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Impacts of COVID-19 on aircraft usage and fuel consumption: a case study on four Chinese international airports

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Abstract

COVID-19 pandemic starting in early 2020 has greatly impacted human and industrial activities. Air transport in China shrank abruptly in February 2020, following a year-long gradual recovery. The airline companies reacted to this unprecedented event by dramatically reducing the flight volume and rearranging the aircraft types. As the first major economy that successfully controls the spread of COVID-19, China can provide a unique opportunity to quantify the medium-long impacts on the air transport industry. To quantify the corresponding changes and to elucidate the effects of COVID-19 in the wake of two major outbreaks centered in Wuhan and Beijing, we analyze twelve flight routes formed by four selected airports, using the Automatic Dependent Surveillance-Broadcast (ADS-B) data in 2019 and 2020. Our results show that the total flight volume in 2020 reduced to 67.8% of 2019 in China. The recovering time of flight volume was about 2-6 months, dependent on the severity. In order to unwind the severe challenge, airlines mainly relied on aircraft B738 and A321 between February and June in 2020 because the fuel consumption per seat of these two aircraft types is the lowest. Besides, fuel consumption and aircraft emissions are calculated according to the Base of Aircraft Data (BADA) and the International Civil Aviation Organization's Engine Emissions Databank (ICAO's EEDB). At the end of 2020, the ratios of daily fuel consumption and aircraft emissions of 2020 to 2019 rebounded to about 0.875, suggesting the domestic commercial flights were nearly fully recovered. Our results may provide practical guidance and meaningful expectation for commercial aircraft management for other countries.

Keyword: COVID-19; ADS-B; Flight volume; Aircraft usage; Fuel consumption; Aircraft emissions.

1 Introduction

The outbreak of the Coronavirus pandemic 2019 has an unprecedented effect on public life worldwide (Huang et al., 2020), as the virus can infect both humans and a wide range of animals (Velavan and Meyer, 2020). A global response is imperative to reduce the spread of the COVID-19 pandemic and slow down the number of new cases. Many countries raised their infectious disease response activities to the highest alert levels (Chang et al., 2020) and adopted a combination of containment and mitigation activities, including school shutdown, travel restrictions, industries, and construction activities suspension (Huang et al., 2020). China, the United States, and several other countries have instituted temporary travel restrictions to slow down COVID-19 spread (Fauci et al., 2020), while most countries closed borders too late to contain the spread of COVID-19 (Sun et al., 2021a).

As presented by Zhang et al. (2020b), aviation is one of the most significant initial contributors to the COVID-19 spread. Many countries then reduced air transport associated with pandemic centers. As a result, there was a sharp decrease in the number of domestic and international passenger flights. International markets suffered a more severe depression than domestic markets (Sun et al., 2020), except air logistics airlines suffering less depression (Li, 2020), and ultra-long-haul flights outperforming other business models (Bauer et al., 2020). From the perspective connectivity with other airports, the Southern hemisphere undergoes a more severe drop than the Northern part (Sun et al., 2021b). According to the International Civil Aviation Organization, by the end of March 2020, more than 20 commercial airlines had stopped flights entirely, and about 12 airlines stopped all international flights all over the globe. These aviation losses caused a damaging decline in the World's GDP by 0.02% to 0.12% in the first quarter of 2020 (Iacus et al., 2020). Immediate policy designs are necessary to alleviate the impact of COVID-19 on the airline industry around the globe (Maneenop and Kotcharin, 2020). For example, governments have prioritized maintaining air transport connectivity (Abate et al., 2020), and airlines have adopted the typical crisis response strategies of retrenchment, persevering, innovating, and exit (Albers and Rundshagen, 2020). Due to the preliminary control of COVID-19 in some countries, international air travel bans are relaxed to recover the economy (Zhang et al., 2020a), which may lead to a likelihood of the aviation business rebounding at a slower pace with V-shape and U-shape recovery (Serrano and Kazda, 2020).

Significantly disrupted aviation caused a subsequent reduction in fuel consumption and aircraft emissions. Fuel consumption influences airlines' profit and aircraft emissions can affect the environment and climate (Xue et al., 2020). For example, the contribution of CO_2 is estimated to represent 36%-51% of the total aviation radiative forcing of climate, including short-term climate forcers (Kärcher, 2018; Terrenoire, 2019). In addition to CO_2, NO_x emission from fuel combustion is estimated to account for about 65% of the global total NO_x emission (Bauwens et al., 2020). NO_x also induces some extra consequences for climate and human health (Atkinson et al., 2018). Thus, accurate fuel burn estimation models are necessary to evaluate the amount of fuel consumption and CO_2 emissions (Seymour et al., 2020). The Aircraft Performance Model Implementation software is developed to simulate the global commercial flight fuel burn and emissions during 2006-2011 (Wasiuk et al., 2015). Fuel consumption and CO_2 emission of a specific route are estimated by cluster analysis on historical trajectory data (Pagoni and Psaraki-Kalouptsidi, 2017). To better calculate aircraft fuel burn during ground operations, Kim and Baik (2020) used aircraft trajectory data acquired from an airport surface surveillance system. Different from the methods mentioned above, our study uses the ADS-B (Automatic Dependent Surveillance-Broadcast) data to calculate the fuel consumption and aircraft emissions based on the International Civil Aviation Organization's Engine Emissions Databank (ICAO's EEDB) and Base of Aircraft Data (BADA), because ADS-B data are easily accessible.

Although the immediate impact of COVID-19 on aviation has been actively studied (Naboush and Alnimer, 2020; Serrano and Kazda, 2020), the medium- and long-term impacts are still unclear, as air travel in most of the major countries is still struggling to rebound to the level before the pandemic. However, China's successful control of COVID-19 provides us with a rare opportunity to quantify the impacts, as its domestic air demand has largely recovered by the end of 2020. In this study, we analyzed the two-year ADS-B data and calculated flight volume, aircraft usage, fuel consumption, and aircraft emissions among routes between four selected major Chinese international airports, Beijing (ZBAA), Shanghai (ZSSS), Guangzhou (ZGGG), and Wuhan (ZHHH). Since two of the cities were epicenters of the major outbreaks in the early and middle of 2020, our study allows us to elucidate both the abrupt decline and the year-long recovery of domestic aviation. Therefore, our study may shed some light on how the air travel activity was impacted both in different countries and at different pandemic stages.

The paper is organized as follows. Section 2 describes the dataset and the methodology. Section 3 shows the results. Section 4 discusses the impacts and concludes the paper.

2 Datasets and Methods

2.1 Flight datasets and cleaning

Current strategic plans for Air Traffic Management envisage a transition from radar control to Communications, Navigation, and Surveillance/Air Traffic Management (CNS/ATM). Automatic Dependent Surveillance-Broadcast (ADS-B) is a surveillance technology. As an indispensable part of the Next Generation Air Transportation System and the Single European Sky ATM Research project (Gugliotta, 2009), ADS-B works by having aircraft transponders receive satellite signals and transponder transmissions to determine the precise positions of aircraft via the Global Navigation Satellite System (GNSS) (Valovage, 2007). **Fig. 1** shows the schematic diagram of the ADS-B working principle. ADS-B data shown in **Table 1** can be recorded and accessible from the Flightradar24 (https://www.flightradar24.com).

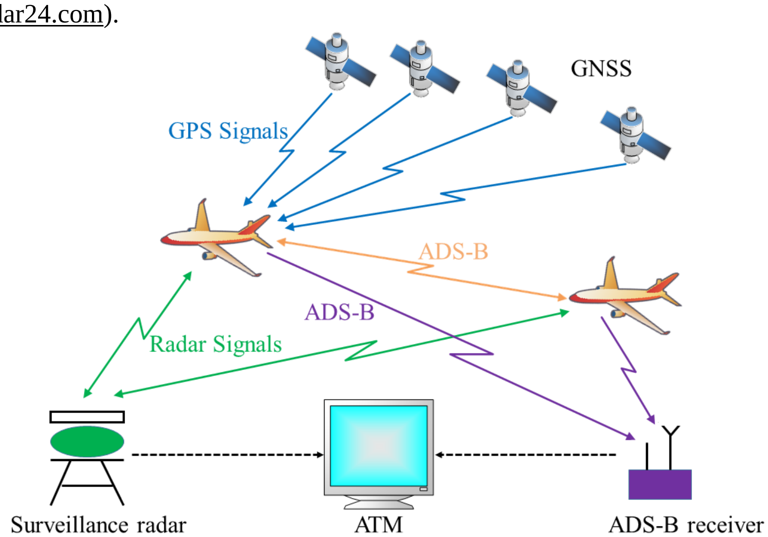

Fig. 1. Schematic diagram of the ADS-B working principle.

Table 1. Time series ADS-B data.

Call sign	A/C Type	Time	Longitude °	Latitude °	Height (ft)	Speed (kt)	Heading °
AAR721	A321	03:05:30	114.15858	22.39456	4375	189	252
AAR721	A321	03:05:31	114.15812	22.39437	4375	189	252
AAR721	A321	03:05:32	114.15709	22.39407	4350	190	252
AAR721	A321	03:05:33	114.15665	22.39391	4350	190	252
AAR721	A321	03:05:34	114.15562	22.39358	4325	190	252

The data analysis process is presented in **Fig. 2**. Data cleaning has to be performed before analyzing the ADS-B data. The cleaning contains three parts. (1) At the time t_i, the aircraft flight height H_i should satisfy $H_i \in [H_{min}, H_{max}]$, where H_{max} denoted the maximum flight height depending on the aircraft performance, and H_{min} denotes the minimum flight height constrained by the airport elevation. (2) The true airspeed TAS_i should satisfy $TAS_i \in [TAS_{min}, TAS_{max}]$, where TAS_{min} and TAS_{max} are the minimum and maximum operation speeds, respectively. These two values are constrained by the flight envelope, which is available from the Base of Aircraft Data (BADA). (3) Flight height change rate R_i should satisfy $R_i \in [-RD_{max}, RC_{max}]$, where RC_{max} and RD_{max} are the maximum climb rate and the maximum descent rate. These two values are both positive and related to aircraft performance. The method for calculating R_i is based on two adjacent time-series ADS-B data at the time t_i and t_{i+1}:

$$R_i = (H_{i+1} - H_i)/(t_{i+1} - t_i) \tag{1}$$

Combining the flight plans and aircraft types, we can calculate the flight volume in different flight routes and aircraft usage.

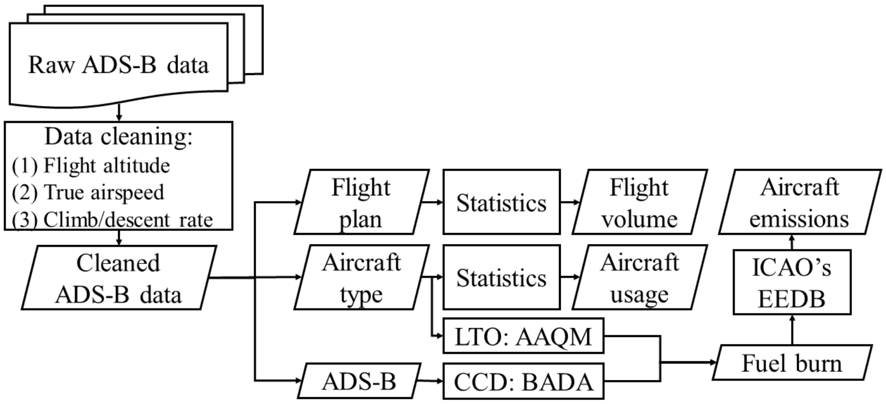

Fig. 2. Process of data analysis.

2.2 Fuel consumption and aircraft emission calculation models

The flight operation contains two cycles, Landing and Take-off (LTO) and Climb/Cruise/Descent (CCD), with the boundary of altitude 3,000 ft above the airport elevation (Society of Automotive Engineers, 2009). **Fig. 3** presents comprehensive explanations of flight phases in detail. In the departure step, the aircraft operational sequence is engine start, taxi to the runway, holding on the ground (sometimes), take-off roll to lift-off, initial climb to power cutback, acceleration, and clean-up and en-route climb. In the arrival step, the sequence is the final approach and flap extension, flare, touchdown and landing roll, taxi from the runway to parking stand/gate, and engine shutdown.

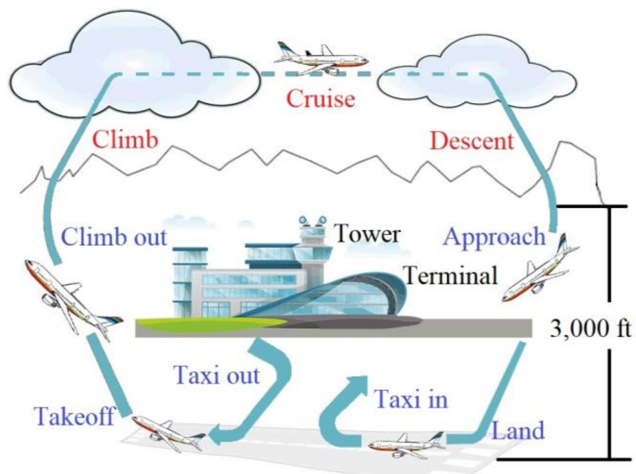

Fig. 3. Operational flight cycle.

2.2.1 Fuel consumption in LTO

Due to the ADS-B data availability, the exact time of approach, taxi and ground idle, take-off, and climb out in the LTO cycle cannot be determined precisely. Therefore, we refer to the Airport Air Quality Manual (AAQM) (International Civil Aviation Organization (ICAO), 2011) to estimate the Time-In-Mode (TIM) and thrust setting as shown in **Table 2**. Four operating phases (approach, taxi and ground idle, take-off, and climb out) are numbered with $i = 1, 2, 3, 4$, respectively.

Table 2. ICAO reference of Time-In-Mode (TIM) and thrust level during the LTO cycle.

Operating phase	Mode number	Time-in-mode (min)		Thrust level (%)
Approach	1	4		30
Taxi and ground idle	2	26	7 (taxi in)	7
			19 (taxi out)	
Take-off	3	0.7		100
Climb out	4	2.2		85

The fuel consumption in LTO ($\mathcal{F}C_{LTO}$ in kg) can be calculated by the below formula:

$$\mathcal{F}C_{LTO} = N_e \times \sum_i (TIM_i \times F_i) \quad (2)$$

where N_e denoted the number of engines of each aircraft type; TIM_i and F_i (in kg/min) represent the operation time and fuel flow in the i^{th} mode as shown in **Table 2**. The exact values of F_i are related to aircraft types and the thrust level, which can be accessible from ICAO Aircraft Engine Emissions Databank (EEDB) (https://www.easa.europa.eu/node/15672).

2.2.2 Fuel consumption in CCD

According to the BADA, the fuel consumption during the CCD cycle can be estimated based on the flight phase FP_i and the aerodynamic configuration AC_i. Here FP_i is categorized using the flight height change rate R_i.

$$FP_i = \begin{cases} Climb & R_i \geq RC_{min} \\ Level & -RD_{min} \leq R_i \leq RC_{min} \\ Descent & R_i \leq -RD_{min} \end{cases} \quad (3)$$

where RC_{min} and RD_{min} are both positive, denoting the minimum climbing rate and the minimum descending rate, respectively. The subscription i denotes the quantity at a given time t_i. AC_i is determined using the following,

$$AC_i = \begin{cases} Approach & FP_i = Descent \;\&\; H_i \leq 8{,}000\,ft \\ Clean & else \end{cases} \quad (4)$$

The fuel consumption in CCD ($\mathcal{F}C_{CCD}$ in kg) can be calculated by the following formula using the time-series ADS-B data:

$$\mathcal{F}C_{CCD} = N_e \times \sum_i ((t_{i+1} - t_i) \times F_i) \quad (5)$$

The nominal fuel flow, F_i (in kg/min) can then be calculated based on (Wang et al., 2020):

$$F_i = \begin{cases} F_{CR,i} & FP_i = Level \;\&\; AC_i = Clean \\ F_{min,i} & FP_i = Descent \;\&\; AC_i = Clean \\ \max\{F_{nom,i}, F_{min,i}\} & AC_i = Approach \\ F_{nom,i} & Others \end{cases} \quad (6)$$

where:

$$F_{min,i} = C_{f_3} \times (1 - H_i / C_{f_4}) \quad (7)$$

$$F_{nom,i} = C_{f_1} \times (1 + 3.6 \times TAS_i / (1.852 \times C_{f_2})) \times T_i / 1000 \quad (8)$$

$$F_{CR,i} = C_{fcr} \times F_{nom,i} \quad (9)$$

Here C_{f_1} (in kg/(min·kN)), C_{f_2} (in knots), C_{f_3} (in kg/min), C_{f_4} (in feet), and C_{fcr} (dimensionless) are fuel flow coefficients, available from BADA. TAS_i (in m/s) is the true airspeed, available from ADS-B data. The thrust T_i (unit in Newtons) can be calculated by:

$$T_i = m_i \times (g \times R_i + TAS_i \times C_i) / TAS_i + D_i \quad (10)$$

Here m_i (in kg) is aircraft weight; g is the gravitational acceleration (9.8 m/s^2); the change rate C_i can be calculated as:

$$C_i = (TAS_{i+1} - TAS_i) / (t_{i+1} - t_i) \quad (11)$$

and the aircraft drag D_i (in Newtons) is obtained as followed:

$$D_i = [C_{D0} + C_{D2} \times (C_{L,i})^2] \times \rho_i \times TAS_i^2 \times S/2 \quad (12)$$

where ρ_i is the atmosphere density (in kg/m^3) related to flight altitude; S (in m^2) is the total area of aircraft wings; C_{D0} and C_{D2} are related to aircraft types and flight phase FP_i, available from BADA (Nuic, 2010). The lift coefficient $C_{L,i}$ at a given t_i is calculated as

$$C_{L,i} = (2 \times m_i \times g)/(\rho_i \times TAS_i^2 \times S) \quad (13)$$

2.2.3 Calculation of aircraft emissions

CO_2, SO_2, H_2O (g), NO_x, and CO are the primary pollutants, which are labeled with $j = 1, 2, 3, 4, 5, 6$. According to the International Civil Aviation Organization's Engine Emissions Databank (ICAO's EEDB), aircraft emission for a given pollutant E_j (in gram) is the product of fuel consumption $\mathcal{FC}$ (in kg) and the engine emission indices (EI_j) (in g/kg), which are available from (Society of Automotive Engineers, 2009),

$$E_j = \mathcal{FC} \times EI_j \quad (14)$$

3 Results

3.1 Development of the COVID-19 cases

Fig. 4 provides the number of daily new cases of COVID-19 in Beijing, Shanghai, Guangdong, and Hubei provinces. The twelve flight routes are formed by Beijing (ZBAA), Shanghai (ZSSS), Guangzhou (ZGGG, the provincial capital of Guangdong), and Wuhan (ZHHH, the provincial capital of Hubei) airports. Three essential features in the graph are worth pointing out. First, the number here includes domestic cases that were believed to be infected within China and imported cases from abroad, confirmed at the immigration ports, and then quarantined and treated immediately. Therefore, only the domestic cases would induce alert to the air travel between the airports we are interested in. Second, the spikes in Shanghai in early April (http://news.sina.com.cn/o/2020-04-12/doc-iirczymi5796291.shtml) and from August to December, and the spikes in Guangdong in early June and from August to December are due to the imported new cases. Third, the massive spike in middle February in Hubei is due to a correction of previous reports when the new criteria were applied. Therefore, the two significant outbreaks that severely affected domestic air travel are the one that occurred in Wuhan Hubei from January 23 to early March and the one that occurred in Beijing from middle June to early July. As the epicenter, the complete lockdown in Wuhan lasted 76 days until April 8, during which no commercial flights were allowed (http://www.xinhuanet.com/english/2020-04/08/c_138958718.htm).

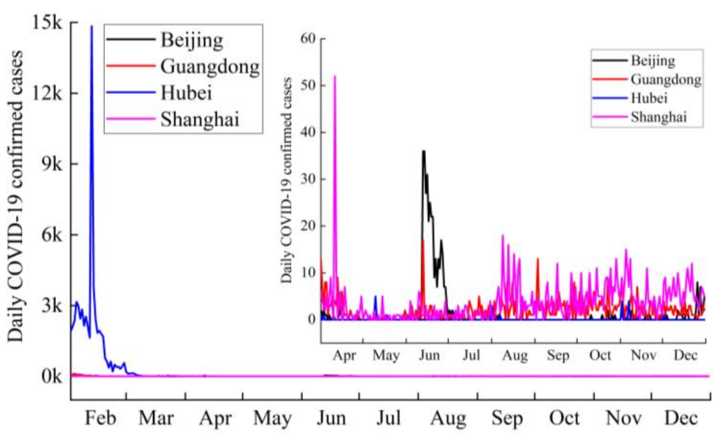

Fig. 4. Daily COVID-19 confirmed cases in different provinces in 2020 (https://github.com/eAzure/COVID-19-Data/blob/master/xlsx%E6%A0%BC%E5%BC%8F/china_provincedata.xlsx).

3.2 Flight volume

COVID-19 pandemic breakout in 2020 resulted in significantly fewer trips compared to 2019. **Fig. 5** illustrates the distribution of the total number of flights for each flight route. For simplification, (ZBAA, ZSSS) denotes flight routes from ZBAA to ZSSS and from ZSSS to ZBAA combined. In 2019, flight volume in (ZBAA, ZSSS) was the highest, with flight volume 24453, followed by (ZGGG, ZSSS) 21819. Due to the impact of COVID-19, there was a tremendous decrease in flight volume in 2020 compared to 2019. Flight volume in (ZGGG, ZSSS) became the highest, with 19187 accounted. Herein, the flight volume ratio is introduced to show the variation from 2019 to 2020. It is clear that flight volume ratios in flight routes connecting to Wuhan (ZHHH) are the smallest, especially in (ZBAA, ZHHH) (2731/8234=0.332) and (ZHHH, ZSSS) (2250/4830=0.466). This is because Wuhan was the epidemic center, and the Wuhan international airport was shut down for all commercial flights for straight 76 days. The total flight volume in 2020 (56430) was only 67.8% of that in 2019 (83189).

Fig. 6 compares the flight volume for selected (a) domestic flight routes in China, (b) domestic flight routes in other major countries, and (c) international flight routes. It is evident that by the end of 2020, the commercial flights between major cities in China have largely recovered to the volume before the pandemic due to the successful control of COVID-19. However, the number of domestic flights within the US, Germany, Australia, and England was vastly reduced throughout 2020, except for two occasions between Sydney and Melbourne. The international flight volume also experienced the same trend, even between China and other countries. Apparently, the much slower decline of COVID-19 cases in other major countries than China was to blame.

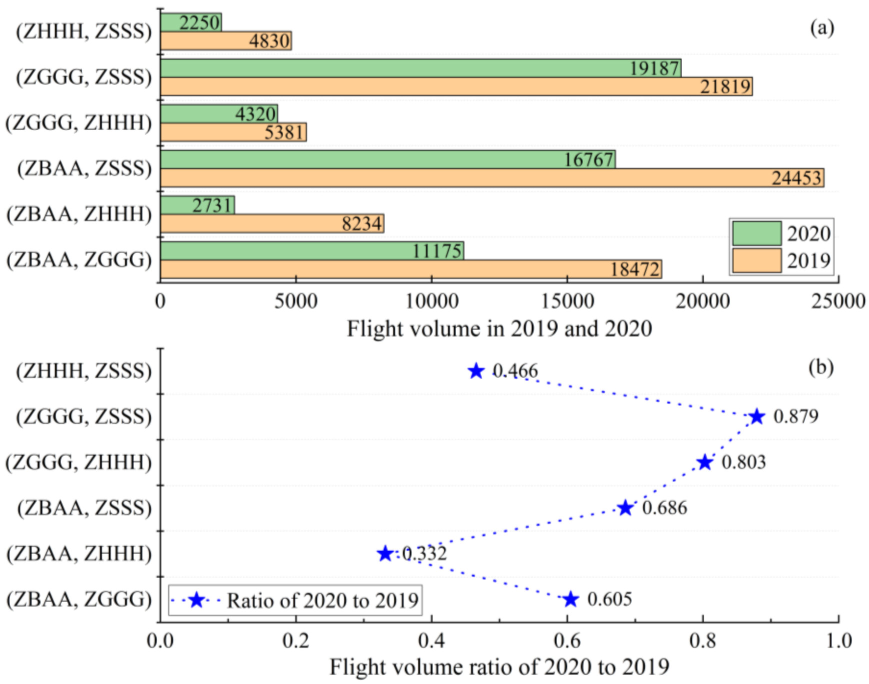

Fig. 5. Flight volume statistics. (a) the flight volume between 2019 and 2020 in the bar chart, (b) the ratio of 2020 to 2019 shown in blue stars.

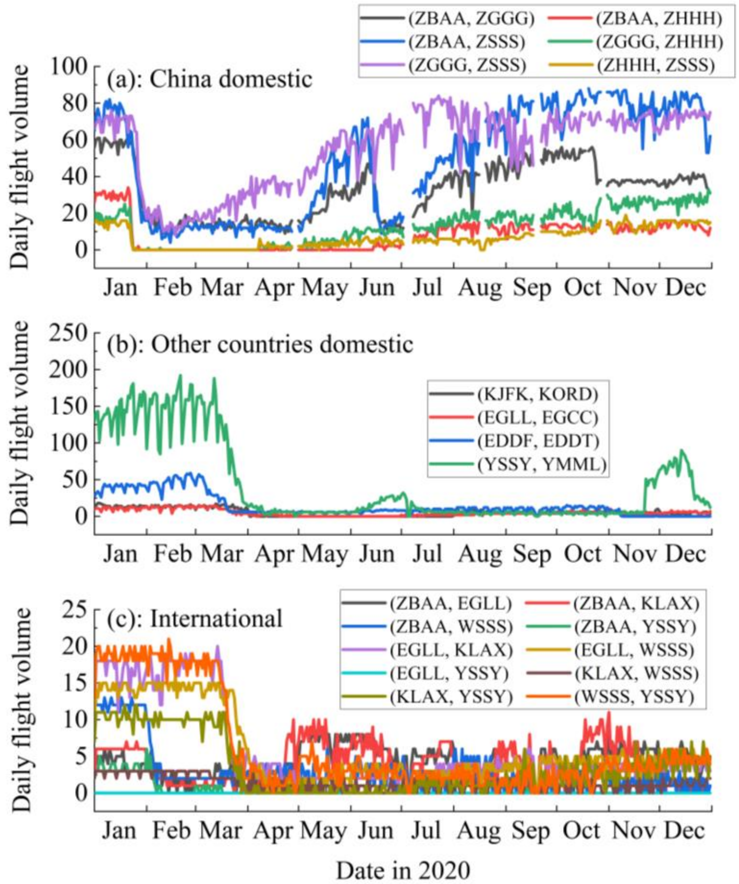

Fig. 6. The daily flight volume in 2020 for different domestic and international routes. The airport (outside China) code designation is as follows: KJFK, John F Kennedy; KLAX, Los Angeles; KORD, Chicago O'Hare; EGLL, London Heathrow; EGCC, Manchester; EDDF, Frankfurt am Main; EDDT, Berlin-Tegel; YSSY, Sydney Kingsford Smith; YMML, Melbourne; WSSS, Singapore Changi.

3.3 Aircraft usage

This section shows the airline companies' response to fewer passengers from the perspective of aircraft usage. Because fuel consumption differs in terms of aircraft types and affects airlines' financial performance, accommodation of different aircraft types became a critical way to unwind the declined demand. There were seven aircraft types (A320, A321, A332, A333, B738, B77W, B788) widely used for the selected flight routes. **Fig. 7** (a) shows B738 and A333, two types of the most frequently used aircraft, accounted for the majority of the decrease. Interestingly, there was a slight increase in flight volume in A321 and A332. **Fig. 7** (b) and **Fig. 7** (d) show a comparison in the percentage of aircraft types between 2019 and 2020. The percentage of B738 accounted for the majority part in 2019 (43.6%) and 2020 (38.4%). Percentages of A320, A321, and A332 experienced an increasing trend, especially A321 from 6.4% to 11.7%. **Fig. 7** (c) shows the monthly percentage of usage of different aircraft types. A320 and A321 were used relatively widely in Feb-May 2020, with a remarkable increase in market share. Simultaneously, the percentages of A332, A333, B77W, and B788 all declined. The passenger capacities of different aircraft types are shown in **Fig. 7** (f). The passenger capacities of A320, A321, and B738 are 150, 185, and 180, fewer than other aircraft types. **Fig. 7** (e) shows fuel consumption per seat in different flight routes in different aircraft types. The variation between the different routes is due to the travel distance. However, we can easily notice that, for the same route, B738 is the most fuel-saving for each seat than other aircraft types, followed by A320 and A321. This is why the usage of B738 only suffered a brief decline in volume in February, as shown in **Fig. 7** (c), while the usage of A320 and A321 in percentage even jumped to its highest from February to April. Therefore, we can conclude that airlines adopted tactical adjustments by using relatively economical aircraft such as A320, A321, and A738 to reduce cost because fewer passengers traveled by airplane. The percentages of A333, B77W, and B788 decreased because these three aircraft are much larger and heavier than other aircraft types. Such transformation in market share among different aircraft types in China lasted until August when the fleet configuration before the pandemic was restored.

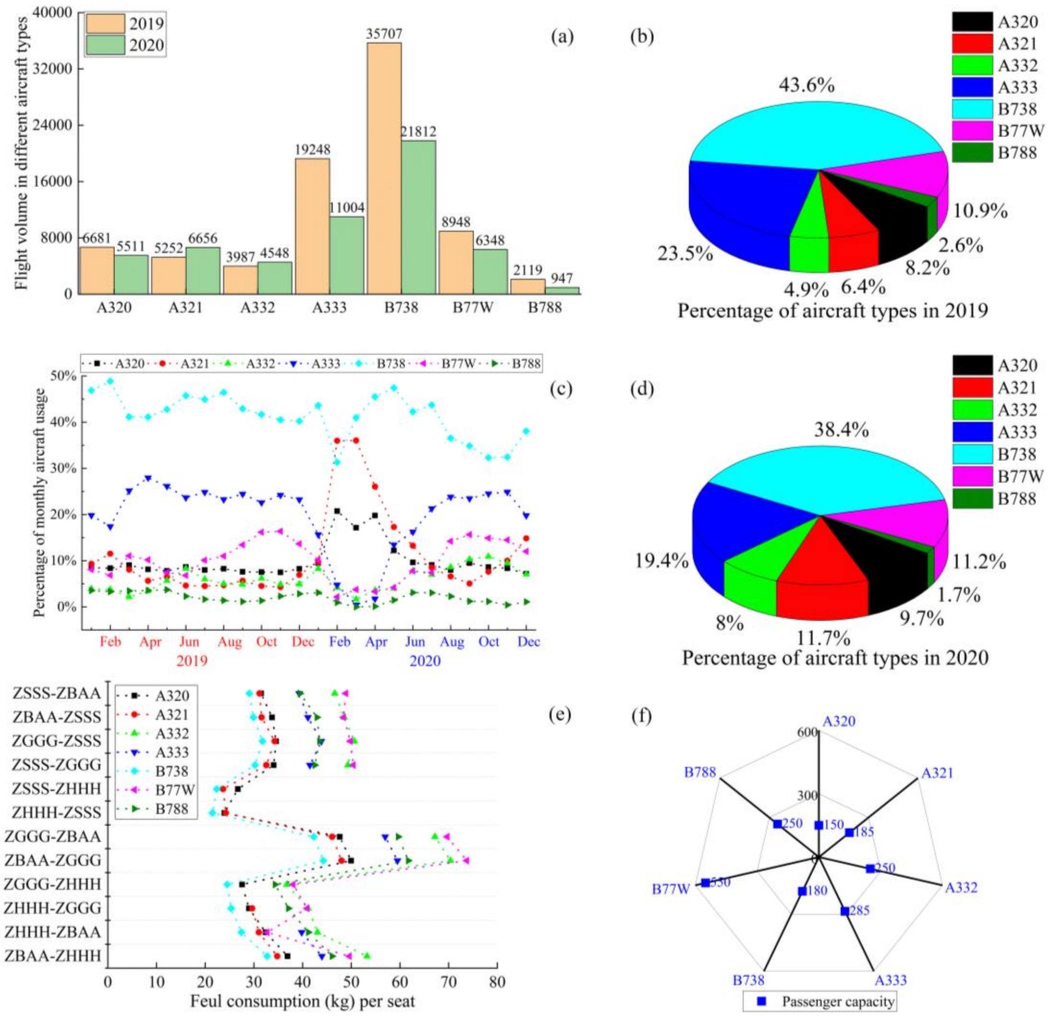

Fig. 7. Flight volume in different aircraft types during the study period, aircraft passenger capacity, and fuel consumption per seat in different flight routes. (a) Flight volume in the seven most popular aircraft types. (b) Percentage of aircraft types in 2019. (c) Percentage of aircraft usage. (d) Percentage of aircraft types in 2020. (e) Fuel consumption per seat in different flight routes. ZBAA-ZSSS denotes the flight route from ZBAA to ZSSS. (f) Passenger capacity of different aircraft types.

3.4 Fuel consumption and aircraft emissions

To compare the difference in fuel consumption and aircraft emissions between 2019 and 2020, we investigate the changes in four quarters, shown in **Table 3**. The ratio of 2020 to 2019 is ~0.38 in Q1 and Q2, and ~0.85 in Q3 and Q4. CO_2, SO_x, and H_2O emission ratios of 2020 to 2019 are the same as fuel consumption because emissions of CO_2, SO_x, and H_2O are proportional to fuel consumption (Lai et al., 2020). However, NO_x and CO emissions ratios are slightly different because engine thrust level affects NO_x and CO emissions. The high temperature in the internal engine accelerates NO_x formation, so less NO_x is generated during the taxi-in and taxi-out mode with a low engine thrust level of 7% (Li et al., 2020). In contrast, CO emissions in taxi-out and taxi-in modes are much higher than other modes of LTO because lower thrust level results in incomplete fuel burning, leading to more significant CO emissions. It can be summarized from **Table 3** that fuel consumption and aircraft emissions reduced significantly (over 60%) in the first half-year 2020 and gradually returned to more than 80% in the second half-year 2020.

Table 3. Quarterly fuel consumption and aircraft emissions (in units of ton), and the ratio of 2020 to 2019.

Year	Quarter	Fuel	CO_2	H_2O	SO_X	NO_X	CO
2019	Q1	2445	7702	3057	2.4	63.8	5.1

	Q2	2357	7424	2946	2.4	61.4	4.9
	Q3	2440	7685	3050	2.4	64.0	5.2
	Q4	2799	8816	3498	2.8	74.2	6.1
2020	Q1	925	2912	1156	0.9	23.8	2.0
	Q2	883	2783	1104	0.9	22.5	1.9
	Q3	2033	6405	2542	2.0	54.5	4.5
	Q4	2448	7710	3059	2.4	64.4	5.5
Ratio: $\frac{2020}{2019}$	Q1	0.378	0.378	0.378	0.378	0.372	0.385
	Q2	0.375	0.375	0.375	0.375	0.367	0.378
	Q3	0.833	0.833	0.833	0.833	0.852	0.862
	Q4	0.875	0.875	0.875	0.875	0.868	0.901

We also compare the change in daily fuel consumption to quantify the short-term and medium-short impact of COVID-19. **Fig. 8** shows a sharp decrease in fuel consumption starting January 23, 2020 (indicated by the purple dot line), when the lockdown in Wuhan was announced. During the lockdown, daily fuel consumption values in the flight routes connecting to Wuhan in 2020 were zero. Fuel consumption started a noticeable increase after the Labor Day holiday on May 1, 2020. However, another travel restriction starting June 14 (indicated by the orange vertical dot line) was due to the secondary COVID-19 outbreak in Beijing because some COVID-19 cases caused by salmon were confirmed. Therefore, we can see a subsequent sharp decrease in fuel consumption in flight routes connecting to Beijing. At the end of 2020, the daily fuel consumption was nearly equal to that at the beginning of 2020. Likewise, aircraft emissions were also in the same trends because of proportional relation to fuel consumption.

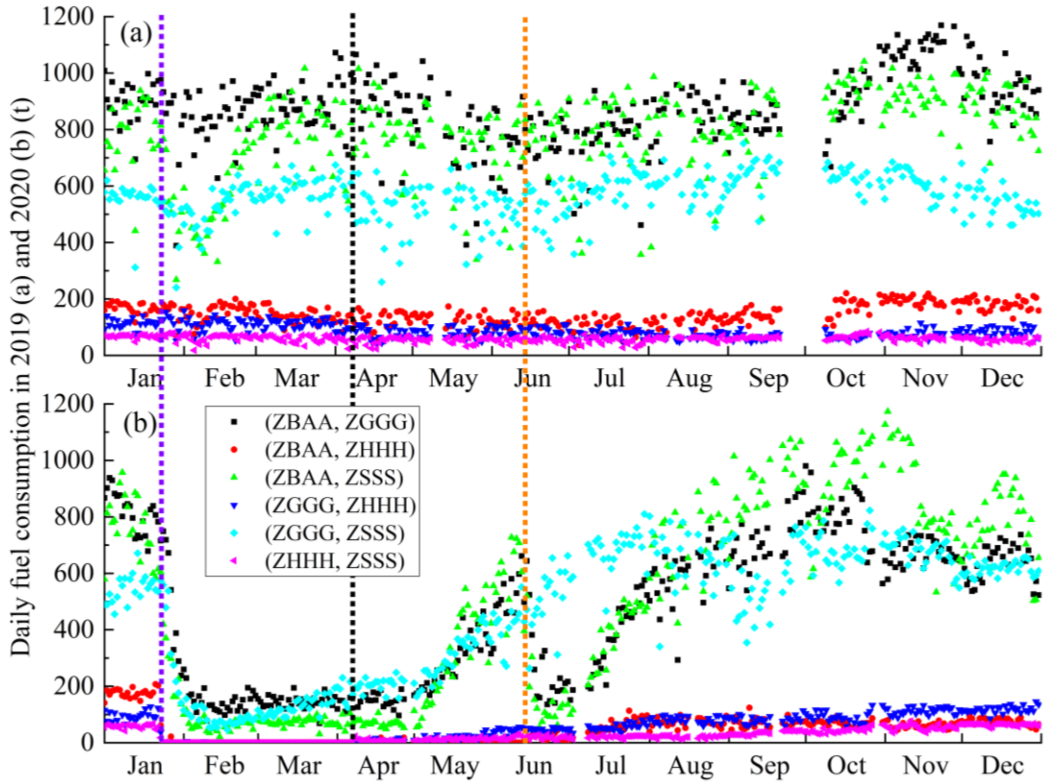

Fig. 8. Daily fuel consumption in 2019 (a) and 2020 (b) in different flight routes. The plot gaps are due to the missing data.

4 Conclusions and Discussion

The COVID-19 pandemic has caused a global lockdown and significantly reduced flight volume since January 23, 2020. In this study, four representative airports (Beijing, Shanghai, Guangzhou, and Wuhan) in China are selected because of their political, economic importance and the centre stage during the pandemic. We focused on twelve domestic flight routes formed by four airports to investigate the short-term and medium-term impact of COVID-19 on flight volume, aircraft usage, fuel consumption, and aircraft emissions from commercial flights.

Detailed analysis shows several important results. The total flight volume ratio of 2020 to 2019 is 67.8% for the selected Chinese domestic routes. The fuel consumption and aircraft emissions in the first half year of 2020 were reduced to ~ 0.38 of that in 2019; the ratio rebounded to ~ 0.85 in the second half of 2020. This is a straightforward conclusion as a result of decreased air travel activity associated with COVID-19. The findings in this research can help the aviation authorities with the assessment of aircraft emission impact and environmental impact for the green and sustainable air transport system in the future. The international travels connecting major cities in China to other countries were still severely impacted. Therefore, the long-term recovery for the air industry in the domestic market is leading the international market. Comparison analysis also shows that domestic flights in other major countries (the US, Germany, Australia, England) were also significantly lagged behind China, suggesting the COVID-19 control as the critical factor.

Thanks to the successful control of COVID-19, at the end of 2020, the commercial air travel activity in these routes has mostly fully recovered. In the domestic market, the initial recovery of flight volume between non-epicenter cities (Guangzhou and Shanghai) took as long as six months from middle February to July (**Fig 6a, 8b**). Different from the initial recovery, we believe that the reopening of the epicenter Wuhan on April 8, 2020, injected significant confidence in the safety of air travel. Therefore, much faster recovery rates are found in May, one month after the reopening, and in July another month after the outbreak in Beijing. This suggests that the sustained low number of new COVID-19 cases would lead to a fairly fast recovery of air travel on a time scale of ~ 1-2 months. The recovery time may differ in different cities and countries due to government measures, people awareness, and medical conditions. However, for a certain city or country, there may be some characteristics or features, which are related to the resilience of air transportation systems. Preference for smaller aircraft is a natural choice of airline companies to reduce financial damage. Our calculation shows that aircraft A320, A321, and B738 were more widely used for flight plans compared with other aircraft types because these models have the lowest fuel consumption per seat. The empirical situation in China can somehow provide a true and promising benchmarking for future commercial flight management. We hope other countries can learn the successful experience from China and recover flight operation as soon as possible. During the recovery phase, airlines could reduce some unnecessary costs and make good use of the existing aircraft such as converting passenger aircraft to cargo aircraft.

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