportation (USDOT, 2022). Finally, data on energy consumption is from British Petroleum Statistics (BP 2022). Depending on the availability of the data, time series are gathered to obtain the most observations possible. The list of variables and acronyms is summarised in Table 1.

Table 1 Variables definition

Variable name	*Definition*	*Code*	*Unit*	*Source*
CO_2 emissions	Carbon dioxide emissions	CO_2	Million metric tons of carbon dioxide	US EIA
Air transportation	Freight transport by air	AIR	Million ton-miles of freight	US DoT
Rail transportation	Freight transport by rail	RAIL	Million ton-miles of freight	US DoT
Highway transportation	Freight transport by highway	HWT	Million ton-miles of freight	US DoT
Water transportation	Freight transport by water	WT	Million ton-miles of freight	US DoT
Pipeline transportation	Freight transport by pipeline	PT	Million ton-miles of freight	US DoT
Economic growth	Gross domestic product	GDP	Constant 2015 US$	WDI
Energy consumption	Primary energy consumption	EC	Primary energy consumption	BP Statistics

3.2 Model estimation

The model specification also incorporates data from the following studies by Li et al. (2017), Adedoyin et al. (2021), and Ozturk et al. (2022), since this is the first study to evaluate the connection between economic growth, transportation modes, energy usage, and CO_2 emissions. This paper utilises similar functions as that of Li et al. (2017), which are:

$$CO_2 = f(AIR, GDP, EC) \tag{1}$$

$$CO_2 = f(RAIL, GDP, EC) \tag{2}$$

$$CO_2 = f(HWT, GDP, EC) \tag{3}$$

$$CO_2 = f(WT, GDP, EC) \tag{4}$$

$$CO_2 = f(PT, GDP, EC) \tag{5}$$

CO_2 is the dependent variable, whereas other varied factors constitute the independent variables. In model 1, dependent variables are air transportation (*AIR*), *GDP* and energy consumption (*EC*) respectively. In model 2, explanatory variables are rail transportation (*RAIL*), *GDP* and *EC* respectively. Highway transportation (*HWT*), *GDP* and *EC* are the dependent variables of model 3. In the model 4 and model 5 water transportation, pipeline transportation, *GDP* and *EC* are the dependent variables respectively. The fundamental assumption in the framework of the model chosen is that air pollution in the USA will be negatively impacted by transportation modes. The following is the econometric models developed using equations (1), (2), (3), (4), (5) and based on time series data:

$$\log CO_{2t} = \beta_0 + \beta_1 \log AIR_t + \beta_2 \log GDP_t + \beta_3 \log EC_t + \mu_t \quad (6)$$

$$\log CO_{2t} = \beta_0 + \beta_1 \log RAIL_t + \beta_2 \log GDP_t + \beta_3 \log EC_t + \mu_t \quad (7)$$

$$\log CO_{2t} = \beta_0 + \beta_1 \log HWT_t + \beta_2 \log GDP_t + \beta_3 \log EC_t + \mu_t \quad (8)$$

$$\log CO_{2t} = \beta_0 + \beta_1 \log WT_t + \beta_2 \log GDP_t + \beta_3 \log EC_t + \mu_t \quad (9)$$

$$\log CO_{2t} = \beta_0 + \beta_1 \log PT_t + \beta_2 \log GDP_t + \beta_3 \log EC_t + \mu_t \quad (10)$$

In the aforementioned equations, t stands for a time series (1980–2022). Each β denotes the relevant variable's slope coefficient, while the final μ denotes the estimation residual. All variables are examined logarithmically to reduce variance.

3.3 Methodology

3.3.1 Phillips Perron and augmented Dickey-Fuller (ADF) unit root tests

The stationarity of a time series may be determined statistically via the use of a method known as the unit root test. The fact that the variables comprising the time series are non-stationary is evidence that the data in question include a unit root. In this paper, Philips-Perron and ADF unit root tests were used to determine whether data has unit root or not for level and first difference forms. The individual intercept least-squares approach serves as the foundation for the PP and ADF unit root methods (Mohsin et al., 2022). The equations for these tests are shown as below:

$$\Delta y_t = \alpha_0 + \alpha y_{t-1} + \sum_{i=1}^{p} \beta_j \Delta y_{t-1} + \varepsilon_t \quad (11)$$

$$\Delta y_t = (p-1) y_{t-1} + \varepsilon_t \quad (12)$$

The PP test equation is given by equation (12). In 1988, Pierre Perron and Peter C.B. Phillips developed the well-known Phillips-Perron (PP) test, a unit root test. The integration of the data series at the first order is tested using the PP test. In the aforementioned equations, y_t with respect to t time stands in for high order autocorrelation and represents the first difference operator. y_{t-1} displays how variables behave endogenously. The ADF [equation (11)] test is more suited for use with finite data, whereas the PP test offered a non-parametric adjustment to t-test statistics. Both equations' ε_t terms provide robust measurements for unknown errors.

3.3.2 Cointegration test of Johansen

The results of the unit-root test show that the cointegration and coefficient estimation techniques used in this study are appropriate for estimating the true parameters of an economic model when all variables are assumed to be stable at the first difference. The Johansen technique is used to test the cointegration inquiry. The null hypothesis is rejected since the probability values at $r = 0$ and $r \leq 1$ are statistically significant, as shown by the trace statistics. There is no cointegration if $r = 0$; there is at most one if $r \leq 1$; there are at most two if $r \leq 2$; there are at most three if $r \leq 3$; and there are at most four if $r \leq 4$. As a result, the findings support the presence of cointegration.

3.3.3 ARDL long run estimation

Pesaran et al. (1999, 2001) established the autoregressive distributed lag model (ARDL) that was used in this study. The ARDL model offers a number of important advantages over other time-series techniques. Under conditions of zero-order stationary I(0) and first-order stationary I(1), the original sequence of benefits offered by the ARDL model may be used. The autoregressive distributed lag (ARDL) method is also famous for its ability to show both short-term and long-term scientifically true relationships between factors at the same time. This feature lets you look at all the connections between various factors in a more thorough way, which helps you guess what the next trend will be more accurately. The ARDL method also gives stable values of long-duration coefficients that are asymptotically normal, which makes the predictions more accurate (Arjun et al., 2020). The ARDL models of the study are given below:

$$\begin{aligned}\Delta \log CO_{2t} = {} & \beta_0' + \sum_{i=1}^{p} \beta_1' \Delta \log CO_{2t-i} + \sum_{i=0}^{q} \beta_2' \Delta \log AIR_{t-i} + \sum_{i=0}^{q} \beta_3' \Delta \log GDP_{t-i} \\ & \sum_{i=0}^{q} \beta_4' \Delta \log EC_{t-i} + \lambda_1 \log CO_{2t-1} + \lambda_2 \log AIR_{t-1} + \lambda_3 \log GDP_{t-1} \\ & + \lambda_4 EC_{t-1} + \varepsilon_t \end{aligned} \tag{13}$$

$$\begin{aligned}\Delta \log CO_{2t} = {} & \beta_0' + \sum_{i=1}^{p} \beta_1' \Delta \log CO_{2t-i} + \sum_{i=0}^{q} \beta_2' \Delta \log RAIL_{t-i} + \sum_{i=0}^{q} \beta_3' \Delta \log GDP_{t-i} \\ & \sum_{i=0}^{q} \beta_4' \Delta \log EC_{t-i} + \lambda_1 \log CO_{2t-1} + \lambda_2 \log RAIL_{t-1} + \lambda_3 \log GDP_{t-1} \\ & + \lambda_4 EC_{t-1} + \varepsilon_t \end{aligned} \tag{14}$$

$$\begin{aligned}\Delta \log CO_{2t} = {} & \beta_0' + \sum_{i=1}^{p} \beta_1' \Delta \log CO_{2t-i} + \sum_{i=0}^{q} \beta_2' \Delta \log HWT_{t-i} + \sum_{i=0}^{q} \beta_3' \Delta \log GDP_{t-i} \\ & \sum_{i=0}^{q} \beta_4' \Delta \log EC_{t-i} + \lambda_1 \log CO_{2t-1} + \lambda_2 \log HWT_{t-1} + \lambda_3 \log GDP_{t-1} \\ & + \lambda_4 EC_{t-1} + \varepsilon_t \end{aligned} \tag{15}$$

$$\begin{aligned}\Delta \log CO_{2t} = {} & \beta_0' + \sum_{i=1}^{p} \beta_1' \Delta \log CO_{2t-i} + \sum_{i=0}^{q} \beta_2' \Delta \log WT_{t-i} + \sum_{i=0}^{q} \beta_3' \Delta \log GDP_{t-i} \\ & \sum_{i=0}^{q} \beta_4' \Delta \log EC_{t-i} + \lambda_1 \log CO_{2t-1} + \lambda_2 \log WT_{t-1} + \lambda_3 \log GDP_{t-1} \\ & + \lambda_4 EC_{t-1} + \varepsilon_t \end{aligned} \tag{16}$$

$$\Delta \log CO_{2t} = \beta_0' + \sum_{i=1}^{p} \beta_1' \Delta \log CO_{2t-i} + \sum_{i=0}^{q} \beta_2' \Delta \log PT_{t-i} + \sum_{i=0}^{q} \beta_3' \Delta \log GDP_{t-i}$$
$$\sum_{i=0}^{q} \beta_4' \Delta \log EC_{t-i} + \lambda_1 \log CO_{2t-1} + \lambda_2 \log PT_{t-1} + \lambda_3 \log GDP_{t-1} \quad (17)$$
$$+\lambda_4 EC_{t-1} + \varepsilon_t$$

In equations (13), (14), (15), (16) and (17), Δ denotes the first difference operation, p and q are the optimum lags, β_0' denotes the constant, ε_t denotes the error term, t denotes time, β_j' denotes the short-term coefficients (ranging from 1 to 8), and λ_j denotes the long-term coefficients (ranging from 1 to 8).

3.3.4 Causality test

Granger's (1969) causality analysis was carried out after long-term estimation results. This study employs Granger causality for its numerous benefits, in terms of probability theory (Raihan and Tuspekova, 2022). The ability of this test to study a huge number of lags, while disregarding higher-order lags, is the fundamental advantage of using it. Y is lead to 'Granger-cause' X if it can be used to forecast the future of another time series X. The length of the time series for these two variables is T, with X_t and Y_t (t = 1, 2, …, T) being their values at time t. The time series X_t and the time series Y_t may be modelled using a bivariate autoregressive model:

$$X_t = \sum_{l=1}^{p} \left(a_{11,1}, X_{t-1} + a_{12,1}, Y_{t-1} \right) + \varepsilon_t \quad (18)$$

$$Y_t = \sum_{l=1}^{p} \left(a_{21,1}, X_{t-1} + a_{22,1}, Y_{t-1} \right) + \varepsilon_{ut} \quad (19)$$

where p is the order of the model, $a_{ij,1}$ (i, j = 1, 2) are model coefficients, and ε_t and $\varepsilon_u t$ are residuals. Estimating coefficients using ordinary least squares and detecting Granger causality between X and Y using F tests.

4 Empirical findings

4.1 Descriptive statistics

Results of the normality tests (Jarque-Bera, kurtosis, skewness, and probability) and the summary measures between variables are shown in Table 2. There are 41 samples in each variable covering the time period from 1980 to 2020 in the USA. If the skewness value is close to 0, then the data are regularly distributed. To further characterise the series' deviation from the normal distribution, calculated its kurtosis. The empirical data indicates that all series have values less than 3, making them platykurtic. In addition, all parameters, excluding AIR and EC, are normal according to their Jarque-Bera probabilities.

Table 2 Descriptive statistics of variables

	CO_2	*AIR*	*EC*	*GDP*	*HWT*	*PT*	*RT*	*WT*
Mean	5,261.123	12,014.65	87.73723	1.36E+13	1,876,169	974,099.8	1,378,455	767,340.7
Median	5,262.067	12,845.23	91.84500	1.39E+13	1,875,725	1,005,219	1,465,960	745,640.8
Maximum	6,015.545	20,150.53	97.42963	2.09E+13	2,717,233	1,103.602	1,851,229	1,023,637
Minimum	4,383.943	4,172.926	69.30191	7.08E+12	1,256,800	818,836.5	810,000.0	539,469.9
Std. dev.	466.5464	4,203.752	8.726447	4.23E+12	352,364.6	80,695.78	327,958.0	163,225.1
Skewness	−0.074259	−0.377706	−0.836818	0.005557	0.191664	−0.310282	−0.344834	0.102395
Kurtosis	2.047985	2.457083	2.291874	1.728965	2.192839	1.761498	1.660993	1.450170
Jarque-Bera	1.663364	1.550519	5.916976	2.894713	1.430556	3.438184	4.064544	4.378674
Probability	0.435316	0.460584	0.051897	0.235191	0.489056	0.179229	0.131037	0.111991
Sum	226,228.3	516,629.9	3,772.701	5.86E+14	80,675,268	41,886,291	59,273,554	32,995,648
Sum sq. dev.	9,141,953	7.42E+08	3,198.337	7.52E+26	5.21E+12	2.73E+11	4.52E+12	1.12E+12
Observations	43	43	43	43	43	43	43	43

4.2 Unit root test results

At the beginning of the process, the series' first-order stationarity must be proved. In essence, As stated by Jordan and Philips (2018), the dependent variable must satisfy condition I(1), and the other series must remain stable at I(1) before being integrated further. Phillips Perron and ADF unit root tests were conducted for this aim. The results of both tests are shown in Table 3. The results of the tests showed that the existence of a unit root is denied for all series, implying a first-order integration of all variables.

Table 3 ADF and PP tests' results

Augmented Dickey, Fuller (ADF)				
	I(0)		*I(1)*	
Variables	*With intercept*	*With intercept and trend*	*With intercept*	*With intercept and trend*
$logCO_2$	–1.363622	0.090820	–2.794096*	–7.326719***
logGDP	–1.920091	–1.029686	–5.477138***	–5.833662***
logEC	–2.551045	–0.878975	–3.506221**	–6.983074***
logAIR	–2.264965	–1.676340	–4.975244***	–5.171541***
logRT	–1.314810	–0.759106	–6.122243***	–7.084710***
logHWT	–1.329253	–2.870032	–7.932731***	–7.785202***
logWT	–0.775369	–2.943175	–2.891248*	–2.839923
logPT	–1.816491	–1.554190	–6.259211***	–6.257389***
Phillips and Perron (PP)				
	I(0)		*I(1)*	
Variables	*With intercept*	*With intercept and trend*	*With intercept*	*With intercept and trend*
$logCO_2$	–1.297491	–0.874632	–6.545441***	–7.197841***
logGDP	–2.121955	–1.018371	–5.477138***	–5.837997***
logEC	–1.265822	–1.346379	–6.239204***	–6.540444***
logAIR	–2.129577	–1.735225	–5.037231***	–5.195308***
logRT	–1.313145	–0.562472	–6.134828***	–6.464193***
logHWT	–1.329253	–2.851096	–8.039313***	–7.878192***
logWT	–0.687970	–2.507229	–7.417279***	–7.312368***
logPT	–1.955657	–1.819870	–6.259735***	–6.258014***

4.3 Johansen cointegration results

A summary of the Johansen cointegration computations, including Eigenvalues and t-statistics at critical values of 0.05, is shown in Table 4. To compare, an eigenvalue is a non-zero vector that shifts when a linear transformation is performed, while the trace test counts the series of linear combinations in a time series. At the 5% level of significance, the results of the trace test's T-statistic suggest the existence of a cointegrating vector between the variables. Through these calculations, we learn that the USA' CO_2 emissions, GDP, energy consumption, air travel, rail travel, highway travel, and water transport all exhibit long-term cointegration. Results indicate that there is no cointegration in model 5. The cointegration test of Johansen produces predicts of all cointegrating vectors, indicating that cointegration regression should be performed.

Table 4 Johansen-Juselius cointegration tests' results

Null hypothesis	*Eigen value*	*Trace stats*	*0.05 critical value*	*Prob.*
Model 1 (AIR)				
r = 0	0.731724	94.68859	47.85613	0.0000*
r ≤ 1	0.484709	42.05908	29.79707	0.0012*
r ≤ 2	0.239331	15.53818	15.49471	0.0493*
r ≤ 3	0.108542	4.595896	3.841465	0.0320*
Model 2 (RAIL)				
r = 0	0.583235	89.45056	47.85613	0.0000*
r ≤ 1	0.569203	54.44124	29.79707	0.0000*
r ≤ 2	0.323457	20.75652	15.49471	0.0073*
r ≤ 3	0.120282	5.126147	3.841465	0.0236*
Model 3 (HIGHWAY)				
r = 0	0.580435	87.94275	47.85613	0.0000*
r ≤ 1	0.508368	53.20132	29.79707	0.0000*
r ≤ 2	0.380185	24.80030	15.49471	0.0015*
r ≤ 3	0.132095	5.666912	3.841465	0.0173*
Model 4 (WATER)				
r = 0	0.674892	94.36896	47.85613	0.0000*
r ≤ 1	0.508562	49.42504	29.79707	0.0001*
r ≤ 2	0.323540	21.00823	15.49471	0.0067*
r ≤ 3	0.125694	5.372977	3.841465	0.0204*
Model 5 (PIPE)				
r = 0	0.500758	71.55671	47.85613	0.0001*
r ≤ 1	0.485375	43.77011	29.79707	0.0007*
r ≤ 2	0.273421	17.19744	15.49471	0.0275*
r ≤ 3	0.104639	4.421129	3.841465	0.0355*

Notes: The ideal lag length is used for calculating the HQ, AIC, and SC (lag 1).
A critical value of 5% is considered statistically significant and is denoted by '*'.

4.4 ARDL long run coefficient estimation

After ensuring that the econometric conditions were met and that both a short-run and a long-run relationship existed between the variables of interest, we proceeded with the ARDL estimation in order to determine the impact, both positive and negative, that economic factors have on CO_2 emissions in the US Estimations of ARDL long-term coefficients are presented in Table 5. The findings of the study indicate that an expanding economy and a rise in energy consumption have a large and beneficial effect on CO_2 emissions over the course of a long stretch of time. Across models (1, 2, 3, 4, 5), a 1%

increase in GDP growth leads to a 0.38%, 0.43%, 0.44%, 0.44%, and 0.41% increase in carbon dioxide in long-term. These findings are aligned with Akadiri and Adebayo (2022) on India, Karaaslan and Çamkaya (2022) on Turkiye, Raihan et al. (2022) in Bangladesh, Shabani et al. (2022) in ECO countries, Ge et al. (2022) on China, Weimin et al. (2022) on globalised countries, and Peng et al. (2022) in BRICS countries.

In the same way, a 1% increase in energy use across models (1, 2, 3, 4, 5) leads to a long-term increase in CO_2 emissions of 1.09%, 0.91%, 0.94%, 0.97%, and 0.94%, respectively. In contrast to Mohsin et al. (2022) in Asian countries these results are supported with the studies of Ge et al. (2022) on China, Jin et al. (2022) on developed countries, Karaaslan and Çamkaya (2022) on Turkey, Mujtaba et al. (2022) on OECD countries, and Acheampong et al. (2022) on EU countries.

Table 5 ARDL long-term coefficient estimation results

Variables (CO_2 dependent variable)	*Coefficient*	*Std. error*	*t-Statistics*	*Prob.*
Model 1 (AIR)				
AIR	–0.039069***	0.013374	–2.921150	0.0071
GDP	0.380517***	0.095048	4.003414	0.0005
EC	1.093899***	0.075147	14.55683	0.0000
Model 2 (RAIL)				
RT	0.030998	0.028363	1.092933	0.2853
GDP	0.436283***	0.097317	4.483105	0.0002
EC	0.914595***	0.083585	10.94204	0.0000
Model 3 (HIGHWAY)				
HWT	–0.004616	0.013992	–0.329883	0.7446
GDP	0.448435***	0.100710	4.452722	0.0002
EC	0.940463***	0.075244	12.49892	0.0000
Model 4 (WATER)				
WT	–0.033600	0.031633	–1.062179	0.2987
GDP	0.442991***	0.103489	4.280582	0.0003
EC	0.977615***	0.081420	12.00711	0.0000
Model 5 (PIPE)				
PT	–0.063516**	0.024150	–2.630078	0.0144
GDP	0.415771***	0.095333	4.361251	0.0002
EC	0.942213***	0.072884	12.92762	0.0000

Note: The symbols ** and *** indicate 5% and 1% statistical significance, respectively.

Long-term relationship between transportation modes and CO_2 emissions are also examined in different models, which are the primary focus of the study. Long-term CO_2 emissions are negatively impacted by air transportation, pipeline transportation, and water transportation. Transport by air, and via pipeline are statistically significant, but transport by water is statistically insignificant. Findings of the model 1 indicate that a rise in air freight transportation leads to a reduction in CO_2 emissions over a period of more than forty years. The unexpected result may be explained by the progress in aviation technology, enhanced fuel efficiency, and strict regulatory restrictions that have greatly decreased the environmental impact of air freight throughout the years. Similarly, the findings suggest that the use of pipeline transportation leads to a decrease of 0.06% in carbon dioxide (CO_2) emissions over a period of 42 years. The explanation for this phenomenon might lies in the comparative energy efficiency and reduced emissions of pipelines in comparison to alternative methods of transporting goods, together with ongoing enhancements in pipeline infrastructure and operations. These observations emphasise the capacity of particular transportation methods to support long-term sustainability objectives. On the other hand, rail and highway transportation have statistically insignificant negative effects on CO_2 emissions. The model 1 outcome agrees with Chatti and Majeed (2022), but it is inconsistent with Habib et al. (2022) and Gyamfi et al. (2022). In line with Ben Jebli and Belloumi (2017) long-term CO_2 emissions rise with the use of rail transportation, as predicted by model 2. In line with Chatti and Majeed (2022), model 3 is supported that the highway transportation results in increasing CO_2 emissions. There are not many studies related to transportation modes and CO_2 emissions relations in holistic approach. That makes this study distinctive in the literature.

Table 6 Diagnostic analysis

Diagnostic statistic tests	*F-stat. (P-Value)*	*Results*
Model 1 (AIR)		
Breusch-Godfrey LM	0.439318 (0.6496)	No problem of serial correlations
Breusch-Pagan-Godfrey	0.834829 (0.6087)	No evidence of heteroscedasticity
Ramsey RESET test	0.182216 (0.6731)	Model specified correctly
Jarque-Bera	3.838703 (0.1467)	Estimated residual is normal
Model 2 (RAIL)		
Breusch-Godfrey LM	0.518889 (0.6023)	No problem of serial correlations
Breusch-Pagan-Godfrey	0.545918 (0.8716)	No evidence of heteroscedasticity
Ramsey RESET test	0.271171 (0.6075)	Model specified correctly
Jarque-Bera	0.972296 (0.6149)	Estimated residual is normal
Model 3 (HIGHWAY)		
Breusch-Godfrey LM	0.226565 (0.7993)	No problem of serial correlations
Breusch-Pagan-Godfrey	1.021048 (0.4707)	No evidence of heteroscedasticity
Ramsey RESET test	0.720412 (0.4792)	Model specified correctly
Jarque-Bera	0.515445 (0.7728)	Estimated residual is normal
Model 4 (WATER)		
Breusch-Godfrey LM	0.260574 (0.7730)	No problem of serial correlations
Breusch-Pagan-Godfrey	0.682094 (0.7611)	No evidence of heteroscedasticity
Ramsey RESET test	0.699601 (0.4115)	Model specified correctly
Jarque-Bera	0.279862 (0.8694)	Estimated residual is normal
Model 5 (PIPE)		
Breusch-Godfrey LM	2.392883 (0.1137)	No problem of serial correlations
Breusch-Pagan-Godfrey	1.256673 (0.3023)	No evidence of heteroscedasticity
Ramsey RESET test	0.191492 (0.6656)	Model specified correctly
Jarque-Bera	0.943164 (0.6240)	Estimated residual is normal

Figure 1 CUSUM, CUSUMSQ and AIC graph for model 1 (see online version for colours)

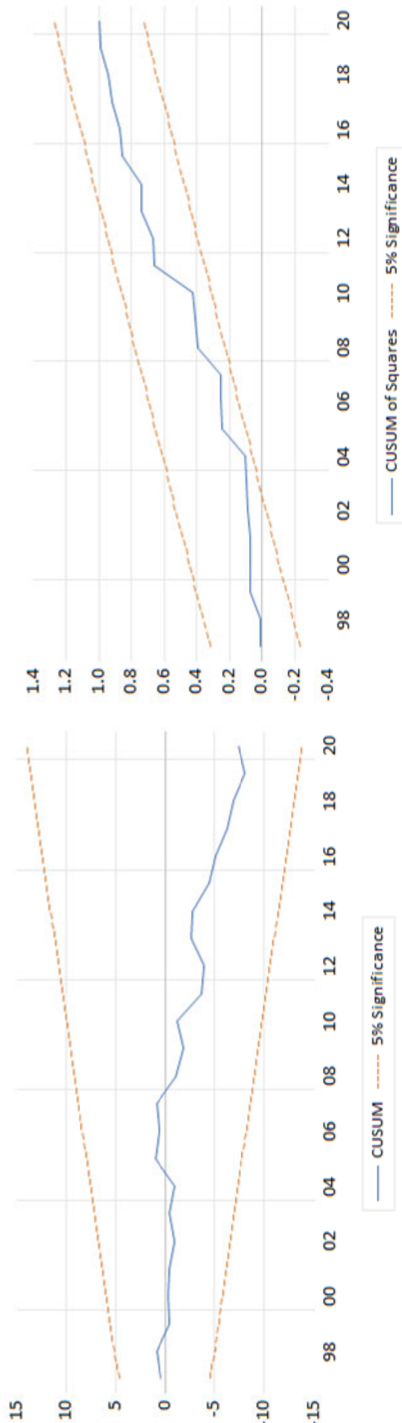

Figure 2 CUSUM, CUSUMSQ and AIC graph for model 2 (see online version for colours)

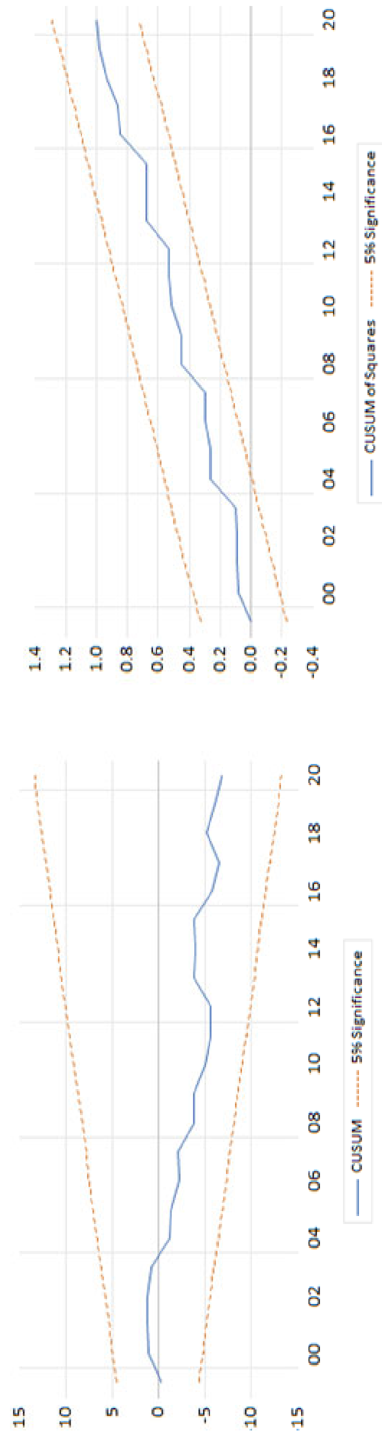

Figure 3 CUSUM, CUSUMSQ and AIC graph for model 3 (see online version for colours)

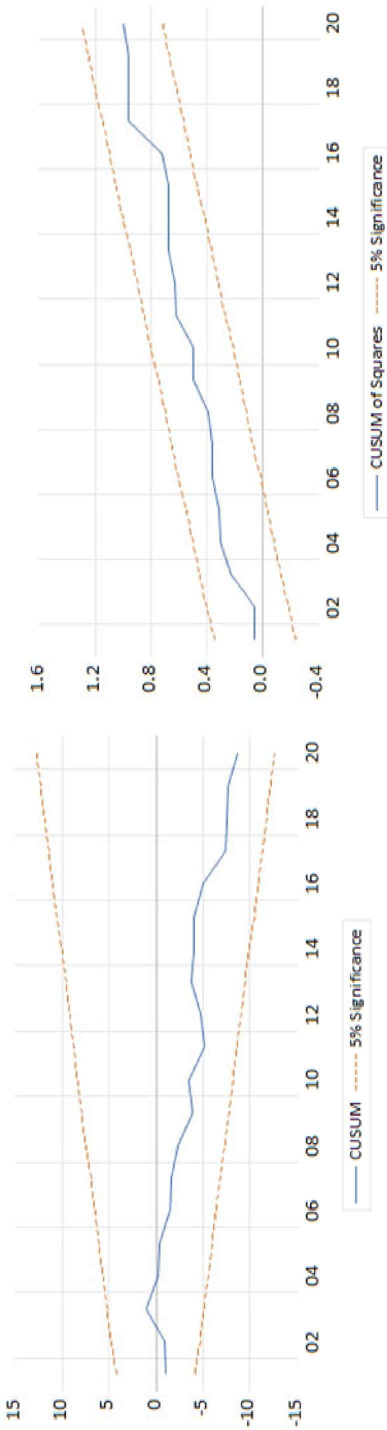

Figure 4 CUSUM, CUSUMSQ and AIC graph for model 4 (see online version for colours)

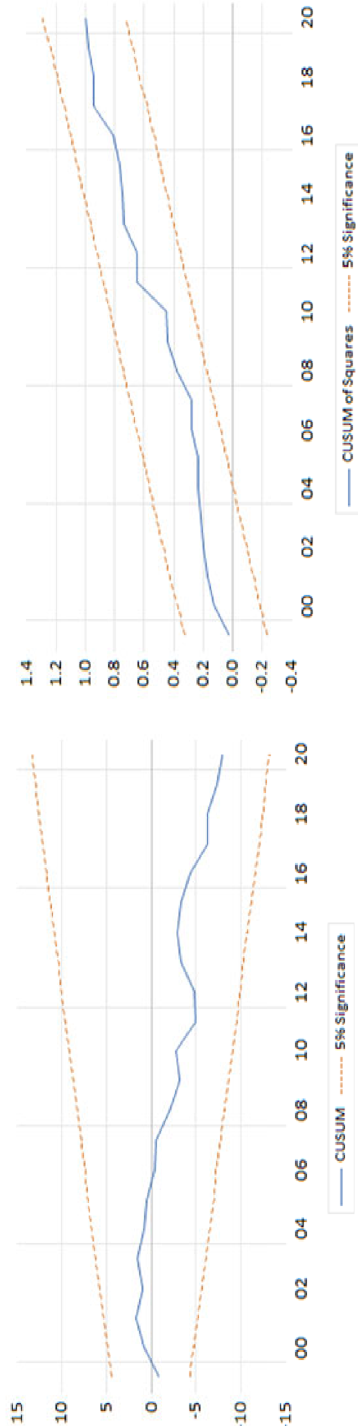

Figure 5 CUSUM, CUSUMSQ and AIC graph for model 5 (see online version for colours)

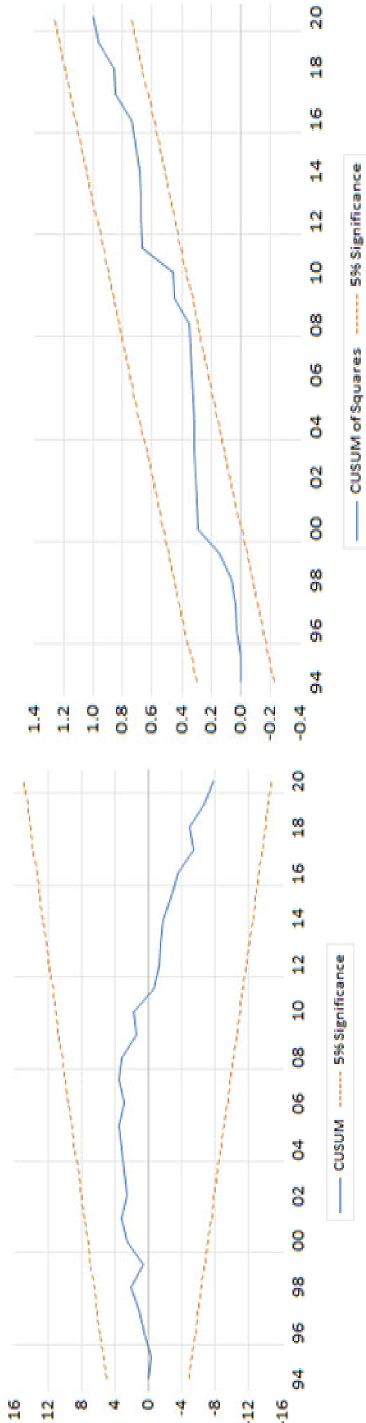

Table 7 Pairwise Granger causality results

Null hypothesis	*F-Statistics*	*Prob.*	*Null hypothesis*	*F-Statistics*	*Prob.*	*Null hypothesis*	*F-Statistics*	*Prob.*
AIR≠CO2	3.87774**	0.0301	RAIL≠CO2	1.22202	0.3069	WATER≠CO2	0.63549	0.5357
CO2≠AIR	2.51319*	0.0955	CO2≠RAIL	0.06265	0.9394	CO2≠WATER	2.55329*	0.0922
EC≠CO2	0.38644	0.6823	EC≠RAIL	0.33988	0.7142	EC≠WATER	2.08104	0.1400
CO2≠EC	0.00625	0.9938	RAIL≠EC	1.61155	0.2140	WATER≠EC	0.76355	0.4736
GDP≠CO2	1.22073	0.3073	GDP≠RAIL	0.70930	0.4989	GDP≠WATER	0.53415	0.5909
CO2≠GDP	1.01054	0.3744	RAIL≠GDP	0.91954	0.4081	WATER≠GDP	0.19660	0.8224
EC≠AIR	2.41997	0.1037	HWT≠CO2	1.02292	0.3700	PT≠CO2	4.41885**	0.0194
AIR≠EC	6.29825***	0.0046	CO2≠HWT	2.05000	0.1439	CO2≠PT	4.52727**	0.0178
GDP≠AIR	2.20957	0.1248	EC≠HWT	1.91046	0.1631	EC≠PT	3.47517**	0.0420
AIR≠GDP	2.76803*	0.0766	HWT≠EC	0.62679	0.5402	PT≠EC	3.21577*	0.0522
GDP≠EC	0.73487	0.4868	GDP≠HWT	5.13235**	0.0111	GDP≠PT	1.55755	0.2249
EC≠GDP	1.77785	0.1839	HWT≠GDP	0.57357	0.5687	PT≠GDP	1.70914	0.1958

Note: Significant levels of 10%, 5%, and 1% are indicated by the use of the symbols *, **, and ***.

The results of the reliability tests may be seen in Table 6; they ensure that the chosen direction of analysis is appropriate and accurate. The reliability test covers two of the most important tests: the Breusch-Godfrey Serial correlation and the heteroscedasticity tests. Further, the Jarque-Bera and the Ramsey RESET tests, respectively, proved the cross-check of the model's correctness and the normal distribution of the residuals. In reliability tests, if the null hypothesis is not rejected, it means that the model does not include any of the irregularities often seen in data series, and that the results are accurate and reliable.

The CUSUMSQ, CUSUM, and Akaike information criterion tests are used to ensure model stability. In Figures 1, 2, 3, 4, 5, the graphical representations of AIC, CUSUM, and CUSUMSQ reveal that both are positioned in blue between the top and lower boundaries. Both the lower and upper limit control lines are indicated in red. In both CUSUM and CUSUMSQ, the null line is always represented as a dark shade of black in the middle. The AIC chart depicts the best 20 predicted models according to a criterion that may be used to compare how well different options match the data.

4.5 Granger causality results

Granger causality, which identifies the links between variables, produces the results seen in Table 7. When trying to establish a causal relationship between two variables in the short term, the Granger causality test is the gold standard. At a 10% level of CO_2 output, the impact on air travel is neutral. There is strong evidence that CO_2 emissions affect air transportation. The bidirectional association between CO_2 emissions and air travel has been verified. Expansion of the air transportation has contributed to the consumption of energy in much the same way as it has causality to the pipeline transportation. There is a unidirectional causality from GDP to highway transportation. Also, there is a unidirectional causality from CO_2 emissions to water transportation. In a similar way, there are positive effects that go two ways between pipeline transportation and energy use. Lastly, there is a bidirectional causality among CO_2 emissions and pipeline transportation.

5 Final remarks

As a result of the production of various kinds of greenhouse gases, the average temperature of the planet is steadily increasing. The release of carbon dioxide (CO_2) is a major source of overall emissions of greenhouse gases and undermines the viability of the ecosystem. Maintaining a constant rate of carbon dioxide emissions is widely acknowledged as an effective strategy for mitigating the effects of global warming and advancing the cause of environmentally sustainable activities. This research analyses the link between environmental deterioration (proxied by CO_2 emission) with transportation through five different transportation modes including air, rail, land, water and pipeline with GDP and energy consumption in the context of USA for the period 1980–2022. By examining the connection between CO_2 emissions and all forms of transportation in the USA, including pipeline transportation, the new research is novel and helps close a gap in the literature.

When looking at long-run equilibrium relationships, the ARDL approach, which was introduced by Pesaran et al. (1999, 2001), is used as the investigative tool. According to the estimations provided by ARDL, there is substantial evidence of a link between CO_2 emissions, transportation, energy consumption, and economic growth in the USA over the long-term. A statistically significant negative relationship between CO_2 emissions and air and pipeline transportation is established, but a positive insignificant link among carbon dioxide emissions and rail and highway transportation for the USA. There is also a negative and insignificant relationship between CO_2 emissions and water transportation. A 1% increase in air transportation decreases CO_2 emissions by 0.03% and 1% increase in pipeline transportation decrease CO_2 emissions by 0.06%. Statistically insignificantly, 1% increase in rail transportation increases CO_2 emissions by 0.03%; 1% increase in highway transportation decreases CO_2 emissions by 0.004%; and 1% increase in water transportation decreases CO_2 emissions by 0.03%. Additionally, CO_2 emissions rise by 0.3% and 1.0% for every 1% increase in economic growth and energy consumption, respectively, across all models. Lastly, the ARDL explored long-term relationships while Granger causality test is used to explore all variables' causality relationships. As shown by the granger causality test, the link between CO_2 emissions and air travel is bidirectional, with emissions serving as a cause of air transportation. Second, energy usage and air travel both have a reciprocal causal link. Carbon dioxide emissions from transportation through pipelines, water transportation, and energy use, both increase as a result of the other. There are no causalities found between other modes of transportation and CO_2 emissions.

An important implication and contribution in the area is represented by the fact that the study places an emphasis on the disaggregated impacts of different modes of transportation on CO_2 emissions. Previous research frequently portrays the transportation industry as a single entity, neglecting to take into consideration the subtle distinctions that exist across the modes of transportation, including air, pipeline, water, rail, and highway transportation. The study fills a fundamental gap in the current literature by separating these impacts, which allows it to propose more specific policy suggestions that are suited to each mode of transportation.

According to the findings, the air transportation system in the USA follows the directions provided by the FAA in order to cut down on the amount of carbon dioxide emissions. According to the report that was published by the FAA (2021), the goal is to construct a sustainable aviation system that has a net zero carbon footprint by the year 2050. In order to accomplish this goal, the aviation industry has made significant strides toward implementing more environmentally responsible business practices. It can be seen that the action plans of the FAA, such as developing environmentally friendly aviation fuels, developing innovative aircraft and engine technologies, and increasing operational efficiencies, have begun to show the effects they were intended to have. There is a need to implement clear goals such as FAA's 'Net Zero Emissions by 2050' in other transportation modes such as rail and highway transportation. Long-term CO_2 emissions might be greatly reduced if the transportation sector made increased reliance on sources of renewable energy. Even with renewable energy, to avoid the emissions of energy transportation, it's important to be able to generate electricity merely in site as Yildiz et al. (2022, 2023) suggested in their study. It is possible that these are solar panel installations on the airport's roof. Because of its installation and production capabilities, inefficiencies and emissions that are a by product of manufacturing and transmission will be eradicated.

Based on the results there several policy implications can be made.

1 In air transport, investments should be made in more efficient aircraft technologies and the use of biofuels should be encouraged.

2 For rail transport, it is important to roll out electrified train lines and modernise existing infrastructure.

3 For road transport, increase the use of electric and hybrid vehicles and promote low-emission fuels.

4 For maritime transport, investments should be made in technologies to increase energy efficiency in ships and the use of green energy in ports should be expanded.

5 In pipeline transportation, regular maintenance and modern monitoring systems should be used to prevent leakages, and integration with renewable energy sources should be ensured.

The assumption of a direct link between GDP growth and transportation volumes is based on the theories of economic growth and transportation demand. According to economic theory, transportation is a derivative demand, meaning that as economic activity increases, so does the need for the movement of goods and services. As GDP grows, production, trade and consumption activities increase, which in turn requires greater mobility of goods and people. This relationship is often found in macroeconomic models. Empirical studies also support this relationship. For example, reports published by the World Bank and the OECD show that transportation activities increase during periods of economic growth. Sectoral studies also show that economic growth increases transportation volumes in sectors such as automotive, aviation and maritime. However, this assumption has some limitations. The relationship between GDP growth and transportation volumes may not always be linear; technological innovations, regulatory policies and environmental factors may affect this relationship. Moreover, different sectors and regions may respond differently to this relationship.

Besides, the study has some limitations. Limitations of this study include the fact that other factors such as transport demand, changes in transport modes, changes in travel and transport behaviour, changes in technology, changes in fuel types and fuel prices were not investigated. The assumption of a direct link between GDP growth and transportation volumes is based on the theories of economic growth and transportation demand. According to economic theory, transportation is a derivative demand, meaning that as economic activity increases, so does the need for the movement of goods and services. As GDP grows, production, trade and consumption activities increase, which in turn requires greater mobility of goods and people. This relationship is often found in macroeconomic models. Empirical studies also support this relationship. Studies show that economic growth increases transportation volumes in sectors such as automotive (Kveiborg and Fosgerau, 2007), aviation (Chi and Baek, 2013) and maritime (Akbulaev and Bayramli, 2020). However, this assumption has some limitations. The relationship between GDP growth and transportation volumes may not always be linear; technological innovations, regulatory policies and environmental factors may affect this relationship. Moreover, different sectors and regions may respond differently to this relationship. Therefore, it is important to consider these limitations to discuss the validity of the assumption and make the model more comprehensive. Technological improvements play a critical role in reducing CO_2 emissions across various modes of transportation. While our current model focuses on GDP growth and energy consumption, it is necessary to acknowledge the significant impact of technological and operational improvements on transport emissions (Barth et al., 2015). The automotive industry has significantly reduced CO_2 emissions over the last two decades, thanks to engine efficiency, the proliferation of hybrid and electric vehicles, and improvements in fuel quality (Nicolas, 2000). The aviation sector has made significant progress in areas such as the development of more fuel-efficient aircraft and the potential use of sustainable aviation fuels (SAF)(Sustainable Aviation Fuel Market Size, Trends and Industry Report 2028, 2023). The maritime industry has accelerated its efforts to reduce CO_2 emissions over the last decade with the adoption of energy efficiency technologies and the transition to cleaner fuel alternatives such as LNG (Bouman et al., 2017). Rail transportation is increasing its sustainability through innovations such as the expansion of electrified networks and the use of regenerative braking systems (Mckinsey, 2023). Incorporating these technological developments into emissions models provides a more complex but more accurate and comprehensive understanding. Future research should aim to integrate these factors, considering the adoption rates of new technologies, the impact of regulatory policies and the potential for innovation. In this way, the dynamics affecting transport emissions can be better understood and will support the transition to a more sustainable transport system. In this way, it will be possible to develop more holistic and effective strategies for policy makers.

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