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Tapdig Imanov, Hatice Imamoglu

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Aviation impact on air quality: evidence from countries with highest air traffic

Tapdig Imanov* and Hatice Imamoglu

Department of Business Administration,
Faculty of Economics, Administrative and Social Sciences,
Cyprus Science University,
Dr Fazıl Küçük Caddesi, Ozanköy, 99320,
Kyrenia/TRNC Mersin 10, Turkey
Email: timanov@yahoo.com
Email: haticeimamoglu@hotmail.com
*Corresponding author

Abstract: The current study aims to analyse the relationships between air transportation and carbon dioxide emissions employing the data from 20 countries in different geographical locations to discover the role of the aviation industry impacts on air quality. The analysis was performed by considering pool ordinary least square (POLS), random effect (RE), fixed effect (FE), fixed effect robust, fixed effects Driscoll and Kraay methods using panel data covering years from 1990–2014, to examine the effect of passenger and cargo transportation on environmental quality. Findings reveal that air passenger transportation has a significantly enhances environmental degradation due to a rise in the consumption of fossil fuels, which contributes to an increase in the volume of carbon dioxide emissions. On the other hand, air freight transportation lessens the negative effect of destruction on air quality. The result suggests focusing on new generation aircraft concepts and technologies under fuel strategy scenarios proposed by International Civil Aviation Organization (ICAO) and International Air Transport Association (IATA). Entry to service new generation aircrafts enable use of biofuel with reduced fuel flow which is feasible in order to mitigate CO₂ emission level.

Keywords: air transportation; aviation; CO₂ emission; environment; air quality.

JEL codes: E10, L93, Q51.

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Biographical notes: Tapdig Imanov has received a Master of Science in Aviation Engineering and Management. He received his Bachelor's in Aircraft Engineering and Maintenance in 1989 from Kiev National Aviation University and Master's degree in 2021 from University of Kyrenia. His research interests include aircraft maintenance, management, and innovation in the aviation industry.

Hatice Imamoglu is an Associate Professor and Doctor of Finance. She received her Bachelor's in Industrial Engineering in 2005, Master's in Banking and Finance in 2013, and Philosophical degree in Finance in 2018. She is focusing on time series and panel data analyses. Her research interests include finance, macroeconomics, innovation, tourism, energy, and environmental issues.

1 Introduction

Air transportation remains a highly demanded carrier mode concerning quality, timesaving and economic development. It ensures considerable international and domestic air networks, contributing to the growth of the aviation industry, having a positive effect on the global economy (Wolfe et al., 2016).

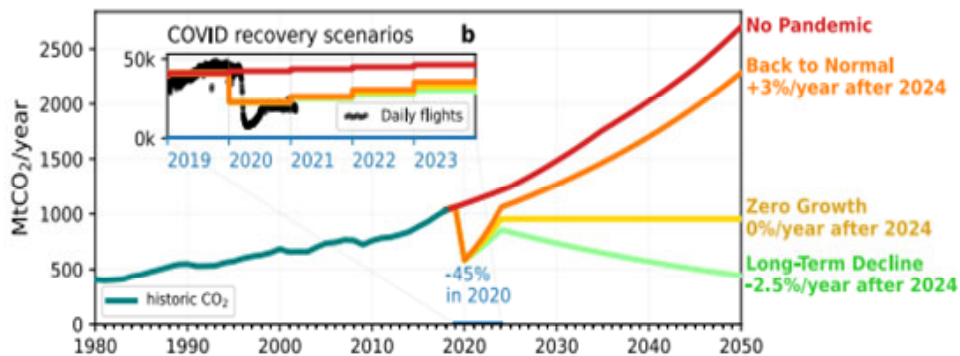
However ecological challenges from aviation become a more serious and main concern in the context of environmental degradation, which air transportation has continuously increased over the past years. According to International Air Transport Association (IATA, 2022) analysis, airline operations continue to recover after the pandemic period, meanwhile over 300 airlines share 83% of global air traffic. Almost all airline markets, including the Middle East region, North American carriers, the European Union (EU) airlines, and the Latin American region have shown more than 100% growth rates, meanwhile, the biggest movers in the international passenger markets were the Asia-Pacific airlines. Taking into account the environmental factors, the rapid growth of the aviation industry harms the whole ecosystem of the planet, impacting air quality and pollution, global warming and climate change, and finally human health (Kuzu, 2018; Dinc, 2020).

Aircraft-related carbon dioxide emission exceeds hundred times per hour more than other ground transportation vehicles. The emissions from global aviation contributed about 2.4% per year before the COVID-19 pandemic (IPCC, 2014), and counted nearly one billion tons annually (Kimbrough, 2022). The rise in passenger air travel and cargo transportation consequently contributes to the increase in the carbon dioxide emission rate emitted from aircraft engines thus rendering a significant negative effect on environmental degradation (Shirmohammadi et al., 2017).

A striking example of the impact of aviation on the environment, which is a source of CO₂ emissions, was shown by the widespread pandemic around the world. Since the beginning of the COVID-19 pandemic implemented travel restrictions across borders by air, many airlines in most countries have involuntarily grounded aircraft fleets (cargo aircraft excluded) pushing on the airline industry to bear a huge financial crisis (Gössling, 2020). While a case has appeared to significantly reduce carbon dioxide emissions and other environmental pollutants caused by aviation (Le Quéré et al., 2020). This was another indication of the necessity of decarbonisation of the aviation industry to avert ecological degradation and global warming. These required the fastest solution to reach net zero fuel ensuring sustainable aviation fuel (SAF) project (IPCC, 2018). Using SAF (biofuel) is an alternative to traditional jet fuel with the same properties in order to power the aircraft engines without any upgrade or alteration in engine design projects. Mixture

of both fuels to provide engine operations can reduce harmful emissions by nearly 80%, (Airbus, 2024). Most recently, Qantas Airways and Airbus have jointly setup a biofuel refinery for the SAF project in the early-stage of development, investing 200 million USD (Airbus, 2022). The EU's target is to build seven new plants for biofuel production to make approximately 2.2 M tonnes every year of green fuel. Repsol has created a significant amount of SAF to carry out test flights for British Airways-owned carriers such as Iberia, Air Europa, and Vueling (Landauro et al., 2023). In the aviation industry, the aircraft engines are the main sources of carbon dioxide emissions, which burn more than one billion litres of fuel per day, equivalent to 3.16 kg of CO₂ per kilo of jet fuel (ICAO, 2017; COG, 2024). In addition, the aircraft engines are emitting a considerable amount of nitrogen oxide (NO_x) at cruise level upper layer of the troposphere, causing a chemical reaction and formation of clouds by the trails of condensations violating the radiative balance of methane (CH₄), ozone (O₃), stratospheric water vapour (H₂O) and other gasses (Chen and Gettelman, 2013; Lee et al., 2021). The aggregate historical trend of atmospheric CO₂ emissions naturally increases over the many thousands of years (Inman, 2008), and the gathered carbon dioxide emissions of aviation between the period from 1940 to 2019 consist of about 33 gigatons of carbon dioxide (Gt CO₂), (Klöwer et al., 2021). The carbon dioxide emissions from global aviation in 2019 only, have been counted as nearly 1 billion (Gt CO₂) tonnes, Figure 1 (Moran et al., 2018).

Figure 1 Historical and future annual carbon dioxide (CO₂) emissions of aviation (see online version for colours)



Source: Klöwer et al. (2021)

Increasing the commercial flights in the near future will harm environmental quality, as the CO₂ emissions continue to accumulate and dominate over the effects of current preventive actions (Klöwer et al., 2021). However, the high-temperature combustion processes in aircraft engines produce particulate matter (PM) and nitrogen oxides (NO_x), which are significant pollutants. Apart from human health damage, both emitted organic compounds have notable impacts on the environment-altering properties of atmospheric chemistry and the Earth's radiation balance (Miake-Lye et al., 2016; Miake-Lye and Hauglustaine, 2022). Taking force on the way to transfer the use of biofuels by 2050 the CO₂ emissions will be lowered, even in case of increased air traffic. Lowering the carbon dioxide emissions year-by-year over the next decades, expected to reach by using mixed fuels. Because of fewer particles contained in components, synthetic and biofuels generation of contrails will be lowered by using a less carbonised fuel (Burkhardt et al.,

2018; Voigt et al., 2021; Karcher et al., 2021). There are various research papers concerning environmental degradation, which elaborated on the relationship between carbon dioxide emissions associated with numerous factors. Most of the studies focused on air quality and environmental degradations, by testing influences of different variables applying econometric functions models.

The current study is examining the relationship between carbon dioxide emissions (CO_2) and air transport, involving relevant factors such as GDP, energy, and fuel consumption, and analysing the specific countries and nearby regions with the highest traffic flow to analyse the impact of carbon dioxide emissions from aircraft engines on air quality. However, the study has certain limitations due to unavailability of the updated data omitted from 2015 and toward, which has potential bias in measurement, hence affecting the accuracy of the real outcomes if compared with current flight congestion and environment situation selected countries.

Despite this, the study and its findings have made a significant contribution, addressing a gap in the literature, indicating a useful direction towards obtaining renewed databases in involved countries, and providing valuable guidance for future research that can utilise both time series and panel datasets. In addition, the result of the study should prompt decision-makers to focus on the level of produced emissions and air pollution scale driven by aircrafts. It is a motivation for airlines, enabling them to predict purchase next generation aircrafts with SAFs able to reduce the level of aviation-related CO_2 emission level and mitigation environmental degradation.

Focusing on aviation impact on the environment, the purpose of the study is to analyse the panel data, utilising the econometric statistical method to determine the relationship between environment and air transportation in the top 20 countries with the highest air traffic flow. This study is designed following: Section 2 reviews the literature, Section consists of theoretical settings, Section 4 includes data and methodology, Section 5 describes empirical results and discussion, and Section 6 concludes.

2 Literature review

The world economy is dependent on energy sustainability and its potential is inevitable for the consumption of its resources throughout the world. The use of energy resources, in turn, is one of the important components of the source of the environmental pollutant. Upon interpretation that aviation is one of the sources of damage to the environment, it must be accepted that overall aviation activities are linked to the use of industrial energy and fossil fuels, in the same energy family. The argument expressed, the energy industry and energy supply sectors are the primary source of air pollution created by CO_2 emissions was supported in the study of Neagu and Teodoru (2019), referring to major developed and emerging nations at the global scale. The study concludes by emphasising the need to take economic complexity into account when developing national targets for energy and economic policies.

The study by Adedoyin et al. (2021) has simulated improvement policy testing the relationship between energy consumption (ENG) and the pollution of the environment in Japan covering periods between 1970 and 2018 by using an original dynamic model for autoregressive distributed lag (ARDL) and Kernel-based regularised least squares (KRLS) has been conducted panel data analysis. The empirical results of the study confirmed that CO_2 emissions have a significant long-term relationship with GDP per

capita and renewable energy, while air transport is significant in the short run. Therefore, a unit by an increment of alternative energy usage contributes to lessening the carbon dioxide emission accordingly in the long and short term.

Sharif et al. (2019) examined the relationship between CO₂ and ENG by comparing the effect of alternative and conventional energy applications. The result confirmed the effectiveness of renewable energy which contributes to reducing the impact of environmental degradation while decreasing ecological hazards. Although a study carried out by Apergis et al. (2010) contradicts the findings above mentioned investigations conducted by Sharif et al. (2019) and Adedoyin et al. (2021).

Frondel et al. (2010) also argued that even renewable energy sources will not be effectively significant in the reduction of CO₂. Menyah and Wolde-Rufael (2010) supported the position that the application of alternative energy sources does not yet been improved at a target level to contribute to decreasing carbon-dioxide emissions significantly. The European Environment Agency (EEA, 2021) most recently, has analysed relationships between air transport and the environment and validated the influence of the air transportation system on environmental quality, motivated that the whole transportation system is the largest consumer of the world's oils and fuels. In turn, it brings air pollution, caused by CO₂ emissions and particulates. In the context of growth of the aviation industry, the most appropriate solution to reduce aircraft-induced carbon dioxide emissions remains rapid transfer to the biofuels concept, as a renewable energy source to be an alternative to fossil-based jet fuel. Using the respective plants for renewable energy production, which is able extraction an adequate amount of CO₂ from the air will at least partially down the emission level. These advances allow recycling carbon dioxide and greenhouse gas (GHG) management for sustainable development, which is the vision for the route to achieving net-zero carbon emissions from aviation (Yao et al., 2020). However, the decarbonised fuel is unlikely will contain full carbon dioxide neutral at the initial stage of production (Klöwer et al., 2021). Bozkurt and Yusuf (2014) have investigated the interrelation between GDP and energy usage on carbon-dioxide emissions for Turkey in the period between 1960 and 2010 and found adverse effects of ENG on CO₂ emissions, while GDP has demonstrated a positive impact on it.

Hassan and Nosheen (2018) studied the effect of air transportation on CO₂ emissions in combination with other gasses produced by aircraft engines from 1990 to 2017 in Pakistan by utilising the ARDL methodology, the result revealed a considerable relationship between commercial air transportation and carbon dioxide emissions both in the short run and long run. Hence, Schäfer and Waitz (2014) stated that despite increasing demand for air travel, there is a tendency decreasing of carbon dioxide emissions, which will continue during the following 20 years, however, the evaluations of Overton (2022) stated that the aviation industry is producer of 3.5% of global anthropogenic GHGs emissions. Referring to the report European Association, Mooney et al. (2014) concluded that the airline industry is the source of 4% of the overall EU GHG emissions, although the European Environmental Agency (EEA, 2007) stated that the level of carbon dioxide emissions emitted from foreign airlines in the EU enlarged for about 96% during the period from 1990 and 2005.

The empirical study performed by Stolyarova (2013) investigated the relationship between carbon dioxide emissions and GDP by utilising panel data for 93 nations that cover the period between 1960 and 2008. The results of dynamic panel data estimations

revealed the short-run relationship between carbon-dioxide emissions with income. Graver et al. (2020) have examined to define the most carbon-emitted countries with involved commercial airline operations in 2019. The study provides evidence that the USA is still a major producer of CO₂ emissions from aviation. Collectively, 28 EU member countries are the second after the USA having a source of emissions, and China is the 3d largest country that emitted carbon dioxide into the atmosphere.

Finally, the five top countries are Japan, China, the UK, the USA, and Germany respectively. Germany and its territories emitted half of global passenger transport-related CO₂ in 2019. Lo et al. (2018) examined the aircraft-related carbon-dioxide emissions by applying the panel data for each flight departure from Lombardy (Italy) airport covering the years from 1997 to 2011 and the result found that aircraft size and route distance increases total emissions CO₂ hence negatively impacting on air quality. The availability of data and resources constrains the study's accuracy. The primary issue is the poorly defined aircraft model, which uses theoretical distance instead of actual flight distance. Second, CO₂ emissions are not an actual measurement of each flight but rather a proxy. Moreover, Givoni and Rietveld (2010) investigated the efficiency of emission influenced on air quality by analysing flights of middle and long-range aircraft types A320 and B747 in the destinations from London to Amsterdam and between Tokyo to Sapporo. The results suggested the impact of aircraft size and flight distance that contributes to air pollution more than a short distance. Scotti and Volta's (2015) study reveal that European airlines are increasingly evaluating available seats per kilometre (ASK) and revenue per passenger kilometre (RPK), while also identifying the factors that impact air quality. Given the current limitation of fuel efficiency, factors such as aircraft size, load factor, and increased flight duration contribute to the increase in harmful emission intensity. Brugnoli et al. (2015) investigated the level of aircraft-related carbon dioxide emissions in European countries and found that the emission rate decreased concerning per occupation of aircraft seat availability. There is a suggestion that such results have been reached by the airline's effort's significant savings in fuel costs and the development of technical progress of the oil manufacturers producing jet fuel for the aviation industry. Kharina and Rutherford (2015) identified the average reduction of fuel burns by entering service of new-generation aircraft by nearly 45% between 1968 and 2014, which in turn influenced the reduction of CO₂ emissions accordingly. They also argue that technological progress in the associated industry is the main determinant of this outcome; however, the need to develop a meaningful CO₂ standard will significantly help industry to meet its environmental goals.

On the other hand, Liu et al. (2017) applied the production decomposition analysis (PDA) method which defines factors in changes in CO₂ emissions by using a panel dataset for the airlines based in China for the period 2007–2013. The study obtained meaningful results based on empirical analysis that discovered that changes in revenue per tonne-kilometres (RTK) are the main factor impacting the rise of civil aviation-related carbon-dioxide emissions, while changes in energy intensity become a key factor for most airlines which contribute to decreasing CO₂ emissions. Due to drawback in modernise aircraft and engine technology airlines should continue to improve flight operational efficiency by optimising fuel consumption and ground operations.

The footprints of CO₂ emissions still have a negative implication in the atmosphere arising from a radiative effect, which has a destructive effect on air quality. These impacts are quantified by their effective radiative forcings (ERF), nowadays the main

concept to accept in traditional scope, concerning environmental quality (Sherwood et al., 2015). The impact of aviation on the environment is fundamental because of engine exhaust gas (EGT) emissions, which present different pollutant particulates, emitted by aircraft engines impacting air quality, meanwhile violating atmospheric radiative balance (Abrantes et al., 2021). Radiative forcing is integrating the total backward of past GHG emissions which measures the present-day radiation stability level. In this context, Boucher et al. (2021) investigated the radiative forcing as a result of aviation activities and found that the aviation sector has a considerable impact on anthropogenic climate change through CO₂ and radiative forcing, in turn declining atmospheric air quality.

Abrantes et al. (2021) suggest that one of the decisions on environmental issues is a quantitative calculation of the aviation impact of global CO₂ emissions. For this purpose, have been developed several methods and methodologies in recent years to overcome this problem to reduce its effect on air quality. In this context, aviation biofuels have the potential to fill the gap to carbon-neutral growth.

Reynolds et al. (2007) have developed an Aviation Integrated Model (AIM), choosing a policy assessment method able to analyse the relationship between the aviation sector and environmental behaviour. Jimenez et al. (2012) have suggested a numerically controlled fleet estimation model which dynamically simulates a commercial aircraft fleet based in the USA. Tetzloff and Crossley (2014) proposed to develop route optimisation software to define optimal allocations of aircraft movements in the controlled airspace for tracking air safety. The study by Hassan et al. (2015) offered an integrated circuit framework for future estimation of the National Airspace features in consideration using operational and technological modernisations, including employing biofuels. Hollingsworth et al. (2008) and Schaefer (2012), introduced an acceptable measurement tool for quantifying and accurate clarification and quantifying CO₂ levels caused by consuming jet fuels, referring to the development of new technologies for the global air transport system. In order to simplify determining accurate emission levels, Schilling et al. (2016), Moolchandani et al. (2017) and ICAO (2019) offered completely different concepts as a development and use of a new alternative fuel. Several studies are concentrated implementation of modern technologies, hereby the studies of Owen et al. (2010) and Randt et al. (2015) have been focused on the investigation of new-generation aircraft technologies, Terekhov et al. (2018) conducted an analysis attempting to redesign aircraft configurations and Ploetner et al. (2017) and Hassan and Mavris (2020) in their papers intended to define an element of aircraft technologies to achieve best operational performances.

This study will show the real environmental portrait of selected countries directly associated with the high aviation industry concentration. Referring to various literature reviews and relevant publications there are expectations in the future by 2050 to reduce the aviation-related carbon dioxide emission level. The future implementation is considering entry to service a new generation aircraft with modernised engine types while reducing fuel consumption. The next step of further reducing CO₂ emissions will have to come mainly from the development of sustainable alternative fuels which are currently in progress in several EU countries and Australia. Based on the International Aviation Transport Association (IATA) and International Civil Aviation Organization (ICAO) strategies, the development of aviation biofuels will have the biggest global achievement in the sphere of the aviation industry, substantially reducing GHG emission level produced by aircraft engines, which is expected to reach by 2050.

3 Theoretical framework

3.1 Theoretical setting

The functional setting of this paper is based on investigating the impact of aviation-related CO₂ emissions on air quality in the 20 selected countries. The panel dataset that covers 1990 to 2014 will be employed for empirical estimations. The main variables of interest of this study include passenger and cargo air transportation as a main contributor to the source of emissions, while gross domestic product (GDP), energy, and fuel flow are selected as the other determinants of the model. The following equation (1) is proposed to formulate the function as follows:

$$CO2_{it} = f(GDP_{it}^{\beta_1}, ENG_{it}^{\beta_2}, FF_{it}^{\beta_3}, AIRF_{it}^{\beta_4}, AIRT_{it}^{\beta_5}) \quad (1)$$

The established static relationship using the panel data, will allow to define the nexus between proposed variables are modeled according to equation (2):

$$\ln \ln CO2_{it} = \beta_0 + \beta_1 \ln GDP_{it} + \beta_2 \ln ENG_{it} + \beta_3 \ln FF_{it} + \beta_4 \ln AIRF_{it} + \beta_5 \ln AIRT_{it} + \alpha_i + u_{it} \quad (2)$$

where

CO₂ amount of carbon dioxide

GDP gross domestic product

ENG energy consumption

FF total fuel flow rate

AIRF cargo air transportation

AIRT passenger air transportation

i number of country

t year

ln natural log of the variables

u_{it} error term

α_i country fixed effect (FE).

3.2 Development of hypothesis

Technological development and alternative fuel concepts might contribute to decreasing carbon dioxide emission CO₂ emitted by aircraft operations in emerging and developing countries. Consequently, further growth of production plants for biofuel processing can speed up the improvement of environmental degradation and reformation in air quality in a better way. In order to reach the objectives of reducing carbon dioxide emissions in this study, the proposed and developed hypothesis are consist as following:

H1 Cargo air transportation has an impact on the air quality.

H2 Passenger air transportation has an impact on the air quality.

The next section proposes particular panel regression for testing suggested hypotheses, furthermore the study will provide the several empirical estimations for each specific country after controlling a set of variables.

4 Data and methodology

4.1 Data

The primary dataset for the current study is withdrawn from the World Bank (2019) which refers to quantitative analysis based on econometric application of statistical data to produce empirical outcomes. The variables of this study included the GDP, ENG, fossil fuel usage (FF), and passenger and cargo air transportation (AIRT and AIRF), respectively. The selected data for panel analysis was extracted from the database contained in World Development Indicators (World Bank, 2019). The qualitative method relies on data collection from open sources, incorporating current expert opinions, environmental trends, aviation outlook publications, and literature reviews of scientific articles to examine the relationship between the aviation sector and environmental phenomena. Despite the environmental issue being broadly examined, the topic in the literature, its solution, and interactions with economic growth, energy resources, and civil aviation activities remain disputable among scientists. In order to investigate the feasibility to promote air quality, this study is considering 20 countries with highest air traffic, covering the period between 1990 and 2014. As an experiment utilised the most congested airspace of these countries, taken into consideration to find out the level of carbon dioxide emission. Table 1 presents the detailed information about the variables of interest that utilise in this study. This study is focused on 20 countries with rates of passenger carriers indicates before the pandemic period and since 1990, the passenger traffic steadily increased and reached its peak at the end of 2019 upon the beginning of the COVID-19 period (World Bank, 2019). List of the countries that are used to construct the panel set illustrated in Table 2.

Table 1 Variables of study

<i>Variable</i>	<i>Definition</i>
Depended variable	
CO ₂	Carbon dioxide measured by aviation emission
Independent variables	
GDP	Gross domestic product per capita (constant 2010 US\$)
ENG	Energy consumption rate selected countries
FF	Fuel usage rate selected countries
AIRT	Passenger air transportation
AIRF	Cargo air transportation

And list of the countries that have been in consideration in this study listed in Table 2 accordingly.

Annual data of GDP, ENG, fossil fuel usage, as well as passenger and cargo air transportation are presented in logarithmic mode. Before performing empirical analysis, descriptive statistics of all of the series under consideration and their correlation coefficients are presented in Table 3 and Table 4, respectively.

Table 2 List of countries with congested traffic flow according to passengers carried in 2019

<i>Rank</i>	<i>Country</i>	<i>PAX volume (M)</i>	<i>Year</i>
1	USA	926,737,000	2019
2	China	659,629,070	2019
3	India	167,499,120	2019
4	UK	142,392,530	2019
5	Japan	130,233,350	2019
6	Turkey	111,028,630	2019
7	Germany	109,633,750	2019
8	Brazil	102,917,550	2019
9	South Korea	92,434,080	2019
10	Indonesia	91,323,150	2019
11	Spain	88,237,170	2019
12	Australia	76,850,000	2019
13	France	71,289,280	2019
14	Malaysia	63,623,130	2019
15	Austria	46,476,600	2019
16	Netherlands	46,358,460	2019
17	Singapore	43,050,720	2019
18	Saudi Arabia	39,350,310	2019
19	Italy	27,760,300	2019
20	Finland	14,610,550	2019

Source: World Bank (2019)

Table 3 Descriptive statistics

<i>Variable</i>	<i>Obs</i>	<i>Mean</i>	<i>Std. Dev.</i>	<i>Min</i>	<i>Max</i>
CO ₂	502	12.67323	1.372393	10.01279	16.11876
GDP	502	27.47535	1.259979	24.98454	30.50459
FF	502	4.34523	0.209424	3.742006	4.605138
ENG	502	7.923736	0.755242	5.86139	8.99428
AIRF	502	7.576061	1.33122	3.98713	10.61196
AIRT	502	17.23773	1.13822	14.74456	20.45277

Notes: CO₂ is the amount of carbon dioxide emission; GDP is the gross domestic product; ENG is the energy consumption; FF is the total fuel flow rate by aircraft; AIRF is cargo air transportation; and AIRT is the cargo transportation.

Table 4 Correlations matrix

	<i>CO₂</i>	<i>GDP</i>	<i>FF</i>	<i>ENG</i>	<i>AIRF</i>	<i>AIRT</i>
<i>CO₂</i>	1					
<i>GDP</i>	0.8989	1				
<i>FF</i>	0.1479	0.07	1			
<i>ENG</i>	0.1807	0.0644	0.2708	1		
<i>AIRF</i>	0.5818	0.6806	0.3458	0.3993	1	
<i>AIRT</i>	0.8196	0.8894	0.1779	0.1412	0.8119	1

Notes: *CO₂* is the amount of carbon dioxide emission; *GDP* is the gross domestic product; *ENG* is the energy consumption; *FF* is the total fuel flow rate by aircraft; *AIRF* is cargo air transportation; and *AIRT* is the cargo transportation.

4.2 Empirical methodology

As introduced in the previous section, to test the equation (1) will be considered econometric methodology approaches, by applying pool ordinary least square (POLS), random effect (RE), FE, fixed effect robust (FE robust), fixed effects Driscoll and Kraay (FE dris-kraay) methods for estimation under the statistical structure.

The pooled OLS assumes that all entities in the applied panel dataset are considered to have the same underlying characteristics, there are no unobservable entity-specific effects. On the other hand, the REs model evaluates multiple parameters in the panel data over time, treating unobserved effects as random. For fixed or non-random values of the variables in linear regression, a FEs model eliminates mean differences between observations in the indicator group and all other observations. FEs robustness is a useful tool for controlling and estimating heteroskedasticity when the error term variability differs across observations, making the statistical inference more reliable. FEs with Driscoll and Kraay standard errors method is particularly useful in panel data settings for estimation, it is a FE estimation combining the Driscoll and Kraay standard errors to control error terms of autocorrelation across time and cross-sectional dependence.

5 Result and discussion

At the initial stage, The POLS and REs estimations will be performed. Next, Breusch-Pagan Lagrange multiplier test will be conducted to choose between OLS and RE estimations. The multiplier test results of Breusch-Pagan Lagrange dictate to conduct REs estimation which is suitable for further analysis, because of the rejection of the null hypothesis that variances across objects equal to zero, as per Table 5.

Secondly, FEs estimations will be conducted to proceed with model estimations. Moreover, the Hausman test will be employed to test whether the individual characteristics are correlated with the regressors (Greene, 2008). Since the null hypothesis is rejected by the Chi-Square of the test statistics, the FEs estimation is preferable to analyse the functional relationship of the model, according to the data presented in Table 5.

Table 5 Hausman test and diagnostics of the model

<i>Other tests/diagnostics</i>	<i>Test statistics</i>	<i>Prob.</i>
Hausman test	102.34	0.000
Breusch and Pagan LM test	4,531.45	0.000
Pesaran CD test	2.552	0.010
Heteroskedasticity test	1,646.44	0.000
Lagrange- multiplier test for serial correlation	55.357	0.000

The cross-sectional dependence is a problem for macro-panels with a longer time range (Baltagi, 2005). Nonetheless, for better perceiving the nature of the dataset it is necessary to conduct three mandatory diagnostic tests which include heteroscedasticity, cross-sectional dependence, and serial correlation presented in Table 5.

- 1 Based on a modified Wald test for groupwise heteroskedasticity, the results indicate the presence of heteroskedasticity.
- 2 Pesaran CD test provides evidence of cross-sectional dependence due to influencing common considerations of all-country observations with similarities.
- 3 Finally, the Lagrange-Multiplier test for serial correlation assumes existence of first-order autocorrelation.

It should be noted that, in the proposed model, there exist discrepancies in heteroskedasticity, cross-sectional dependence, and serial correlations. To avoid a biased statistical outcome in the evaluation of the panel-based regression model, it is considered inappropriate to ignore the obtained data. To perform the heteroskedasticity control, the robust FE estimation model is necessary, because a reliable estimation of FE ensures a robust outcome, considering the heteroskedastic nature of the dataset. To control the cross-sectional dependence, the model will also be estimated by applying the FE estimation with Driscoll and Kraay standard errors to control, proposed by Hoechle (2007). The FE in regression with Driscoll and Kraay standard errors suggested that the error structures are serially correlated, heteroskedastic as well as a possible lag correlated between groups. The FE estimation (Driscoll and Kraay) ensures an equitable statistical result by controlling for cross-sectional dependence (FE dris~kraay). Rejection of the F-statistic evidence that all models are having a significant explanatory power in all used FE estimation types, Table 6.

Evidently, GDP is statistically significant and positive, which contributes to CO₂ emissions. Consequently, POLS and RE effects estimations provide the same parameter estimations. GDP is highly significant and has a positive effect on air pollution ($\beta = 0.363$, $p < 0.01$). On the other hand, FE, FE robust, and FE dris~kraay estimations revealed similar findings ($\beta = 0.296$, $p < 0.01$). This implies that a raise in GDP increases the volume of CO₂ emissions. Referring to studies carried out by Fan et al. (2006), Cherniwchan (2012), Bozkurt and Yusuf (2014) and Uddin and Wadud (2014), similar results have been obtained which comply with the current paper.

Besides, the statistically significant and positive relationship of the ENG has been observed in all five estimations. According to POLS and RE estimations, ENG is highly significant and has a positive effect on environmental degradation, ($\beta = 0.363$, $p < 0.01$). On the other hand, FE, FE robust, and FE dris~kraay estimations revealed similar

findings, ($\beta = 0.846$, $p < 0.01$). This indicates that an increase in ENG will increase the volume of carbon dioxide emissions, parallel to the findings of Wang et al. (2013), Mohiuddin et al. (2016) and Asumadu-Sarkodie and Owusu (2017). Taking into account, the fact that ENG is one of the main contributors to environmental pollution affecting air quality, Cetin et al. (2015), Cheema and Javid (2015), Li et al. (2016) and Sinha et al. (2017) suggested making a stern environmental and energy policy, and recommended the government to implement new procedures to transfer renewable ENG in the industrial sector. Note that countries should be focused on the long-term benefits of renewable energy at least to achieve the goal of restricting GHG emissions up to 2030. Economy growth and development of heavy industries require a huge energy demand, which unavoidable increases CO₂ emissions (Kim and Worrell, 2002), while Karali et al. (2014) argue that continued economic growth will drive the development of science and new technology, which improves energy efficiency; hence, reduces ENG and CO₂ emissions.

Table 6 Estimation results

	(1) <i>OLS</i>	(2) <i>RE</i>	(3) <i>FE</i>	(4) <i>FE robust</i>	(5) <i>FE dris-kraay</i>
<i>Dep. variable CO₂</i>					
GDP	0.363*** 0.000	0.363*** 0.000	0.296*** 0.000	0.296*** 0.000	0.296*** 0.000
ENG	0.742*** 0.000	0.742*** 0.000	0.846*** 0.000	0.846*** 0.000	0.846*** 0.000
FF	1.216*** 0.000	1.216*** 0.000	1.178*** 0.000	1.178*** 0.000	1.178*** 0.000
AIRF	-0.051*** 0.000	-0.051*** 0.000	-0.050*** 0.000	-0.050** 0.016	-0.500** 0.011
AIRT	0.032** 0.039	0.032** 0.039	0.043*** 0.002	0.043 0.310	0.043*** 0.004
C	-8.658*** 0.000	-8.658*** 0.000	-7.657*** 0.000	-7.657*** 0.000	-7.657*** 0.000
R square	0.921	0.921	0.923	0.923	0.923
Observations	501	501	501	501	501
Wald test	4,575.72	4,574.42	-	-	-
Wald test (p-level)	0.000	0.000	-	-	-
F test	-	-	1,140.41	88.49	14,271.40
F test (p-level)	-	-	0.000	0.000	0.000

Note: The symbols (*, ** and ***) denote rejection of the null hypothesis at the 10, 5 and 1% levels respectively.

Notably, aircraft are a high consumer of fossil fuel (FF). This paper provides the positively significant effect of the fossil fuel usage in all five estimations as well. The pooled OLS and RE estimations provide the same parameter, ($\beta = 1.216$, $p < 0.01$). This indicates that a rise in the consumption of fossil fuels by 1% increases environmental degradation by 1.216% which contributes to an increase in the volume of carbon dioxide

emissions. Furthermore, the FEs estimations, FE, FE robust, and FE dris~kraay, found increasing effect, ($\beta = 1.178$, $p < 0.01$). Commercial flights and the whole aviation industry is associated with the use of energy, particularly depending on fossil fuel consumption. Increasing passenger travel by air is an indicator of flight frequencies, meanwhile, sources of higher CO₂ emissions in the atmosphere negatively impact the air quality.

Moreover, the basic records of statistically significant and negative effects relationship of freight air transportation are observed in estimations. The pooled OLS and REs highly significant and negative effect of AIRF at 1 % significance level, ($\beta = -0.051$, $p < 0.01$), on the other hand other estimations suggests the lessen effect at 5 % significance level, ($\beta = -0.50$, $p < 0.05$), respectively. Increasing cargo air transportation (AIRF) by 1% will decrease the volume of CO₂ emission by about 0.05%. These findings are contradicted by Gurney et al. (2009), Park and Lee (2011), Wen et al. (2017) and Hassan and Nosheen (2018). Stewart (2009) confirmed that air cargo transportation contributes to CO₂ emissions, however, to pinpoint its estimation is incorrect, because passenger aircraft also partially carried the freight. Aviation authorities estimate that air freight's impact on the environment is about 20%–25% of the total amount of global aviation CO₂ emissions (Bridger, 2009). Average CO₂ emissions from air freight per tonne-kilometre, for long-haul flights are significantly higher than rail, sea, and road transportation which accounts for about 665 g/km (Borken et al., 2003; EEA, 2009).

Finally, the result of the study shows enhancing impact of passenger air transportation (AIRT) on CO₂ emission level. The pooled OLS and REs estimations suggest, 1% increase in ART will increase the volume of CO₂ emission by about 0.032%, ($\beta = 0.032$, $p < 0.05$), on the other side, FE, FE robust, and FE dris~kraay estimations suggests, 1% increase in ART will increase the volume of CO₂ emission by about 0.043%, ($\beta = 0.043$, $p < 0.05$). This indicates that a rise in passenger air transportation will contribute to the volume of carbon dioxide emissions. The literature about the destructive effect of air transportation on environmental quality has been empirically tested and provides evidence by few studies (see Lo et al., 2018; Bahadir, 2022; Kongbuamai et al., 2023).

Fossil fuel's impact on the environment by producing CO₂ emissions inventories has begun as a vital exercise based on production and consumption at the national scale (Marland et al., 1985). Quantification of fossil fuel CO₂ emissions at the largest space and time influence is emerging as a critical need in the carbon cycle and climate change (Gurney et al., 2009). Globally, the aviation sector is the consumer of huge quantities of fossil fuels and millions of barrels of oils daily. At the present, the use of fossil fuels and burns are contributing to nearly 2.5% of aircraft-related CO₂ emissions affecting air quality and there is an expectation to rise to 22% by 2050 (Hassan and Nosheen, 2018). Demand for air transportation is far beyond requirements, because of the intensity of the population growth rate, which forces the aviation sector to use a high number of fossil fuels and ENG. Thus, substandard energy usage leads emit high carbon and other non-CO₂ emissions. Furthermore, commercial aircraft have more fuel consumption than the later newly developed aircraft. In this context, implementation of the biofuel can lower carbon dioxide emissions by 60% along with compliance with the clean transportation concept and fuel efficiency (Byrne, 2017). The estimation result concerning intercept (c) in suggested regression models provides a negative and significant effect on environmental degradation. It proves that the precautions that has been taken to reduce emissions have been successfully implemented.

6 Conclusions

The current study aims to analyse the relationships between air transportation and carbon dioxide emissions, using the data of 20 countries, selected from different continents, with the most congested air traffic flow over the airspace, performed the analysis of the results to check compliance with the objectives set by ICAO (2017) and IATA (2021) on environmental strategy. The formulated research questions accounted to find out a solution to reduce aviation-related CO₂ emission levels and deduction of the GHGs pollutant.

The main findings of this paper indicate that income level (GDP), energy usage (ENG), fossil fuel consumption (FF), and air passenger transportation (AIRT) boost air pollution at the $\beta = 0.296$, $\beta = 0.846$, $\beta = 1.178$, $\beta = 0.043$ respectively. On the other hand, air freight (AIRF) lessens air pollution, $\beta = -0.500$. It is important to highlight that all the countries under investigation exert a negative trend in CO₂ emission levels, $\beta = -7.657$. The result of this paper reveals the air passenger transportation enhances the environmental degradation; however, air freight transportation lessens the destruction effect on air quality. Panel data analyses within econometric results validate the significant and positive relationship between the aviation industry and air pollution globally, as well as have a statistical relationship with its determinants, i.e., ENG, fossil fuel usage, and economic growth.

The alternative solution involves using green energy in next-generation aircraft to reduce levels of chemical pollutants and limit the spread of carbon dioxide emissions from fossil fuel consumption at certain thresholds. The transition to SAF concepts will significantly improve the environment by reducing carbon dioxide emissions, preventing degradation, and improving air quality. The use of emerging technologies in airports and their implementation in air traffic management will help to mitigate further aviation impacts on the environment. Therefore, the study's results are crucial for policymakers, aviation industry authorities, and scientists, especially those dedicated to investigating climate change and environmental issues.

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