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The impact of COVID-19 on air passenger demand and CO_2 emissions in Brazil

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ABSTRACT

This paper estimates the impact of the COVID-19 on air travel demand and emissions in Brazil, the largest aviation market in Latin America. Combining detailed flight data and data on combustion emission factors, we estimate the CO_2 emissions of domestic flights. A Bayesian structural time-series model was used to estimate the impact of COVID-19 on daily trends of air travel demand and emissions. The COVID-19 caused a reduction of 68% in national passengers and 63% in total CO_2 emissions compared to what would have occurred if the pandemic had not happened. Despite such a sharp drop, fuel efficiency decreased after the COVID-19 outbreak, and passenger demand recovered to 64.2% of pre-pandemic levels by the end of 2020. The fast recovery in domestic flights by December 2020 indicates that the emissions could soon return to pre-pandemic levels, demonstrating the challenges of reducing emissions in the aviation sector in the short term.

1. Introduction

The outbreak of the COVID-19 pandemic and the subsequent halt of economic activities has made more visible the effects of human activity on the environment. Recent studies have shown how the disruption of daily activities caused by the new coronavirus (SARS-CoV-2) has had important implications for waste management, environmental noise levels, and environmental emissions (Saadat et al., 2020; Zambrano-Monserrate et al., 2020). According to one estimate, the COVID-19 pandemic led to an 8.8% reduction in global CO_2 emissions (−1551 Mt CO_2) in the first half of 2020 compared to the same period in 2019 (Liu et al., 2020). A fast-growing literature is bringing new evidence that the pandemic has had short-term effects in improving air quality in different countries (Li et al., 2020; Muhammad et al., 2020) and in specific urban areas in India (Mahato et al., 2020), China (Li et al., 2020; Pei et al., 2020; Wang and Su, 2020), Italy (Collivignarelli et al., 2020) and Brazil (Dantas et al., 2020; Nakada and Urban, 2020). However, most of these studies are based on estimates of pollutants using satellite data (Muhammad et al., 2020; Wang and Su, 2020) or local air quality sensors (Dantas et al., 2020; Li et al., 2020; Nakada and Urban, 2020), which capture overall levels of air quality without identifying the role played by specific emission sources.

Daily data on emissions by economic sector or activity type is lacking for most countries, particularly amongst developing nations (Anderson et al., 1996; Liu et al., 2020). Moreover, little attention has been paid to the impact the COVID-19 pandemic has had on air travel CO_2 emissions, one of the fastest-growing sources of emissions globally (Graver et al., 2019; Abate et al., 2020). Two exceptions to this are the works of Le Quéré et al. (2020) and Liu et al. (2020), who analyze the effect of COVID-19 on CO_2 emissions globally and for different countries by economic sector, including aviation (see below).

In this study, we examine the impact of the COVID-19 pandemic on the daily number of air passengers and CO_2 emissions in Brazil, responsible for over 41% of the domestic flights in the region (ALTA, 2019). We examine how passenger demand dropped in 2020 compared to previous years, looking at how travel patterns have changed and which international and national routes have been most affected. Combining detailed data on fuel consumption of individual flights and IPCC guidelines on emissions inventory, we use a top-down approach to estimate daily CO_2 emissions from commercial aviation in Brazil between 2017 and 2020. Finally, a Bayesian structural time-series model was used to estimate the impact of COVID-19 on daily passenger and CO_2 emissions. This allows us to estimate how much CO_2 emissions were avoided compared to a counterfactual scenario in which the pandemic had not taken place. It also becomes particularly relevant to understand how the aviation sector in Brazil has been affected since the country became one of the most important hotspots of the COVID-19 pandemic in the world (de Souza et al., 2020).

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In several countries, national and local governments responded to the COVID-19 pandemic by adopting non-pharmaceutical interventions, including the promotion of teleworking, and the restriction of public events, commercial activities, schools, etc. in order to increase social distancing (Hale et al., 2021). As a consequence, the number of daily flights worldwide was down almost 80% by early April 2020 with a relatively quick upturn after May (IATA, 2020a; 2020b) Globally, the number of air passengers dropped by approximately 60.2% in 2020 compared to 2019 (IATA, 2021).

Global CO_2 emissions and fuel use from civil aviation have increased three-fold in the last four decades, from an average rate of 15 Tg (10^{12} g) CO_2/year in the period 1960–2018 to 44 Tg CO_2/year between 2013 and 2018 (Lee et al., 2021). CO_2 projections scenarios between 2000 and 2050 indicate an increase by the ratio of 2.0–3.6, depending on the scenario (Owen et al., 2010). These projections suggest that emissions in developing regions could increase by factors of 15–20, for the high growth scenarios (Owen et al., 2010). In 2018, global emissions from all commercial operations in the aviation sector totaled 918 Tg (Graver et al., 2019). The precise impact of the COVID-19 pandemic on this figure is not yet fully understood, although passenger demand in 2020 has reached record low levels due to lockdown measures and shrinking economic activity (ITF-OECD, 2020).

Two recent studies have found that the aviation sector had one of the largest reductions in energy use and CO_2 emissions in 2020 globally due to COVID-19 (Le Quéré et al., 2020; Liu et al., 2020). According to their estimates, global aviation emissions decreased by 60% until the end of April 2020 (Le Quéré et al., 2020), and by 43.9% in the first 7 months of 2020 compared to the same period in 2019 (Liu et al., 2020). Nonetheless, these studies only capture a partial picture of the pandemic impact during the first months of 2020. By the time of the publication of those studies, there were great uncertainties about how the pandemic would unfold and about how the aviation sector would recover until the end of 2020. One study analyzed data for the entire year of 2020 (Bauranov et al., 2021), but it focused specifically on the United States. The authors found that CO_2 emissions produced by the US domestic air traffic dropped by 37.4% in 2020 compared to 2019 (Bauranov et al., 2021).

Moreover, the methods used in these studies estimate aviation emissions based on aggregate data (Le Quéré et al., 2020), considering a strong assumption about a global constant of CO_2, emission factor per km flown (Liu et al., 2020), which are known to generate less reliable emissions estimates (Graver et al., 2019).

This paper advances the literature in different ways. First, it presents the full annual impact of the COVID-19 on air travel demand and emissions in 2020 for Brazil, the 10th largest aviation market in the world and the largest market in Latin America. Second, this study deploys a more rigorous method to estimate daily CO_2 emissions on a flight-by-flight basis considering detailed information on fuel consumption and the number of passengers of each flight. Finally, this paper uses a cutting-edge Bayesian structural time-series model to identify causal effects of COVID-19 on aviation emissions, in contrast to presenting a simple descriptive analysis that compares emissions levels in different years, as done in previous studies.

The remainder of this paper is organized as follows. Section two describes the data and methods used in the analysis. Section three presents the results, looking at how the number of air passengers and emissions were affected by the COVID-19 pandemic. Finally, section four presents the final remarks and discusses some environmental insights that can be drawn from this global pandemic amid the first signs of recovery in air travel demand.

2. Data and methods

2.1. Air traffic data

Daily air passenger flows were analyzed using public data produced by Brazil's Civil Aviation Agency (ANAC) from January 2017 to December 2020 and downloaded using the flightsbr package in R (Pereira, 2022).[1] These data bring detailed information on every international flight to and from Brazil, as well as domestic flights within the country. The data include, among others, information on airports of origin and destination, flight duration, aircraft type, payload capacity (maximum allowable gross weight of the aircraft), and the number of passengers. Total fuel consumption (in liters) was only available for domestic flights, which accounted for approximately 84% of all air traffic movement and 79% of all passengers in the country in 2020. In this study, we only considered flights with regular commercial routes that had at least one paying passenger, which accounted for more than 96% of all air traffic in Brazil. The remaining 4% included air taxis (1%), cargo flights (2%), and non-regular routes (1%).

A limitation of this database is that fuel consumption information reported in the ANAC data is missing for 0.28% (1161 out of 408,680) of domestic flights in 2020 and 0.15% (1245 out of 811,170) in 2019. This occurs when international companies have the first/last leg of their trip within the Brazilian territory because these carriers do not report fuel consumption to ANAC. Due to low levels of missing information, we believe this limitation should not significantly affect the results of this study. Another limitation of the data set is that it does not track the trajectories of individual passengers. Consequently, passengers who make connections and change to flights with different numbers/companies are counted in the origin-destination pair of the last leg of the trip. Another limitation of this database, less relevant to this study, is that it might overestimate the total number of passengers from international flights disembarking in Brazil. This may occur when a passenger makes a connection in Brazil and changes flight/air carrier before going to her final destination in another country, for instance, Argentina or Colombia. As such, the numbers of inbound international passengers presented in this paper should be read as the estimate of passengers who disembarked or had a national connection in a Brazilian city.

We calculated the kilometers flown by each flight considering the geographical coordinates of the airport locations based on ANAC database downloaded via the 'flightsbr' package (Pereira, 2022). Distances were calculated considering Great-circle distances to account for the Earth's curvature.

2.2. Emission estimates

The bulk of emissions produced by aircraft come from the combustion of fuel with air in the combustion chamber of the engine. This combustion generates several pollutants such as carbon dioxide (CO_2), nitrogen oxide (NO_X), H_2O vapor, methane (CH_4), carbon monoxide (CO), particulate matter (PM)(Morten Winther et al., 2019), and ultrafine particles (Stacey, 2019). In this study, we calculated aviation emissions using the Tier 1 method by IPCC (IPCC, 2019). To do so, we combine data on the total fuel consumption of each individual domestic flight reported by ANAC with combustion emission factors to CO_2 emissions and calculated, Carbon dioxide estimates (E) of each flight using the following equation

$$E = Fc \cdot \rho \cdot Ef \cdot Hv,$$

where Fc is the total fuel consumption (liters), ρ is the density of aviation kerosene (kg/liter), Ef is the emission factor (kg CO_2/TJ) and Hv is the mean heating value (TJ/kg). The fuel emission factor is based on IPCC Guidelines (IPCC, 2019), the density of aviation kerosene, and the mean heating value come from the Brazilian Energy Research Office (EPE, 2020). By combining these data with fuel consumption and

[1] The computational code written in R to reproduce the analysis, results, and figures of this paper is shared openly at https://github.com/ipeaGIT/anac_covid.

passenger per flight, we were able to estimate daily CO_2 emissions and emissions per passenger for every national commercial flight in Brazil between 2017 and 2020.

To calculate the daily emissions, we considered the fuel consumed in a given flight to be burned on the same day of departure. This way, the CO_2 emissions of an overnight flight are assigned to the day of departure. Our method assumes no significant change in technology from 2019 to 2020, even though this could be adjusted for longer-term scenario analysis (Owen et al., 2010).

Because the Tier 1 method adopted in this paper relies on reported information on fuel consumption, it can give more accurate emission estimates than the methods used in previous studies (Graver et al., 2019; Bauranov et al., 2021). The total fuel consumption, reported for each flight, is a result of a combination of factors such as trip distances, landing/take-off (LTO) and climb/cruise/descent (CCD) times, aircraft and engine categories, load, and total passengers. The use of aviation kerosene consumption information generates more accurate results compared to aircraft performance models, which tend to underestimate fuel consumption and often require validation of results and correction factors (Graver et al., 2019; Bauranov et al., 2021). The methodological approach of this paper also allows for more robust results compared to other studies that estimate emissions based on OAG Global flight numbers (Graver et al., 2019; Le Quéré et al., 2020; Liu et al., 2020) or that assumes a constant emission factor per km flown across the whole fleet of aircraft (Liu et al., 2020) or by aircraft type (Bauranov et al., 2021).

The method used in this study is similar to the one used by the Brazilian civil aviation agency to generate official estimates for the emissions inventory. ANAC adopts two approaches in their emissions inventory, which are IPCC Tier 1 (top-down analysis) and Tier 3 (bottom-up) (ANAC, 2019). Tier 1 is based on total fuel consumption reported by the Brazilian Energy Research Office (EPE), which aggregates other fuel uses, such as military aviation, helicopters, and ground-based equipment. The Tier 3 method uses detailed data on fuel consumption for each flight stage, which involves more assumptions and requires data sets not publicly available, such as the ICAO Turboprop Engine Emissions Database (ANAC, 2019). Both approaches present very similar results. Between 2010 and 2018, total emissions estimated by ANAC using the Tier 1 method were only 5.2% higher on average (confidence interval between 2.4% and 8.9%) than the estimates based on the Tier 3 method. This difference is largely due to non-commercial-aviation sources. The method used in this study follows the Tier 1 approach, with the difference that we analyzed fuel consumption information for each flight from ANAC microdata. The results obtained with our method are also very similar to official ANAC estimates based on the Tier 3 method. When compared to official annual emissions estimates based on Tier 3 between 2005 and 2018, our estimates were only +2.8% (min. −4.48%, 1st quartile 1.39%, 3rd quartile 5.56%, max. 6.68%) higher than the official estimates from ANAC.

In this study, we compare the fuel efficiency for the pre and post-period of the pandemic outbreak in Brazil. We estimate emissions for aircraft models with a minimum capacity of 40 seats, in order to avoid charter or small group trips, such as Cessna aircraft's flights. The analysis included Airbus, Boing, Embraer, and Aerospatial/Alenia aircraft. Fuel efficiency, $FE(pax \cdot km \ / \ L)$, is given by the expression

$$FE = \sum_{i=1}^{n} \frac{Passenger_i \cdot \Delta d_i}{\Delta V_i},$$

where $Passenger_i$ is the number of passengers in the flight $i(pax)$, Δd_i is the flight distance (km), ΔV is the volume of consumed fuel (L) and n is the total number of flights by the selected aircraft.

2.3. Inferring impact of COVID-19

We use a Bayesian structural time-series model (BSTS) (Brodersen et al., 2015) to infer the causal impact of the COVID-19 pandemic on daily trends of air travel demand and CO_2 emissions. In this particular case, the BSTS model uses a group of synthetic control time series to predict the counterfactual trend of air travel levels that would have occurred had the pandemic not taken place. A BSTS model was preferred because, compared to other time series and difference-in-differences methods, it accounts for time-varying influences and confounding factors such as holidays and weather conditions, which allows us to isolate the sole impact from COVID-19. For a formal explanation of the BSTS and its application in the transport sector, see the works of Brodersen et al. (2015) and Hu and Chen (2021), respectively.

In this study, a synthetic control was built using the daily number of passengers observed in 2017, 2018, and 2019 as predictor variables for the number of passengers in 2020. Similarly, we used daily estimates of CO_2 emissions for 2017, 2018, and 2019 as a synthetic control to predict the expected emission levels in 2020 without a pandemic. These time series were strongly predictive of the daily number of passengers and emissions in the period from 2020/02/01 to 2020/03/15, right before the first business day after the first confirmed COVID-19 death in Brazil on March 12th (de Souza et al., 2020). The analysis was conducted using the 'CausalImpact' R package (Brodersen et al., 2015).

3. Results

The COVID-19 pandemic led to a sharp drop in the number of daily passengers of both national and international flights in the second half of March, the date of the first confirmed death by COVID-19 in Brazil (Fig. 1A). Soon after the outbreak of the new coronavirus in Brazil, in April 2020, the number of international inbound passengers dropped 97% while national movement fell by 94% compared to April 2019. This drop coincides with the period when state and local governments across Brazil started to introduce lockdown measures to contain the spread of SARS-CoV-2, even though no governmental restriction on national air travel was implemented in the country (de Souza Santos et al., 2021). Passenger numbers stabilized at the beginning of April, with the first signs of recovery emerging in May and June. By the end of 2020, domestic and international passenger movement was still only 64.2% and 20.7% of pre-pandemic levels observed in December/2019, respectively.

COVID-19 also caused a sudden drop in international flights, with fewer passengers arriving from all major international connections (Fig. 1B). Most European countries and China had a steeper drop in passengers due to international travel restrictions to inbound flights imposed by the Brazilian government in March 2020 (Verdélio, 2020). Since then, there have been no direct flights from China and very few flights from Italy to Brazil. Nonetheless, it's possible that some passengers from these countries have kept arriving in Brazil via indirect flight connections. Meanwhile, passenger movements arriving in Brazil from Europe and South America started showing strong signs of recovery after July 2020.

After the outbreak of SARS-CoV-2 in Brazil, between March 15 and December 31st, 2020, there were on average approximately 89.0 thousand daily passengers on domestic flights (Fig. 2A, black line). The results of the Bayesian structural time-series model suggest that, in the absence of COVID-19, the expected number would have been 279.2 thousand (95% CI: 267.7k, 290.9k) passengers per day (Fig. 2A, blue line). Summing up all avoided passengers (Fig. 2B), our estimates suggest that COVID-19 caused a 68% reduction (95% CI: 72%, −64%) in the number of national passengers between March and December 2020 compared to what would have been expected had the pandemic had not occurred. This is slightly higher than the drop in passenger numbers observed globally (60.2%) and in any specific region such as Latin America (60.6%), North America (60.8%), Europe (67.4%), and Asia (53.4%) (IATA, 2021).

The reduction in travel demand was followed by a substantial decrease in air travel emissions. We estimate that air passenger aviation

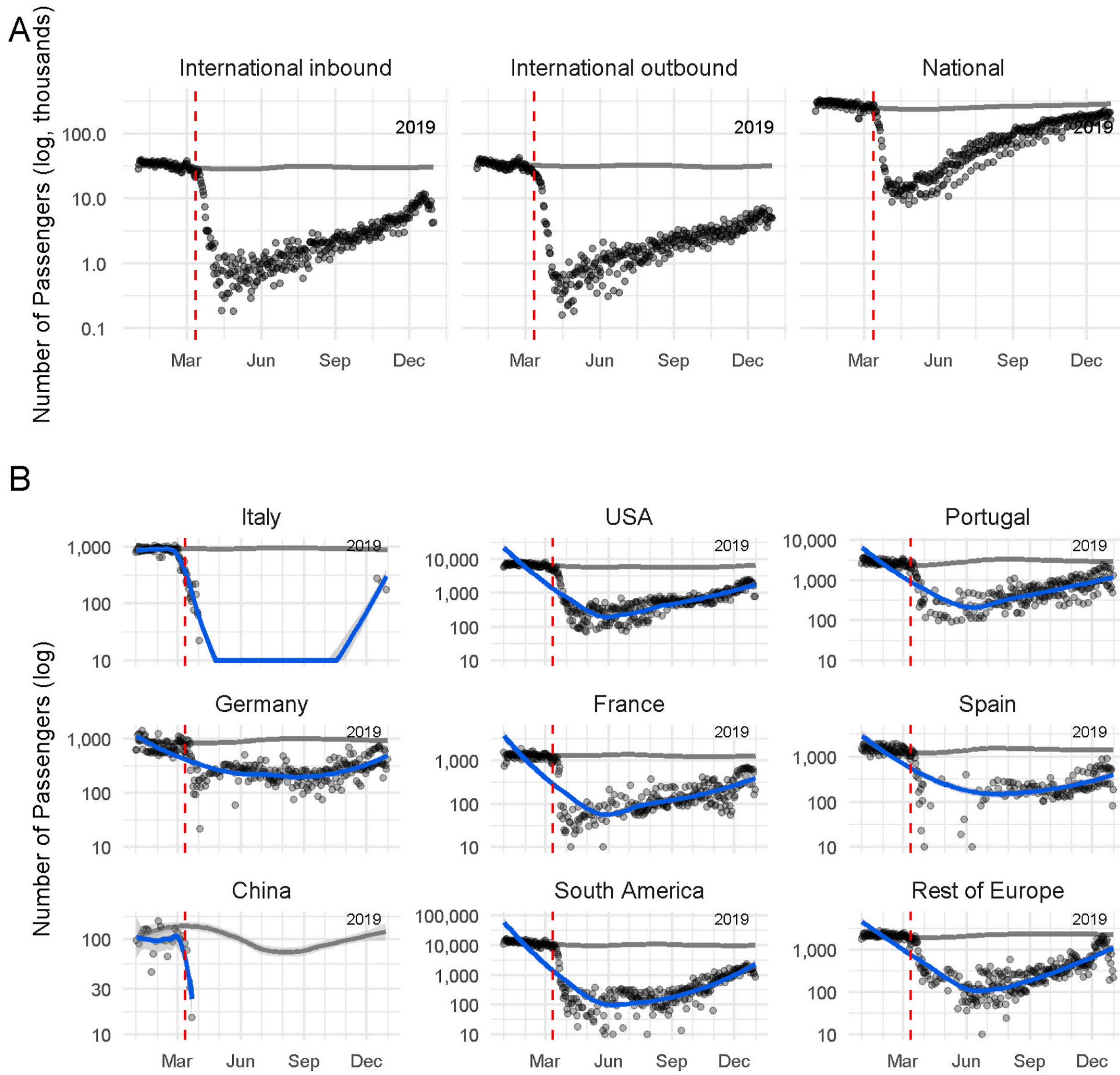

Fig. 1. (A) Drop in national and international passengers (B) Drop in passengers arriving in Brazil from top countries and regions. Obs. The vertical dashed line indicates March 15th, the date of the first confirmed death by COVID-19 in Brazil.

in Brazil emitted approximately 4.51 million metric tons (MMT) of CO_2 in 2020 (Fig. 2C, black line). Without the pandemic, domestic air travel activity in Brazil would have emitted approximate two times as much CO_2 in 2020, totaling 9.2 MMT (95% CI: 7.9, 10.5). Based on these counterfactual estimates, the COVID-19 pandemic caused a drop of 63% (95% CI: 67%, −60%) in daily CO_2 emissions, from 24.7 to 9.1 thousand tonnes per day between March 15 and December 31st (Fig. 2C). Comparatively, this is a much higher impact than the 37.4% drop observed in the US domestic aviation market (Bauranov et al., 2021). During this period, the COVID-19 pandemic in Brazil avoided a total of 4.6 (95% CI: 4.8, −4.4) MMT of CO_2 emitted to the atmosphere, an amount equivalent to one year of CO_2 emissions from all domestic flights in France (Graver et al., 2019).

The impact of COVID-19 on the country's air-travel network was unevenly distributed across space. Comparing the geographic patterns of air traffic 45 days before and after the first confirmed death by Covid in Brazil, for example, we observe that shorter flights and flights to local and regional hubs were the most affected (Fig. 3A). As previously noted by Candido et al. (2020), this is largely in part because shorter flights can be more easily replaced by land transport (cars and buses). As a consequence, there was an 8.8-fold reduction in the number of passengers in flights shorter than 1000 km, compared with a 4.4-fold reduction in those flying longer than 2000 km (Fig. 3B), and there was a 25% increase in average traveled distances in domestic flights (Fig. 3C). As previously noted by Abate et al. (2020), this retraction towards a hub-and-scope network can have negative repercussions by increasing average trip length and increasing the environmental footprint of the air transport sector.

Finally, we observe that COVID-19 has also led to a reduction in the environmental efficiency of airlines measured in terms of emissions per passenger (Fig. 4A). This occurred as a result of the combined impact of the pandemic in terms of both fewer passengers and longer trips on average. This effect is significantly larger in the subsequent month after the COVID-19 outbreak, which reflects how quickly passengers responded to the pandemic by canceling trips, causing a sharp decline in passenger numbers. From May onwards, air companies gradually recovered efficiency to pre-pandemic levels as travel demand started to climb back, and airlines reduced service levels and reallocated passengers to minimize the number of flights with too many empty seats.

This reorganization of flights can be seen in Fig. 4B. This figure

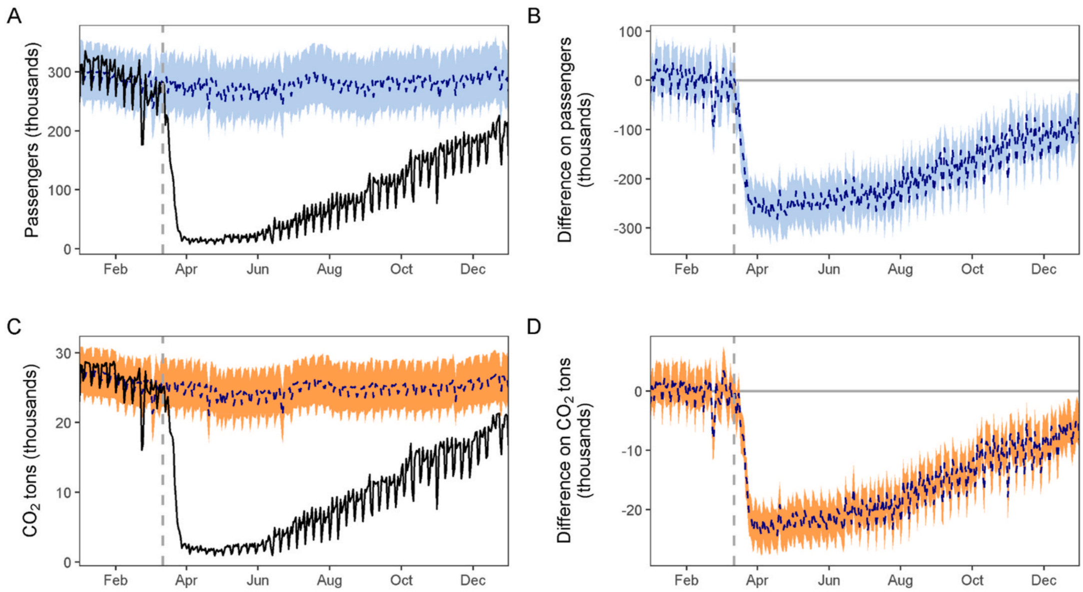

Fig. 2. Daily number of passengers and CO_2 emissions observed in the data and in counterfactual estimates for domestic flights in Brazil, 2020. Obs. The vertical dashed line indicates March 15th, the date of the first confirmed death by COVID-19 in Brazil. Panels (A) and (C) show observed data in the black line, and estimated counterfactual in the blue line, with 95% Confidence Intervals presented in shaded areas. Panels (B) and (D) show in the blue line the difference between observed data and counterfactual predictions, with 95% Confidence Intervals presented in shaded areas.

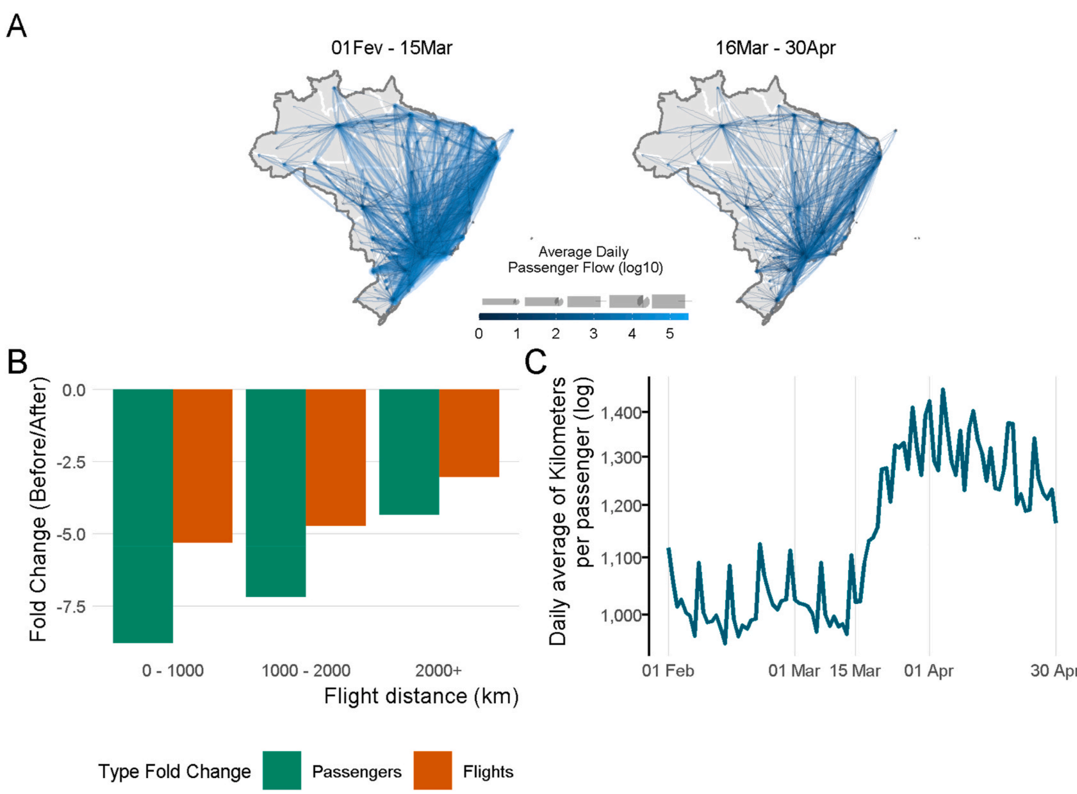

Fig. 3. Change in air traffic network and the number of passengers (A), Fold change in the number of passengers and flights by distance (B), and daily average distance traveled by a passenger in Brazil (C).

shows the average fuel efficiency and distance by aircraft sizes (given by the maximum available seats) before and after the Covid outbreak. It shows that aircraft had a substantial reduction in environmental efficiency (Y-axis) while most of them were reallocated to routes that were on average longer than before the pandemic (X-axis). Although the average distances differed slightly between pre and post covid outbreaks, the main reason for a significant drop in fuel efficiency was due to lower passenger occupancy. In summary, while the COVID-19 pandemic caused a substantial reduction in total CO_2 emissions in 2020, it also reduced the environmental efficiency of the aviation sector in Brazil, increasing the level of carbon emissions per passenger. In Panel (B), differences in efficiency and distances were statistically significant

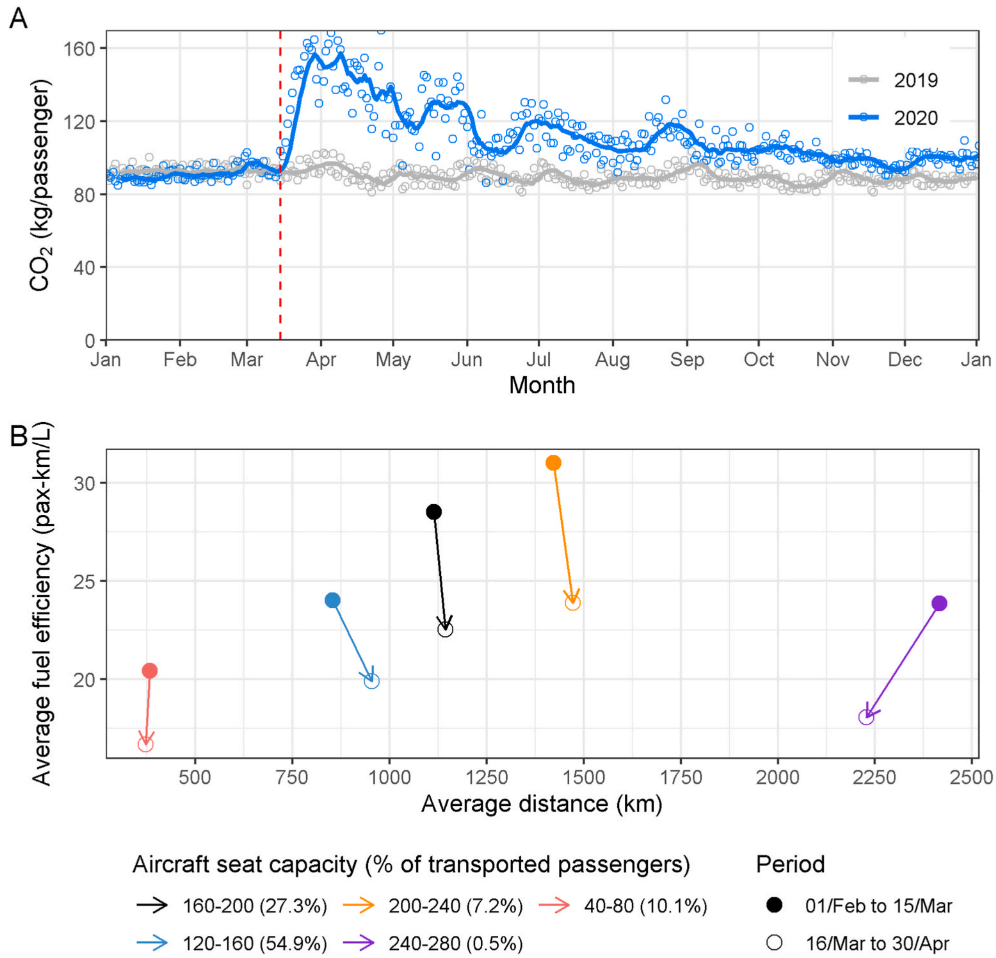

Fig. 4. Daily CO_2 emissions in 2019 and 2020 (A) and change in the relationship between fuel efficiency (pax-km/L) and average distance pre- and post-covid outbreak by the size of aircraft. Obs. In panel (A), dots represent daily estimates, while lines represent a seven-day rolling average and vertical dashes represent the date of the first confirmed death by COVID-19 in Brazil.

for all aircraft sizes ($p < 0.05$). These results are similar to recent findings for the United States, where aviation emissions dropped by 37.4% compared to 2019, and emissions per passenger doubled in the period of April to August 2020 (Bauranov et al., 2021).

As a consequence of the reduced passenger per flight, the average flight weight dropped for all aircraft seat capacity ranges. For the seat ranges of 40–80, 120–160, 160–200, 200–240, and 240–280, the drop in total weight carried (TWC) by aircraft was 16%, 20%, 22%, 23%, and 27%, respectively. TWC includes cargo load, mail, baggage, and passenger. Passenger per flight had a similar effect as the TWC, being proportional to the seating capacity. The extreme values were the seat ranges of 40–80 and 240–280, with 19% and 32% of passenger per flight drop, respectively. On the whole, the load factor has also decreased in the period after the COVID-19 outbreak, as a consequence of a drop in flight occupancy. This measure is given by the ratio between TWC (in kg) and the capacity payload (kg). From the period of 01/Feb - 15/Mar to 16/Mar - 30/Apr, the average load factor decreased from 0.64 to 0.50, respectively.

4. Conclusion and policy implications

This study analyzed the impact of the COVID-19 pandemic on air travel demand and CO_2 emissions in Brazil, looking also at how the pandemic affected airline network structure and the environmental efficiency of the aviation sector in the country. The outbreak of the new coronavirus in Brazil in March 2020 caused a sudden and significant drop in the number of air passengers and CO_2 emissions, with a relatively quick recovery after May. Using a Bayesian structural time series model, we find that, between March 15th and December 31st, 2020, the number of passengers decreased by 68% while emissions declined 63% compared to a counterfactual scenario if the pandemic had not occurred. Our estimates suggest that the COVID-19 pandemic avoided 4.6 million metric tons of CO_2 emitted to the atmosphere by the aviation sector in 2020 in Brazil. Finally, we also find that the reduction in travel activity triggered by the pandemic was stronger in shorter routes connecting to local and regional airports, increasing the average distance traveled by passengers and reducing the environmental efficiency of air services.

One limitation of the method used in this paper is that it does not distinguish emissions from individual flight phases such as the landing and take-off (LTO) cycle and the climb, cruise, and descent (CCD) cycle from overall emissions. Other pollutants, such as NO, NO_2, PM, CO, and HC are not directly estimated by fuel consumption, and use specific fuel-flow specific algorithms (Lee et al., 2021), which are based on flight stage times. Moreover, this inventory only focuses on flight emissions. It does not cover emissions from ground/airport activities, nor does it cover air travel by helicopters or military aviation. Further research is needed to examine the extent to which a detailed account of all flight cycles and ground activities could improve the accuracy of emissions estimates from the aviation sector. Another limitation of this study is that it does not account for emissions of cargo flights. Although cargo flights represent only 2% of all national flights in Brazil, air freight was affected differently than air passenger demand. Previous estimates show a shorter average recovery time (Gudmundsson et al., 2021) since some segments of air cargo have been essential to moving medical supplies to tackle the COVID-19 pandemic, and to address the increasing demand for online trade in many business sectors. Further research would be needed to investigate how the demand for cargo flights was affected by COVID-19 in the Brazilian context and the environmental implications of this impact.

From a policy perspective, the findings of this paper are telling of the challenges in promoting a green recovery with a more sustainable aviation sector. In Brazil, the aviation sector has only been able to marginally improve its environmental efficiency in recent years despite several policies to modernize operations, air traffic flow management, and aerodrome's infrastructure (Calçado et al., 2019). Despite years of climate policy, it took a global pandemic coupled with the worst economic crisis since the Great Depression (Zumbrun, 2020) to bring about a substantial reduction in air travel emissions. And even though this could be the largest drop in emissions since the end of the Second World War (Evans, 2020), it only took 9 months since the pandemic started in Brazil so that travel demand and CO_2 emission levels reached 64% of pre-pandemic levels for domestic flights. This relatively quick recovery reflects how hard it can be to achieve a significant and sustained reduction in emission levels in the aviation sector.

Against this background, in the context of policymaking, it is noteworthy that most governments in countries with the largest aviation markets, including Brazil, stepped in to bail out air companies without any environmental conditions attached (Abate et al., 2020; Gössling, 2020). During the pandemic, aviation companies worldwide mitigated the effects of reductions in passenger demand by converting idle passenger aircraft to cargo purposes, and others intensified cargo activities to fill the void left by belly capacity (Gudmundsson et al., 2021). However, the effects of these measures are likely to be short-lived. In order to implement mitigation policies that become effective in the long term, governments need to partner with airlines and research centers to mobilize different strategies such as the introduction of alternative fuels, changing engines for more efficient models (Fan et al., 2012), improving the air traffic flow management, and taxing aviation to incentivize greeners solutions (Simões and Schaeffer, 2005). In particular, the use of alternative fuels such as biodiesel, hydrogen, and synthetic kerosene show a promising potential to bring a more sustainable use in the areas of non-renewable energy and greenhouse gas emissions (Gössling et al., 2021), but these alternatives are still significantly more expensive than conventional aviation kerosene (Saynor et al., 2003).

The relatively fast recovery of domestic flights after the COVID-19 outbreak observed in Brazil and other parts of the world (IATA, 2020b; ITF-OECD, 2020) suggests that deep decarbonization of the transport sector can only be achieved with more energy-efficient transport modes (Simões and Schaeffer, 2005). From this perspective, governments should invest more heavily in rail infrastructure to replace aviation for medium and long-distance trips, especially in countries with large territories like Brazil and the United States. This crisis could serve as an opportunity to rethink nationwide transport systems and act more aggressively on regulation and innovation targets for cleaner transportation.

There are still great uncertainties about if and when emission levels from the aviation sector will fully recover to pre-pandemic levels. A study shows that global passenger demand is expected to recover to pre-pandemic levels by late-2022, with the most optimistic scenario for mid-2022 and the most pessimistic by 2026 (Gudmundsson et al., 2021). The speed of this recovery is expected to increase with the progress of vaccination numbers worldwide. However, given the unequal distribution of vaccines between rich and poor nations, we can expect that the recovery of the aviation sector will significantly vary across countries and probably be significantly slower for international travel. For instance, passenger traffic in Asia has already shown a faster recovery compared to North America and Europe (Gudmundsson et al., 2021).

Finally, the COVID-19 pandemic has triggered substantial changes in travel behavior, which has led us to rethink what constitutes necessary travel (Stoll and Mehling, 2020). The drastic reduction of travel and the more widespread use of telework, online meetings, and conferences prompted by the pandemic have yielded large emission reductions (Klöwer et al., 2020; Riggs, 2020). Nonetheless, large uncertainties remain about the extent to which these short-term behavior changes will outlast the pandemic period and lead to a sustained reduction of emissions in the aviation sector and in transportation more broadly.

CRediT authorship contribution statement

João Pedro Bazzo Vieira: Writing – original draft, Conceptualization, Investigation, Methodology, Software, Validation, Data curation. **Carlos Kauê Vieira Braga:** Writing – original draft, Methodology, Software. **Rafael H.M. Pereira:** Writing – original draft, Conceptualization, Methodology, Supervision.

Declaration of competing interest

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

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