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Determinants of air transport CO_2 emissions in OECD countries

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ABSTRACT

Whether advanced economies can meet their emission reduction targets and effectively address climate change remains a critical global concern. OECD countries account for approximately one-third of global CO_2 emissions, highlighting their pivotal role in achieving sustainable development goals. The air transport industry is one of the fastest-growing sectors globally and aims to achieve net-zero emissions by 2050. Unlike previous studies that primarily focus on total emissions or cross-sectoral comparisons, this study examines the specific determinants of air transport CO_2 emissions in OECD countries. Using panel data from 38 member states over the period 2013–2023, the analysis is conducted in three stages. First, key drivers of air transport CO_2 emissions are assessed at the aggregate level. Second, countries are grouped into two broad geographic regions to investigate regional heterogeneity through separate regressions. Third, a country-specific analysis is conducted for the top emitters to explore national trends. This multi-level approach provides a comprehensive understanding of emission dynamics at macro, regional, and national scales. The findings indicate that GDP growth, GDP per capita, and international tourism significantly increase air transport CO_2 emissions, while international trade appears to have a mitigating effect. These results carry important policy implications for OECD countries as they strive to meet their emission reduction commitments, and the 2050 net-zero target.

1. Introduction

Global CO_2 emissions have emerged as one of the most critical challenges facing humanity today. The combustion of fossil fuels in production processes and industrial activities has significantly contributed to the sharp rise in global CO_2 emissions. Emissions increased from 16.9 $GtCO_2e$ in 1974 to 35.5 $GtCO_2e$ in 2021, more than doubling over this period [20,47]. Although various international agreements such as the Kyoto Protocol (1997), the Paris Agreement (2015), and the Glasgow Climate Pact (2021) have set targets to reduce CO_2 emissions and combat climate change, the pace of emissions growth has accelerated in recent decades. For example, while the annual growth rate of CO_2 emissions was approximately 1% between 1990 and 1999, it surpassed 5% between 2011 and 2021[1] [20,47]. These recent trends underscore the urgent need for stronger international cooperation and the implementation of more stringent climate policies.

The Kyoto Protocol (1997) adopted under the United Nations Framework Convention on Climate Change (UNFCCC), established binding greenhouse gas emission reduction targets for industrialized nations. In 2015, the Paris Agreement succeeded the Kyoto Protocol, introducing a more inclusive and flexible framework for global climate action. While such agreements provide a roadmap for countries to implement measures aimed at reducing emissions, identifying and analyzing the underlying drivers of emission increases has become increasingly important. Given that OECD countries account for more than 30% of global CO_2 emissions [20], it is essential to investigate the factors contributing to the rise in their emissions.

OECD countries constitute a significant share of global air passenger traffic and hold a substantial portion of global air freight transportation. They are home to many of the world's busiest and most advanced airports, which function as vital hubs not only for passenger traffic but also for cargo movement. According to 2021 data, OECD countries accounted for approximately 60% of global air freight (measured in million ton-kilometers), 57% of air passengers, and 61% of registered carrier departures worldwide [78]. Given their prominent role in international air transport, this study focuses on air transport-related CO_2 emissions in OECD countries, as they represent a considerable share of both international air passenger and air freight transportation.

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[1] Carbon dioxide emissions from flaring are the sum of carbon dioxide emissions from energy, methane emissions as carbon dioxide equivalent and carbon dioxide emissions from industrial processes.

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As of 2018, the air transport industry was responsible for approximately 12% of transportation-related CO_2 emissions. Between 2000 and 2019, CO_2 emissions from the air transport industry increased by an average of 2% annually [76]. In 2022, global CO_2 emissions from the transport sector reached approximately 8 Gt CO_2, representing a 3% increase compared to 2021 [44]. Current data highlight that the air transport industry is the second-largest contributor to anthropogenic CO_2 emissions worldwide. Furthermore, since 1995, while the global gross domestic product (GDP) has expanded by an average of 2.8% per year, Revenue Passenger-Kilometers (RPK) have increased by an average of 5.0% annually [43]. The rapid growth in air transport activities, coupled with the corresponding rise in energy consumption, has substantially amplified the sector's environmental impact. Consequently, it is crucial to identify the key determinants of CO_2 emissions within the air transport industry.

In this study, we conducted a systematic literature review to identify potential determinants of CO_2 emissions in the air transport sector. Existing research has predominantly focused on variables such as economic growth, GDP or GDP per capita [5,15,63,68], energy consumption or energy usage [1,5,9,85], trade, trade openness, and international trade [4,7,32,84,85], foreign direct investments (FDI) [16,69,84], and urbanisation [63,83,84] as key factors influencing CO_2 emissions. However, the literature encompasses a wider array of determinants beyond these commonly examined variables. Some studies have also investigated the effects of renewable and non-renewable energy sources [9,32], liberalization, liberalization, democratization, and political democracy [16,55], industrialization [13], and tourist arrivals [7]. Based on these insights, this study develops a research model incorporating variables that are most frequently employed in the literature.

The factors influencing CO_2 emissions are multidimensional, and their thorough evaluation is critical for designing effective policies to reduce emissions in the future. According to Aller et al. [7], GDP per capita is among the most robust determinants of CO_2 emissions. Furthermore, high-income countries tend to produce greater carbon dioxide emissions, and in the absence of energy-saving policies, pollution levels increase alongside income growth [70]. For instance, in European Union countries, a 1% increase in GDP leads to a 0.2011% rise in CO_2 emissions in the short term, while a 1% increase in GDP results in a 0.3525% increase in emissions in the long term [61]. Therefore, high-income countries need to focus more on energy-saving policies to reduce the short- and long-term effects of their emissions. This study investigates the determinants of air transport-related CO_2 emissions in OECD countries, which are generally classified as upper-middle and high-income nations. These countries exceed the global average in economic development, productivity, and living standards. To analyze the determinants of air transport CO_2 emissions in this context, we employ GDP growth (annual %) and GDP per capita (constant 2015 US$) as key variables. While developing countries typically experience high GDP growth rates despite relatively low GDP per capita, developed countries tend to have higher per capita income but lower economic growth rates.

Foreign direct investment (FDI) plays a crucial role in the development of countries by fostering economic growth and facilitating the transfer of technological innovations. However, the introduction of non-green technologies through FDI can contribute to increased CO_2 emissions [81]. In particular, direct investments in developing countries may lead to environmental degradation by accelerating the extraction of natural resources such as oil and forest products. Additionally, foreign firms from developed countries may engage in environmentally harmful activities in host countries where environmental regulations and policies are weak or poorly enforced. Similarly, international trade can exacerbate environmental degradation by accelerating economic production in countries lacking stringent environmental controls [85]. Both foreign direct investment and net trade in goods and services are likely to increase the number of operations within the airline industry, potentially leading to higher CO_2 emissions.

International tourism can significantly contribute to economic development, particularly in developing countries, by supporting employment and alleviating poverty [73]. However, it can also drive a substantial increase in energy consumption due to the expansion of energy-intensive activities. International tourism elevates energy demand especially in sectors such as transportation, accommodation, and food services, making it one of the most energy-consuming industries. Furthermore, the transportation sector is widely recognized as the primary source of energy consumption and environmental degradation associated with international tourism [49]. Therefore, international tourism is expected to be a key determinant influencing CO_2 emissions from air transport. In addition, urban population growth contributes to increased CO_2 emissions due to higher traffic volumes and congestion in cities [53]. Population concentration in specific regions or metropolitan areas can lead to intensified use of air transportation. Moreover, congestion at airports located in central hub regions may exacerbate the environmental impacts of air transport. Consequently, CO_2 emissions related to urban populations are likely to have a significant effect on air transport emissions.

Numerous studies have investigated the determinants of CO_2 emissions across different contexts. For instance, research has focused on OECD countries [21], small open economies [36], low-income countries [68] and European Union countries [61]. Additionally, various factors influencing CO_2 emissions have been explored from multiple perspectives, including those related to the transportation sector [38,52], macroeconomic determinants of CO_2 emissions based on tourist arrivals [54,73], determinants of O2 emissions depending on the role of renewable and non-renewable energy [32] have been examined from various perspectives.

The factors influencing CO_2 emissions in the aviation industry have been explored in a limited number of studies. Lo et al., [55] analyzed all flights departing from Lombardy, Italy, between 1997 and 2011, considering variables such as average aircraft size, route distance (km), fuel price, and available seat kilometers (ASK) within this specific region. Similarly, Falk & Hagsten [35] examined determinants of carbon dioxide equivalent emissions generated by airline passengers in Austria during 2014–2016. Their findings indicated that socio-demographic, regional, and seasonal factors significantly affected CO_2 emissions. Specifically, individuals with children and those residing in crowded households contributed to lower emissions, whereas residents of the capital city were responsible for the highest emissions. However, to the best of our knowledge, no study has comprehensively analyzed the determinants of air transport CO_2 emissions at a broader scale. Furthermore, there is a lack of research focusing on OECD countries using variables established in the existing literature. Therefore, this study aims to fill this gap by empirically investigating the determinants of air transport CO_2 emissions in OECD countries through a rigorous and scientifically sound analysis. Given the substantial share of OECD countries in global CO_2 emissions and the scale of their aviation activities, this research seeks to contribute meaningfully to the literature. Additionally, by integrating insights from prior studies on CO_2 emission determinants and the relationship between air transport and emissions, this study addresses an important gap in the field.

The remainder of this study is organized as follows. Section 2 reviews the literature on the potential determinants of CO_2 emissions and the relationship between air transport and CO_2 emissions. Section 3 details the methodology employed, including the panel data analysis techniques. Section 4 presents the empirical findings along with their discussion. Finally, Section 5 concludes the study.

2. Literature review

In recent years, environmental concerns and CO_2 emissions have attracted considerable attention within academic research. The targets established under the Paris Agreement have not only focused the interest of researchers but also heightened awareness among policymakers, decision-makers, and the general public regarding environmental issues. Consequently, scholars have examined CO_2 emissions and related environmental challenges from diverse perspectives. The literature is abundant with studies addressing policies aimed at reducing CO_2 emissions [6,31,67,74,82] and factors determining CO_2 emissions [36,45,47]. Furthermore, the literature includes studies focusing on the Environmental Kuznets Curve (EKC), which is based on the interaction between economic growth and environmental degradation [12,27,37,60,86].

Numerous environmental studies have investigated the factors influencing CO_2 emissions and their respective impacts. As shown in Table 1, much of the existing literature employs variables such as economic growth, per capita income, energy consumption, international trade, and foreign direct investment to analyze the determinants of CO_2 emissions. In these studies, CO_2 emissions typically refer to the total emissions generated by all economic activities within a country. However, just as total emissions vary across countries, the contribution of individual sectors to emissions may also differ significantly between nations. While extensive research has addressed the determinants of CO_2 emissions across various industries, this study specifically focuses on the aviation sector; hence, a review of literature related to CO_2 emissions in aviation has been undertaken.

In this study, the literature on CO_2 emissions in the aviation sector is categorized into four main groups: (i) studies modeling the impact of technological advancements and policy instruments on CO_2 emissions, often utilizing scenario and simulation-based analyses to provide future projections; (ii) studies investigating the effects of crisis periods, such as the Covid-19 pandemic, on aviation-related emissions; (iii) studies exploring the relationship between factors like operational efficiency and flight distance, and their influence on CO_2 emissions at the airport level; and (iv) studies analyzing how the number of flights, passenger volumes, and macroeconomic variables affect emissions.

In 2022, ICAO member states jointly adopted a net zero carbon emissions target (LTAG) by 2050. This is critical to achieving net zero carbon emissions in aviation. However, there are serious uncertainties about whether this target will be achieved by 2050. In this context, there are studies in the literature in which scenario or simulation-based future predictions are made regarding CO_2 emissions originating from the air transport industry. Chèze et al. [23] examined the positive contribution of technological progress to global aviation CO_2 emissions. The scenario-based study predicts that CO_2 emissions from aviation will increase, contrary to the targets. Anger [11] examines the relationship between CO_2 emissions and macroeconomic activities in the EU based on a simulation model within the framework of the European Emission Trading Scheme. The findings of the study expect reductions of up to 7.4% in emissions released by the aviation industry. Simões and Schaeffer [72] examined CO_2 emissions from aviation activities in Brazil in the context of global climate change through trend projections and proposed emission reduction strategies. The findings of the study indicate that CO_2 emissions from aviation activities in Brazil could potentially decrease by an average of approximately 28.5% per year until 2023. In this context, the existing literature generally suggests the possibility of a decline in CO_2 emissions in the future. However, whether the net-zero carbon emissions target set for 2050 can be achieved remains uncertain.

During times of crisis, aviation operations experience a significant decline. As a result of the reduction in flight operations, CO_2 emissions also decrease. The COVID-19 pandemic is considered one of the greatest challenges faced by the global economy, as production activities nearly came to a halt worldwide. The aviation industry has been one of the sectors most affected by the crisis caused by the Covid-19 pandemic. In studies examining the relationship between the Covid-19 pandemic and CO_2 emissions from the aviation industry, Sajid et al. [66] modelled CO_2 emissions from the transportation of emergency first aid materials in response to the Covid-19 pandemic. They found a close relationship between the number of doses (or total population) needed by countries, technology and economic development levels, and CO_2 emissions. Lyu et al. [57] investigated the long-term effects of CO_2 emissions from the aviation industry in China using flight information from the aviation industry. They found that CO_2 emissions from the aviation industry in China were on an upward trend, but there was a significant decline due to Covid-19. Therefore, it is acknowledged that while CO_2 emissions from aviation sources temporarily decrease during crisis periods, this declining trend is not considered to be permanent in the long term.

One of the important stakeholders of the aviation industry is airports. Ensuring operational efficiency at airports can reduce CO_2 emissions. There have also been studies in the literature examining aviation-related CO_2 emissions on an airport basis. Loo et al. [56] compared the CO_2 emission efficiencies of Athens International Airport (AIA) and Hong Kong International Airport (HKIA). They found that HKIA performed better in terms of CO_2 emission efficiency. Howitt et al. [41] developed a new methodology to calculate CO_2 emissions generated at an airport used for air cargo transportation in New Zealand. They found that CO_2 emissions generated in short-haul aviation were higher than those generated for long-haul journeys. In another study, Amizade et al. [10] focused on the relationship between commercial air traffic CO_2 emissions and fleet utilization in the European Union. The results of the study show an improvement in fuel efficiency and a reduction in CO_2 emissions for passenger and cargo traffic. Therefore, CO_2 emissions can be reduced by reducing congestion at airports and improving operational performance by using aircraft more efficiently.

In the aviation industry, there are also studies analysing the effects of the number of flights, the number of passengers carried and various macroeconomic variables on aviation-related emissions. In studies on CO_2 emissions in the aviation industry, Alonso et al. [8] found a direct relationship between revenue passenger kilometres (RPKs) and CO_2 emissions for EU countries. In another study using aviation industry data, Demir [29] investigated the relationship between flight and passenger numbers and CO_2 emissions from aviation based on scenarios. The study predicts that an increase in flight numbers and passengers to be carried will lead to an increase in emissions from aviation.

There are a limited number of studies examining the relationship between CO_2 emissions from the aviation industry and macroeconomic variables. Avotra et al., [14] investigated the asymmetric relationship between aviation, energy consumption, renewable energy, trade expansion, oil prices, per capita income, and carbon emissions from aviation in Pakistan. They found that a positive shock to the aviation industry increases per capita CO_2 emissions in the long run, while shocks to trade expansion and renewable energy use affect carbon emissions from aviation. Jahanger et al., [46] examined the impact of aviation, environmental tax, globalization, and green innovation on the amount of emissions in G7 countries. The findings of the study showed that green innovation, environmental tax, and globalization contribute to reducing the amount of emissions, but aviation activities increase the amount of emissions. Habib et al., [39] investigated the impact of passenger and air cargo transportation in the aviation industry on aviation carbon emissions in G20 countries. They found that aviation passenger and air cargo transportation activities have an impact on CO_2 emissions. In addition, they found that economic growth, urbanization, and tourism increase emissions.

This study investigates the determinants of CO_2 emissions in air transport. The primary factors influencing demand in the air transport industry are per capita income and the level of economic development. According to Chi [24], passenger transport tends to increase with economic growth in the long term. Hakim & Merkert [40] confirms the long-term causality from GDP to air passenger traffic. In this study, GDP growth and GDP per capita are used as determinants of air transport CO_2 emissions. We expect the demand and number of operations to increase depending on the increase in economic development and per capita income. This also confirms that air transport CO_2 emissions will increase. Foreign direct investment (FDI) and net trade in goods and services are key factors shaping the spatial network structure of the global airline

Table 1
Summary of empirical studies on CO_2 emissions – economic variables.

Study	Period	Units	Determinants	Methodology	Results
A'yun and Anggrayni [15]	1970–2020	United States	Economic growth, energy consumption, forest area, urbanization	Vector Error Correction Model (VECM)	Economic growth, energy consumption, and FDI significantly affect CO_2 emissions in the long term.
Ab-Rahim and Xin-Di [1]	1991–2010	ASEAN+3 countries	Economic growth, energy consumption, urbanisation, trade openness, transportation	Pedroni Cointegration Test and Granger-Causality based on VECM	Economic growth, energy consumption, and trade openness are significant determinants of CO_2 emissions in ASEAN+3.
Adebayo et al. (2021)	1971–2014	Egypt	Economic growth, energy usage, urbanization, gross capital formation	ARDL, Gradual shift causality	There is a positive and significant relationship between energy use and CO_2 emissions. GDP growth positively affects CO_2 emissions.
Adebayo et al., [4]	1980–2018	MINT economies	Economic growth, energy usage, trade, urbanization	ARDL PMG model, Dumitrescu-Hurlin Causality test	CO_2 emissions are positively linked to energy use and urbanization but negatively linked to trade. There is a unidirectional causality from CO_2 to urbanization.
Aller et al. [7]	Various	Multiple countries globally	GDP per capita, fossil fuels share, urbanization, industrialization, democratization, trade, FDI	Bayesian Model Averaging, Cluster-LASSO model selection	CO_2 emissions per capita negatively impact GDP per capita, fossil fuel share, urbanization, industrialization, democratization and the environment.
Amin et al. [9]	1980–2014	European countries	Economic growth, renewable energy consumption, urbanization	Second-generation panel long-run estimates, non-causality test	Increases in renewable energy consumption reduce carbon emissions from transportation. Urbanization has a statistically insignificant positive effect on pollution.
Aslam et al. [13]	1971–2019	China	GDP, industrialization, agriculturalization	Nonlinear ARDL model	GDP and industrialization have asymmetric effects in direction and magnitude on CO_2 emissions in the long run. GDP, industrialization and agriculturalization have short-run effects on CO_2 emissions.
Bae et al. [16]	Various	15 post-Soviet Union independent (PSI) countries	Economic growth, corruption, political democracy, economic freedom, energy efficiency, FDI	GMM approach	There is a linear relationship between GDP and CO_2 emissions. GDP affects CO_2 emissions directly and indirectly through corruption. Corruption affects CO_2 emissions directly and indirectly through GDP.
Chin et al. [25]	Various	Malaysia	Economic growth, vertical intra-industry trade, bilateral FDI	Autoregressive distributed lag, decomposition-type threshold methods	According to the EKC curve, economic growth is the largest contributor to CO_2 emissions. Vertical intra-industry trade with China and bilateral foreign direct investment from China are important determinants of CO_2 emissions.
Dogan and Seker [32]	1980–2012	European Union countries	Renewable energy, non-renewable energy, real income, trade openness	Dynamic ordinary least squares estimator, Dumitrescu-Hurlin non-causality approach	Renewable energy and trade reduce carbon emissions. Non-renewable energy increases CO_2 emissions. The EKC hypothesis is supported. There is bi-directional causality between renewable energy and carbon emissions.
Georgatzi et al. [38]	1994–2014	12 European countries	Environmental policy stringency, climate change mitigation technologies (CCMT), infrastructure investments	FMOLS, DOLS, Granger causality test	Infrastructure investments do not affect CO_2 emissions from the transport sector. There is a strong bi-directional causality between the stringency of environmental policy and CO_2 emissions from the transport sector.
Lo et al. [55]	1997-2011	Italy	Aircraft size, route distance, technical progress, liberalization	Econometric model applied to panel data	Aircraft size increases total emissions but reduces emissions per available seat kilometres (ASK). Route distance increases total emissions but decreases emissions per ASK. Technical progress reduces CO_2 emissions per ASK.
Padilla and Jadotte [63]	Not specified	Developing countries	GDP per capita, agriculture share, daily minimum temperatures, urbanization, active population	Regression-based inequality decomposition method	N-shaped relationship with GDP per capita; agriculture share, and average daily minimum temperatures reduce emissions; urbanization and active population increase emissions.
Queiroz JÃnior et al. [65]	Not specified	21 countries	Air traffic movements, number of airports, GDP	Data envelopment analysis (DEA) and clustering method	South American countries such as Colombia and Chile have lower air traffic movement efficiency compared to European countries such as the UK and Germany.
Shah et al. [68]	2000-2020	Low-income countries	Trade FDI, urbanization, GDP per capita, population density, domestic credit to private sector	Panel data techniques	Trade FDI, urbanization and GDP per capita are the main contributors to CO_2 emissions. Trade openness has a positive but insignificant effect.
Shahbaz et al. [69]	Not specified	China	Public-private partnerships, technological innovations, economic growth, exports, FDI	Bootstrapping autoregressive distributed lag modelling (BARDL)	Public-private partnerships in energy increase emissions; technological innovations reduce emissions. Economic growth shows an inverted-U shaped relationship with emissions (Kuznets curve hypothesis). Exports and FDI increase emissions.
Umar et al. [75]	1981-2020	Pakistan	Exports, gross capital formation, energy use	ARDL analysis	Exports have an inverse relationship with CO_2 emissions. Energy utilization increases emissions. The relationship between exports and CO_2 emissions is unidirectional.
Zheng et al. [83]	Not specified	73 Chinese cities	Population size, secondary industry proportion, energy consumption	Linear mixed effect model	Population size, secondary industry proportion, energy consumption structure, urbanization level, and economic level generally increase CO_2

(*continued on next page*)

Table 1 (*continued*)

Study	Period	Units	Determinants	Methodology	Results
			structure, urbanization level, economic level		emissions. Urbanization level is not significant. Environmental Kuznets curve varies across cities.
Zhou et al. [84]	1980-2014	China	Economic structure, energy consumption structure, income, urbanization, FDI, total trade	Time series analysis (ADF test, KPSS test, Johansen cointegration, VECM model)	Economic structure and energy consumption structure have significant impacts on CO_2 emissions. Bidirectional causal links found between emissions and economic structure/ energy consumption. GDP, urbanization, and trade also influence emissions.
Zmami and Ben-Salha [85]	1980-2017	Gulf Cooperation Council countries	Per capita GDP, energy consumption, urbanization, international trade, foreign direct investments (FDI)	STIRPAT model and PMG-ARDL approach	Validity of the Environmental Kuznets Curve hypothesis. Energy consumption and FDI lead to more environmental degradation in the long run. Urbanization positively impacts the environment. Trade and FDI have mixed impacts.

system. According to Bannò & Redondi [17], FDIs foster the opening of new routes. Kiracı & Battal [50] identify variables that influence air transport activities, though their impact is relatively limited. In this study, it is assumed that foreign direct investment and net trade in goods and services have the potential to increase air transport activities. Therefore, it is thought that these variables may have an indirect effect on air transport CO_2 emissions. Air transport and other travel and transportation services are affected by international inbound and outbound tourism activities. According to Rehman Khan et al., [64], the arrival and departure of international tourists significantly affect passenger transport and related revenues. Moreover, the bidirectional relationship between inbound and outbound tourism and air transport services has been confirmed. Therefore, this study assumes an increase in air transport, particularly driven by international tourism. As a result, air transport CO_2 emissions will also be influenced by the growth of international tourism. Additionally, airline operations play a critical role in urban and regional development. The spatial and temporal patterns of air passenger flows are not independent of the population structure of the region [28]. In this study, urban population was used as one of the determinants of air transport CO_2 emissions. As urban populations increase, individuals are expected to travel more frequently for reasons such as work, education, health, and vacation, and urbanization is generally associated with higher income levels.

The literature on CO_2 emissions from air transport remains limited, with no empirical studies specifically focused on OECD countries. Moreover, to the best of our knowledge, no comprehensive study has systematically analyzed the determinants of CO_2 emissions in air transport. The original contribution of this study lies in expanding beyond the commonly used variables by incorporating key factors such as international tourism and urban population, thereby proposing a more comprehensive model. Consequently, this study is expected to be the first to systematically investigate the determinants of air transport CO_2 emissions in OECD countries, providing valuable theoretical and methodological insights to the literature.

3. Data and research methodology

This study investigates the determinants of air transport CO_2 emissions in OECD countries, using data from 38 member countries over the period 2013 to 2023. A total of 418 observations per variable were analyzed through panel data techniques. The variables were sourced from the OECD Data Explorer, World Development Indicators (WDI), and the statistical agencies of the respective countries. Details of the variables employed are provided in Table 2. While many studies have explored the determinants of CO_2 emissions in general, this research uniquely focuses on factors specifically influencing air transport-related CO_2 emissions.

In this study, we employed Air transport CO_2 emissions as the dependent variable. The independent variables are listed as foreign direct investment (FDI), GDP growth (GDP), international tourism (INT), net trade in goods and services (TRD), and urban population URP.

Table 2
Dependent and independent variables.

Abbreviation	Variable	Source
ATE	Air transport CO_2 emissions	OECD Data Explorer
FDI	Foreign direct investment, net (BoP, current US$)	World Development Indicators
GDP	GDP growth (annual %)	World Development Indicators
INT	International tourism, number of arrivals	WDI/National Statistical Offices
TRD	Net trade in goods and services (BoP, current US$)	World Development Indicators
URP	Urban population (% of total population)	World Development Indicators
GDPPC	GDP per capita (constant 2015 US$)	World Development Indicators

The research model of the study is as follows.

$$\mathrm{ATE}_{it} = \beta_0 + \beta_1 \mathrm{FDI}_{it} + \beta_2 \mathrm{GDP}_{it} + \beta_3 \mathrm{INT}_{it} + \beta_4 \mathrm{TRD}_{it} + \beta_5 \mathrm{URP}_{it} + \beta_6 \mathrm{GDPPC}_{it}\ \varepsilon_{it} \tag{1.1}$$

The dependent variable of the model is ATE. β_0 is the slope parameter. i sub-index indicates OECD countries. t sub-index indicates annual data. In this study, we used panel data analysis as a method. Different types of data are used in econometric analyses and different analysis methods are used depending on the characteristics of the analysed data set. The data subject to econometric analyses; panel data, which is a combination of cross-sectional data and time series and contains information in time/unit dimension, is called panel data analysis. Panel data analysis method has various advantages over time series and cross-sectional data. Panel data used in panel data analysis are superior to horizontal cross-section data and time series in many respects. Panel data provides more accurate parameter estimates since it contains more sample diversity and degrees of freedom than horizontal cross-section data and time series. In addition, panel data analysis allows the construction and testing of complex models and behavioural hypotheses. Since panel data analysis includes intertemporal relationships and specific information of the units, it allows unobservable variables to be controlled more easily. The method reveals the dynamic nature of economic behaviour and enables more consistent forecasts by bringing together data from different units. Panel data analysis also allows for more robust analysis results since it contains information on the time dimension of the units and helps to investigate homogeneity rather than heterogeneity [30].

Panel data, which is a combination of horizontal cross-sectional data and time series and contains information in time/unit dimension, provides more robust results when used in econometric analysis. In general, the panel data model is shown as follows.

$$\mathrm{Y}_{it} = \alpha_0 + \beta_{it} + \varepsilon_{it} \tag{1.2}$$

In panel data analysis, it is crucial to perform several pre-tests on the series to ensure the robustness of the results. First, cross-sectional dependence test is performed on the series. In this way, it is decided which of the first generation or second-generation unit root tests will be applied in the stationarity test. After determining the stationarity level of the series, model identification test is performed. In the next step, variance and autocorrelation tests are applied to the model. In the last stage, some corrections are applied to obtain robust standard errors.

In the first stage of the analysis, logarithmic transformations were applied to the variables Air Transport CO_2 Emissions, International Tourism, and GDP per Capita to stabilize variance and meet the assumptions of the model. Due to the presence of cross-sectional dependence across all variables, the CADF panel unit root test was employed. The results indicated that Air Transport CO_2 Emissions, Net Trade in Goods and Services, Urban Population, and GDP per Capita are stationary at first difference, whereas the remaining variables are stationary at level. Furthermore, the Hausman test results supported the use of the fixed effects model. To assess potential violations of model assumptions, heteroskedasticity and autocorrelation tests were conducted. The Modified Bhargava et al. Durbin-Watson and Baltagi-Wu LBI statistics indicated no evidence of autocorrelation. However, the Modified Wald test for groupwise heteroskedasticity revealed the presence of heteroskedasticity at the group level. To address this issue, the fixed effects model was estimated using standard errors clustered at the country level. This estimation strategy is widely accepted in the literature for panel data settings with unit-specific variance structures.

4. Results

This section presents the panel regression results. The analysis is divided into three parts. The first part reports the results for all OECD countries. The second part provides subgroup analyses, where OECD countries are classified based on their geographical regions. The third part focuses on individual regression results and graphical illustrations for countries with the highest air transport CO_2 emissions. Descriptive statistics are shown in Table 3. For the OECD group, air transport CO_2 emissions reach a maximum value of 2.00E+08. Among these countries, the United States, which has a highly active air transport industry, exhibits the highest emissions. Lithuania has the lowest Air transport CO_2 emissions value with 1147. Air transport CO_2 emissions of Lithuania, Slovenia and Estonia in the EU region are lower than other OECD countries. Foreign direct investment is maximum 2.18E+11 and minimum -3.45E+11. FDI was highest in Japan in 2019 and lowest in the United States in 2018. GDP growth was realized as maximum 24.475 and minimum -11.167. Due to the recessionary effect of the Covid-19 effect on the economy, many OECD countries experienced negative growth in 2020. Ireland, Türkiye, Chile and Colombia are the countries that achieved growth above 10% after Covid-19. The average growth in OECD countries for the period 2013-2023 is 2.298%. International tourism data shows a maximum of 93 million and a minimum of 190 thousand. The highest number of tourists arriving is in France. OECD countries reached the lowest number of tourists in 2020 and 2021. Net trade in goods and services had a maximum of 2.61E+11 and a minimum of -9.51E+11. While Germany is the OECD country with the highest value in net trade in goods and services, United States has the lowest value. In urban population, Belgium has the maximum value with 98.18% while Slovenia and Slovak Republic have the lowest value. The maximum GDP per capita is 110425 and the minimum is 5891. The country with the highest GDP per capita is Luxembourg, while the lowest is Colombia.

Table 3
Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
Air transport CO_2 emissions	418	1.11E+07	2.69E+07	1447.00	2.00E+08
Foreign direct investment	418	5.46E+09	5.16E+10	-3.45E+11	2.18E+11
GDP growth	418	2.298	3.319	-11.167	24.475
International tourism	418	16805000	20505000	190000	93200000
Net trade in goods and services	418	1.32E+09	1.17E+11	-9.51E+11	2.61E+11
Urban population (% of total population)	418	78.211	11.067	53.332	98.189
GDP per capita (constant 2015 US$)	418	37101.91	23158.70	5891.96	110425.90

4.1. Panel regression results for OECD countries

An important aspect to consider in regression analysis is the correlation among independent variables. In this study, the correlations between the independent variables were examined, and no evidence of multicollinearity was found. Additionally, several diagnostic tests were conducted for the panel data analysis, including tests for cross-sectional dependence, model specification, unit roots, autocorrelation, and heteroskedasticity. The detailed results of these tests are provided in the appendix. Based on the outcomes of these preliminary analyses, a regression model incorporating robust standard errors was employed to ensure reliable and efficient estimation.

In the panel data analysis, both Fixed Effects (FE) and Random Effects (RE) models were estimated for model selection. Additionally, pooled OLS estimates were included for comparison. The Hausman test used to compare the models revealed a correlation between the explanatory variables and individual fixed effects, indicating that the Random Effects model is inconsistent ($\chi^2(4) = 35.20$, $p < 0.01$). Based on this result, the Fixed Effects model was preferred. However, for the purpose of comparative analysis and to assess the consistency of the results, the RE and Pooled OLS estimates are also presented in the table. This allows for the observation of the impact of different modeling approaches on the estimates and the evaluation of the direction and significance of the variables across models.

Table 4 presents the panel regression results. The findings of the analysis indicate that GDP growth has a positive and significant effect on Air transport CO_2 emissions. In OECD countries, GDP growth causes an increase in Air transport CO_2 emissions at 10% significance level. International tourism (number of arrivals) is another variable that has a positive and significant effect on Air transport CO_2 emissions. Therefore, as international tourism increases in OECD countries, air transport CO_2 emissions also increase. The final variable influencing air transport CO_2 emissions is net trade in goods and services. Net trade in goods and services has a negative effect on air transport CO_2 emissions at 10% significance level. GDP per capita has a positive effect on air transport CO_2 emissions. Foreign direct investment and urban population do not have any significant impact on air transport CO_2 emissions. Foreign direct investment and urban population do not have any significant impact on air transport CO_2 emissions. The results obtained from the Fixed Effects (FE), Random Effects (RE) and Robust Fixed Effects models are similar. The similarity of the results may mean that the robustness of the standard errors in the Robust FE model does not significantly change the underlying relationships between the variables. Therefore, the consistency between these models supports the reliability of the findings regardless of the applied method.

4.2. Regional panel regression results

In this study, countries were classified according to their geographical regions, and the regression analysis was repeated for each subgroup. The aim was to examine the influence of geographical factors on the determinants of air transport CO_2 emissions. Accordingly, two panels were created. The decision to limit the analysis to two panels was based

Table 4
Panel regression analysis results.

	Fixed effect			Random effect			Robust FE		
ATE	Coef.	Std. Err.	t	Coef.	Std. Err.	z	Coef.	Robust SE	t
FDI	2.20E-13	6.80E-13	0.33	5.00E-13	5.40E-13	0.92	2.20E-13	3.30E-13	0.68
GDP	7.10E-02	9.20E-03	7.65***	7.10E-02	8.20E-03	8.56***	7.10E-02	1.00E-02	6.79***
INT	1.90E-01	4.90E-02	3.77***	4.80E-02	2.20E-02	2.22**	1.90E-01	4.10E-02	4.53***
TRD	-1.40E-12	1.10E-12	-1.37	-1.10E-12	1.00E-12	-1.09	-1.40E-12	8.30E-13	-1.72*
URP	-3.00E-01	8.10E-01	-0.37	-1.30E-01	1.70E-01	-0.77	-3.00E-01	1.00E+00	-0.29
GDPPC	1.90E+00	4.60E-01	4.10***	-9.50E-03	4.40E-02	-0.22	1.90E+00	5.80E-01	3.27***
Cons	-2.10E+01	4.80E+00	-4.48***	-4.50E-01	4.90E-01	-0.92	-2.10E+01	6.00E+00	-3.56***

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

on the insufficient number of countries and observations in other regions, which would have compromised the reliability of the results. The first panel includes data from countries in the European region, while the second panel focuses on countries in the American region[2].

Table 5 presents the analysis results. While the regression findings are generally consistent across both panels, the Urban Population variable exhibits contrasting effects: it has a positive impact on air transport CO_2 emissions in Panel I (European countries) but a negative effect in Panel II (American countries). This difference may be due to the limited number and frequency of international flight connections in countries like Colombia, Chile, and Costa Rica, despite urbanization growth. In contrast, the Schengen Area facilitates easy travel for urban populations in Europe via short-distance and low-cost airlines such as Ryanair and WizzAir. These shorter flights may contribute to higher emission levels. Additionally, the effects of GDP and international tourism on air transport CO_2 emissions are more pronounced in the American region compared to the European region.

4.3. Country-level results

In this section, individual regression analyses of the eight countries with the highest air transport CO_2 emissions are presented graphically. In this context, individual analyses were conducted for the countries with the highest air transport CO_2 emissions.

Fig. 1 visualizes the temporal evolution of air transport CO_2 emissions for the United States, the United Kingdom, Turkey, and Germany, along with the results of a model developed to capture this variation. The findings clearly indicate that, while air transport emissions exhibited a general upward trend between 2013 and 2019, they experienced a dramatic decline in 2020 across all observed countries due to the impact of the COVID-19 pandemic. The high explanatory power of the econometric models (as reflected in the R^2 values) suggests that the variables employed offer a robust analytical framework for understanding and forecasting changes in air transport emissions. At the country level, notable differences emerged in both emission levels and recovery trajectories. While the United States maintained relatively high emission levels, Turkey exhibited a steeper and more volatile decline. In contrast, the United Kingdom and Germany followed a more stable pattern over time.

Fig. 2 illustrates the temporal evolution of air transport CO_2 emissions for Japan, Canada, South Korea, and France, alongside the results of a model developed to capture these dynamics. The results indicate that air transport emissions generally followed an upward trend between 2013 and 2019. However, significant declines were observed in 2020 and 2021, primarily due to the near-complete halt in airline operations caused by the COVID-19 crisis. Moreover, the consistently high R^2 values across all countries suggest that the econometric model exhibits strong explanatory power. At the national level, noticeable differences were observed in both the magnitude of emissions and the pace of recovery across the countries analysed.

5. Discussion

This study analysing the determinants of air transport CO_2 emissions for OECD countries has several notable findings. In the study, we found that GDP growth has a positive and significant effect on air transport CO_2 emissions. According to Marjanović et al. [58], the effect of GDP growth on CO_2 emissions may change over time due to differences in technology and regulatory policies. Acaravci and Ozturk [2] find evidence of a long-run relationship between per capita carbon emissions and real gross domestic product (GDP) per capita for Denmark, Germany, Greece, Iceland, Italy, Portugal and Switzerland. Sikder et al. [71] find that economic growth increases CO_2 emissions by 0.17% in the long run for 23 developing countries. Similarly, there is evidence of bidirectional causality between CO_2 emissions and economic growth in middle-income countries [22]. Acheampong [3], in his study for 116 countries, found that carbon emissions have a positive effect on economic growth. The environmental Kuznets curve (EKC) has an important place in the literature on CO_2 emissions and economic growth and development. According to the EKC hypothesis, the relationship between per capita income and CO_2 emissions is approximately inverted U-shaped. In countries aiming for development, environmental damage increases as GDP per capita increases due to the increase in production. After the level of development reaches a certain level of saturation, environmental damage tends to decrease. Özokcu and Özdemir [62] analysed the relationship between income and CO_2 emissions in the context of the Environmental Kuznets Curve (EKC) for the period 1980-2010 in 26 OECD countries. The findings rejected the EKC hypothesis that environmental degradation cannot be solved by economic growth. In a similar study, Churchil et al., [26] tested the EKC hypothesis for the period 1870-2014 in 20 OECD countries. The findings show that the EKC hypothesis is valid only for nine out of 20 countries. Unlike previous studies in the literature, this study focuses specifically on air transport CO_2 emissions rather than total CO_2 emissions. Therefore, whether the EKC hypothesis is valid in terms of the relationship between air transport CO_2 emissions and GDP growth is beyond the scope of this study. On the other hand, the effect of GDP per capita on air transport CO_2 emissions was also examined in the research model. GDP per capita is related to the purchasing power of individuals, unlike GDP growth. GDP per capita is high in developed economies and in other countries. GDP per capita is one of the basic variables supporting airline activities [19]. A high GDP per capita causes individuals to allocate a higher budget to activities that will support airline operations such as holiday travel. Therefore, air transport CO_2 emissions are higher in countries where GDP per capita is high, while air transport CO_2 emissions increase faster in countries where GDP per capita increases at a higher rate.

The results of the study reveal that international tourism (number of arrivals) has a significant positive effect on air transport CO_2 emissions. In particular, the fact that international tourism activities are generally

[2] Canada, United States, Mexico, Costa Rica, Chile, Colombia

Table 5
Regional results of panel regression analysis.

	Panel I			Panel II		
ATE	Coef.	Std. Err.	t	Coef.	Std. Err.	t
FDI	4.1E-13	6.1E-13	0.68	1.6E-14	1.5E-13	0.11
GDP	6.8E-02	1.3E-02	5.11***	5.9E-02	7.9E-03	7.50***
INT	3.0E-01	5.9E-02	5.09***	1.8E-01	8.4E-02	2.19*
TRD	-1.9E-12	1.4E-12	-1.32	-5.3E-13	3.2E-13	-1.64
URP	1.2E+00	6.6E-01	1.89*	-2.0E+00	4.8E-01	-4.05***
GDPPC	1.4E+00	5.4E-01	2.62**	2.6E+00	1.3E+00	1.98
Cons	-1.8E+01	5.8E+00	-3.05***	-2.7E+01	1.3E+01	-2.00

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

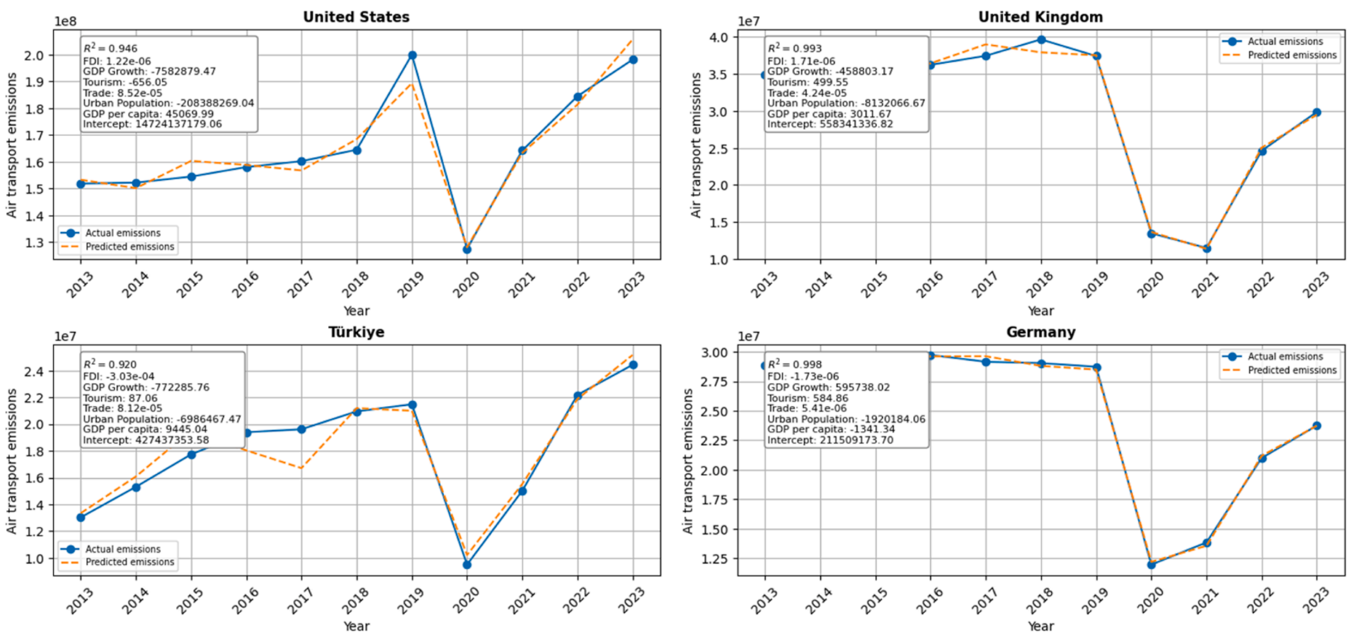

Fig. 1. Air transport CO_2 emissions and socio-economic indicators – Group I.

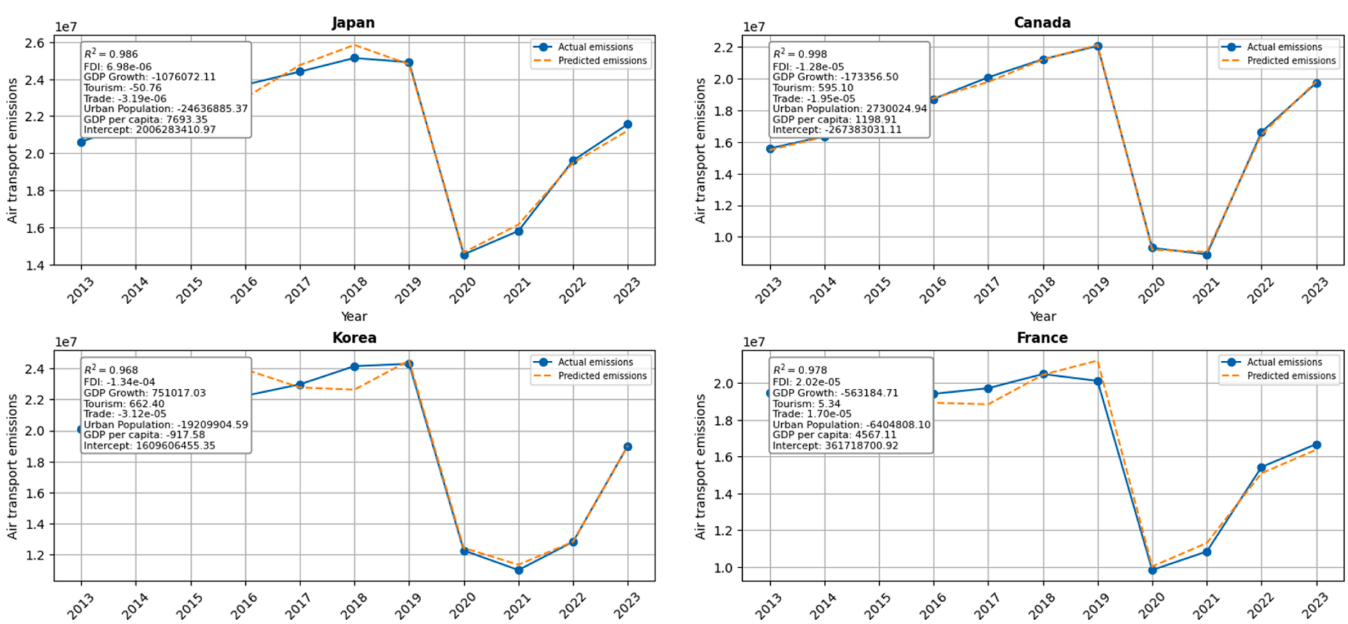

Fig. 2. Air transport CO_2 emissions and socio-economic indicators – Group II.

carried out through the air transportation industry makes it reasonable for a positive relationship to emerge. There are no studies in the literature that directly examine the relationship between air transport CO_2 emissions and international tourism, but studies that examine the relationship between international tourism activities and CO_2 emissions support our findings. Katircioglu et al., [49] found that international tourism activities are an important catalyst for the increase in CO_2 emission levels in Cyprus. In a similar study, Ben Jebli and Hadhri [18] examined the dynamic causality relationship between international tourism and CO_2 emissions from transportation for the top ten international tourism countries. The results of the study revealed that there is a bidirectional causality between international tourism and CO_2 emissions due to energy use. On the other hand, some studies in the literature provide evidence that, for certain segments, an increase in environmental tourism activities reduces CO_2 emissions [33,79]. Although these studies are valid for specific segments and not for the general case, they carry hopeful assumptions that environmental tourism and environmental transportation can reduce CO_2 emissions. In our study, however, there is considerable evidence that international tourism activities increase air transport CO_2 emissions in OECD countries.

Net trade in goods and services is the trade in goods and services between residents and non-residents in a country. Not only commercial airline passenger flights, but also flights related to cargo transportation are included in the scope of trade in goods and services. Although less than 1% of the goods in the world's global trade system are transported by air freight, 35% of their value is carried by air freight [42]. Therefore, trade in goods and services is expected to affect air transport CO_2 emissions. The findings of the study reveal that net trade in goods and services has a negative effect on air transport CO_2 emissions in OECD countries. There is evidence in the literature that an increase in trade volume increases CO_2 emissions, but after 2005, trade in certain sectors led to emission reductions [77]. In a similar study, Xu et al. [80] found that the volume of CO_2 emissions from interregional trade in China has increased significantly but with a downward trend. Jiang and Guan [48] emphasized that OECD economies have a less carbon-intensive lifestyle and that there is a significant difference in the increase in CO_2 emissions between OECD and non-OECD economies for the period after the 2008-2011 global financial crisis. There is strong evidence in the literature that there are significant differences between international trade and CO_2 emissions depending on the level of development of countries. According to Essandoh et al. [34], CO_2 emissions have a negative long-run relationship with trade for developed countries, while Kozul-Wright and Fortunato [51] find that trade increases the emissions burden in less industrialized countries. The intensive investment in renewable energy as well as nuclear energy in OECD countries reduces the potential for international trade to increase CO_2 emissions in these countries. Muhammad et al. [59] reveal that renewable energy consumption (REC) is negatively related to CO_2 emissions in OECD countries. There is no study in literature that examines the relationship between international trade and air transport CO_2 emissions. However, in parallel with the studies in the literature, the results of our study provide strong evidence that the EKC hypothesis is valid as OECD countries prefer greener production processes.

The research findings indicate that the primary variables positively influencing air transport CO_2 emissions are GDP growth, international tourism, and GDP per capita. Accordingly, increases in economic growth, tourism activities, and individual income levels are associated with higher levels of air transport emissions. Under these circumstances, achieving the aviation industry's net-zero emissions target by 2050 will require a range of critical policy decisions by regulators. In this context, the development of environmentally friendly transportation policies and the promotion of investments in emission-reducing technologies—such as subsidies for sustainable aviation fuels—could significantly contribute to reducing air transport CO_2 emissions. To offset and gradually reduce rising CO_2 emissions, the implementation of carbon pricing mechanisms (such as carbon taxes or emissions trading systems) and the integration of airlines into these frameworks may become necessary. Additionally, improving the efficiency of flight operations at airports can help prevent unnecessary fuel consumption by aircraft, thereby reducing emissions. Furthermore, since international tourism contributes to higher CO_2 emissions, it is essential to support green tourism practices that are oriented toward lower-emission alternatives. In conclusion, to mitigate CO_2 emissions from air transport, policymakers must design comprehensive emission reduction strategies that enhance operational efficiency and promote environmentally sustainable practices.

6. Conclusion

This study focuses on the determinants of air transport CO_2 emissions in OECD countries, which generally represent developed economies with strong infrastructure in transportation, the service sector, and technology. A defining characteristic of these countries is their commitment to environmental policies and support for sustainable development goals. Given their well-developed transportation infrastructure and significant share of global air transport activities, OECD countries provide an ideal context for this analysis. The air transportation industry is among the fastest-growing sectors worldwide. Despite various environmental policies and emission reduction targets, achieving the 2050 zero-emission goal remains a critical challenge. The strategies adopted by OECD countries to eliminate aviation emissions are not only vital for their own sustainability but also essential for meeting the ICAO CORSIA targets and setting an example for other nations. This study empirically investigates the effects of foreign direct investment (FDI), GDP growth (GDP), international tourism (INT), net trade in goods and services (TRD), and urban population (URP) on air transport CO_2 emissions across 38 OECD countries during the period 2013–2023. Panel data analysis techniques are employed to capture the dynamic relationships among these variables.

Although there are many studies examining the determinants of CO_2 emissions in the literature, the lack of studies examining the determinants of air transport CO_2 emissions is extremely important in terms of filling the gap in the literature. The results of the study show that the increase in GDP increases air transport CO_2 emissions. Furthermore, there is a close relationship between air transport and tourism activities. International tourism visits are usually made via air transport. Therefore, one of the variables in our model was international tourism (number of arrivals). The results of the study show that the increase in international tourism activities has a positive effect on air transport CO_2 emissions. Since the tourism sector has a high growth rate, it is possible that air transport CO_2 emissions from international tourism will increase in the future not only in OECD countries but also in other countries.

The regional panel regression results indicate that both GDP growth and international tourism are key drivers positively influencing air transport CO_2 emissions in both the European and American regions. However, the impact of urban population on air transport emissions differs across regions: it is positive in Europe but negative in the Americas. Additionally, GDP per capita is found to have a significant positive effect only within the European region. These findings suggest that regional differences are not a decisive factor in shaping air transport CO_2 emissions. Therefore, similar policy approaches aimed at environmental sustainability could yield consistent outcomes across these regions. At the country level, the results reveal that a significant number of OECD countries follow a comparable trajectory in air transport CO_2 emissions. While emissions exhibited a general upward trend from 2013 to 2019, a dramatic decline was observed across all examined countries in 2020 and 2021 due to the impact of the Covid-19 pandemic. Since 2022, air transport CO_2 emissions have shown signs of a renewed upward trend.

This study also investigates the impact of trade in goods and services on air transport CO_2 emissions. The model results indicate that an increase in trade is associated with a reduction in air transport CO_2 emissions. This negative relationship may reflect OECD countries' strong emphasis on efficiency-oriented practices in international trade logistics and their adoption of lower-emission transportation modes. Given the unexpected nature of this finding, we recommend further in-depth research to better understand the underlying causes of this negative association within OECD countries. It is important to note that this study is limited to data from 2013 to 2023 for OECD countries. While the analysis provides valuable insights into the general trends influencing air transport CO_2 emissions, different outcomes may arise when examining other time periods. This represents a limitation of our study. Future research could extend this work by exploring both short- and long-term relationships between air transport CO_2 emissions and a wider range of socio-economic factors. Such investigations could be conducted either at the individual country level or through broader cross-country panel analyses. Additionally, future studies may incorporate dynamic effects of policy interventions, technological progress, and structural changes in the aviation sector over time to provide a more comprehensive understanding.

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Ethics statement

Not applicable because the paper uses archival data from a public domain and does not state or imply any personal information

CRediT authorship contribution statement

Kasım Kiracı: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors have no conflicts of interest to declare.

Appendix

Tables A1, A2, A3.

Table A1
Correlation matrix.

	FDI	GDP	INT	TRD	URP	GDPPC
FDI	1					
GDP	-0.0309	1				
INT	-0.0591	-0.0358	1			
TRD	0.1744	0.0086	-0.2903	1		
URP	0.1507	-0.0746	-0.0180	-0.0774	1	
GDPPC	0.1137	0.0300	-0.0551	0.0054	0.3473	1

Table A2
Cross-sectional dependence test results.

	Test	Statistic	Prob.
ATE	Breusch-Pagan LM	3465.45	0.0000
	Pesaran scaled LM	72.6584	0.0000
	Bias-corrected scaled LM	70.7584	0.0000
	Pesaran CD	43.9644	0.0000
FDI	Breusch-Pagan LM	855.494	0.0001
	Pesaran scaled LM	3.05344	0.0023
	Bias-corrected scaled LM	1.15344	0.2487
	Pesaran CD	-1.33519	0.1818
GDP	Breusch-Pagan LM	4610.78	0.0000
	Pesaran scaled LM	103.203	0.0000
	Bias-corrected scaled LM	101.303	0.0000
	Pesaran CD	66.0452	0.0000
INT	Breusch-Pagan LM	4921.85	0.0000
	Pesaran scaled LM	111.499	0.0000
	Bias-corrected scaled LM	109.599	0.0000
	Pesaran CD	66.3883	0.0000
TRD	Breusch-Pagan LM	2215.68	0.0000
	Pesaran scaled LM	39.3282	0.0000
	Bias-corrected scaled LM	37.4282	0.0000
	Pesaran CD	7.67439	0.0000
URP	Breusch-Pagan LM	6921.63	0.0000
	Pesaran scaled LM	164.831	0.0000
	Bias-corrected scaled LM	162.931	0.0000
	Pesaran CD	66.5207	0.0000
GDPPC	Breusch-Pagan LM	5561.78	0.0000
	Pesaran scaled LM	128.566	0.0000
	Bias-corrected scaled LM	126.666	0.0000
	Pesaran CD	73.0911	0.0000

Table A3
CADF panel unit root test results.

Variable	Stat	Critic Value		
		1%	5%	10%
log_ATE	-1.090	-2.26	-2.11	-2.03
Δlog_ATE	-2.272*	-2.26	-2.11	-2.03
FDI	-2.908*	-2.26	-2.11	-2.03
GDP	-2.334*	-2.26	-2.11	-2.03
log_INT	-2.903*	-2.26	-2.11	-2.03
TRD	-1.527	-2.26	-2.11	-2.03
ΔTRD	-2.732*	-2.26	-2.11	-2.03
URP	-1.780	-2.26	-2.11	-2.03
ΔURP	-3.659*	-2.26	-2.11	-2.03
log_GDPPC	-0.821	-2.26	-2.11	-2.03
Δlog_GDPPC	-2.026***	-2.26	-2.11	-2.03

Data availability

Data will be made available on request.

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