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The imperativeness of environmental quality in the United States transportation sector amidst biomass-fossil energy consumption and growth

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A B S T R A C T

The recent historical increase in energy-related CO_2 emissions globally have put the United States of America's (USA) transportation sector in the spotlight, courtesy of the significantly high pollutant emissions from this particular sector. Taking a cue from this, this paper follows sustainable development goals of the United Nations, and investigates the impact of biomass energy consumption, fossil fuel energy consumption, and economic growth (GDP) on carbon dioxide (CO_2) emissions in the transportation sector of the USA. In doing so, this study also employs the Gregory-Hansen cointegration, Hatemi-J cointegration, cointegration regression (FMOLS, DOLS, and CCR), and Spectral Breitung-Candelon causality test for the period between 1981Q1 and 2019Q4. The findings reveal that (i) a significant nonlinear cointegration among the environmental quality determinants is observed, using the threshold cointegration test. This test determines the structural breaks endogenously and combines two cointegration tests, namely the Gregory-Hansen Cointegration and Hatemi-J Cointegration tests; (ii) while the use of biomass energy consumption and real GDP have a negative effect on CO_2 emissions in the transportation sector, the rising fossil fuel energy consumption is associated with increasing the CO_2 emissions that are stemming from the transportation sector; (iii) in the long-run, biomass energy consumption, fossil fuel energy consumption, and real GDP cause CO_2 emissions to stem from the transportation sector in the USA at different frequency levels. In general, the current study offers policy insights for the transportation sector of the USA and other similar economies that replicate the same conditions.

1. Introduction

Over the years, greenhouse gas (GHG) emissions have been considered to be the primary reason for climate change. This realization has necessitated the invention and introduction of initiatives such as the mitigation policies of GHG emissions by global governments and intergovernmental organizations. In the last few decades, several climate change frameworks that are directed towards mitigating carbon dioxide (CO_2) emissions (which are the main components of the GHG emissions) have been reviewed consistently in order to suit the socioeconomic and environmental targets of the world (e.g., the United Nations Framework Convention on Climate Change, UNFCCC[1]). In 2015, a new set of sustainable development goals (SDGs) was identified in various critical international summits so as to aim to reduce GHG emissions through the UNFCCC. However, even after such discussions have taken place, the world has yet to experience relief from the dilemma of

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[1] Detailed information on The United Nations Framework Convention on Climate Change (UNFCCC) is available at https://unfccc.int/.

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Nomenclature

ADF	Augmented Dickey-Fuller
BEVs	Battery Electric Vehicles
Btu	British Thermal Units
CO_2	Carbon Dioxide
CCR	Canonical Cointegrating Regression
DOLS	Dynamic Ordinary Least Squares
EIA	Energy Information Administration
EVs	Electric Vehicles
FMOLS	Fully Modified Ordinary Least Squares
FRED	Federal Reserve Economic Database
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HEVs	Hybrid Electric Vehicles
TBEC	Biomass Energy Consumed by the Transportation Sector
TCO_2	Carbon Dioxide in the Transportation Sector
TFEC	Fossil Fuel Energy Consumption by the Transportation Sector
PHEVs	Plug-in Hybrid Electric Vehicles
SDGs	Sustainable Development Goals
UNFCCC	United Nations Framework Convention on Climate Change

decoupling economic growth from global warming. This is primarily because of the significant contribution of CO_2 emissions in the earth's atmosphere due to the global and national economic activities that people indulge in, e.g., tourism, industrial manufacturing and transportation (Ji et al., 2020; Ike et al., 2020).

For instance, in the USA, the transportation sector was reported to have consumed around 28% of the total energy in the year 2019. This figure resulted from a spike in energy consumption over the years, compared to a contribution of 23.5% in the 1960s (IEA, 2020). It is important to note that most of these energy sources come from liquid carbon-based fuels, which actively lead to GHG emissions, and as a result, poor air quality for us to enjoy. The USA economy may be a leading economy of the world, but at the same time, it is also a leader in harmful carbon emissions. Moreover, statistics showed that about 28% of the GHG emissions experienced by the USA in the year 2018 are associated with their transportation sector, thus making this sector the most significant contributor to anthropogenic GHG emissions (see Table 1) (EPA, 2020). Hence, the current study focuses on energy-related determinants, which contribute to the increase in CO_2 emissions in the transportation sector of the USA. This study can offer policy insights for the USA's transportation sector and other global economies which are characterized by similar features, e.g., China. Moreover, in this research, linkages and comparisons are made between the USA and China so as to get a better understanding of the dynamics of the possible environmental hazards that may or may not unfold in the future (Alola et al., 2019; Umar et al., 2020b). Thus, the current study can contribute towards achieving a sustainable global climate.

The dual challenge that the transportation sector is primarily facing revolves around the most efficient and effective way to keep the world moving while also reducing emissions. In the next 20 years, the transportation sector is expected to be the leading force which will drive, and increase the demand for global energy. In developed countries, the transportation sector accounts for the largest end-use of energy, and in most developing countries, it is the quickest growing end-use of energy. The rise in energy consumption is considered to be one of the key causes of today's global environmental issues that pertain specifically to the transportation sector (Ercan et al., 2016). In developed countries like the USA, these concerns become even more prominent due to the rapidly growing transportation sector (Alirezaei et al., 2017; Ercan et al., 2017). The USA transportation sector consumes about 30% of the country's total energy resources and accounts for 92% of the energy demand for petroleum. Furthermore, almost 70% of the overall oil consumption in the USA accounts for the volume of fuel that is required to satisfy the demand for transportation, and about 65% of the fuel is used by private vehicles operated by individuals (EIA, 2018). Such a high consumption of fuel makes the transportation industry the leading carbon emitter in the world. In the past 40 years, the global transportation sector's GHG emissions rose by 250%, from 2.8 Gt CO_2e in 1970 to 7.0 Gt CO_2e, by the year 2010. If the same trends continue, such emissions could hit a spike of an astounding 12 Gt CO_2e/year by 2050, without any mitigation activities in the pipelines (Edenhofer et al., 2014). Similarly, transportation can also be considered as a significant source of air pollutants that contribute to about 12–70% of the world's pollution of a particulate matter (WHO, 2020).

The transportation sector has proliferated and has subsequently maintained its connection and relevance to developed and developing countries' economic growth. However, significant environmental hazards are associated with this increased energy consumption and the subsequent CO_2 emissions in the environment (Mercure and Lam, 2015). Over the last few decades, newer renewable energy sources, such as bioenergy, hydropower, geothermal, solar, wind energy, and ocean energy, are being explored as probable alternatives to carbon-powered fuel. Moreover, it can be said that a more practical approach in tackling environmental problems is now being taken into consideration by some (Owusu and Asumadu-Sarkodie, 2016). By the year 2030, transportation centric energy consumption and CO_2 emissions will increase by more than 50%, and transportation-related CO_2 emissions are projected to increase from one-third to one-half of the global emissions in developing and transition countries (IEA, 2019). Unfortunately, the nature and contribution of the transportation sector to national and global economic growth is such that it is

Table 1
The US GHG emission components by end-use sector in 2018.

	Carbon dioxide	Methane	Nitrous oxide	Fluorinated gases	Total GHGs
Residential	992.70	4.90	10.10	34.70	1042.40
Commercial	863.60	128.90	16.10	62.20	1070.80
Agricultural	86.20	298.30	358.30	0.60	743.40
Industrial	1601.30	263.20	36.50	47.20	1948.20
Transportation	1834.70	1.40	12.90	38.50	1887.50
Total GHG emissions	5378.50	696.70	433.90	183.20	6692.30
Transportation share of total	34%	0%	3%	21%	28%

Source: US Environmental Protection Agency (US EPA, 2020).

considered to be the most challenging sector when it comes to make efforts to reduce global emissions (Onn et al., 2018; Zheng et al., 2019). Although a reduction in emissions was observed in the year 2017, an increase of 3.1% in CO_2 emissions was recorded in 2018 (IEA, 2019). Consequently, the dynamics above for the transportation sector carbon emissions still remain the main reason for the ubiquitous demand for renewable energy sources (Destek and Sinha, 2020; Nguyen and Kakinaka, 2019).

Moreover, with the global concerns raised on CO_2 emissions dynamics, the demand for clean energy sources seems to have increased globally (Dong et al., 2018; Liu and Lin, 2018). The reason for this is hinged on the perspective that the introduction of clean energy sources can reduce CO_2 emissions by at least 0.4 billion tons in the year 2020 (WHO, 2015). In this context, it is noteworthy that biomass energy is one of the most important renewable energy sources and happens to be more attractive than other forms of renewable energy. The biomass energy source is a type of cleaner renewable energy that is capable of reducing pollution (Dogan and Inglesi-Lotz, 2017; Wang, 2019). However, this assertion is a contradictory one. For example, some studies revealed that biomass energy reduces CO_2 emissions (Bilgili et al., 2016; Inglesi-Lotz and Dogan, 2018), while Solarin et al., 2018 suggested that biomass energy replicates the role of fossil fuels by growing the CO_2 emissions.

Meanwhile, the majority of the studies focus on examining the role of energy consumption in carbon abatement strategies, but the trend of CO_2 emissions in the transportation sector is less studied. For example, Saboori et al. (2014) used time-series data from 1960 to 2008 to explore the two-way long-term relationship between energy consumption and CO_2 emissions in the road transportation sector of OECD countries. Xu and Lin (2018) studied the drivers (population, economic growth, energy intensity, urbanization, freight and passenger transportation) of CO_2 emissions in the transportation sector for China. Solaymani (2019) analyzed the CO_2 emissions of the seven major transportation carbon emitters (the USA, China, India, Russia, Japan, Brazil, and Canada) and found the USA and China are the main contributors to transportation CO_2 emissions. Recently, Georgatzi et al. (2020) investigated the possible determinants of CO_2 emissions caused by the activities of transportation sector in 12 European countries from 1994 to 2014. In particular, none of the aforementioned studies consider the CO_2 emissions from biomass energy, even though about 5 quadrillion British thermal units (Btu) of total primary energy use in the USA is from biomass source (EIA, 2020). Moreover, the study of Aslan (2016) showed that biomass energy consumption could lead to the increase of economic growth in the USA, and if so, more biomass energy can be used in the future. Thus, it is vital to incorporate biomass energy consumption during the examination of CO_2 emissions in the transportation sector, which is the main motivation of this paper.

Based on the above motivation, this study largely contributes to the literature in several ways. Firstly, the selection of the USA's transportation sector is hinged on the fact that this sector is the largest emitter of carbon (see Table 1), and until now, studies in this context are sparse. The USA's transportation sector consumes a large amount of energy. This need for energy consumption is inspired by its massive population of 328.2 million, with real GDP per capita $65,223. In the USA, The average budget for households in 2018 was approximately 60,000 dollars, and after this staggering figure, the next big expenditure of 9800 dollars (16%) was allotted to the transportation sector (BTS, 2019). For this reason, this study aims to provide a valuable policy directive on the country's transportation system, and at the same time, it offers an important lesson for a global outlook on how to tackle this issue and maintain a sustainable living. Secondly, this study aims to provide a breakthrough in the efforts to underpin the biomass energy consumption and CO_2 nexus, and also highlights the relevance of the biomass energy portfolio to the transportation sector in the USA. In this regard, the potential impact of the transportation sector on environmental sustainability is uniquely put forward in this study. Lastly, the FMOLS, DOLS, and CCR measures are applied to study the long-term effects of the main influencing factors of CO_2 emissions in the USA transportation sector. These approaches remove the endogenous problem of cointegration regressors, and additionally, they minimize the problems that stem from the long-term association between the equation of cointegration and the changes in stochastic regression. Among the key policymakers and governments, there have been discussions regarding the existence of a positive or negative relationship between variables. These considerations can lead to the strengthening of the transportation sector by exploring innovative technologies that especially focus on environmental sustainability in the USA.

The sections of this study are organized as follows: Section 2 portrays the modes of transportation in the USA, while section 3 reviews the literature on CO_2 emissions in the USA's transportation sector. Section 4 shows the variables description, theoretical framework and the empirical modeling. Section 5 discusses the econometric methodologies. Section 6presents the analysis and discussions of the results, while Section 7 concludes the study by providing policy implications, limitations, and future research avenues.

2. The modes of transportation in the United States

The USA is the third-largest populated country globally, consists of 50 states that have, and are connected, via a vast transportation network system. The USA transportation system is divided into two categories; highway and non-highway. This system is mainly used for passenger and freight transport, as shown in Fig. 1. Table 2 shows the number of highway and non-highway transportation in the USA, as well as the number of registered motorcycles (8,666,185) and trucks (13, 233, 910), respectively, in 2018. This table also shows that the growth of these vehicles has doubled in 1990 when it comes to their contribution in highway transportation. Other modes of transportation have also shown a considerable increase. Additionally, in non-highway transportation: rail, air, and water traffic numbers have shown a

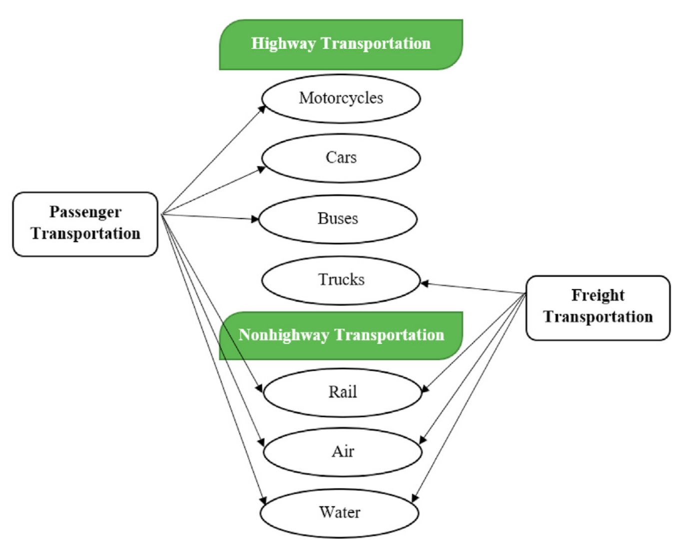

Fig. 1. Modes of transportation.

Table 2
Number of highway and non-highway transportation in the US, 1990 and 2018.

	1990	2018	Growth (%)
Highway Transportation			
Motorcycles	4,259,462	8,666,185	103.46
Passenger Cars	181,975,051	192,856,211	5.98
Buses	626,987	992,152	58.24
Trucks	6,195,876	13,233,910	113.59
Transit Vehicles	93,430	135,426	44.95
Nonhighway Transportation			
Air			
Air carrier	6083	7475	22.88
General aviation	198,000	211,749	6.94
Rail			
Class I, freight cars	658,902	293,742	(55.42)
Class I, locomotive	18,835	26,086	38.50
Amtrak, passenger train car	1863	1403	(24.69)
Amtrak, locomotive	318	431	35.53
Water			
Nonself-propelled vessels	33,597	32,828	(2.29)
Self-propelled vessels	8236	9310	13.04
Oceangoing self-propelled vessels	636	182	(71.38)
Recreational boats	10,996,253	11,852,969	7.79

Source: US Department of Transportation, Bureau of Transportation Statistics (BTS, 2020).

significant overall increase in the last 29 years.

The USA transportation sector is recognized as one of the most intensive systems in their energy consumption. Due to the increased numbers in both highway and non-highway transportation, the USA faces detrimental environmental problems that are proving to be hazardous for the eco-system. Table 3 shows that the highway mode accounted for 82% of USA transportation energy consumption. This essentially means that trucks and cars remain the main contributors to chemical emissions in the air. However, it must be brought into consideration that the non-highway modes account for the rest of the USA transport energy consumption.

An increase in the number of highway and non-highway modes, and energy usage in the transportation sector is posing a threat to the environment. It is noteworthy that the transportation sector is responsible for 34% of the CO_2 emissions and 28% of all GHG emissions. Table 4 shows that highway vehicles account for the majority of CO_2 emissions, while the air traffic also has a significant contribution to the CO_2 emissions in the non-highway mode.

Table 4
Transportation CO_2 Emissions (Million metric tons) by Mode in the US, 1990 and 2017.

	1990	2017	Growth (%)	Percentage of total	
				1990	2017
Highway Transportation					
Passenger Vehicles	926.60	1059.00	14.29	63%	59%
Trucks	237.70	449.70	89.19	16%	25%
Total Highway (1)	1164.30	1508.70	29.58		
Percentage of Highway	79%	84%			
Non-Highway Transportation					
Air	187.40	173.10	(7.63)	13%	10%
Rail	38.50	41.30	7.27	3%	2%
Water	44.40	40.20	(9.46)	3%	2%
Pipeline	36.00	41.40	15.00	2%	2%
Total Non-Highway (2)	306.30	296.00	(3.36)		
Percentage of Non-Highway	21%	16%			
Total (1 + 2)	**1470.60**	1804.70	**22.72**	**100%**	**100%**

Source: US Environmental Protection Agency (EPA, 2020).

3. Drivers of CO_2 emissions in transportation: A synopsis

In large economies such as the USA and China, carbon emissions from the transportation system remain one of the main components of national emission accounting. When it comes to the transportation sector, according to various studies, energy consumption, population, and economic growth consistently remain the primary determinants in the possible increase of carbon emissions in the air. Thus, this peculiar connection paves the way for the attainment of a sustainable and environmentally friendly transportation sector (Xu and Lin, 2015). Indicatively, to test this phenomenon, Lu et al. (2007) employed the Divisia index approach. During the period of 1990–2002, this task was undertaken in order to investigate the impact of the population intensity, vehicle fuel intensity, and economic growth, among others measures, on carbon emissions from the highway vehicles in Germany, Japan, South Korea, and Taiwan. The study's results revealed that rapid economic growth is a crucial determinant of increased CO_2 emissions. Except in the case of Germany in 1993, and Taiwan during the period of 1992–1996, the energy conservation performance in the observed countries was found to mitigate CO_2 emissions significantly. However, while Ercan et al. (2016) closely examined the determinants which contribute towards increased carbon emissions in the USA transportation sector, their study essentially revolved around the

Table 3
Transportation energy consumption (trillion btu) by mode in the US, 1981 and 2017.

	1981	2017	Growth (%)	Percentage of total	
				1981	2017
Highway Transportation					
Motorcycles	27	57	111.11	0.15%	0.21%
Passenger Cars	8693	6339	(27.08)	46.84%	23.84%
Buses	145	220	51.72	0.78%	0.83%
Trucks	5687	15,252	168.19	30.64%	57.36%
Total Highway (1)	14,552	21,868	50.27		
Percentage of Highway	78%	82%			
Non-Highway Transportation					
Air	1453	2231	53.54	7.83%	8.39%
Rail	541	537	(0.74)	2.92%	2.02%
Water	1270	1130	(11.02)	6.84%	4.25%
Pipeline	742	825	11.19	4.00%	3.10%
Total Non-Highway (2)	4006	4723	17.90		
Percentage of Non-Highway	22%	18%			
Total (1 + 2)	**18,558**	**26,591**	**43.29**	**100.00%**	**100.00%**

Source: US Department of Energy, Energy Information Administration (EIA, 2020).

theory that increasing the use of public transportation in the USA will lead to the mitigation of carbon emissions by a considerable level. They found that carbon emissions in the USA could be reduced by 766,000 tons annually, and this measurement could elevate to 61.3 million tons annually by 2050, if the public transportation ridership is respectively increased by 9%–25%.

Similarly, in China, where pollutant emissions per volume are the second-highest in the world, the economic growth, urbanization, and energy efficiency are among the primary determinants of the carbon emissions from the transportation sector (Sun et al., 2019; Xu and Lin, 2018). For instance, Xu and Lin (2015) employed the nonparametric additive regression models to the Chinese provincial panel data, for the period 2000–2012, in order to examine the determinants of the country's transport sector's carbon emissions. Interestingly, the study found that there is a nonlinear effect of the country's economic growth on the transport sector's CO_2 emissions, thus supporting the Environmental Kuznets Curve hypothesis. Additionally, Xu and Lin (2015) also found that the nonlinear effect of urbanization on the transportation sector's CO_2 emissions followed an inverted "U-shaped" relationship, while the energy efficiency improvement followed a positive "U-shaped" relationship. However, while investigating the state-level transportation sector carbon emissions determinants, Wang et al. (2011) utilized the logarithmic mean Divisia index approach over the period under consideration being the years 1985–2009. As a result of their investigation, Wang et al. (2011) found that the annual economic growth rate was responsible for the increase in CO_2 emissions, specifically from the transportation sector. These emissions measured an increase from 79.67 Mt in 1985, to 887.34 Mt in 2009, thus making the highways transport the highest contributors of CO_2 emissions. For the purpose of studying in detail, Wang et al. (2018) disintegrated the CO_2 emission factors of freight and passenger transportation in China. The results showed that the CO_2 emissions of freight and passenger transportation were dependent on the population and per capita GDP for both freight and passenger transportation.

Furthermore, in addition to suggesting the need for an effective carbon abatement policy, Chester and Horvath (2009) pointed out that the transportation sector's GHG emissions are much significant in the case of rail transportation, followed by roads and then aviation, in that order. At the same time, Cui and Li (2015) acknowledged roadway, railway, airway, and waterway as the four main transportation sectors in the world's 15 most powerful economies (Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, Mexico, Russia, Spain, South Korea, United Kingdom, and the United States). In the study, Cui and Li (2015) found that the two-year period (2005–2007) of low labor productivity in Japan is associated with a significant decline in the transportation sector's CO_2 emissions. Indicatively, among these 15 countries, Japan is reported to have the most substantial potential for saving and controlling environmental damage when considering the average carbon dioxide emissions. Cui and Li (2015) maintained that the influencing factors in transportation emissions are grouped together under the realm of transportation structure (such as freight turnover volume), energy structure (such as electric power, gasoline, kerosene, and diesel), technological structure (such as transportation technology research and development efficiency), and the management measures (such as tax policies). The study found that the total energy consumption in the transportation sector in the 15 countries examined significantly hampers the sector's carbon efficiency. Engo (2019) studied the decoupling relationship between Cameroon's consideration of the transportation industry and energy-related CO_2 emissions and found that CO_2 emissions increase with the extension and expansion of the transportation industry.

Considering the other side of the spectrum, non-oil energy, and low carbon energy sources are effectively being utilized in order to mitigate the effects of the transportation sector's carbon emissions (Gambhir et al., 2015; Zhang et al., 2016). In the case of China, Gambhir et al. (2015) forecasted different scenarios which considered the impact of both oil and low-carbon energy initiatives on the country's road transport sector's CO_2 emissions. In order to revert China's status as the leading global carbon emitter, Gambhir et al. (2015) observed that the ongoing efforts and policy directions were geared at reducing the country's road transport CO_2 emissions from 2.1 $GtCO_{2,}$ to 1.2 $GtCO_2$ by the year 2050. The study also implied that the reduction by over 40% in the oil product demand by 2050 would entail a comprehensive development initiative by China; however, the low-carbon scenario cost is 1.3% higher than the business-as-usual scenario, still remains a challenge. In a similar perspective, Zhang et al. (2016) opined that biofuel would remain the transportation sector's primary measure for devising a carbon mitigation strategy, for both China and the USA.

Among the available transportation alternatives, electric vehicles (EVs), Battery Electric Vehicles (BEVs) plug-in hybrid electric vehicles (PHEVs), and Hybrid Electric Vehicle (HEVs) have reemerged as strong opponents of carbon-emitting vehicles. Over the last few decades, the USA, China, and the European Union (EU), among others, have devised strategies, plans, and incentives, which are at different levels of inception and development, for the introduction of EVs, BEVs, PHEVs, and HEVs. Onat et al. (2019) observed that an eco-efficiency analysis of EVs in all the 50 states in the USA was conducted. They found that the most environmentally friendly option to access useable energy was the solar charging scenario. Faria et al. (2013) used the life cycle assessment method to link gasoline vehicles and EVs based on their environmental and economic impacts on the EU. Similarly, Onat et al. (2014) also evaluated the environmental impact of conventional, electric, battery, hybrid, and plug-in hybrid vehicles in the USA. These effects were based on a range of 19 indicators that encapsulated and aimed to analyze three charging scenarios. They have found that BEV has the lowest greenhouse gas emissions, and its energy consumption falls at the lowest ecological footprint per unit.

The USA is the second-largest emitter of CO_2 in the world. Moreover, the transportation sector is a fossil fuel-intensive and high emission sector that has become a significant contributor to the growth of CO_2 emissions in the USA. However, even the most recent contributions made by extant studies that are more relevant to this paper have not evaluated the impact of biomass energy consumption and fossil fuel energy consumption on CO_2 emissions in the transportation sector. Hence, this study is the first attempt to establish the impact of decisions intended to reduce CO_2 emissions in the environment to the best of the authors' knowledge. Despite the successful prospects of the carbon mitigation advantage that biofuel possesses, the study found that the biofuel-led decarbonization strategy of the transportation sector is less spontaneous and practical as compared to the adoption of the same policy on other transportation modes.

4. Variables description, theoretical framework, and empirical modeling

4.1. Variable source and description

The data set of this paper consists of four variables that have been considered in the case of the USA. These include CO_2 emissions in the transport sector ($lnTCO_2$), biomass energy consumed by the transportation sector (lnTBEC), fossil fuel energy consumption (lnTFEC), and the real GDP (lnGDP). As per the availability and consistency of the information available, the data for all variables start from 1981Q1 to 2019Q4, which constitutes to a total of 156 quarterly observations for each variable, and comes from two independent sources; the US Energy Information Administration (EIA, 2020) and the Federal Reserve Economic Database (FRED, 2020). The 7th, 8th, 12th, and 13th Sustainable Development Goals (SDGs) of the United Nations (UN) provide the basis for choosing the relevant variables for this study's purpose. In this regard, the UN SDGs have a strategic platform to help countries identify and resolve the key threats.

CO_2 emissions are part of the 13th SDG that aims to improve environmental sustainability by mitigating GHG emissions. These emissions lead to an increase of CO_2 in the environment, which actively contributes to global warming and eventually poses an unacceptable danger to human lives. The increased use of fossil fuels would have significant negative impact on climate change if measures to constrain and control GHG are not taken. Energy efficiency and the increased renewable energy use can help to mitigate climate change and reduce catastrophic risks that humans and other species are potentially exposed to. Biomass is present everywhere globally and can be used as a reliable and sustainable local energy source to replace fossil fuels. A sustainable way to reduce GHG emissions in the environment is to convert biomass into energy. Technologies for biomass-to-energy and its ability to use waste's energy potential are related to 7th and 12th SDGs. These innovations will be the key to successfully achieving these two goals. In this regard, SDG 12 aims to control urban waste and considers waste as an essential resource for energy production. Meanwhile, SDG 7 aims to improve the infrastructure and modernize technologies to provide safer and more efficient energy alternatives in all countries to foster productivity and protect the environment. Economic growth is part of the 8th SDG aiming to ensure complete vocational opportunities and decent jobs for all qualified workers. The objective of high productivity and full employment is to improve work prospects and industry dynamics for unemployed masses.

4.2. Theoretical framework

Many factors contribute towards CO_2 emissions in the environment. Examples of these include biomass energy consumption, fossil fuel energy consumption, and real GDP, which affect the sustainability of the environment. Biomass energy consumption can bring environmental sustainability to the country. In the discussions that revolve around climate change policies, as well as the approaches that are considered valid for sustainable growth around the world, biomass energy consumption happens to be an integral part of the efforts towards sustainability (Pata, 2018; Wang, 2019). As one of the leading sources that can be used for reducing CO_2 emissions, biomass energy plays a vital role. Moreover, it is also expected that biomass energy consumption shall inversely affect carbon emissions since it provides new and efficient means of producing and consuming energy. By altering the trend of energy production and use, with the help of biomass energy, the world could efficiently facilitate and lead to economic growth, and reaffirm its environmental protections (Baul et al., 2018). In this regard, the use of advancement in biomass resources provision would act as a firm foundation for a renewable energy network that encourages sustainable living. The use of biomass energy is considered one of the most important sources of green energy, serving as an alternative to fossil fuel energy consumption, mainly because it is clean and abundant.

The majority of GHG emissions are accounted for by fossil fuel energy consumption (Asongu et al., 2020). The USA is responsible for more GHG emissions, which are consistent with its large population and relative level of economic development. The use of fossil fuels for the transportation sector is mainly the result of global CO_2 emissions. As a result, CO_2 emissions are projected, and their use continues to rise. If the trend continues, this will have a positive effect on the growth of CO_2 emissions. In an effort to ensure stable economic growth and environmental protection at the same time, many countries are dealing with the same kind of dilemmas and challenges. Countries' economic growth drives intensive energy use, resulting in ever-increasing CO_2 emissions. Thus, it is safe to fathom that pollution is directly proportional with economic growth and development. On the other hand, economic development and growth have led to the introduction of new energy-saving and carbon-intensive technologies. The development of new, low carbon technologies will allow lower CO_2 emissions to be released into the atmosphere, but with the same energy production level to fulfill energy-related needs on a long-term basis (Sinha et al., 2020). This realization demonstrates that the long-run relationship between GDP and CO_2 emissions is negative.

4.3. Empirical modeling

Given the arguments above, a framework is developed in this study by introducing biomass energy consumption, fossil fuel energy consumption, and economic growth into the examination of the CO_2 emissions, in the USA economy. According to the purpose of this study, the basic model specification is given as:

$$CO_{2t} = f(TBEC_t + TFEC_t + GDP_t) \tag{1}$$

where, CO_{2t} indicates carbon dioxide emissions; $TBEC_t$ represents biomass energy consumption; TFEC is financial development; $TFEC_t$ indicates fossil fuel energy consumption; and $RGDP_t$ represents economic growth. It is worth mentioning that the variables are used in the natural logarithm form in the estimated models to avoid heteroscedasticity issues (Zaidi et al., 2019). A log-linear time series function in equation (2) can be rewritten as follow:

$$\ln CO_{2t} = \lambda_0 + \lambda_1 \ln TBEC_t + \lambda_2 \ln TFEC_t + \lambda_3 GDP_t + \varepsilon, \tag{2}$$

where λ_0 is the intercept, λ_1, λ_2, and λ_3 are the parameters and ε is the residual term. The sign expected is based on the theoretical structure suggested in this study. Biomass energy consumption is expected to negatively impact CO_2 emissions, i.e., $\frac{\partial CO_{2t}}{\partial TBEC} < 0$. On the other hand, fossil fuel energy consumption is expected to positively impact CO_2 emissions, i.e., $\frac{\partial CO_{2t}}{\partial TFEC} > 0$. The role of economic growth is still uncertain, which may be positive or negative i.e., $\frac{\partial CO_{2t}}{\partial GDP_t} \neq 0$. Fig. 2 shows the basic flow chart of the analysis.

The flow chart in Fig. 2 indicates the step-by-step procedure employed in the investigation. By considering the 7th, 8th, 12th, and 13th goals of the SDG, the TBEC, TFEC, RGDP, and CO_2 are selected as the variables of interest over the period from 1981Q1 to 2019Q4. The first step is to investigate the stationarity of the variables by employing the Zivot-Andrew (2002). In the second step of the estimation process, two cointegration methods, namely Gregory and Hansen (1996) and Hatemi-j (2008), are applied to examine the long-run relationship between CO_2 emissions and its determinants. In the third step, in order to gain access to the applied long-term effect studies on this particular discipline, the cointegration regression (FMOLS, DOLS, CCR) is used. Finally, the last step of the process pertains to performing due checks, which gauge the robustness, for which the causality analysis of the frequency domain approach is used.

Table 5 shows the descriptive statistics of the variables, source of data, and their respective codes, where ln denotes the logarithmic transformation of the series.

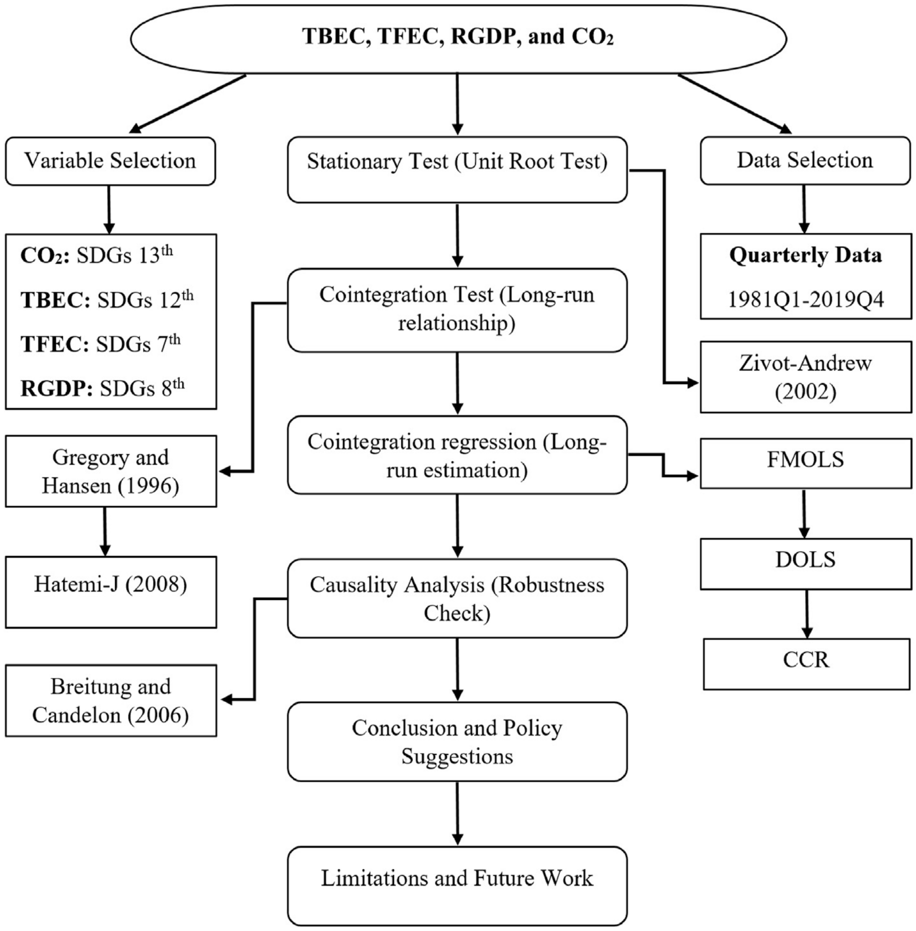

Fig. 2. Flow chart of the analysis.

Table 5
Variable description and common statistics.

Period	1981Q1-2019Q4			
Variable	CO_2 Emission in the Transportation Sector	Biomass Energy Consumed by the Transportation Sector	Fossil Fuel Consumed by the Transportation Sector	Real GDP
Unit of Measurement	(Million metric tons)	(Trillion Btu)	(Trillion Btu)	(Billions of Chained 2012 Dollars)
Code	lnTCO2	lnTBEC	lnTFEC	lnGDP
Source	US Energy Information Administration			FRED
Mean	2.633	1.707	3.781	4.084
Median	2.649	1.529	3.797	4.120
Maximum	2.716	2.585	3.859	4.284
Minimum	2.509	0.220	3.657	3.832
Std. Dev.	0.051	0.620	0.051	0.133
Skewness	−0.612	−0.064	−0.635	−0.331
Kurtosis	2.342	2.096	2.344	1.844
Jarque-Bera	12.570	5.418	13.283	11.546
Probability	0.002	0.067	0.001	0.003

Outcomes of Table 5 include average, median, maximum, minimum, standard deviation, skewness, kurtosis, and Jarque-bera test of normality. The average value of $lnTCO_2$ is 2.63 (million metric tons), lnBEC is 1.70 (trillion Btu), lnFEC is 3.78 (trillion Btu), and lnGDP is 4.083 (billions dollars, 2012). In terms of standard deviation, the most volatile variable is lnTBEC, which is 0.61 and lnGDP, which is 0.13, respectively. The volatility of lnTBEC is mainly linked with rising population growth and increasing demand for energy. Moreover, the summary statistics (through box plots) of all the variables, i.e., $lnTCO_2$, lnTBEC, lnTFEC, and lnGDP, are reported in Fig. 3, covering the period from 1981Q1 to 2019Q4.

A boxplot, also known as box and whisker diagram, is an intelligently designed descriptive statistics measure that summarizes the entire distribution of data and displays its center and the

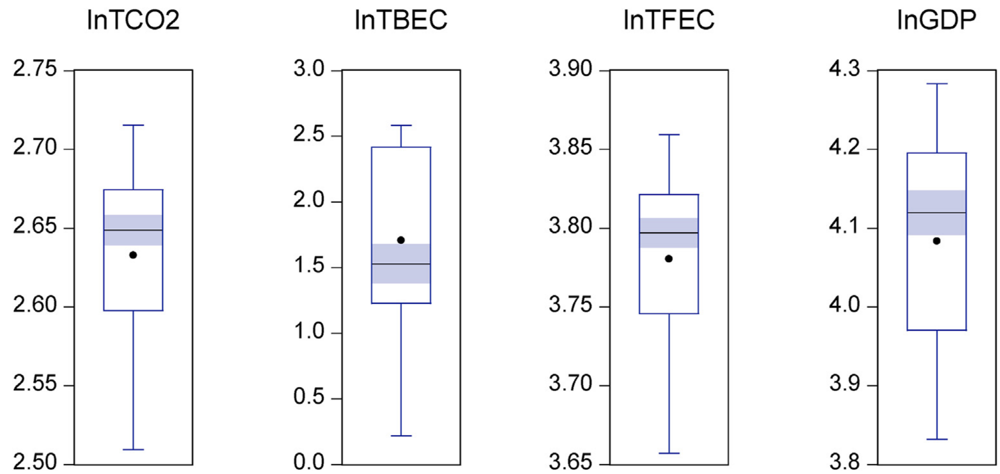

Fig. 3. Box plots summary statistics of all the time series variables.

spread merely using few primary elements (McGill et al., 1978). Fig. 3 highlights that the distribution of lnTBEC is the most volatile and positively skewed as the mean lies above the median line. On the other hand, lnTFEC, which represents fossil fuel consumed by the transportation sector, has higher values, but the overall distribution is negatively skewed. All these facts highlight that a small number of players in the transportation sector, who has a significantly bigger share in the overall consumption, stops using fossil fuel and start to use biomass energy in the consumption. This change could probably be the reason for the negatively skewed distribution of CO_2 emissions in the transportation sector, as depicted by the placement of mean, which is lower than the median.

5. Econometric methodology

The estimation process is divided into four steps. The first step of the procedure investigates the stationarity of the series, and also reveals if there is any potential evidence of a structural break. In the second step of the estimation process, in order to make observations about the long-run relationship between CO_2 emissions and its determinants, two cointegration methods are applied. In the third step, in order to gain access to the applied long-term effect studies on this particular discipline, the cointegration regression (FMOLS, DOLS, CCR) is used. Finally, the last step of the process pertains to performing due checks, which gauge the robustness, for which the causality analysis of the frequency domain approach is used.

5.1. Stationary test

The main aim of this study is to investigate the impact of biomass energy consumption, fossil fuel energy consumption, and economic growth on CO_2 emissions in the transportation sector in the USA. Hence, for this purpose, as an initial test, the Z.A. unit root test (Zivot and Andrews, 2002) is used in this study in order to explore the level of integration of the order in which the time series variables are arranged. The Z.A. unit root test considers the endogenous structural breaks in the series, and it addresses other weaknesses of the unit root test techniques. If the time series is non-stationary at a particular level, it refers to the unit root, but if the first differences in the time series are stationary, it means that the series can be integrated into stage 1 or I (1).

5.2. Cointegration test

As a next step in the present study, the cointegration property is examined for the purpose of determining the long-term relationship between the variables. In the cointegration testing process, the study generally uses the ADF test statistics, Z_a and Z_t, as formulated by (Engle and Granger, 1987) and (Phillips, 1987), so as to investigate the presence of cointegration. A critic of the conventional cointegration methods is that it is assumed that the cointegration relationship does not change or remains static throughout the process of empirical research. This assumption is deemed to be too unrealistic to be accurate, especially when longer periods of time are in question (Seker et al., 2015). Therefore, Hatemi-j (2008) approach (referred to here as the HJ test) is employed here not only to complement the use of the threshold cointegration tests that are proposed by Gregory and Hansen (1996) (referred here as GH test) but also to explore the long-term relationships. For the purpose of this study, these tests include the endogenous changes in the model with a dummy level and inclination. Moreover, one and two unknown structural fractures can be recorded using the GH and HJ tests (Ghosh and Kanjilal, 2016). By taking the CO_2 emissions as a dependent variable regime, and replacing the model with the GH and HJ, the following equations (3) and (4) are presented:

GH approach

$$\begin{aligned} CO_{2t} = {} & \alpha_0 + \alpha_1 D_{1t} + \beta_{01} \ln RGDP_t + \beta_{11} D_{1t} \ln RGDP_t + \beta_{02} \ln TFEC_t \\ & + \beta_{12} D_{1t} \ln TFEC_t + \beta_{03} \ln TBEC_t + \beta_{13} D_{1t} \ln TBEC_t + \varepsilon_t \end{aligned} \quad (3)$$

HJ approach

$$CO_{2t} = \alpha_0 + \alpha_1 D_{1t} + \alpha_2 D_{2t} + \beta_{01} \ln RGDP_t + \beta_{11} D_{1t} \ln GDP_t + \beta_{21} D_{2t} \ln GDP_t + \beta_{02} \ln TFEC_t + \beta_{12} D_{1t} \ln TFEC_t + \beta_{22} D_{2t} \ln TFEC_t + \beta_{03} \ln TBEC_t + \beta_{13} D_{1t} \ln TBEC_t + \beta_{23} D_{2t} \ln TBEC_t + \varepsilon_t \tag{4}$$

where α_0 denotes the intercept before a shift, and, α_1 and α_2 represent the shift in the intercept at the time of the first and second structural break. Moreover, β_{01}, β_{02}, and β_{03} refer to the slop coefficient prior to the shift. β_{11}, β_{12}, and β_{13} are showing the slope changes at the time of the first structural break. Similarly, β_{21}, β_{22}, and β_{23} denote the slope change at the time of the second structural break. In addition to these equations, the dummy variables that represent the first and second structural breaks are given by equations (5) and (6).

$$D1t = 0 \text{ if } t \le [n\tau_1] \text{ and } D1t = 1 \text{ if } t > [n\tau_1] \tag{5}$$

$$D_2t = 0 \text{ if } t \le [n\tau_2] \text{ and } D2t = 1 \text{ if } t > [n\tau_2] \tag{6}$$

The date of the pairwise breaks is estimated with unknown parameters $\tau_1 \in (0,1)$ and $\tau_2 \in (0,1)$. In order to test the null hypotheses of no cointegration, the bias-corrected modified ADF*, Z_t*, and Z_α* tests of the GH and HJ are considered via the estimating equations (3) and (4) for each of the possible structural breaks (Ahmad et al., 2019; Wei et al., 2019).

$$ADF* = \inf_{\tau \in T} ADF(\tau) \tag{7}$$

$$Z_t^* = \inf_{\tau \in T} ADF(\tau) \tag{8}$$

$$Z_\alpha^* = \inf_{\tau \in T} ADF(\tau) \tag{9}$$

The GH is responsible for determining the range of T used, when T=(0.15n, 0.85n), $\tau_1 \in T_1(0.15, 0.70)$ for GH, and $\tau_2 \in T_2(0.15 + \tau_1, 0.85)$ for the HJ test. These two regimes lead to a shift in the critical values of the approximate asymptotic for the cointegration test, as this shift is associated with the HJ. Then, the structural breaks are inferred from equations (7)–(9), and the comparison of the smallest values of (7), (8), and (9) is made with the critical values from the GH and HJ, and also with the no cointegration null hypotheses test (Wei et al., 2019; Ahmad et al., 2019). Eventually, when the ADF*, Z_t*, and Z_α* test statistics are smaller than the GH table critical values, the null hypothesis is rejected.

5.3. Cointegration regression

By setting up the cointegration regression, the FMOLS, DOLS, and CCR methods, that have been respectively proposed by Phillips and Hansen (1990), Stock and Watson (1993), and Park (1992), are employed in order to examine the integration coefficients of the explanatory variables. When it comes to this particular study, except for the second-order bias and the non-centrality, the three approaches named above use different correction mechanisms. Thus, it makes logical sense to use these approaches as an additional measure to check and confirm the robustness. It is noteworthy that the FMOLS corrects the implied data, and provides estimates for the removal of the genetic factor, specifically in the parameter estimates. On the other hand, the CCR will only correct data and then select the relationships that represent the accurate relationship from the canonical relationship class (Guan et al., 2020). Conversely, the DOLS contains abbreviation parameters that correct the non-systemic bias and the second-order bias. An integral characteristic of these techniques is that they apply to both stationary and non-stationary variables (Umar et al., 2020a). In this regard, there is no consensus on which methods are best; as a result, different methods are applied and tested.

5.4. Robustness check: causality analysis

As a final step of this research, a frequency domain causality test, developed by Breitung and Candelon (2006) based on the early work of Geweke (1982) and Hosoya (1991) is conducted. The Breitung and Candelon (2006) approach is employed for the purpose of determining the causal relationship of lnGDP, lnTFEC, and lnTBEC with lnTCO_2 emissions in the USA, at different frequencies. The main difference between the frequency-domain approach and the time-domain approach is that the frequency-domain approach tests the degree of a specific time-series variation and the 'time-domain' approach that tells us when a certain variation takes place within a particular time series (Guan et al., 2020). The frequency-domain approach allows for the observation of the nonlinearities and the high or low causality frequencies. Breitung and Candelon (2006) suggest that the seasonal variations on a small dataset can be eliminated across the frequency domain. Therefore, the frequency can be effectively measured by the nonlinearities and causality cycles defined by Breitung and Candelon's (2006) approach. The test allows us to measure the causalities between the variables that are considered in the particular time series at both low and high frequencies. In other words, the Breitung and Candelon (2006) frequency domain causality test helps us to distinguish between permanent causality (long term) variables, and temporary one (short-term) variables between a particular time series.

6. Results and discussions

The findings of the Z.A. unit root test have been listed in Table 6 with the time series structural breaks. The results reveal that at a certain level, none of the variables in the series are stationary. After finding the first difference, it appears that all the series variables are stationary with the intercept and trend. This gives us an indication that the significant and statistical evidence of a structural break may have affected the stationary property. These structural breaks in the variables are mainly associated with the economic tremors that the economy has experienced. These tremors can be associated with the ups and downs that occur in the different sectors of the economy. However, on a macro level, these shocks or tremours may eventually get significant enough to influence and perhaps even contribute considerably to the global financial crises, oil price shocks, and the Asian financial crises. The observed break periods for the CO_2 emissions and the real GDP are 2007Q4, and 2008Q1,

Table 6
Zivot andrew unit root test.

	Series in Levels			
	$lnTCO_2$	lnTBEC	lnTFEC	lnGDP
C&T	−4.607 (2007Q4)**	−4.045 (2006Q2)**	−4.224 (2007Q4)**	−4.640 (2007Q4)**
Series in First Differences				
C&T	−6.273** (2008Q1)**	−6.107** (1996Q4)**	−6.107** (2008Q1)**	−5.647** (2008Q1)*

Note: C&T denote constant and trend in the ZA unit root test, respectively. The ** and * implied the 5% and 10% statistical significant levels, respectively. The numbers in parenthesis ( ) represent breakpoints.

Table 7
Threshold cointegration test.

Gregory-Hansen Cointegration Test				Hatemi-J Cointegration Test			
ADF	−10.00 (1993Q3)***			ADF*	−9.818*** (0.326) (0.500)		
Z_t	−10.20 (1993Q3)***			Zt*	−9.869*** (0.340) (0.513)		
Z_a	−125.04 (1993Q3)***			Za*	−130.412** (0.340) (0.506)		
Asymptotic Critical Values							
	1%	5%	10%		1%	5%	10%
ADF	−6.89	−6.32	−6.16	ADF*	−7.833	−7.352	−7.118
Z_t	−6.89	−6.32	−6.16	Zt*	−7.833	−7.352	−7.118
Z_a	−90.84	−78.87	−72.75	Za*	−140.135	−123.870	−116.169

Notes: The numbers in parenthesis ( ) represent breakpoints. The optimal lag for the models is determined by Bayesian criterion. The***, ** and *and denote the 1%, 5% and 10% statistical significant levels, respectively.

while for the biomass energy consumption these are experienced in 1996Q4 and 2006Q2. Additionally, the break period for fossil fuel energy consumption is 2007Q4, while for the transportation sector, it is 2008Q1. It is observed that a structural break occurred mainly during the global financial crisis of 2007–2008, and this span of time coincided with the increasing energy shortages experienced by the USA since the year 2000 (Pimentel et al., 2002). The US Energy Information Administration (EIA 2019) has taken a stance that states that, in the 1990s, the veterans of the most prestigious sustainable energy promotion law, particularly pertaining to the wind projects, and the biomass plants, introduced the Energy Policy Act of 1992. This was later abolished and revised in the year 2005.

The relationship of cointegration among the variables of interest, which are prevalent amidst unknown structural breaks, is examined after affirming the stationarity of the series. For this purpose, cointegration tests with structural breaks have been performed and the results are presented in Table 7, the results of the regime-switching cointegration analyses. The upper section in Table 7 shows the estimated cointegration parameters according to Gregory–Hansen (GH) and Hatemi-J (HJ), respectively, while the lower section lists the asymptotic critical values. With some additional program lines, all the statistical output presented and put forth in Table 7 is obtained using the Gauss codes from GH and HJ. The HJ model involves carrying out a cointegration analysis with two unknown breaks, while the GH model examines the cointegration with a single point, characterized unknown regime shift in the constant, and the parameters using *ADF*, Z_a, *and* Z_t, as explained in the methodology section.

The immediate results obtained, by referring to the structural break cointegration analyses performed by both models in this article, show that CO_2 emissions coincide with all the considered variables. These approaches further confirm that there is statistical evidence of nonlinear cointegration, and the CO_2 emissions indeed cointegrate with all the variables that carry a significant level of 1%. Consequently, these outcomes support the existence of a long-term association between CO_2 emissions, and all the selected explanatory variables that have been considered in the proposed model. Furthermore, these results may focus on accentuating the existence of a robust and long-term relationship of CO_2 emissions with biomass energy consumption, real GDP, and fossil fuel energy consumption.

The test results of the unit root and cointegration tests from Tables 6 and 7 show that the examined variables are 1 (1), i.e., the order of integration is one, and the estimated long-term elasticities are also implied. As outlined in Section 4 of this study, the CO_2 emissions from the transportation sector, with the other variables in consideration, are estimated using the three estimation methods, namely FMOLS, DOLS, and CCR (see Table 8). The estimates of the elasticity show that if the biomass energy

Table 8
Cointegrating regression.

	FMOLS	DOLS	CCR
lnTBEC	−0.102** <-5.896>	−0.093** <6.284>	−0.117** <5.709>
lnTFEC	1.075**<153.558>	1.036** <133.144>	1.032** <138.463>
lnGDP	−0.028** <-5.421>	−0.032** <-5.491>	−0.028** <-5.044>
C	−1.162** <-90.671>	−1.160** <-93.583>	−1.163** <-87.059>
R-squared	0.999	0.999	0.997
S.E. regression	0.001	0.001	0.001

Notes: The numbers in < > represent test statistics of the estimated coefficients. The optimal lag for the models is determined by SIC. The 1%, 5% and 10% statistical significant levels are respectively denoted as**, *, and [a].

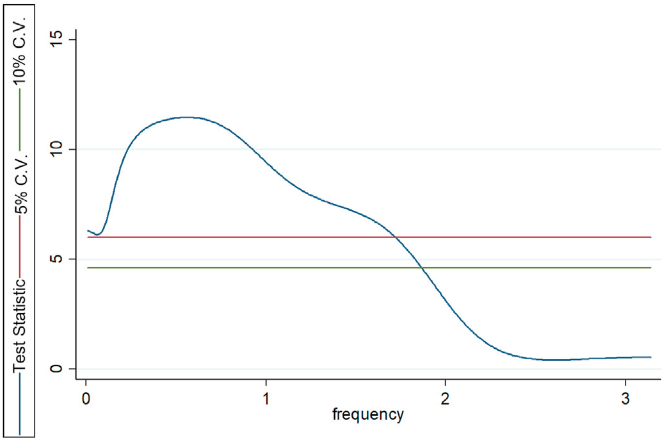

Fig. 4. Spectral Breitung-Candelon Causality from lnGDP to lnTCO_2.

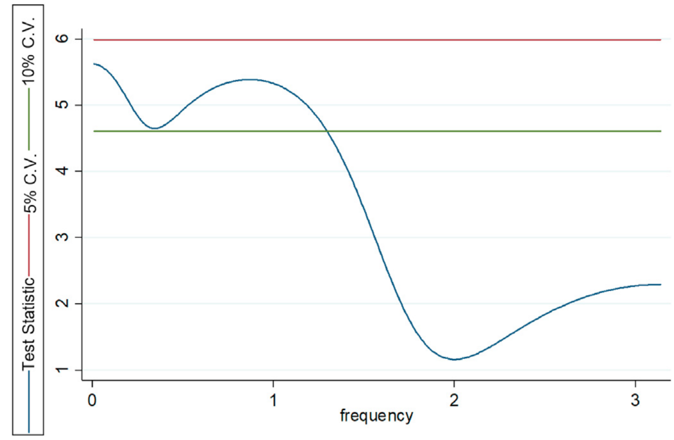

Fig. 5. Spectral Breitung-Candelon Causality from lnTBEC to lnTCO_2.

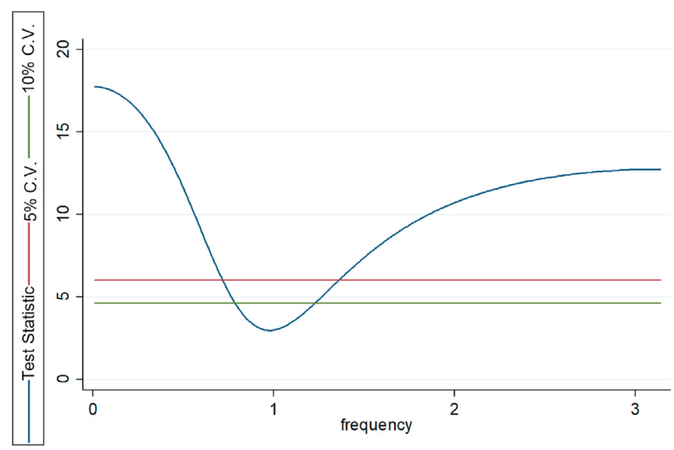

Fig. 6. Spectral Breitung-Candelon Causality from lnTFEC to lnTCO_2.

consumption increases by 1%, this will reduce CO_2 emissions in the transportation sector by 0.117% (CCR), 0.102% (FMOLS), and 0.093% (DOLS). This is in the case when the time frame that are considered pertains to the long term. Therefore, the observation that there exists an indirect link between biomass energy consumption and CO_2 emissions in the transportation sector of the USA can be positively concurred. This clearly means that biomass energy consumption contributes towards the control of carbon emissions. Following this development, a logical action point would be to integrate the level of biomass energy consumption with the transportation sector, and thus, its development should be promoted (Mandova et al., 2018). Another possible reason for the inverse relationship of biomass energy consumption and carbon emissions, is that in the year 2016, 5% of the total energy consumption in the USA was obtained from biomass, which contributed to almost 12% of the total renewable energy resource use in the USA. Biomass is considered one of the main determinants that have led to the decline of fossil fuel energy consumption (Bilgili et al., 2016). Most certainly, the findings of this study can be linked with the outcomes of (Dogan and Inglesi-Lotz, 2017; Kim et al., 2020).

This computation of the elasticity suggests that a 1% increase in fossil fuel energy consumption, in the long term, will generally increase the CO_2 emissions in the transportation sector by more than 1%, between 1.075% (FMOLS), 1.036% (DOLS) and 1.032% (CCR). These results compel us to advise policymakers that the focus needs to shift on lowering fossil fuel energy consumption. This can primarily be done by introducing new and improving the existing energy efficiency measures, which will help save energy in the long run. Although it is not easy to directly make a comparison between the results of the current study and the existing studies, mainly due to the differences in the geographical context, it is reassuring to observe that the long-term flexibility variables in the current study are reasonably consistent. According to the United States Environmental protection Agency, the rise in carbon emissions, as a result of fossil fuel consumption, is valid and authentic. This is validated by the statistical data, which shows that the total contribution of greenhouse gases, in the USA, consists of emissions coming from various sectors. To be specific, 28.2% of these gases can be attributed to transportation, 26.9% to electricity production, 22% to industry, 12.3% to commercial and residential use, 9.9% to agriculture, and 11.6% to land use and forestry, respectively. This shows that a greater demand for non-renewable sources of energy, such as fossil fuel consumption, will cause carbon emissions to rise. These outcomes are in line with the results of (Lotfalipour et al., 2010; Shahbaz et al., 2019).

Meanwhile, a negative and significant coefficient for lnGDP suggests that increasing the real GDP will reduce CO_2 emissions in the transportation sector in the long term between 0.028% (CCR), 0.032% (DOLS), and 0.028% (FMOLS). This implies that a future increase in the real GDP will cause a reduction in CO_2 emissions. The outcomes from this study adhere to the intricacies of the Brundtland curve hypothesis, which supports the U-shaped environmental Kuznets curve for the USA. Since the USA is deemed to be a developed country, and as suggested by Brundtland, there could and should be more investment in cleaner production technologies and greener energy sources, which will aid in the decline of pollution. Moreover, more light needs to be shed on developing greener and environmentally friendly technology, which could reduce carbon emissions in the atmosphere. These outcomes are supported by the work of (Aye and Edoja, 2017; Sinha et al., 2020).

Additionally, the Breitung and Candelon (2006) frequency domain causality technique provides a robustness check to this whole theory that this study supports. This approach allows us to evaluate data on causality measures that are tested at different frequencies. Figs. 4–6 illustrate the results for the whole sample period taken into consideration. The relationship among these variables was analyzed at the frequencies of 2–3, 1–2, and 0–1, and showed that there exists a relationship between these variables in the short-term, medium-term, and long-term. Simultaneously, these results also show that 0–1 can be defined as a permanent causality, and 2–3 as a temporary causality. The upper line (red), and the bottom line (brown) display a statistically significant level of 5% and 10%, respectively, in Figs. 4–6. On the other hand, the (blue) curves show statistical inferences suggesting various interval frequencies (0, π).

Fig. 4 visually presents the causal link in the frequency domain from biomass energy consumption to CO_2 emissions in the long term, specifically from the transport sector, at a significance level of 10%. This result does not come as a surprise because the extant literature discusses how biomass energy sources have an impact on CO_2 emissions, which should lead towards improvements in the future. Interestingly though, in Fig. 5, the fossil fuel energy consumption test statistics are higher than a significance level of 5%, which means that fossil fuel energy consumption is the cause of CO_2 emissions in the transport sector at all frequencies that range from low to high. Furthermore, Fig. 6 shows that the investigation for robustness revealed a permanent causal relationship between the real GDP and CO_2 emissions in the long and medium-term transportation sectors. The null hypothesis of real GDP does not Granger cause of CO_2 emissions is rejected at a significance level of 5% for the frequencies of 0–1.8. They stated that economic growth had a robust environmental impact in the long term, which means that more attention to economic growth can positively impact the quality of the environment. It can also be concluded that long-term causality is the most evident feature in the findings, particularly when it is considered from the viewpoint of the frequency domain causality method.

7. Conclusion, policy suggestions, limitations, and future perspectives

7.1. Conclusion

The growing global concern for the hazardous effect of pollutant emissions, especially among the large economies, has continued to compel more research, intergovernmental interventions, and innovative policy strategies. Considering that the consolidated amount of pollutant emissions from China, India, and the USA accounted for 85% of the net increase in emissions in 2018 (IEA, 2018), this study considers the importance of the need to critically examine the transportation sector of the USA and its contribution in this regard.

- In so doing, the impact of biomass energy usage, fossil fuel energy usage, and real GDP, on the CO_2 emissions is examined empirically.
- Furthermore, by investigating the contribution of the transportation sector in the overall pollutant emissions of the USA, this study employs the contemporary approaches of the Gregory-Hansen cointegration, Hatemi-J cointegration, cointegration regression and the Spectral Breitung-Candelon causality test.
- The results of the threshold cointegration test reveal that there exists a significant nonlinear cointegration among the variables, specifically with the use of endogenous structural breaks and a combination of two cointegration tests (namely Gregory-Hansen Cointegration and Hatemi-J Cointegration tests).
- Moreover, the investigation postulates that consuming biomass energy to fuel the transportation sector and studying its relationship with real GDP shows a positive impact, of the association between these two variables, on the quality of the environment.
- This critically implies that an increase in fossil fuel energy consumption in the transportation sector is linked to a significant subsequent increase in CO_2 emissions in the USA's transportation sector.
- Additionally, the long-run impact of biomass energy consumption, fossil fuel energy consumption, and real GDP on CO_2 emissions in the country's transportation sector is also deemed to be significant.

7.2. Policy suggestion

The results of this study indicate that policymakers should set aims and objectives for the introduction of different sustainable transportation options.

- Proactive measures should be taken to improve biomass energy consumption in the transportation sector, such as adopting more efficient processes, making better use of by-products, and changing energy usage. The production and use of biomass energy for transportation is an alternative to fossil fuels and can help solve several environmental problems. It can help reduce the accumulation of CO_2 emissions and establish a safe, clean, and sustainable alternative to petroleum.
- Biomass energy consumption can provide a way to reduce oil dependence and promote decarbonization in the transportation sector without changing vehicle inventory and distribution infrastructure. They will play an important role in replacing fossil fuels suitable for aircraft, ships, and heavy road transportation.
- Currently, biomass energy only accounts for 2% of the total global transportation fuel, but emerging transformative technologies have huge growth potential in the coming decades. Governments should be aware of this situation, and begin to formulate and implement long-term development plans. Developing a more substantial market for domestically produced biomass energy in the USA will help alleviate the negative impact of trade deficit and contribute to the positive economic trends in the USA transportation sector.
- The basic aim of the trading programs is to work towards setting up environmental goals, at national or regional levels, in order to define a maximum limit on the volume of pollution that sources are permitted to emit into the environment. In the case of the transportation sector, the economic importance and scale should be measured so as to help determine the costs that are to be incurred in order to change the characteristics of the vehicle fleet and to influence the eventual decision to drive. The regulatory policies that already exist in the transportation sector might be unified in a GHG cap-and-trade structure. This may aid in estimating the implications of this choice for an increased efficiency of the economy, especially when considering this as an effort to achieve an overall mitigation effect.
- Fuel taxes will help to bring a positive change in the transportation sector. In the short-run, vehicle drivers may change their discretionary habits of driving, for example, in order to save fuel, they may prefer to drive slower or may also increase fuel efficiency by increasing the tire pressure. Moreover, at the point of purchase, tax payments or tax benefits tend to have a more substantial impact on the consumers' choice. Buyers who prefer low-emission, private cars can significantly reduce tax payments at the time of registration, while buyers of high-emission vehicles have to pay higher taxes. This measure can be ensured by exempting value-added tax from low-emission vehicles. Levying a carbon tax can also encourage lower CO_2 emissions, and if implemented, it will add to the low carbon direction of the transportation sector. Successful implementation by using financial instruments to address environmental

externalities would also set a precedent in macro-level policy formulation.

- In the transportation sector, carbon-neutral synthetic fuels, a mix of electrification, biofuels, solar, and hydrogen, could further decarbonize roads, trains, air, and shipping. Other renewable energy sources such as hydrogen and solar energy can also help to reduce the CO_2 emissions that are caused by fossil fuels. The consideration of hydrogen as a fuel could lead to an additional and intensive focus of its energy, providing potential in domestic manufacture and use in fuel cells for high efficiency, zero-emission electric vehicles.
- For the transportation sector, energy efficiency is critical. The use of technologies such as the EV, BEVs, PHEVs, and HEVs would help to improve fuel efficiency and reduce possible GHG emissions. The modal change also has a high potential for providing energy-efficient solutions that could lead to sustenance. Such improvements include groundbreaking mobility services, including car-sharing, improved accessibility, and autonomous driving. Furthermore, measures need to be taken to maintain minimum emission standards for vehicles and prioritize electric vehicles' access within the city. Besides this, the government should also adopt several technologies and initiatives to replace non-renewable energy resources with renewable energy resources and reduce the dependency on fossil fuel sources to mitigate greenhouse gas emissions.
- In specific terms, in order to cut down pollutant emissions from personal automobiles (since there is a relatively high volume of personal automobiles in the USA, as compared to other advanced economies, such as the major EU states), a stronger and more proactive approach to the use of energy-efficient automobiles should be encouraged across all the states of the country. For instance, the GHG emissions can be reduced by 1.7 tons annually by switching from a vehicle that uses 20-mpg, to a vehicle that uses 25-mpg. This is practically possible because both of these models are approved by the Green Vehicle Guide and Fuel Economy insight of the United States Environmental Protection Agency (US EPA, 2019), and the United States Department of Energy (2019), respectively. In addition to the policy that is undertaken on the personal use of automobiles, the industrial use of trucks, and heavy equipment, among others, should also be reduced, and the owners of such vehicles should be encouraged to consider a low emission policy or strategy.
- Also, more regulations in the aviation and maritime sectors that are tailored towards reducing connecting flights, the weight of aircraft, or ship carriages are potential ways of reducing emissions in the transportation sector.
- In general, other socioeconomic or recreational approaches, such as biking and walking, that are considerate towards carbon abatement policies and are also practically obtainable in most European countries, could be strengthened across the USA's different states. Other socioeconomic pathways, including the dissemination of more information that pertains to environmentally-driven attitudinal changes, and the adoption of cost-effective and energy-saving approaches to urbanization, infrastructural development, and economic expansion, could also be undertaken. Besides, more awareness of sustainable driving patterns and culture can contribute to environmental quality.
- The sustainability of the transportation sector usually enhances the size and reach of socioeconomic activities. A wide variety of financial benefits can come from the transportation system, e.g., the ability, productivity, scale economy and opportunities, which can be direct, indirect, or induced.

These initiatives can strengthen sustainability and provide awareness and lessons that will help boost worldwide sustainability.

7.3. Limitations of the current study and future perspectives

The current study is novel from the perspective that it offers an environmental quality insight of the USA transportation sector. In particular, the energy consumption from biomass and fossil sources and economic output are taken into account. Inspite of this novel approach, this study contains some limitations, and there are potential pathways to improve the study in the future consideration.

- The regional heterogeneity in this context has not been taken into account. In this respect, it is hopeful to examine the factors that lead to CO_2 emissions from a regional perspective in future research.
- Moreover, future work should investigate the eco-efficiency of alternative vehicle technologies, such as electric vehicles (EVs), Battery Electric Vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and Hybrid Electric Vehicle (HEVs). Future studies should also analyze the impact of using these vehicles, especially in the context of the environmental sustainability targets that the world's major economies have set for themselves (e.g., China, European Union, United Kingdom, etc.). A strong policy support for such vehicles is expected to be available in order to make an international comparison analysis with the USA.
- While the assessment contained a limited number of indicators, more social, economic, and environmental measures such as urbanization, safety measures, tax policies, and human safety, the driving pattern can also be considered in the future. That extension would enable policymakers to assess the impacts and meet the United Nations' sustainable development goals more accurately.
- Also, a future study could focus on comparing the macro and microgeographic locations as well. In this case, a spatial or cross-sectional state-wide approach could be employed to provide a broader perspective. These factors may also affect CO_2 emissions, but a profound analysis of these nexus goes beyond this paper's scope. Taking these factors into account would help us to understand the empirical potential for reducing CO_2 emissions in the transportation sector.
- While this study was undertaken in the USA's context and framework, this paper could be used for other countries as well to optimize CO_2 emission reduction strategies in their respective transportation sectors.

CRediT authorship contribution statement

Muhammad Umar: Conceptualization, Data curation, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing. **Xiangfeng Ji:** Conceptualization, Visualization, Investigation, Supervision, Writing - review & editing, Funding acquisition. **Dervis Kirikkaleli:** Software, Formal analysis, Validation, Project administration, Writing - original draft. **Andrew Adewale Alola:** Conceptualization, Methodology, Validation, Visualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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