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Air and greenhouse gas pollution from private jets, 2023

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EXECUTIVE SUMMARY

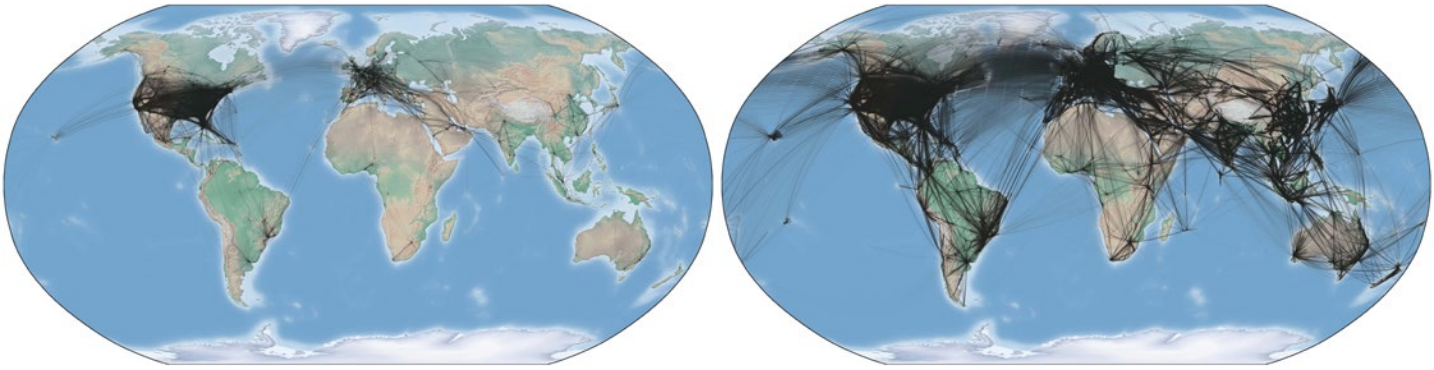
The aviation industry, including commercial, private, and military aircraft, emits about 1 billion tonnes of carbon dioxide (CO_2) annually, making it the seventh-largest source of CO_2 if considered a country. Without significant action, emissions from international aviation could double or even triple by 2050, reaching up to 1,800 million tonnes (Mt), according to the Climate Action Tracker (2024).

While there are several high-fidelity emission inventories for commercial aviation, data on greenhouse gas (GHG) and air pollution from general aviation—including nitrogen oxides (NO_X) and fine particulate matter ($PM_{2.5}$), which impact air quality and human health—remain limited. Private jets were responsible for about 2%–4% of total annual GHG emissions from aviation in 2013–2023. Better data on the magnitude and distribution of private jet pollution could help inform efforts to reduce these emissions through targeted policy measures.

This report quantifies and maps the air and GHG pollution emitted globally by private jets in 2023. We developed both a top-down and a bottom-up emissions inventory for private jet flights using a variety of data sources, such as global flight trajectories, airport coordinates, and engine emission databases. These data allowed us to spatially allocate fuel use and emissions to airports and countries for about 94% of private jet activity globally.

Figure ES1 shows the global distribution of private jet flights (left panel) and commercial flights (jets and turboprops; right panel) in 2023. Private jet activity was overwhelmingly located in the United States, with almost two-thirds (64.6%) of flights departing a U.S. airport. In contrast, commercial jet flights were distributed more widely around the globe, with only about 26% of flights departing U.S. airports.

Figure ES1
Flight trajectories for private jets (left) and commercial flights (right), 2023

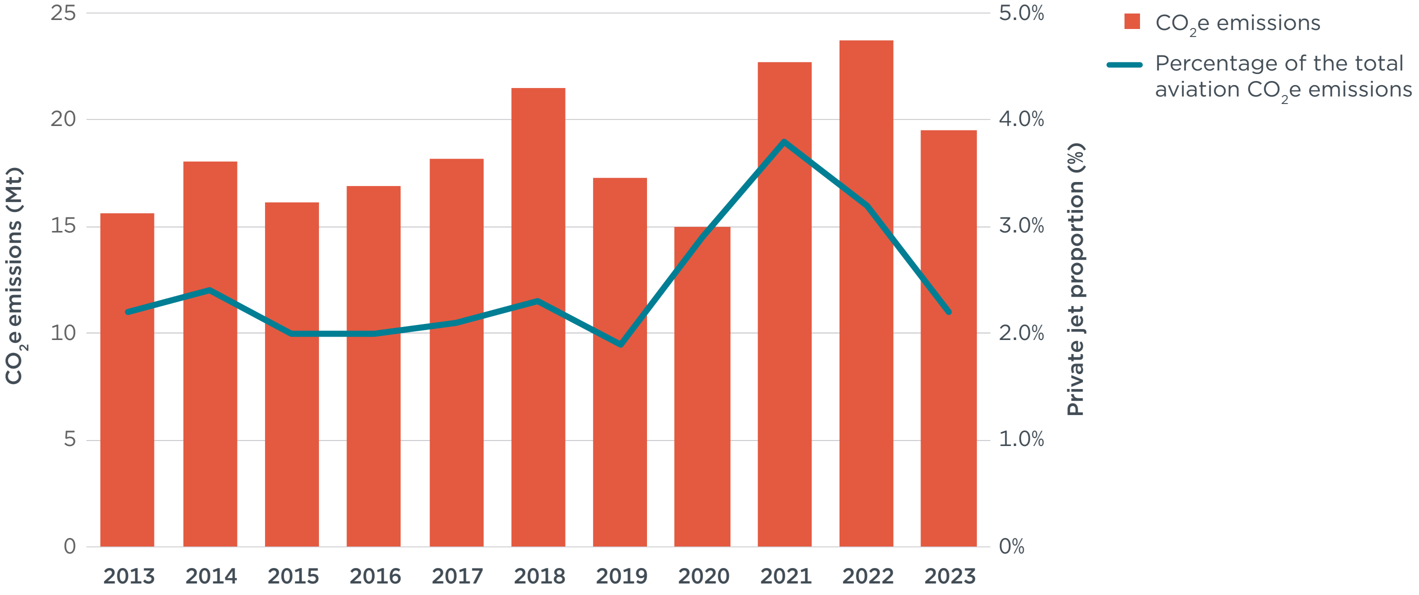


Note: This figure was derived from Spire's 2023 database.

Figure ES2 displays the estimated GHGs from private jets over time based on our top-down emissions inventory methodology. The bars show absolute emissions (in Mt) and the line shows private jets' share of civil aviation (commercial plus private jet) emissions. Greenhouse gas emissions from private jets increased 25% over the past decade, from 15.7 Mt in 2013 to 19.5 Mt in 2023, with significant year-on-year volatility.

Figure ES2

Private jet GHG emissions (bars) and percentage of total aviation GHG emissions (line), 2013 to 2023



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From these results we draw the following conclusions and policy recommendations.

Private jets are a large and growing source of air and climate pollution. A private jet emits about 810 tonnes of GHGs in a typical year, equivalent to 177 passenger cars or nine Class 8 heavy-duty trucks. At their post-COVID peak in 2022, private jets emitted an estimated 23.7 Mt of CO_2-equivalent emissions and accounted for nearly 4% of the civil aviation total. In 2023, private jets collectively emitted more GHGs than all flights departing from Heathrow Airport, the busiest airport in Europe (Heathrow Airport, 2024).

Private jet activity and emissions are overwhelmingly concentrated in the United States. In 2023, private jet flights departing from U.S. airports accounted for more than half (55%) of private jet GHG emissions globally. The states of Florida and Texas generated more private jet flights and GHG emissions than the entire European Union. We found that 18 of the 20 airports with the highest estimated private jet NO_x emissions in 2023 are in the United States.

A typical private jet flight is short-haul (less than 900 km) and lasts less than two hours. This means that the emissions of private jet flights could be reduced through the use of turboprop aircraft, which are much more fuel efficient than turbofan aircraft, and by a modal shift to high-speed rail in regions where it exists, like Europe.

Taxation of private jet flights or GHG emissions could generate substantial revenue to support aviation decarbonization. We find that introducing a global tax on fuels consumed by private flights of approximately $1.59/gallon ($0.42/L)—as proposed in legislation considered by the previous U.S. Congress—could generate up to $3 billion annually, based on a top-down analysis of total annual fuel usage estimated at 5.8 million tonnes.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Aviation is a cornerstone of global connectivity, economic development, and cultural exchange. In 2019 alone, the aviation industry supported 87.7 million jobs worldwide and contributed approximately $3.5 trillion to global gross domestic product (GDP), equivalent to 4.1% of the world's economic output (Air Transportation Action Group, 2020). This level of activity has a steep environmental and social impact. Commercial aviation emitted an estimated 918 million tonnes (Mt) of carbon dioxide (CO_2) in 2019 (Graver et al., 2020). The International Energy Agency estimated that global aviation emissions rebounded from the global COVID-19 pandemic to almost 950 Mt CO_2 in 2023 (Lombardo, n.d.). That would rank aviation as the seventh-largest source of CO_2 if it were treated as country (Joint Research Centre, 2023).

Within the aviation sector, private jets occupy a unique position, catering to a select group of corporate executives and other high net-worth individuals. Ownership models of private jets vary, ranging from full ownership to fractional shares and charter services. Although private jets represent a small fraction of overall aviation activity, they disproportionately contribute to emissions, releasing up to 14 times more CO_2 per passenger than commercial jets and 50 times more than trains (Murphy & Simon, 2021). As the aviation industry faces increasing scrutiny over its contribution to global carbon emissions, a more rigorous examination of private jets' environmental footprint is necessary.

This paper quantifies and maps the greenhouse gas (GHG) pollution emitted globally by private jets in 2023. We develop two emissions inventory methodologies: a top-down approach for estimating global fuel burn and GHG emissions and a bottom-up approach for modeling GHG and air pollution (NO_X and $PM_{2.5}$) at the country and airport levels. The next section reviews the literature on aviation emissions and recent policy efforts to reduce private jet emissions. We then introduce the methods we used to model the fuel burn and CO_2 and air pollution emissions of private jets. From there, we describe the results of our modeling and validate those results against available data. We close with recommendations for policymakers who aim to constrain the growth of private jet emissions. Additional methodological detail and results can be found in Appendices A through D.

RESEARCH AND POLICY CONTEXT

While there are several high-fidelity emission inventories for commercial aviation, data on GHG and air pollution from general aviation are limited. In 2009, private jets and turboprops were estimated to be responsible for about 2% of total aviation GHG emissions, or 20 Mt of CO_2 (General Aviation Manufacturers Association & International Business Aircraft Council, 2009). Gössling and Humpe (2020) applied a top-down assessment to conclude that private jets might have emitted as much as 34 Mt of CO_2 in 2016. In an updated study using high-fidelity Automatic Dependent Surveillance-Broadcast (ADS-B) flight trajectory data,[1] Gössling et al. (2024) concluded that private aviation emitted at least 15.7 Mt of CO_2 globally in 2023.

There are also several regional estimates of private aviation emissions. In the United States, where 60% of all private jets are registered (General Aviation Manufacturers Association, 2020), private jets emitted an estimated 16.3 Mt of CO_2 in 2023, representing 7% of all CO_2 emissions from U.S. aviation. Argus Analytics (2024) tracked 4.7 million business flights (private jets and turboprops) in 2023 globally; the large majority (67%) originated from U.S. airports, with 31% of flights departing from just three states: Florida, Texas, and California. The second-most private flights originated in Europe, accounting for 16.5% of global private flights. Faber and Raphaël (2023) concluded that private jet flights in the top 10 countries in Europe emitted 2 Mt of CO_2 in 2022.

A consistent theme of research on private jet emissions has been the explosive growth in private aviation over the past two decades, which has further accelerated since the COVID-19 pandemic. Murphy and Simon (2021) leveraged European Business Aviation Association data to conclude that greenhouse gas emissions from private jets increased by 31% in the European Union (EU) from 2005 to 2019. Gössling et al. (2024) and the Federal Aviation Administration (FAA; 2024) estimated that CO_2 emissions from private aviation—including private jet, piston, and turboprop flights—jumped by 46% between 2019 and 2023. Health and safety concerns led to an increase in private jet use during the pandemic (Amalfijets, 2024). Looking ahead, the FAA (2024) projects that U.S. private jets will emit 28 Mt of CO_2 in 2044, a 70% increase from 2023 levels.

Given the short duration of many private flights, researchers have also focused on the high emission intensity of private jets and the emissions reduction potential of modal shift. Murphy and Simon (2021) concluded that private jets burn, on average, 10 times more fuel per passenger than commercial aircraft, and that close to half of all intra-EU private flights cover distances less than 500 km. Gössling et al. (2024) and Faber and Raphael (2023) concluded that about half of private aviation flights are less than 500 km in length. This brevity implies that much of the greenhouse gas emissions from private jets could be avoided, either by modal shift to high-speed rail or the use of alternative fuels. U.S. private jet fuel burn and operating hours have remained closely coupled, suggesting only modest (0.4%) annual improvements in fuel efficiency since 2010 (FAA, 2024).

In addition to GHGs, private jets emit air pollutants that impact human health, including nitrogen oxides (NO_X) and fine particulate matter ($PM_{2.5}$). Atmospheric ozone linked to aviation NO_X caused an estimated 53,000 premature deaths in 2015, with $PM_{2.5}$ accounting for an additional 21,000 premature deaths that year (Eastham, 2024). Due to their high-altitude operations, private jets may also contribute disproportionately to persistent condensation trails (Gryspeerdt et al., 2024).

1 ADS-B is a surveillance technology used by most aircraft to broadcast their position in real time to ground and satellite receivers.

In 2021, the International Business Aviation Council committed to achieve net-zero CO_2 emissions by 2050. However, few concrete policy measures are in place to curb private jet emissions. The International Civil Aviation Organization (ICAO) established international fuel efficiency targets for private jets in 2016, but it will not require any jets to make improvements when the targets take full effect in 2028 (Rutherford & Kharina, 2017).

Moreover, private jets are not often subject to the same level of taxation imposed on commercial aviation and other forms of transportation. In 2021, Transport and Environment found that in most European countries, private jet fuel is taxed at a lower rate relative to their GHG emissions per passenger than commercial aviation or automotive fuel, effectively creating a tax advantage for the wealthiest travelers (Murphy & Simon, 2021). Many non-commercial aircraft operators, such as private jets, also are exempt from emissions trading under the EU Emissions Trading System (ETS), as they fall below the 1,000-tonne CO_2 emissions threshold in effect through 2030 (European Commission, 2023a). As a result, these operators are not required to purchase emission allowances, meaning their flights are undertaxed relative to commercial flights. These regulatory differences not only undermine efforts to address aviation's carbon footprint but also highlight the opportunity for targeted policies to ensure private jets contribute their fair share to climate mitigation efforts.

Policymakers in Europe and the United States have taken important steps in the regulation of private aviation. Beginning in 2025, the UK and French governments will tax private jet passengers between £84–£673 (Sentinel Aviation, n.d.) and €420–€2,100 (GlobeAir, n.d.), respectively, depending on flight distance. Meanwhile, various proposals to tax private aviation have failed to advance in the United States, where most private jet activity is concentrated. In 2023, companion bills were introduced in the U.S. House and Senate that would have increased the fuel tax for private jet travel to $1.589/gallon ($ 0.42/L) and devoted the revenue to public transport and climate spending (Fueling Alternative Transportation with a Carbon Aviation Tax Act, 2023).[2] A separate measure would have established tax surcharges on private jets to reduce GHG emissions (Whitehouse, 2023). During the Biden administration, the Internal Revenue Service announced that it would audit private jet tax exemptions claimed by executives (The Associated Press, 2024), but the status of that initiative is uncertain.

Civil society groups, notably the Global Solidarity Levies Task Force, have proposed a luxury aviation tax as a way to raise funds to compensate the Global South for historical damages from climate change (Global Solidarity Levies Task Force, 2024).

2 In January 2025, U.S. Senator Edward Markey of Massachusetts reintroduced the Senate measure for consideration in the 119th Congress; the new bill would increase the federal jet fuel tax to $1.641 per gallon. As this analysis was conducted prior to the reintroduction of the bill, the section on taxing private jets considers the original ($1.589) proposed increase.

METHODOLOGY

We used two methods to estimate global fuel burn and GHGs from private jets: a simplified top-down approach using data on yearly private jet operations and total registered private jets, and a spatially allocated bottom-up calculation using aircraft trajectory data matched to fleet inventories and engine emissions data. The top-down approach was used to estimate global fuel burn and GHG emissions, while the bottom-up approach allowed for estimation of GHG and air pollution (NO_x and $PM_{2.5}$) at the country and airport level.

TOP-DOWN APPROACH

Our top-down approach used FAA general aviation and JETNET data to calculate total fuels consumed and GHGs emitted by private jets globally. The FAA (2023) general aviation data provide insights into U.S. and global private jet fuel consumption and carbon dioxide emissions. Key data points include the estimated average fuel consumed per hour of flight and the average hours flown annually per registered aircraft. JETNET (2023) data provide insights into globally registered private jets. We used the number of registered private jets on an annual basis from 2013 to 2023 to estimate the global fuel consumption and GHG emissions assuming the same average hours flown, as suggested in the FAA dataset.

Top-down fuel consumption and GHG emissions

We first determined the number of private jets in the United States and globally using data from the FAA and JETNET. Using total annual private jet flight hours estimates from the FAA, we calculated the total fuel consumption, factoring in the average fuel burned per hour. As the FAA general aviation data contain no private jet-specific data on flight distance or fuel usage, we used the “all turbojet aircraft” category as a proxy for private jets. We assumed that global private jets had the same average fuel consumption per flight hour and annual flight hours per aircraft as reported in the FAA data. The global top-down fuel burn was calculated using the following equation:

$$TFB = RPJ \times AFC \times AHF$$

Where:

TFB is global fuel burn by private jets;

RPJ is global registered private jets;

AFC is average fuel consumed by U.S. private jets per hour; and

AHF is average hours flown per U.S.-registered private jet.

The average fuel consumed per hour, annual hours operated, and GHGs per U.S. private jet from 2013 to 2023 is shown in Table 1.

Table 1
U.S. private jet activity statistics, 2013 to 2023

Year	Average fuel consumed (kg/h)	Average hours flown per year (h)	Average GHG emissions per U.S. private jet (tonnes CO_2 equivalent)
2013	822.9	299.8	780.6
2014	886.9	313.9	880.8
2015	840.5	285.5	759.2
2016	881.4	279.7	780.0
2017	897.8	285.9	812.1
2018	960.5	314.6	956.1
2019	903.8	263.7	754.1
2020	941.4	217.8	648.8
2021	969.6	318.8	978.0
2022	974.2	324.8	1001.1
2023	930.8	279.9	824.3

Note: Table 1 assumes an energy density of 0.8 kg per L of fuel. Adapted from Federal Aviation Administration, 2023.

We then used a tank-to-wheel (TTW) CO_2-equivalent (CO_2e) emission factor to derive CO_2e emissions from the fuel burn estimates. In our top-down calculation, we used a TTW value of 3.164 kg CO_2e per kilogram fuel burn. The equation used to calculate total TTW emissions is as follows:

$$TCO_2e = TFB \times TTW$$

Where:

TCO_2e is total carbon dioxide equivalent;

TFB is total fuel burn by private jets; and

TTW is tank-to-wake carbon dioxide equivalent per kilogram of fuel.

BOTTOM-UP APPROACH

Our bottom-up approach uses data from Spire, OurAirports, IBA Insight, ICAO, the Engine Emissions Databank (EEDB), and the World Bank to calculate emissions at the airport, country, and regional levels, providing insights into the distribution of private jet flights.

Dataset

Aircraft position data

Spire's ADS-B database was our primary data source for identifying private jet flights by airport and calculating flight distances for our bottom-up analysis. The dataset includes 1-minute interval trajectory data for global flights from January to December 2023 (Spire Aviation, 2023). The data include details on flight departure and arrival time, departure and arrival airports, aircraft type, plane registration, and flight role (commercial, private, etc.).

For this study, we filtered Spire's data for private jets to estimate air pollution based on flight distance, analyzing impacts at the airport and country levels. Aircraft were identified based on the 24-bit ICAO address of the ADS-B transponder, a unique identifier assigned to each aircraft. This information is available for all flights in the

Spire dataset, though the information is inconsistent over time for some aircraft. To harmonize aircraft characteristics, we selected the most common value of each attribute for the same aircraft based on the number of flights. Table 2 shows the shares of valid, invalid, and missing values in the raw data, as well as the share of values we arrived at by using the statistical mode (i.e., the value that appears most frequently in a dataset) per aircraft.

We singled out private jets based on two aircraft attributes. First, we identified specific aircraft types that are designated as private jets in Spire's dataset. Examples include the Embraer EMB 505 Phenom 300 and the Cessna 680A Citation Latitude, which are commonly operated for private or business travel rather than commercial airline services. Aircraft model information was available for 96% of flights in the Spire dataset; a full list of aircraft models we classified as private jets is presented in Appendix D. Second, we identified all aircraft whose role was listed by Spire as "VIP," which denotes private jets as well as commercial aircraft configured for private use (such as Boeing Business Jet and Airbus Corporate Jet aircraft, which are often designated with BBJ or ACJ in their type name).[3] Aircraft role information was available for 56.6% of flights in the Spire dataset.

Table 2

Share of all flights and private jet flights with valid, invalid, or missing values per attribute in the raw 2023 Spire data

Attribute	All flights				Private jet flights			
	Valid	Invalid	Missing	Mode	Valid	Invalid	Missing	Mode
Aircraft type	92.2%	0.1%	7.7%	96.1%	100.0%	0.0%	0.0%	100%
Aircraft role	56.4%	0.0%	43.6%	56.6%	3.4%	0.0%	96.6%	4.3%
Tail number	95.9%	0.6%	3.5%	95.9%	99.3%	0.6%	0.0%	99.3%
Departure airport	91.9%	0.1%	8.1%	—	92.7%	0.2%	7.1%	—
Arrival airport	90.2%	0.1%	9.6%	—	93.5%	0.4%	6.1%	—
Takeoff time	86.7%	0.0%	13.3%	—	90.5%	0.0%	9.5%	—
Landing time	89.1%	0.0%	10.9%	—	95.9%	0.0%	4.1%	—

Note: The Mode column shows the percentage of flights that use the most common value for that attribute for each aircraft (tail number). This reflects how consistently a given value (e.g., aircraft type or role) appears across all flights for the same aircraft.

In total, we identified approximately 3.57 million private jet flights conducted globally in 2023. Of these, 3.49 million (97.8%) were identified based on the aircraft type, roughly 100,000 based on a combination of aircraft type and role, and about 50,000 based on aircraft role.

In the Spire database, approximately 11.7% of private jet flights had incomplete departure or arrival information (Table 3). For these flights, we used the average distance of all flights with complete departure and arrival airport data (1,164 km) to ensure that every flight in the database was taken into account. As we used the departure airport as the reference point for our flight distance calculation, flights with a known departure airport but without a known arrival airport were included in our country- and airport-level analysis using this average flight distance. Flights without departure airport data were excluded from the country- and airport-level analysis but included in the global results.

3 Because the "VIP" value was available only for flights beginning in September 2023, we reclassified all aircraft that were labelled "VIP" after that time as private jets throughout the entire year based on aircraft tail number.

Table 3
Spire data quality and coverage

Status	Median ground time (h)	Flight share
Continuous flight with complete arrival and departure	10.1	79.6%
Incomplete arrival/departure airport	20.9	11.7%
Incomplete routes	22.2	8.7%

We also identified flights with non-continuous routes, using aircraft tail numbers to determine whether a given aircraft departed from the same airport it flew into on the preceding flight. Approximately 8.7% of flights did not depart from the preceding arrival airport. These non-continuous flights had a median ground time twice as long as that of continuous flights. Similarly, flights with incomplete departure or arrival information exhibited double the median ground time. These findings suggest that up to 8.7% of private jet flights may be entirely or partially missing from the ADS-B data and underscore the need for both a top-down and bottom-up approach to account for data gaps and better understand yearly trends.

We used Spire data to calculate the flight time between two airports. Understanding private jet flight time is crucial for evaluating the efficiency that most users gain by flying private compared with taking other modes of transportation. We used the trajectory observation time to account for idling (i.e., taxi) time. The flight time of each flight is calculated as below:

$$T_i = TOE_i - TOS_i$$

Where:

T_i is total flight time for flight i;

TOE_i is flight trajectory observation end in Spire database for flight i; and

TOS_i is flight trajectory observation start in Spire database for flight i.

Airport location data

To calculate actual distances between airports, we used arrival and departure airport coordinates from the OurAirports (2024) database. We merged these data with the departure and arrival airport ICAO codes provided for each flight in the Spire data. The flight distance was then calculated using the Great Circle Distance (GCD) formula (Roy, 2022), which determines the shortest path between two points on a spherical surface, effectively representing the ideal flight distance between airports. We also applied a correction factor based on actual flight trajectories from the Spire dataset to ensure the distances reflected realistic flight paths (see "Bottom-Up Fuel Consumption and GHG Emissions" below).

Aircraft registration data

Aircraft tail numbers from the Spire dataset were cross-referenced with an aircraft fleet database from IBA Insight (2024) to identify corresponding engine configurations. For aircraft lacking direct matches in the IBA database, we assigned representative engines based on the most frequently occurring engine type within the same aircraft model category.

Engine Emission Databank

We used the engine configuration data to estimate emissions using the European Union Aviation Safety Agency's EEDB, which provides emissions information on different engines based on the aircraft type. The EEDB served as our primary source for engine-specific emissions data, including for nitrogen oxides (NO_x) and non-volatile Particulate Matter (nvPM; ICAO, 2024). For consistency, we used the most recent test results available for each engine model in our calculations. In cases where nvPM data were unavailable, we employed smoke numbers (SNs) for estimation, applying ICAO-recommended Smoke Factor (SF) values to predict missing data points following the methodology outlined in the *Airport Air Quality Manual* (ICAO, 2020), as shown in Table 4.

Table 4
SF values used to predict missing SNs in the ICAO EEDB

Engine category	Take-off	Climb-out	Approach	Idle
Most non-DAC engines	1.0	0.9	0.3	0.3
GE CF34 engines	1.0	0.4	0.3	0.3
CFM DAC engines	0.3	0.3	0.3	1.0

Note. Values are derived from the International Civil Aviation Organization, 2020. After populating the missing SN values, we calculated the emission index value using the SCOPE11 method (Ahrens et al., 2023). More detail on the SCOPE11 method is provided in Appendix B. We then used the emission index and emission value to calculate the Landing and Take-Off (LTO) cycle emissions of each flight (see "Bottom-Up Air Pollution Estimation").

World population data

To calculate private jet flights in each country on a per capita basis, we used World Bank population estimates (World Bank Group, 2024) together with Spire data on the number of private jet flights departing each country. We calculated per capita flights as follows:

$$FPC_j = \frac{\sum PJF_j}{P_j}$$

Where:

FPC_j is flights per capita in country j;

PJF_j is the number of private jet flights departing from airports in country j in 2023; and

P_j is the population of country j in 2023.

In addition to analyzing per capita private jet flights, we identified the top countries of origin for private jets traveling to destinations with the highest per capita flight activity.

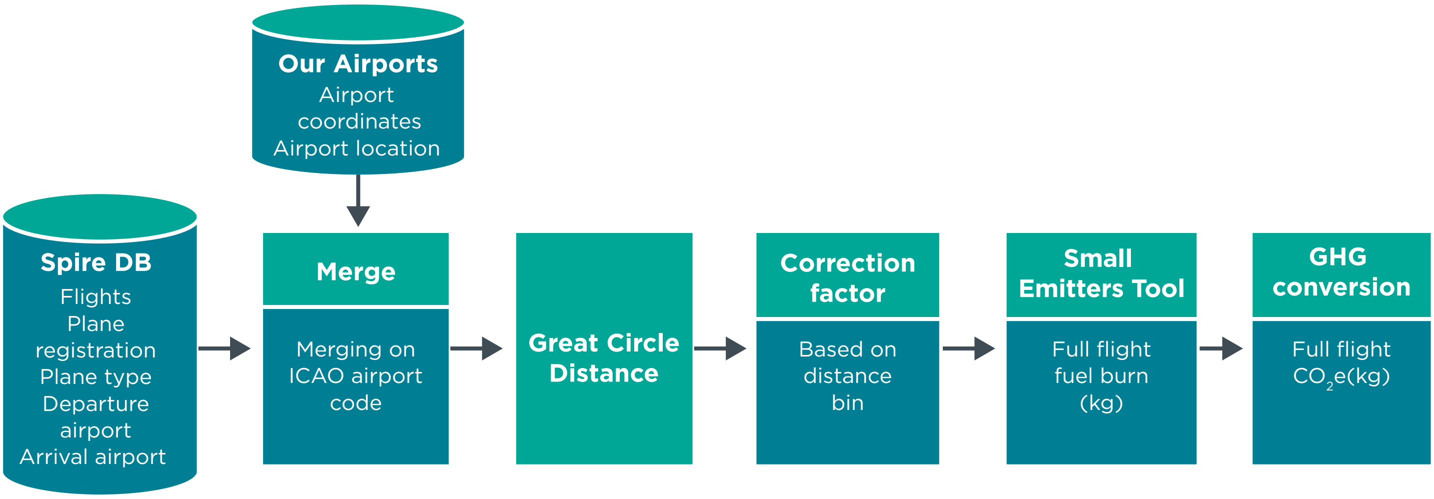
Small Emitters Tool

Flight fuel consumption and associated CO_2 emissions were calculated using Eurocontrol's Small Emitters Tool, which determines full flight fuel burn based on flight distance and aircraft type. For precise aircraft-specific modeling, specific ICAO aircraft type designators were applied to each flight. The European Commission uses the Small Emitters Tool for EU ETS annual compliance reporting, specifically for aircraft operators emitting less than 25,000 tonnes of CO_2 per year (European Commission, 2023a). While the standard methodology includes a 95-km adjustment, we developed a custom distance correction factor, detailed in the next section, to more accurately represent the unique flight patterns of private jets.

Bottom-up fuel consumption and GHG emissions

With our bottom-up analysis, we calculated fuel consumption and CO_2 emissions based on the aircraft type and distance flown. Figure 1 illustrates the methodology of this approach. The distance flown was derived using departure and arrival airport information from Spire. This distance, along with the aircraft type information, was input into the Small Emitters Tool to estimate the full flight fuel burn. We then used the TTW conversion factor to calculate the full flight CO_2e. For the country- and airport-level analysis, we used Spire data on departure and arrival airport locations to identify the route of each flight.

Figure 1
Bottom-up modeling of fuel burn and CO_2 emissions



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We calculated the GCD between origin and destination points using the Haversine formula, which accounts for Earth's spherical geometry (Sinnott, 1984).

$$GCD = 2 \times R \times \arcsin\left(\sqrt{\sin^2\left(\frac{lat_2 - lat_1}{2}\right) + \cos(lat_1) \times \cos(lat_2) \times \sin^2\left(\frac{lon_2 - lon_1}{2}\right)}\right)$$

Where:

GCD	is the great circle distance in kilometers;
R	is the mean radius of Earth (6371.0088 km);
lat_1 and lon_1	are the latitude and longitude of the first point (in radians); and
lat_2 and lon_2	are the latitude and longitude of the second point (in radians).

To reflect more realistic flight paths, we used the trajectory data available from Spire and the GCD to derive correction factors. After missing trajectory sections were linearly interpolated and resampled to 1-min intervals, the real-world ground distance flown was calculated as the sum of distances between each waypoint for each flight. This approach establishes a standardized method to handle incomplete trajectory data and ensures consistency in calculating distances across all flights. While direct distance calculations from ADS-B data could be more precise, they are often subject to data gaps, noise, and irregular update intervals, which can introduce inconsistencies. By aggregating correction factors into distance bins, we mitigated these issues and provided an adjustment for emissions modeling. Correction factors were aggregated to distance bins as follows:

$$corr_i = \frac{\Sigma_i TD}{\Sigma_i GCD}$$

Where:

$corr_i$ is the distance correction factor in distance bins i;

TD is the trajectory ground distance of all flights in distance bins i; and

GCD is the GCD of all flights in distance bins i.

To enable a comprehensive analysis, we established five distance-based flight categories. Regional flights encompass distances below 500 km, while short-haul flights range from 500 to 1,499 km. Medium-haul flights cover distances between 1,500 and 4,000 km, and long-haul flights are from 4,001 to 10,000 km. Finally, ultra-long-haul flights are classified as those exceeding 10,000 km. The correction factor varied by distance bin, as shown in Table 5. For ultra-long-haul flights, a correction factor of 1 was applied because, at such distances, the deviation caused by the Earth's oblate shape becomes negligible, and GCD calculations are highly accurate.

Table 5
Distance correction factor by distance bin

Distance bin	Stage length	Correction factor
Regional	< 500 km	1.219
Short-haul	500–1,499 km	1.076
Medium-haul	1500–4,000 km	1.044
Long-haul	4,001–10,000 km	1.043
Ultra-long-haul	> 10,000 km	1

The GCD was thus adjusted by multiplying it with the correction factor to yield the corrected GCD. To correct abnormalities in flight distance—specifically, several flights by small private jets with fewer than 19 passengers—we identified flights exceeding 12,000 km as outliers and applied the average flight distance in these cases.

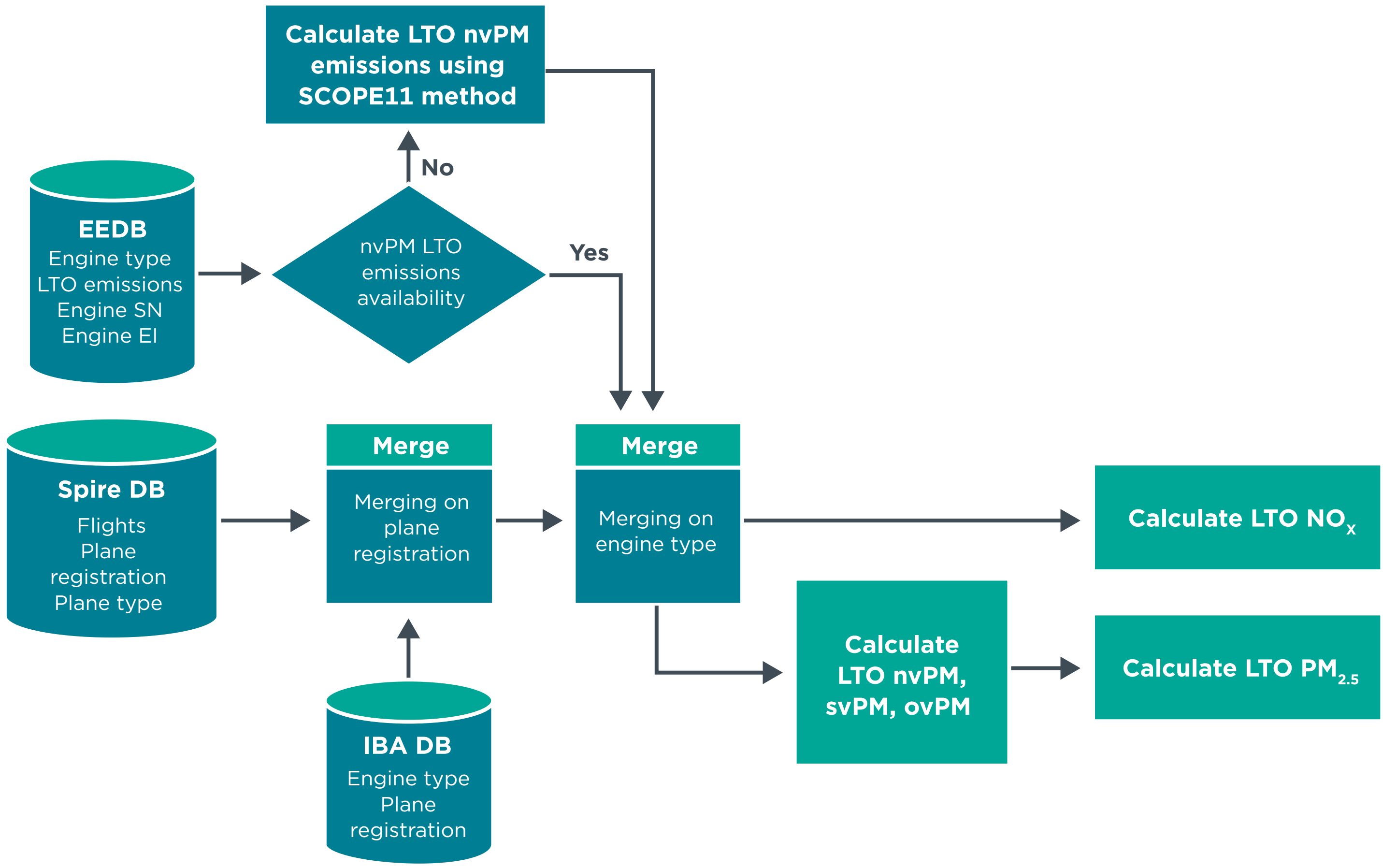
To validate our bottom-up methodology for fuel consumption and emissions calculations, we compared our results for all commercial flights with FAA-reported figures and found a 5% underestimate, demonstrating that the Small Emitters Tool provides a sufficiently accurate basis for our calculations. The CO_2 consumption calculation using the Small Emitters Tool was also compared with the Conklin and de Decker CO_2 calculator, as shown in Appendix A. We compared the values using the average private jet flight distance and found an average difference of 8%, with the highest deviation at 18% and the lowest at -3% among the top 10 most-used aircraft in 2023.

Bottom-up air pollution estimation

In our NO_x and $PM_{2.5}$ calculations, we focused exclusively on LTO emissions as estimated via engine certification standards established by ICAO. The LTO cycle comprises four modes of operation: takeoff, climb, approach, and idle/taxi. Emission quantities are based on test points in each operating mode that approximate thrust conditions. To simplify our modeling, we assigned all emissions from a single operation to the departing airport, assuming that approach and taxi-in emissions at the arrival airport are mirrored on the return flight.

Figure 2 illustrates the methodology we used to model NO_x and $PM_{2.5}$ LTO emissions. The primary data sources were Spire, IBA, and EEDB. There is a slight difference in the methods used to calculate NO_x and $PM_{2.5}$ due to limited $PM_{2.5}$ data for engines in the EEDB database. To address this limitation, we applied the SCOPE11 method to approximate the emission index for $PM_{2.5}$ based on SN values from the NO_x data (Appendix C).

Figure 2
Modeling NO_x and $PM_{2.5}$ LTO emissions



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Estimating NO_x LTO emissions

Private jet engines emit NO_x during high-temperature combustion, in which temperatures often exceed 1600 °C (2912 °F; Prashanth et al., 2021). At these temperatures, nitrogen in the air reacts with oxygen to form nitric oxide (NO) and nitrogen dioxide (NO_2), collectively known as thermal NO_x. The quantity of emissions is influenced by engine design and operational conditions, with high-thrust operations producing considerable output (Stettler et al., 2011). In the atmosphere, NO_x reacts with volatile organic compounds (VOCs) to create ground-level ozone (a smog component linked to respiratory issues) and contributes to fine $PM_{2.5}$, posing significant health risks near airports (Lee et al., 2010). At higher altitudes, NO_x affects global warming by influencing atmospheric chemistry, specifically its role in the short-term production of ozone (O_3) and the destruction of methane (CH_4; Fuglestvedt, 1999).

We used the EEDB to calculate LTO cycle NO_x emissions per engine, which we multiplied by the number of engines on each aircraft. Emissions were then aggregated to the airport level.

Estimating LTO $PM_{2.5}$ emissions

$PM_{2.5}$ emissions are a significant environmental and health concern associated with private jet operations. These fine particles, smaller than 2.5 micrometers in aerodynamic diameter, are primarily emitted during the LTO cycle, particularly at lower altitudes where incomplete combustion occurs (Stettler et al., 2011). $PM_{2.5}$ comprises non-volatile particulate matter (nvPM) formed from soot and trace metal impurities in jet fuel, along with secondary particles produced through atmospheric reactions involving sulfur oxides (SO_x) and NO_x (ICAO, 2019). Near airports, $PM_{2.5}$ exposure has been linked to severe respiratory and cardiovascular health issues (World Health Organization, 2021). Moreover, $PM_{2.5}$ has broader environmental implications, as fine particles can alter cloud microphysics, influencing regional precipitation patterns and contributing to radiation forcing (Righi et al., 2013).

We quantified $PM_{2.5}$ emissions using the EEDB, which provides engine-specific data based on aircraft type and operational profiles (International Civil Aviation Organization, 2024). To calculate final $PM_{2.5}$ values, we added the total nvPM to two kinds of volatile PM—the first derived from fuel sulfur (svPM) and the second from unburned hydrocarbons (ovPM)—per the ICAO (2020) *Air Quality Manual*. For engines listed in the nvPM emission database, the emission calculation follows the same equation as for NO_x (see "Estimating NO_x LTO emissions").

As noted above, for engines without nvPM data in the EEDB, we estimated the emissions index using the SCOPE11 method (Agarwal et al., 2019), where fuel used in each mode is the product of the time in that mode and the fuel flow (kg/s) in that mode. The time in mode (TIM) assumptions for each of the four components of the LTO cycle can be found in the Environmental Protection Agency's (1992) *Procedures for Emission Inventory Preparation:*

$$\textit{fuel in mode } [kg] = \textit{fuel flow } [kg/s] \times TIM[min] \times 60\ [\text{s/min}]$$

Table 6 shows the TIM assumptions used in this analysis.

Table 6
Time in mode assumed for air pollution modeling

Mode	TIM (min)
Take-off	0.4
Climb	0.5
Approach	1.6
Idle/taxi	13

Note. Values are derived from Environmental Protection Agency, 1992.

Aircraft engines produce svPM emissions when fuel containing sulfur is combusted. The level of emissions is directly proportional to the sulfur content of jet fuel. ICAO's *Airport Air Quality Manual* (2020, §3.8) suggests a conversion efficiency of 0.024 (m/m) of sulfur to vPM and sulfur content of 680 parts per million (ppm); 0.068%. Accordingly:

$$\textit{LTO svPM } [mg] = 0.024 \times 0.068\% \times \textit{LTO fuel } [kg] \times 1{,}000{,}000\ [\text{mg/kg}] \times \text{NE}$$

Where:

LTO svPM is total svPM emissions during the LTO cycle;
LTO fuel is total fuel during the LTO cycle; and
NE is the number of engines on the aircraft.

Engines produce ovPM emissions when unburnt hydrocarbons from the fuel adsorb onto a fine particle, adding to its mass. These emissions are largely untested across EEDB engines, so we followed ICAO's method to calculate them by using the CFM56-

2-C1 turbofan aircraft engine as a reference (see ICAO, 2020, §3). The ovPM emissions were assumed to be directly proportional to LTO fuel for all engines in the EEDB:

$$LTO\ ovPM\ [mg] = (4.6 \times TO\ fuel\ [kg] + 3.8 \times CO\ fuel\ [kg] + 4.5 \times App\ fuel\ [kg] + 11.3 \times Idle\ fuel\ [kg] \times \mathrm{NE}$$

Where:

LTO ovPM	is total ovPM emissions during the LTO cycle;
TO fuel	is fuel burn during takeoff, in kilograms;
CO fuel	is fuel burn during climb out, in kilograms;
App fuel	is fuel burn during approach, in kilograms;
Idle fuel	is fuel burn during idle/taxi, in kilograms; and
NE	is number of engines on the aircraft.

The equation to calculate the final $PM_{2.5}$ value is as follow:

$$PM_{2.5}\ [g] = nvPM\ [g] + svPM\ [g] + ovPM\ [g]$$

Where:

nvPM	is non-volatile particulate matter;
svPM	is sulfate particulate matter; and
ovPM	is organic particulate matter.

RESULTS

PRIVATE JET FLIGHTS

Based on 2023 Spire data, our bottom-up analysis identified 22,749 private jets by unique tail number that operated over 3.57 million flights. In terms of global flights in 2023, Table 7 shows the top 10 private jet models seating 19 or fewer passengers (left) and the top 10 models with more than 19 seats converted from commercial types (right).

Table 7
Top 10 aircraft models based on number of seats and number of flights in 2023

19 or fewer seats			More than 19 seats		
Rank	Aircraft model	Number of flights	Rank	Aircraft model	Number of flights
1	Embraer EMB 505 Phenom 300	238,141	1	Boeing 737-700 (BBJ)	11,757
2	Cessna 680A Citation Latitude	167,513	2	Airbus ACJ319-100	9,579
3	Bombardier BD-100-1A10 Challenger 350	145,221	3	Boeing 757-200 (BBJ)	5,743
4	Cessna 560XL Citation XLS	99,139	4	Embraer Lineage 1000	4,708
5	Bombardier BD-100-1A10 Challenger 300	89,030	5	Airbus ACJ320-200	4,294
6	Cessna 525B CitationJet CJ3	76,307	6	Airbus A320-200	2,592
7	Cessna 560XL Citation XLS+	74,962	7	Airbus A321-200NX(LR)	2,309
8	Bombardier Learjet 45	73,202	8	Boeing 737-800(BBJ)	2,228
9	Cessna 560XL Citation Excel	69,703	9	Airbus ACJ318-100	2,164
10	Cessna 680 Citation Sovereign	67,574	10	Airbus A319-100	1,822

Table 7 highlights the dominance of private jets with 19 or fewer seats compared with those with more than 19 seats. In total, private jet models seating 19 or fewer passengers accounted for 97% of all flights. Among these smaller jets, the Embraer EMB 505 Phenom 300 topped the list with 238,141 flights, followed by the Cessna 680A Citation Latitude and Bombardier BD-100-1A10 Challenger 350. Meanwhile, among private jets with more than 19 seats, the Boeing 737-700 Business Jet led with 11,757 flights, along with models from Airbus and Embraer. These larger jets may be favored in some instances for their extended range and larger seating capacity.

The bottom-up analysis data revealed a significant geographical concentration in the United States. Figure 3 shows the top 10 countries in terms of total private jet flights in 2023. An estimated 2.3 million flights departed U.S. airports in 2023, representing almost two-thirds (64.6%) of all global private jet flights. France and the United Kingdom, the second and third most active countries, recorded 80,169 and 73,626 flights, respectively. These figures represented just 2.3% and 2.1% of the global total, highlighting the disparity in private jet activity between the United States and other countries. Canada logged 73,536 flights (2.1% of global activity), while Germany, Italy, Brazil, Mexico, Spain, and Switzerland each contributed less than 2% of global flights.

Figure 3

Share of private jet flights globally for the top 10 countries and regions

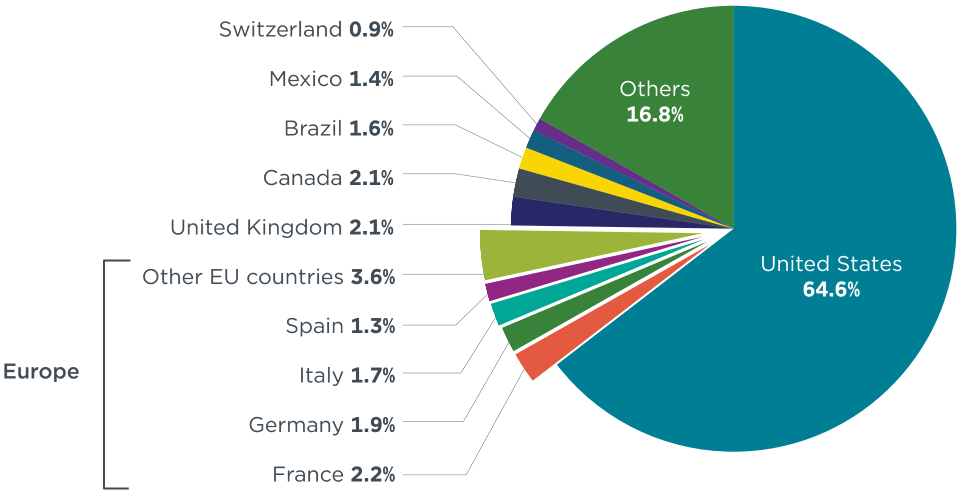

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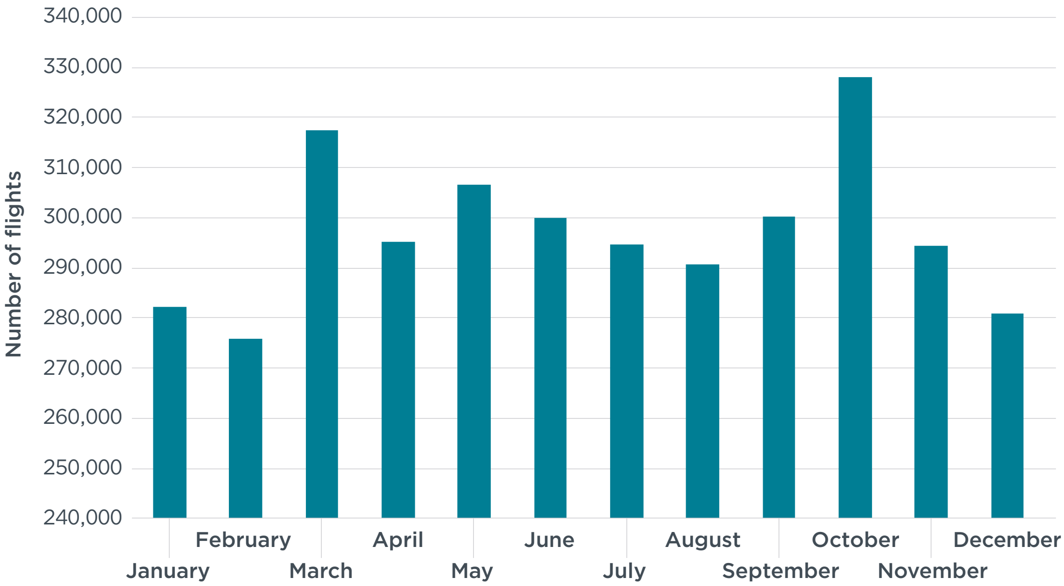
Figure 4 shows global private jet flights in 2023 by month. Activity was relatively stable, averaging 297,150 flights per month. Flights peaked in October (327,955) and March (317,403); the United States played a major role in both surges, accounting for month-over-month increases of 14.2% (25,983 additional flights) in October and 15.6% (29,153 additional flights) in March. The lowest activity levels were observed in February (275,792 flights) and December (280,826 flights). This variation suggests potential seasonal factors influencing private jet operations, such as holidays, fiscal year-end activities, or global events that affect aviation demand.

Figure 4

Global private jet flights by month, 2023



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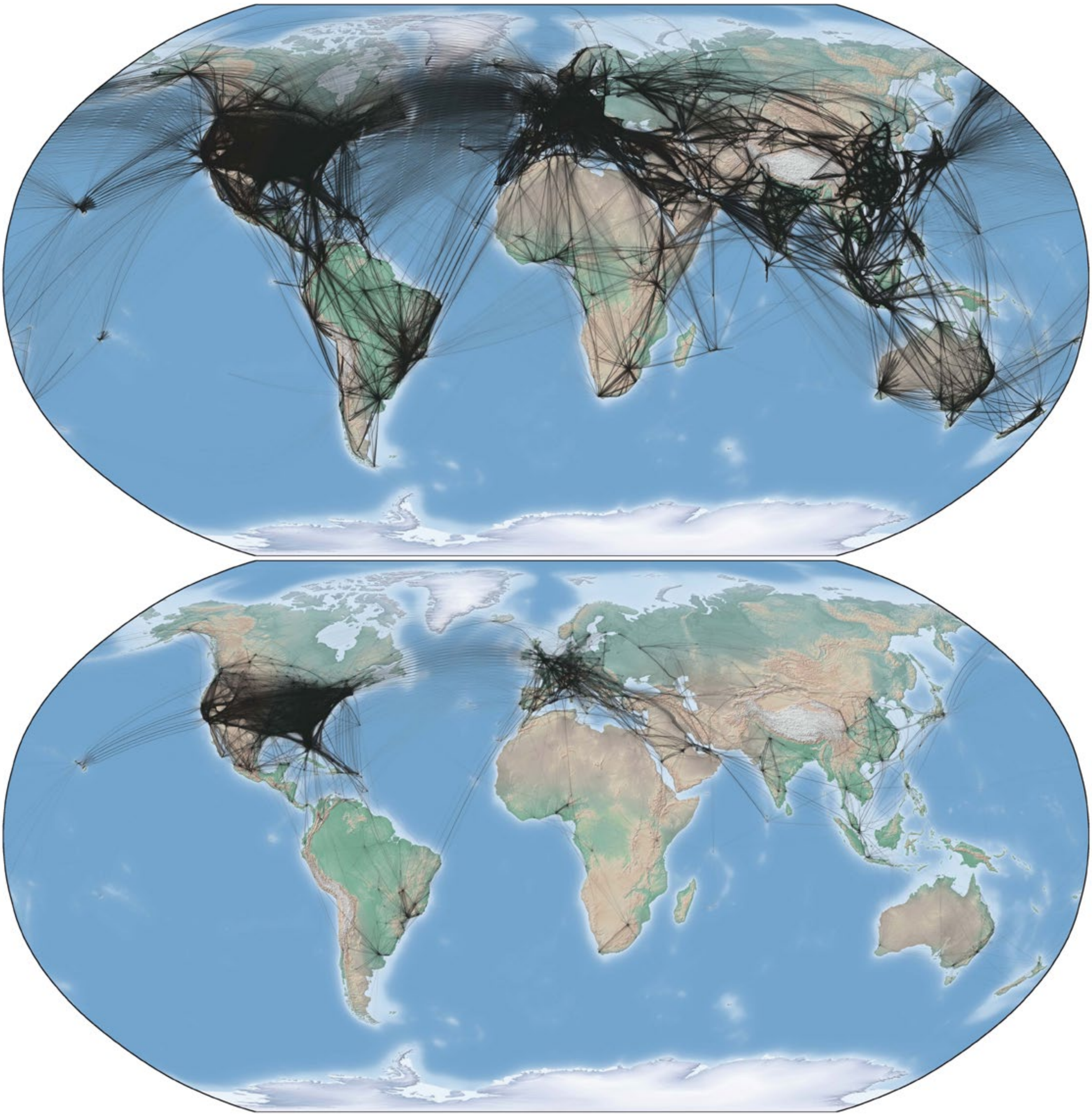
As shown in Figure 5, most private jet flights were concentrated in North America and Europe, while commercial flights were more evenly distributed across continents. This distinction highlights the differing roles of these aviation sectors, with private jets primarily serving niche markets, and underscores the distinct environmental impacts and policy considerations required for each sector.

Figure 5

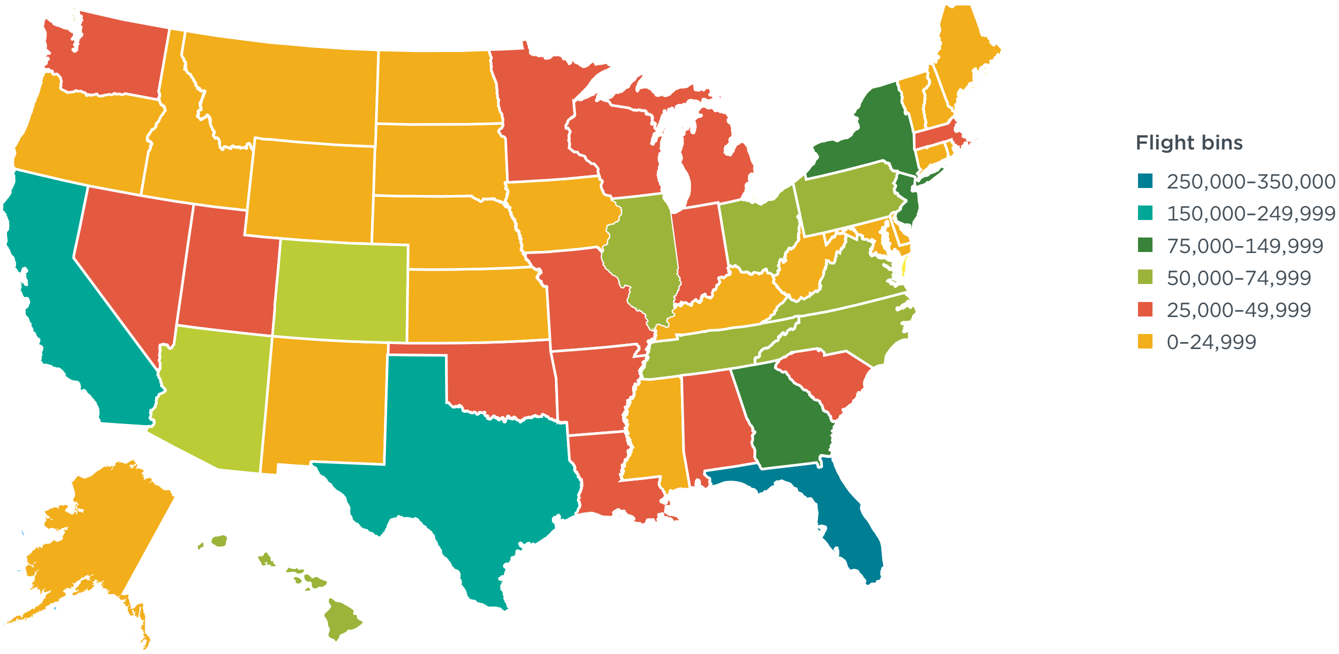
Trajectories of global commercial flights (top) and private jet flights (bottom), 2023



United States

Within the United States, private jet activity is concentrated in highly populated states (Figure 6). Florida leads among the states for private jet departures with 313,672 flights, accounting for 13.7% of the U.S. total. Texas and California follow, with 10.0% and 9.55% of U.S. flights, respectively. These three states also rank first (California), second (Florida; tied with New York), and fourth (Texas) in the number of residents on the Forbes 400, an annual list of the wealthiest people in the United States (Hunter-Hart, 2024). Other notable contributors include New Jersey (4.29%) and Georgia (3.66%).

Figure 6
U.S. private jets flights by state, 2023



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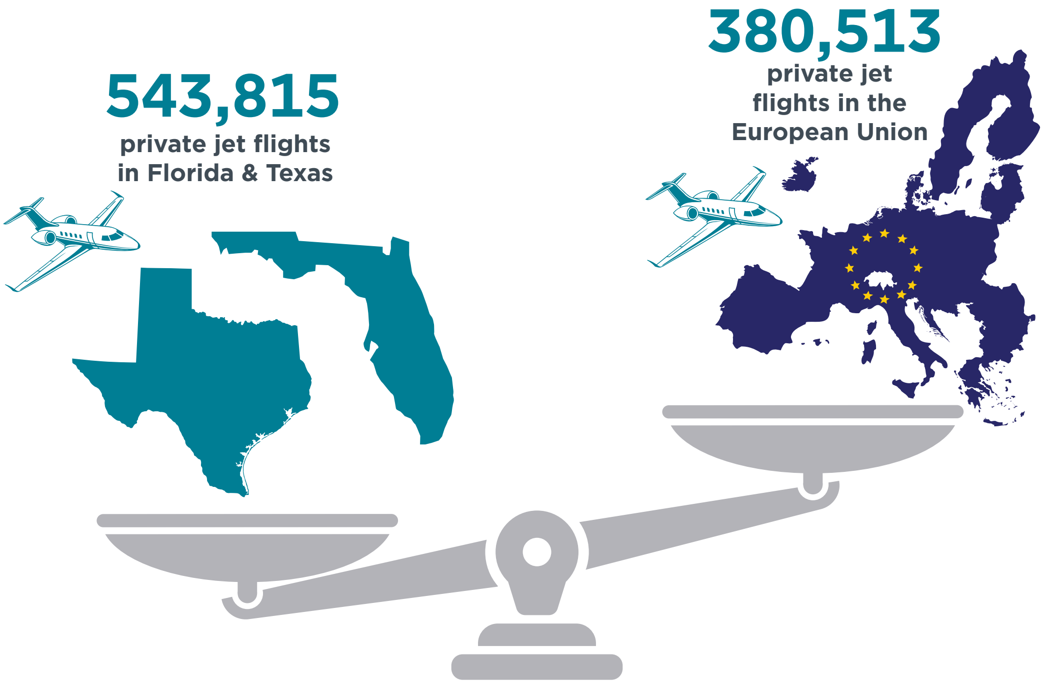
European Union

The European Union recorded 380,513 private jet flights in 2023, of which 71.1% were domestic or intra-EU flights. This number of flights was lower than the combined total for just the U.S. states of Florida and Texas (Figure 7). Most international private jet flights departing from EU countries were destined for the United Kingdom (35,889 flights), Switzerland (22,437 flights), and the United States (8,052 flights).

Figure 7
Private jet flights in the European Union compared with Florida and Texas



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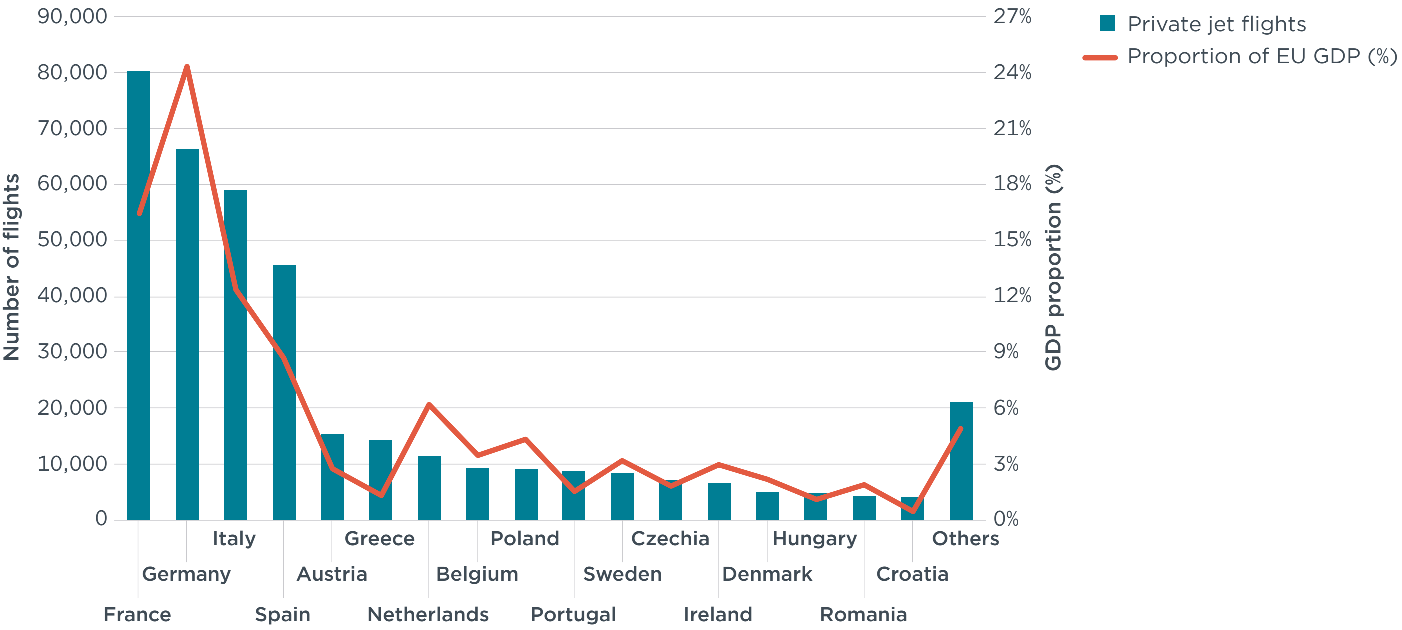
As shown in Figure 8, France led the European Union in private jet activity in 2023 with 80,169 flights, representing 21.1% of the EU total. Germany and Italy followed with 66,337 flights (17.4%) and 58,933 flights (15.5%), respectively, reflecting their roles as key business and travel hubs. Spain accounted for 45,595 flights (12.0%), driven by both business and tourism demand, while Austria, a tourism hotspot, ranked fifth with 15,185 flights (4.0%). Smaller EU countries like Greece (14,332 flights, 3.8%), the Netherlands (11,373 flights, 3.0%), and Belgium (9,416 flights, 2.5%) showed lower activity levels, primarily driven by regional travel.

Figure 8

Private jets flights by EU country, 2023



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Comparing GDP in 2023 to private jet activity shows a correlation between economic size and flight volume. This suggests that private travel patterns generally align closely with economic performance. However, there are notable exceptions to this trend. For example, France, which accounted for 16.4% of the European Union's GDP, had more private jet flights than Germany, which accounted for 24.3%. This difference is likely attributable to international tourism rather than corporate travel trends: France ranked first globally in international tourist arrivals in 2023 (United Nations Tourism, 2024). A similar trend is observed between Austria and Greece, which rank fifth and sixth in private jet activity, despite being 10th and 16th in GDP, respectively.

Flights per capita

The 10 countries with the most outgoing private jet flights per capita in 2023 were predominantly located in the Caribbean and Atlantic Islands, as shown in Table 8. Gibraltar was the exception. By comparison, the three countries with the most private jet flights in 2023 had 687 (the United States), 107 (France), and 117 (the United Kingdom) flights per 10,000 people.

Table 8
Top 10 countries with the most private jet flights per capita

Rank	Country Name	Flights per 10,000 population	Most common origin country
1	Turks and Caicos Islands	9,361	United States
2	Sint Maarten	7,642	
3	The Bahamas	4,626	
4	Cayman Islands	3,979	
5	Bermuda	3,247	
6	British Virgin Islands	2,260	
7	Virgin Islands	1,290	
8	Gibraltar	1,245	Spain
9	Antigua and Barbuda	1,214	United States
10	St. Kitts and Nevis	902	

The top 10 countries in terms of private jet flights per capita were characterized by small populations and strong appeal as tourist destinations for luxury travelers from the United States and, in the case of Gibraltar, from Spain. These islands appeal to affluent travelers drawn to exclusive resorts, private villas, and natural beauty and who prefer private aviation for its flexibility and convenience, particularly in the wake of the COVID-19 pandemic (Gollan, 2021). Moreover, some travel agents market private jet services for island-hopping in the Caribbean (Haute Jets, 2024).

Private jet distance and flight times

Our bottom-up analysis indicated that most private jet operations consisted of regional and short-haul flights. Figure 9 illustrates the number of flights categorized into 250-km distance bins (bar chart) and the cumulative percentage of flights for each distance bin (line chart). Out of all global private jet flights in 2023, 50% were shorter than 900 km, and 75% were shorter than 1,500 km. The most frequent flight distance range was between 250 and 500 km, accounting for about 600,000 flights, followed by the 500–750-km range, with about 500,000 flights. As flight distances increased, the frequency declined sharply; for example, flights over 3,000 km accounted for only 5% of the total.

Figure 9

Number and cumulative proportion of private jet flights by distance bins

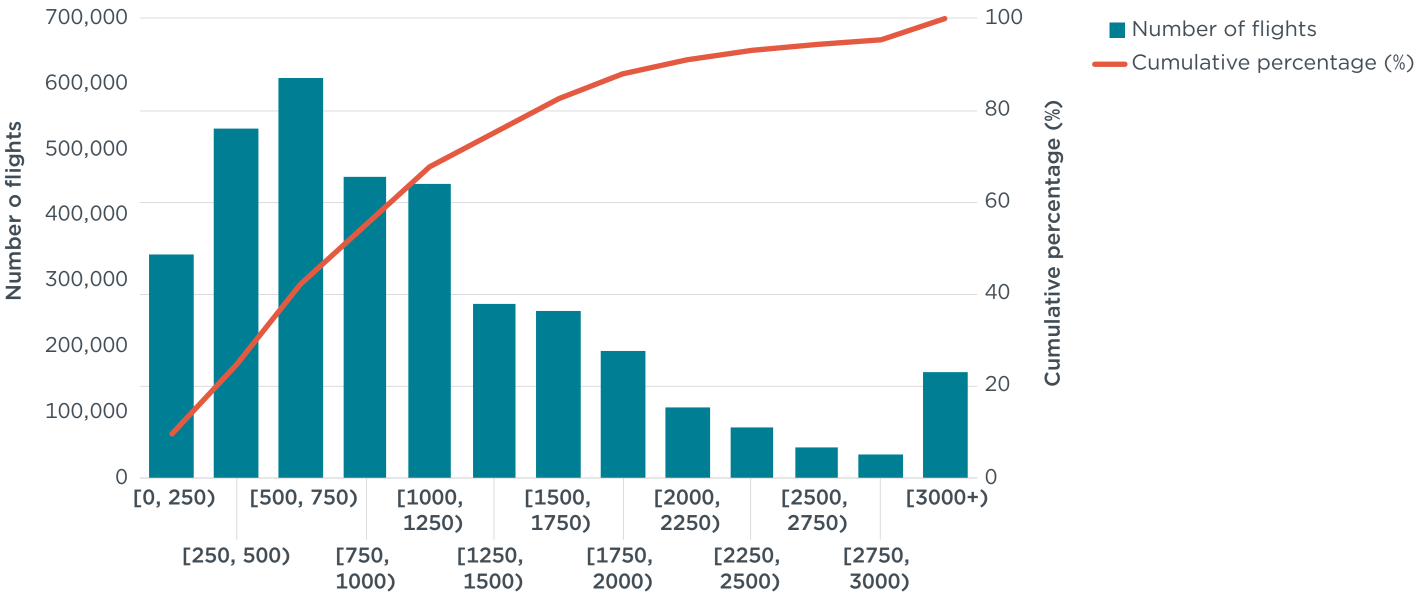

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Table 9 shows the average duration of private jet flights by distance bin. In 2023, flights under 500 km, categorized as regional flights, averaged around 48 min, while short-haul flights (between 500 and 1,499 km) lasted an average of 93 min. Long-haul (4,001–10,000 km) and ultra-long-haul (over 10,000 km) flights had average durations of 417 and 724 min, respectively. The average private jet flight duration was approximately 109 min, indicating a typical short- to-medium-haul operational range. The median duration of private jet flights was 85 min, reflecting the fact that more than half of private jet flights were regional and short haul.

Table 9

Average flight time per distance category

Distance Category	Distance bin	Average flight distance (km)	Average flight time (min)
Regional haul	< 500 km	283	48
Short haul	500–1,499 km	923	93
Medium haul	1,500–4,000 km	2,119	178
Long haul	4,001–10,000 km	5,709	417
Ultra-long haul	> 10,000 km	10,525	724
Average		**1,164**	**109**

The relatively short average flight time aligns with the earlier finding that most private jet operations focus on short-haul and regional travel, underscoring that the primary benefit of private jet travel is convenience and flexibility, not speed or range. The predominance of short-haul, short-duration private jet flights provides a compelling case for exploring alternatives to private aviation, including modal shift to high-speed rail where available (Li et al., 2024) or the use of more fuel-efficient turboprop aircraft (Kilic, 2023).

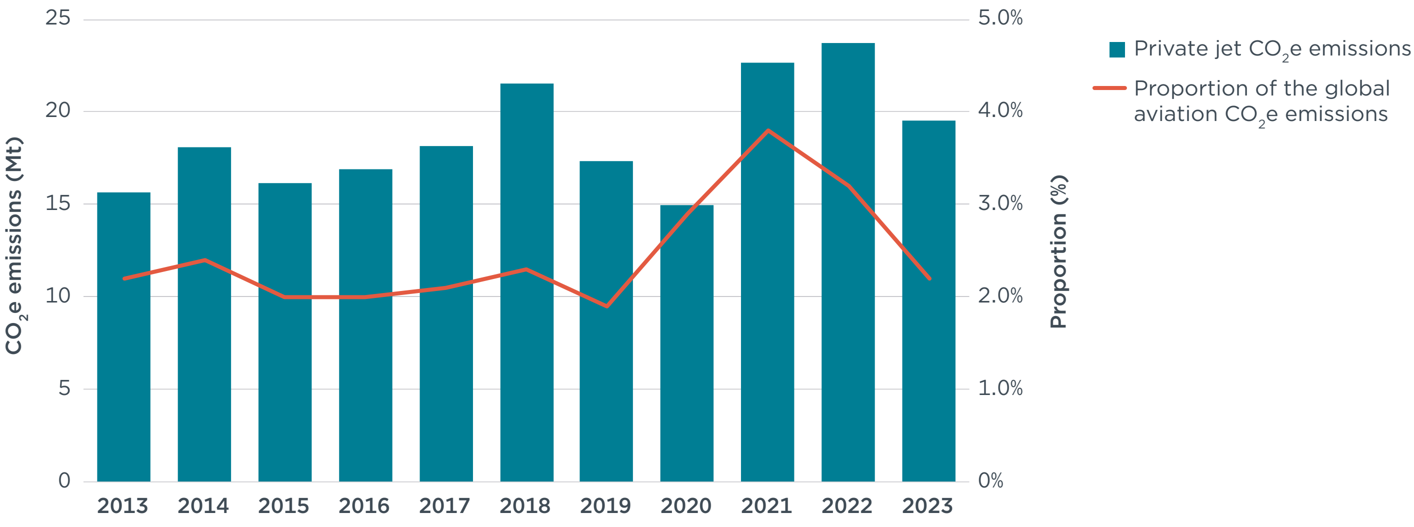
GREENHOUSE GAS EMISSIONS

Top-down approach

Our results indicated an overall increasing trend in GHG emissions from private jets globally between 2013 and 2023. Figure 10 presents estimated private jet CO_2 emissions (bars) and their corresponding share of civil aviation (commercial plus private jet) emissions (line).[4] Absolute GHG emissions from private jets increased 25% over the period, from 15.65 Mt in 2013 to 19.55 Mt in 2023, with significant year-on-year volatility. At their post-COVID peak in 2022, private jets emitted an estimated 23.74 Mt CO_2e and accounted for nearly 4% of the civil aviation total.

Figure 10

Global private jet GHG emissions, 2013–2023



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Peaks in activity occurred in 2014, 2018, and 2022, with a significant decline in 2020 due to the COVID-19 pandemic. Private jets' share of civil aviation CO_2 emissions ranged between 2% and 2.5% most years but increased to nearly 4% in 2021 as private travel surged while commercial aviation remained depressed, reflecting an increased reliance on private aviation amid restrictions and health concerns related to COVID-19. Private jets' share of civil aviation emission subsequently declined to pre-pandemic levels by 2023, when travel patterns shifted amid a normalization of commercial travel for business purposes (Soderlund, 2023). This shift is reflected in the decline of private jet GHG emissions as a proportion of global aviation emissions. These trends coincided with a 8.6% drop in private jet activity (Federal Aviation Administration, 2023) compared to 2022 (Kerry Lynch, 2024).

Bottom-up analysis

Based on the bottom-up analysis, private jets emitted an estimated 18.4 Mt of CO_2e in 2023, totaling more GHGs than all flights departing from Heathrow Airport, the busiest airport in Europe (Heathrow Airport, 2024). This level of emissions translates to an average of 5.15 tonnes of CO_2e per private jet flight globally.

4 This calculation excludes emissions from military aviation, which were estimated to account for approximately 10%–15% of total aviation emissions in 2002 based on Aero2k modeling. Additionally, emissions from turboprop and piston-driven aircraft could not be calculated due to a lack of engine emissions data for these aircraft types.

The bottom-up estimate of 2023 GHG emissions is just 5.9% lower than our top-down estimate of 19.55 Mt. A potential source of error in our bottom-up analysis arises from the 7.1% of flights without a recorded departure airport, for which we applied an average flight distance of 1,164 km, accounting for 1.56 million tonnes of CO_2e. These missing data, along with additional flights not captured in the dataset, could have contributed to the gaps between our top-down and bottom-up results. For example, when applying our top-down analysis, the United States accounts for 13.6 million tonnes of CO_2e, whereas applying our bottom-up analysis results in 10.2 million tonnes.

Table 10 shows the dominance of the United States and European countries in global private jet fuel consumption based on our bottom-up analysis. According to this approach, the United States accounted for 55% of total private jet CO_2e emissions in 2023.

Table 10

Top 20 countries by private jet fuel burn and estimated GHG emissions, 2023

Rank	Country	Fuel burn (thousand tonnes)	GHGs (thousand tonnes CO_2e)	Share of total
1	United States	3,220.66	10,190.17	55.1%
2	United Kingdom	165.95	525.07	2.84%
3	France	146.83	464.58	2.51%
4	Canada	114.22	361.39	1.96%
5	Italy	94.97	300.50	1.63%
6	United Arab Emirates	87.37	276.43	1.50%
7	Spain	80.55	254.86	1.38%
8	Germany	79.96	253.00	1.37%
9	Mexico	68.67	217.28	1.18%
10	Brazil	68.49	216.70	1.17%
11	China	60.26	190.66	1.03%
12	Saudi Arabia	59.31	187.67	1.02%
13	Switzerland	54.44	172.25	0.93%
14	India	50.80	160.73	0.87%
15	Türkiye	43.54	137.76	0.75%
16	Japan	36.40	115.18	0.62%
17	Russian Federation	32.17	101.80	0.55%
18	Australia	31.97	101.15	0.55%
19	Bahamas	26.33	83.32	0.45%
20	Ireland	24.39	77.18	0.42%
	Others	1,293.76	4,011.68	22.15%
Global total		**5,841.04**	**18,399.28**	**100%**

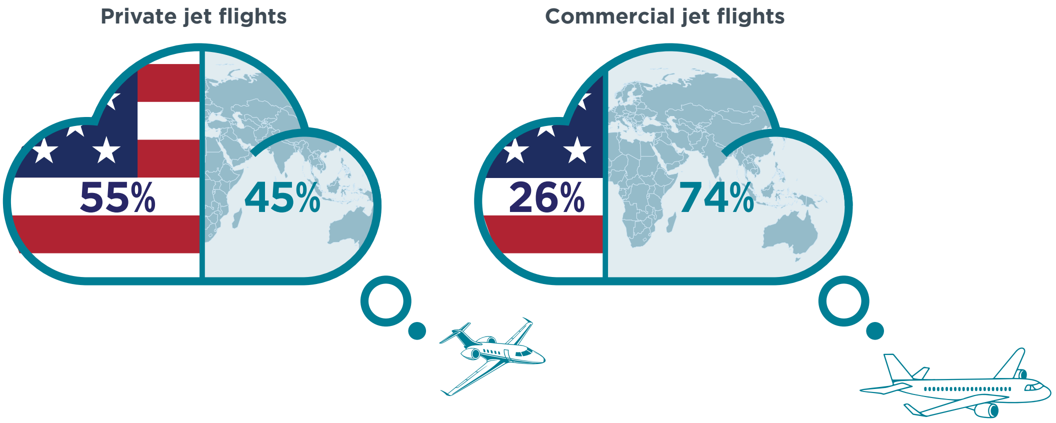
Other top contributors of CO_2e from private jets included the United Kingdom (525.1 thousand tonnes), France (464.6 thousand tonnes), and Canada (361.4 thousand tonnes), each accounting for about 2% of the global private jet total. Private jets departing from the remaining countries in the top 10, including Italy, the United Arab Emirates, Spain, Germany, Mexico, and Brazil, collectively contributed approximately

1.52 million tonnes of CO_2e. In total, the top 10 countries represented 70.7% of global private jet CO_2e emissions, and the top 20 countries represented approximately 77.8%.

United States

Figure 11 illustrates the United States' share of private jet (left) and commercial jet (right) GHG emissions in 2023. While the United States accounted for 55% of estimated private jet emissions, its share of total commercial jet emissions was lower, at 26%.[5] Private jets departing U.S. airports emitted 19 times more GHGs than the second highest emitter, the United Kingdom. These results underscore the opportunity for effective carbon mitigation by targeting high-emission countries and regions, particularly the United States.

Figure 11
GHG emissions from U.S. private and commercial jet flights versus rest of world



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Consistent with the results of the top-down methodology, Florida, California, and Texas were the top three states in terms of GHG emissions (Table 11). Flights departing from Florida (responsible for 1.42 Mt of GHGs) and California (1.24 Mt) collectively accounted for over 25% of U.S. private jet emissions. Texas (938.3 thousand tonnes, 9.1% of the total), New Jersey (686.1 thousand tonnes; 6.7%), and New York (434.5 thousand tonnes; 4.2%) rounded out the top five, collectively accounting for more than 45% of U.S. private jet emissions and 26% of global private jet greenhouse gas emissions.

5 This figure is based on Spire's 2023 database of departing airports, modeled using the Small Emitters Tool.

Table 11

Top 20 U.S. states by private jet fuel burn and GHGs, 2023

Rank	State	Fuel burn (thousand tonnes)	GHGs (thousand tonnes CO_2e)	Share of total
1	Florida	449.5	1,422.1	13.8%
2	California	392.4	1,241.5	12.1%
3	Texas	296.5	938.3	9.1%
4	New Jersey	216.8	686.1	6.7%
5	New York	137.3	434.5	4.2%
6	Colorado	112.2	355.0	3.5%
7	Georgia	97.3	307.8	3.0%
8	Illinois	94.3	298.3	2.9%
9	Arizona	83.3	263.6	2.6%
10	Virginia	82.5	261.1	2.5%
11	Nevada	79.7	252.2	2.5%
12	Massachusetts	74.8	236.6	2.3%
13	North Carolina	70.5	223.0	2.2%
14	Tennessee	69.8	220.8	2.1%
15	Ohio	68.3	216.1	2.1%
16	Pennsylvania	61.3	194.1	1.9%
17	Michigan	58.8	185.9	1.8%
18	Missouri	51.4	162.7	1.6%
19	Washington	47.2	149.2	1.5%
20	Indiana	43.3	137.0	1.3%
	Others	633.46	2,004.27	20.4%
U.S. total		**3,220.66**	**10,190.17**	**100%**

European Union

The EU-27 countries collectively accounted for 1.95 Mt (11.8%) of estimated global GHG emissions from private jets (Table 12). Consistent with the top-down results, France was the largest emitter, accounting for 23.8% of the European Union's total private jet CO_2e emissions. Italy (15.4%), Spain (13.1%), and Germany (13.0%) were other top emitters. Collectively, these four countries constituted close to two-thirds of the GHG emissions of EU-27 countries.

Table 12

Top 20 EU countries by private jet fuel burn and GHGs, 2023

Rank	Country	Fuel burn (thousand tonnes)	GHGs (thousand tonnes CO_2e)	% of total
1	France	146.83	464.57	23.8%
2	Italy	94.97	300.49	15.4%
3	Spain	80.55	254.86	13.1%
4	Germany	79.96	252.99	13.0%
5	Ireland	24.39	77.17	4.0%
6	Portugal	21.83	69.07	3.5%
7	Greece	21.53	68.12	3.5%
8	Austria	17.50	55.37	2.8%
9	Netherlands	15.65	49.52	2.5%
10	Poland	13.82	43.73	2.2%
11	Sweden	13.30	42.08	2.2%
12	Belgium	13.15	41.61	2.1%
13	Czechia	10.51	33.25	1.7%
14	Cyprus	8.89	28.13	1.4%
15	Hungary	7.97	25.22	1.3%
16	Denmark	7.53	23.82	1.2%
17	Romania	5.92	18.73	1.0%
18	Malta	5.54	17.53	0.9%
19	Croatia	4.90	15.50	0.8%
20	Slovak Republic	4.30	13.61	0.7%
	Others	16.99	53.74	2.9%
EU-27 total		**616.03**	**1,949.11**	**100%**

Other countries in the top 10, including Ireland, Portugal, and Greece, each contributed less than 5% of total emissions. Meanwhile, the seven EU countries outside of the top 20 in terms of private jet emissions—comprising smaller countries like Luxembourg, Lithuania, Latvia, Estonia, and Slovenia—collectively accounted for less than 3% of the regional total. These findings highlight the concentration of emissions in a few key countries, suggesting that targeted policies could yield large reductions in GHG emissions within the EU-27.

Emissions per aircraft

Our analysis of emissions per flight found that, within the global fleet of 22,749 registered private jets, each jet emitted an estimated 812.4 tonnes of CO_2e annually on average. This figure is equivalent to the annual GHG emissions of 177 typical passenger vehicles (U.S. Environmental Protection Agency, 2024), or nine trucks of the heaviest vehicle category, Class 8 (U.S. Department of Energy, 2021).

AIRPORT FLIGHT INTENSITY AND POLLUTION

The United States has a commanding share of the top airports in terms of private jet flights, with 18 of the top 20. As shown in Table 13, Teterboro Airport in the U.S. state of New Jersey led with 69,932 flights, followed by Florida's Palm Beach International Airport (39,927) and Texas' Dallas Love Field (34,438). These three airports accounted for 4.0% of all global private jet flights.

Table 13

Top 20 airports by private jet flights and estimated LTO NO_x and $PM_{2.5}$ emissions, 2023

Rank	Airport Name	Country	Flights	NO_x (tonnes)	$PM_{2.5}$ (tonnes)
1	Teterboro Airport	United States	69,932	478.73	4.88
2	Palm Beach International Airport		39,927	250.74	2.38
3	Dallas Love Field Airport		34,438	198.21	2.05
4	Van Nuys Airport		30,778	210.32	2.28
5	Harry Reid International Airport		30,338	202.80	1.93
6	Westchester County Airport		29,298	198.92	2.06
7	Washington Dulles International Airport		27,419	177.39	1.74
8	Miami-Opa Locka Executive Airport		26,636	183.11	1.72
9	Scottsdale Airport		25,335	142.70	1.46
10	William P Hobby Airport		24,447	148.47	1.31
11	Paris-Le Bourget Airport	France	22,837	128.99	1.46
12	Naples Municipal Airport	United States	22,049	131.71	1.15
13	DeKalb Peachtree Airport		21,215	126.42	1.08
14	Chicago Midway International Airport		20,575	124.38	1.12
15	Centennial Airport		20,474	123.77	1.12
16	John Wayne Orange County International Airport		20,172	128.61	1.20
17	Austin Bergstrom International Airport		18,858	113.44	1.04
18	Nashville International Airport		18,660	125.34	0.97
19	Laurence G Hanscom Field Airport		18,204	115.97	1.12
20	Nice-Côte d'Azur Airport	France	16,768	100.25	1.16

Van Nuys Airport, which ranked fourth in terms of private jet flights, has become a "super-hub" post-pandemic for private jet travelers from Hollywood (Stern, 2023). Private jet activity has also increased at other airports. Westchester County Airport, for example, has become a preferred hub for hedge fund managers (Zucker, 2020), reflecting the close relationship between the finance industry and private jet usage and emissions.

The only two non-U.S. airports in the top 20 are both in France: Paris-Le Bourget Airport (ranked 11th, with 22,837 flights) and Nice-Côte d'Azur Airport (ranked 20th, with 16,768 flights). Paris-Le Bourget Airport is recognized as Europe's leading business aviation hub, commonly used for corporate travel and luxury tourism (Groupe ADP, n.d.). Nice-Côte d'Azur functions as the main entry point to the French Riviera, a renowned destination for luxury tourism and affluent travelers (Smith, n.d.).

Nearby communities have complained about noise and air pollution from several of these airports. For instance, residents living near Teterboro Airport have filed complaints with the FAA and the Port Authority, citing noise and pollution caused by aircraft operations (DiTommaso, 2024). Similarly, concerns about heightened noise pollution and air quality Van Nuys have increased due to private jet traffic (Eng, 2023). Residents frequently report disturbances from low-flying jets and health symptoms linked to elevated emissions. These challenges underscore opportunities for stricter regulation of private jet operations and policy measures, such as emissions or fuel taxes to address the impact of these jets.

NO_x and $PM_{2.5}$ emissions

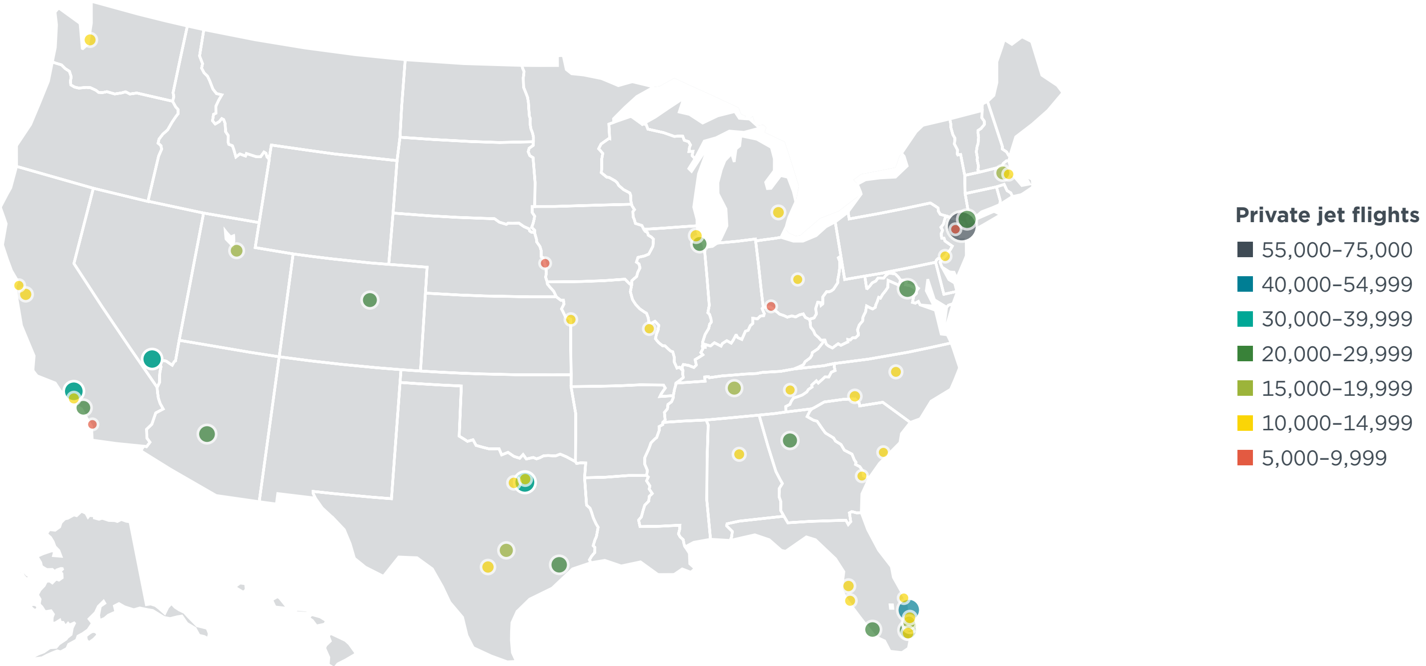
Estimates of LTO NO_x and $PM_{2.5}$ emissions reflect the number of flights from a given airport. Globally, private jets emitted an estimated 21.3 thousand tonnes of LTO NO_x emissions and 203 tonnes of LTO $PM_{2.5}$ emissions across 7,082 airports. Of the 20 airports with the highest estimated LTO NO_x emissions in 2023, 18 are in the United States (Appendix D, Table B4). Teterboro Airport ranked highest, with 478.7 tonnes of NO_x emissions and 4.88 tonnes of $PM_{2.5}$ emissions, followed by Palm Beach International Airport, with 250.7 tonnes of NO_x and 2.38 tonnes of $PM_{2.5}$. Notably, NO_x emissions from private jets at Teterboro Airport alone exceeded the total emissions from all private jets in Canada, which amounted to 450 tonnes. Similarly, estimated $PM_{2.5}$ emissions from private jets at Teterboro Airport (4.88 tonnes) nearly equaled the total $PM_{2.5}$ emissions from private jets across the United Kingdom (4.87 tonnes).

Among the 20 airports with the highest estimated LTO NO_x emissions, only two are outside the United States: Paris-Le Bourget Airport and Nice-Côte d'Azur Airport in France, which emitted 129.0 tonnes and 100.3 tonnes, respectively. The ranking differs slightly for LTO $PM_{2.5}$ emissions, where Canada's Toronto Pearson International Airport joins the list, contributing 1.06 tonnes of $PM_{2.5}$ emissions (Appendix D, Table B5). These findings further highlight the concentration of private jet emissions in the United States and the potential for geographically targeted mitigation strategies to yield large reductions in overall NO_x and $PM_{2.5}$ emissions from private jets.

U.S. airports

The top 50 U.S. airports with the largest number of private jet flights in 2023 were distributed across 23 states, as shown in Figure 12. Florida led with 10 airports, followed by California and Texas, with six each. These three states alone account for 44% of the top 50 airports. Florida has four airports with the most private jet charters: Fort Lauderdale-Hollywood International Airport, Miami Executive Airport, Miami-Opa Locka Executive Airport, and Miami International Airport (Zaher, 2019). These airports serve as hubs for luxury travel, such as cruises to the Caribbean and island-hopping in the Caribbean.

Figure 12
Top 50 U.S. airports by private jet flights, 2023



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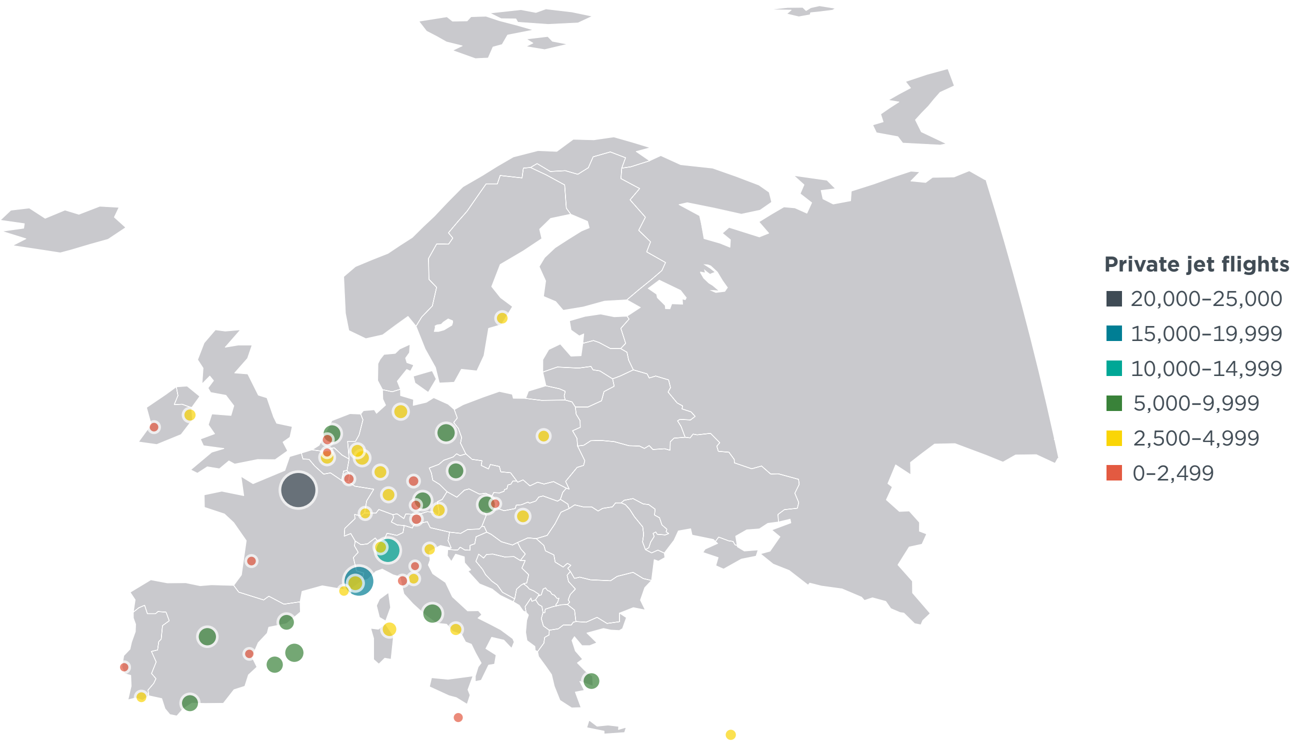
Georgia, Illinois, Massachusetts, Missouri, North Carolina, New Jersey, Tennessee, and Ohio each had two airports in the top 50, while 13 other states, each had one airport in the top 50.

EU airports

In the European Union, the top 50 airports by number of private jet flights were spread across 18 countries (Figure 13), but activity was concentrated in only a few countries. Italy and Germany led with nine airports each, followed by France and Spain, with six each. These four countries collectively accounted for 60% of the top 50 airports.

Figure 13
Top 50 EU airports by rivate jet flights, 2023



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The remaining 14 countries, including Austria (three airports), Ireland, Belgium, Netherlands, and Portugal (two airports each), and smaller contributors such as Czechia, Greece, Hungary, and others (one airport each), hosted the rest of the top 50 airports.

Top domestic route pair

The most common domestic routes for private jets were concentrated in the United States. In 2023, 2,116,512 U.S. flights were domestic, accounting for 91.9% of U.S. private jet flights. Table 14 highlights the top five domestic airport pairs globally. The Harry Reid International Airport–Van Nuys Airport route (connecting Las Vegas, Nevada, and Los Angeles, California) ranked highest with 5,549 flights, contributing an estimated 17.49 thousand tonnes of GHG emissions. All other flights in the top five traveled to and from Teterboro Airport in Teterboro, New Jersey, connecting with airports in Florida, Virginia, and Massachusetts. Collectively, these flights accounted for an estimated 93.1 thousand tonnes of GHG emissions. Although it did not rank among the top five most flown routes, the Teterboro Airport–Van Nuys Airport route generated the highest domestic flight GHG emissions, accounting for an estimated 50.47 thousand tonnes.

Table 14
Top five global domestic route pairs, 2023

Rank	Route	City Pair	Number of flights	Total GHGs (thousand tonnes CO_2e)
1	Harry Reid International Airport–Van Nuys Airport	Las Vegas, Nevada–Los Angeles, California	5,549	17.49
2	Teterboro Airport–Palm Beach International Airport	Teterboro, New Jersey–West Palm Beach, Florida	4,702	36.92
3	Teterboro Airport–Washington Dulles International Airport	Teterboro, New Jersey–Dulles, Virginia	4,461	13.50
4	Teterboro Airport–Miami-Opa Locka Executive Airport	Teterboro, New Jersey–Opa-locka, Florida	3,984	34.17
5	Teterboro Airport–Laurence G Hanscom Field	Teterboro, New Jersey–Bedford, Massachusetts	3,468	8.55

Table 15 shows the top five domestic routes outside of the United States. The top route was in Nigeria, connecting Murtala Muhammed International Airport and Nnamdi Azikiwe International Airport, with 3,115 flights, accounting for an estimated 10.63 thousand tonnes of GHG emissions. The King Khaled International Airport–King Abdulaziz International Airport route in Saudi Arabia ranked second with 2,883 flights, and was the leading non-U.S. domestic flight route in terms of GHG emissions, contributing 29.57 thousand tonnes. The other top domestic private jet routes involved airport pairs in France, Canada, and Brazil.

Table 15
Top five non-U.S. global domestic route pairs, 2023

Rank	Route	City Pair	Number of flights	Total GHGs (thousand tonnes CO_2e)
1	Murtala Muhammed International Airport–Nnamdi Azikiwe International Airport	Lagos, Nigeria–Abuja, Nigeria	3,115	10.63
2	King Khaled International Airport–King Abdulaziz International Airport	Riyadh, Saudi Arabia–Jeddah, Saudi Arabia	2,883	29.57
3	Paris-Le Bourget Airport–Nice-Côte d'Azur Airport	Paris, France–Nice, France	2,326	9.02
4	Montreal / Pierre Elliott Trudeau International Airport–Toronto Lester B. Pearson International Airport	Montreal, Canada–Toronto, Canada	1,763	5.46
5	Congonhas Airport–Santos Dumont Airport	São Paulo, Brazil–Rio de Janeiro, Brazil	1,748	3.74

Top international route pair

Among the top international route pairs (Table 16), the most common was Toronto Pearson International Airport–Teterboro Airport, connecting Toronto, Canada, and Teterboro, the United States, with 2,866 flights. This route pair accounted for an estimated 9.27 thousand tonnes of GHG emissions. The next top route pairs were Paris, France–Geneva, Switzerland (2,655 flights) and Punta del Este, Uruguay–San Fernando, Argentina (1,995 flights). Although it did not rank among the top five international routes in terms of number of flights, the Newark Liberty International Airport–Paris-Orly Airport, connecting the United States and France, generated the highest estimated international flight GHG emissions, of 44.79 thousand tonnes.

Table 16
Top five global international route pairs, 2023

Rank	Route	City Pair	Number of flights	Total GHGs (thousand tonnes CO_2e)
1	Toronto Lester B. Pearson International Airport- Teterboro Airport	Toronto, Canada–Teterboro, New Jersey, U.S.	2,866	9.27
2	Paris-Le Bourget Airport–Geneva Cointrin International Airport	Paris, France–Geneva, Switzerland	2,655	7.19
3	Capitan Corbeta CA Curbelo International Airport–San Fernando Airport	Punta del Este, Uruguay–San Fernando, Argentina	1,995	3.61
4	Lynden Pindling International Airport–Palm Beach International Airport	Nassau, Bahamas–West Palm Beach, Florida, U.S.	1,672	4.12
5	Farnborough Airport–Nice-Côte d'Azur Airport	Farnborough, United Kingdom–Nice, France	1,550	8.71

CONCLUSIONS

We assessed trends in global private jet activity and emissions, using both top-down and bottom-up approaches. Several conclusions can be drawn from our results.

Private jets are a large and growing source of air and climate pollution. We identified a total of 3.57 million private jet flights in 2023, with a typical private jet emitting approximately 810 tonnes of GHGs annually, equivalent to the emissions of 177 passenger cars or 9 Class 8 heavy-duty trucks. At their post-COVID peak in 2022, private jets collectively emitted an estimated 23.74 million tonnes of CO_2e, accounting for nearly 4% of total civil aviation emissions. Our top-down analysis revealed that global private jet operations in 2023 consumed 6.2 million tonnes of fuel, resulting in an estimated 19.5 million tonnes of CO_2e emissions. We estimated that these flights produced 21.3 thousand tonnes of NO_x and 203 tonnes of $PM_{2.5}$ at airports.

Private jet activity and emissions were overwhelmingly concentrated in the United States. In 2023, two-thirds of global private jet flights departed from US airports, accounting for more than half (55%) of estimated private jet GHG emissions. The second and third largest contributors, France and the United Kingdom, trailed with 2.2% and 2.1% of flights, respectively. The U.S. states of Florida and Texas alone generated more private jet flights and GHG emissions than the entire EU-27. Moreover, 18 of the top 20 airports globally by private jet NO_x emissions were in the United States. This concentration of private jet activity implies that U.S. national or state-level policies to reduce private jet emissions could have a substantial impact.

A typical private jet flight is short-haul and lasts less than two hours. Our bottom-up analysis showed that private jet operations were predominantly short-haul. Half of all flights covered distances under 895 km, while 75% were under 1,500 km. Flights over 3,000 km make up only 5% of the total. The median private jet flight in 2023 lasted 85 min, indicating a regional to short-haul operational range. These findings suggest that private jets prioritize convenience and flexibility over speed or range. Private jet flights may therefore be mitigatable by modal shift to high-speed rail in regions like Asia and Europe and by an increased use of turboprop aircraft, which are more fuel efficient than turbofan aircraft. Short-haul flight bans have already been introduced in France, where high-speed rail can compete with air travel in terms of total travel time for short distances. Meanwhile, taxation policies with differentiated rates for turbofan versus turboprop aircraft could incentivize a shift to the latter.

Policy recommendations

Policymakers could consider various measures to reduce the growing emissions of private aviation. Potential policies include tightening fuel efficiency (CO_2) requirements for new private jets (Rutherford & Kharina, 2017); requiring the use of sustainable aviation fuels (SAF), for example under an aviation-wide mandate like ReFuelEU (European Union Aviation Safety Agency, n.d.); and implementing measures to limit the formation of persistent condensation trails (contrails). This last approach may be especially effective because contrails have a large but short-lived climate impact and because private jet flights may be especially likely to form persistent contrails (Gryspeerdt et al., 2024).

In addition, the taxation of private jet flights or GHG emissions could generate substantial revenue to support aviation decarbonization or other priorities. Taxing private jets could simultaneously reduce emissions and generate climate finance revenue by targeting passengers who are ultra-wealthy and less price-sensitive (Collins et al., 2024), allowing tax rates to bridge the 2-5 times cost gap between conventional jet fuel and SAF without heavily impacting commercial aviation. If implemented in 2023, a private jet fuel tax of $1.589/gallon ($0.42/L), as proposed in House and

Senate measures introduced in the last Congress (Fueling Alternative Transportation with a Carbon Aviation Tax Act, 2023), could have generated up to $3 billion globally, based on an estimated 5.8 million tonnes of annual fuel consumption. Additional tax options include distance-based levies, emission-based taxes tied to fuel consumption or pollutant output, and luxury taxes on non-essential flights. These revenues could be directed toward zero-emission aviation technology development, public transportation infrastructure, or loss and damage mitigation in the Global South, promoting a just transition to net-zero aviation.

Future work

This paper presented a medium-fidelity emissions inventory for global private jets in 2023, covering full-flight CO_2 emissions and LTO NO_X and $PM_{2.5}$. Future research could refine and expand this analysis by including full-flight NO_X and $PM_{2.5}$ emissions to create a more comprehensive inventory. Additionally, modeling the contrail impacts of private jets would provide a deeper understanding of their climate effects. Expanding the scope to include all general aviation, such as turboprops and piston engine aircraft, would capture more of the general aviation emission. Updating the inventory with future-year data would allow for the creation of a bottom-up time-series analyses, enabling the identification and tracking of emissions trends over time.

Another avenue for future research is to explore the drivers behind the growing number of private jet flights. This knowledge would support data-driven recommendations for policies such as taxation or regulation of private jet operations to mitigate their environmental impact.

Additional research could inform policies to curb fuel use and emissions from private jets. Given the short average stage length (with 50% of flights traveling less than 900 km), public policies promoting the shift of fossil-fuel private jets to alternatives could be explored, including the shift to high-speed rail where available, the use of turboprops with much better fuel efficiency, and the development of zero-emission planes, notably hydrogen aircraft. Performance standards to boost the fuel efficiency of private jets could also be investigated.

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APPENDIX A. COMPARISON OF FUEL BURN MODELS

Using the Conklin and de Decker CO_2 calculator, we performed comparative analyses of fuel burn across the top 10 aircraft number of flights globally. We applied the same average private jet flight distance of 1,164 km and calculated the difference of the CO_2 modeling result. From Table A1, we see an 8% difference on average, ranging from the highest at 18% and lowest at -4%.

Table A1

Comparison of Conklin and de Decker (C&D) and Small Emitters Tool (SET) modeling results

Aircraft	C&D CO_2 (kg)	SET CO_2 (kg)	Difference (%)
Embraer EMB 505 Phenom 300	2,760	3,115	13%
Cessna 680A Citation Latitude	4,700	4,738	1%
Bombardier BD-100-1A10 Challenger 350	4,280	4,823	13%
Cessna 560XL Citation XLS	3,570	3,673	3%
Bombardier BD-100-1A10 Challenger 300	4,250	5,005	18%
Cessna 525B CitationJet CJ3	2,450	2,655	8%
Cessna 560XL Citation XLS+	3,570	3,673	3%
Learjet 45	2,950	3,468	18%
Cessna 560XL Citation Excel	3,810	3,673	-4%
Cessna 680 Citation Sovereign	4,330	4,580	6%

APPENDIX B. DETAILED STATISTICS

The top 20 countries with the greatest number of private jet flight departures in 2023 are shown in Table B1.

Table B1

Top 20 countries by private jet flights, 2023

Rank	Country	Flights	Rank	Country	Flights
1	United States	2,302,236	**11**	China	24,400
2	France	80,169	**12**	India	22,530
3	United Kingdom	73,626	**13**	Australia	22,401
4	Canada	73,536	**14**	Turkey	19,398
5	Germany	66,346	**15**	Bahamas	19,088
6	Italy	58,933	**16**	United Arab Emirates	16,540
7	Brazil	55,889	**17**	Austria	15,185
8	Mexico	48,521	**18**	Greece	14,332
9	Spain	45,638	**19**	Saudi Arabia	13,841
10	Switzerland	32,923	**20**	Argentina	11,915

The number of flights in the 10 U.S. states with the most private jet flight departures in 2023 are shown in Table B2.

Table B2

Top U.S. 10 states by private jet flights, 2023

Rank	State	Flights
1	Florida	313,672
2	Texas	230,143
3	California	218,989
4	New Jersey	98,339
5	Georgia	84,052
6	New York	80,378
7	Colorado	74,214
8	North Carolina	67,566
9	Illinois	67,493
10	Tennessee	65,433

The number of private jet flight departures in the EU-27 in 2023 are shown in Table B3.

Table B3

EU-27 countries by private jet flights, 2023

Rank	Country	Flights	Rank	Country	Flights
1	France	80,169	**15**	Hungary	4,669
2	Germany	66,346	**16**	Romania	4,164
3	Italy	58,933	**17**	Croatia	4,144
4	Spain	45,638	**18**	Cyprus	3,869
5	Austria	15,185	**19**	Finland	3,226
6	Greece	14,332	**20**	Slovak Republic	2,852
7	Netherland	11,373	**21**	Luxembourg	2,458
8	Belgium	9,416	**22**	Malta	2,335
9	Poland	9,175	**23**	Bulgaria	2,196
10	Portugal	8,883	**24**	Slovenia	1,164
11	Sweden	8,251	**25**	Lithuania	1,161
12	Czechia	7,186	**26**	Estonia	927
13	Ireland	6,662	**27**	Latvia	849
14	Denmark	4,950			

The top 20 airports by private jet estimated LTO NO_x emissions in 2023 are shown in Table B4.

Table B4

Top 20 airports by private jet estimated LTO NO_x emissions, 2023

Rank	Airport Name	Country	NO_x (tonnes)
1	Teterboro Airport	United States	478.73
2	Palm Beach International Airport	United States	250.74
3	Van Nuys Airport	United States	210.32
4	Harry Reid International Airport	United States	202.80
5	Westchester County Airport	United States	198.92
6	Dallas Love Field Airport	United States	198.21
7	Miami-Opa Locka Executive Airport	United States	183.11
8	Washington Dulles International Airport	United States	177.39
9	William P. Hobby Airport	United States	148.47
10	Scottsdale Airport	United States	142.70
11	Naples Municipal Airport	United States	131.71
12	Paris-Le Bourget Airport	France	128.99
13	John Wayne Orange County International Airport	United States	128.61
14	DeKalb Peachtree Airport	United States	126.42
15	Nashville International Airport	United States	125.34
16	Chicago Midway International Airport	United States	125.34
17	Centennial Airport	United States	125.34
18	Laurence G Hanscom Field Airport	United States	115.97
19	Austin Bergstrom International Airport	United States	113.44
20	Nice-Côte d'Azur Airport	France	100.25

The top 20 airports by private jet estimated LTO $PM_{2.5}$ emissions in 2023 are shown in Table B5.

Table B5

Top 20 airports by private jet estimated LTO $PM_{2.5}$ emissions, 2023

Rank	Airport Name	Country	$PM_{2.5}$ (tonnes)
1	Teterboro Airport	United States	4.88
2	Palm Beach International Airport	United States	2.38
3	Van Nuys Airport	United States	2.28
4	Westchester County Airport	United States	2.06
5	Dallas Love Field Airport	United States	2.05
6	Harry Reid International Airport	United States	1.93
7	Washington Dulles International Airport	United States	1.74
8	Miami-Opa Locka Executive Airport	United States	1.72
9	Paris-Le Bourget Airport	France	1.46
10	Scottsdale Airport	United States	1.34
11	William P Hobby Airport	United States	1.31
12	John Wayne Orange County International Airport	United States	1.20
13	Nice-Côte d'Azur Airport	France	1.16
14	Naples Municipal Airport	United States	1.15
15	Centennial Airport	United States	1.12
16	Laurence G Hanscom Field Airport	United States	1.12
17	Chicago Midway International Airport	United States	1.12
18	DeKalb Peachtree Airport	United States	1.08
19	Toronto Lester B. Pearson International Airport	Canada	1.06
20	Norman Y. Mineta San Jose International Airport	United States	1.05

APPENDIX C. SCOPE11 METHOD

The SCOPE11 method uses nvPM emission data as the input. Before the tenth meeting of the Committee on Aviation Environmental Protection (CAEP10), only the particulate-related standard of SCOPE11 was based on the SN. For some engines, nvPM emission data are not available in the EEDB, so only SN measurements can be used to estimate nvPM emissions. In Step 0, calculations are performed sequentially, using the SN to derive nvPM concentration (CI_{mass}), which is then used to compute the nvPM emission index in terms of mass (EI_{mass}).

To derive the nvPM concentration (CI_{mass}), the following equation is used:

$$CI_{mass}\left[\frac{\mu g}{m^3}\right] = \frac{648.4 \times e(0.0766 \times SN)}{1 + e^{(1.099 \times (SN - 3.064))}}$$

The emission index (EI) is calculated by multiplying the concentration (CI_{mass}) by the volumetric flow rate Q_{mode} (measured in m^3/kg). The flow rate Q_{mode} depends on the Air-to-Fuel Ratio (AFR) and the reference by-pass ratio β, given by:

$$Q_{mode}\left(\frac{mg^3}{kg}\right) = 0.776 \times (AFR) \times (1 + \beta) + 0.767$$

The AFR at each of the four LTO points have been estimated by Wayson et al. as 106 at idle, 83 at approach, 51 at climb-out, and 45 at take-off.

A correction factor k_{slm} is used to adjust for measurement system losses. It depends on the reference by-pass ratio β and nvPM concentration (CI_{mass}), calculated as:

$$k_{slm} = ln\left(\frac{3.219 \times CI_{mass} \times (1 + \beta) + 312.5}{CI_{mass} \times (1 + \beta) + 42.6)}\right)$$

The nvPM emission index by mass (EI_{mass}) is derived for each of the four LTO modes as:

$$EI_{mass}\left[\frac{mg}{kg}\right] = CI_{mass} \times Q_{mode} \times k_{slm}$$

For the nvPM emission index by number (EI_{num}), the mean particle size across all modes is used, with the number density calculated by:

$$EI_{num}\left[\frac{particles}{kg}\right] = \frac{EI_{mass}}{\left(\frac{\pi}{6} \times 10^9 \times \frac{GMD}{10^9} \times e^{(4.5 \times (ln(1.8))^2)}\right)}$$

This method allows for a step-by-step derivation of EI_{mass} and EI_{num} from the SN, enabling estimation of nvPM emissions for engines lacking direct nvPM emission data in the EEDB.

APPENDIX D. LIST OF PRIVATE JET AIRCRAFT TYPES

Aircraft type names categorized as private jets for this study are shown in Table D1.

Table D1

Aircraft names categorized as private jets, 2023

Embraer EMB 505 Phenom 300	Embraer Lineage 1000
Cessna 680A Citation Latitude	Airbus A340-300
Bombardier BD-100-1A10 Challenger 350	Dassault Falcon 20D
Cessna 560XL Citation XLS	Raytheon Hawker 800SP
Bombardier BD-100-1A10 Challenger 300	Airbus ACJ320-200N
Cessna 525B CitationJet CJ3	Boeing 757-200(VC-32A)
Cessna 560XL Citation XLS+	Shukoi SSJ 100/95B
Bombardier Learjet 45	Boeing 747-8(BBJ)
Cessna 560XL Citation Excel	Boeing 737-400
Cessna 680 Citation Sovereign	Airbus A340-200
Gulfstream Aerospace GV-SP (G550)	Dassault Falcon 6X
Raytheon Hawker 800XP	Grumman G-1159B Gulfstream II-B
Cessna 750 Citation X	Dassault Falcon 50SurMar
Cessna 510 Citation Mustang	Mitsubishi MU-300 Diamond IA
Cessna 525C CitationJet CJ4	Fokker F70
Bombardier Learjet 60	Sukhoi SSJ 100/95SBJ
Cirrus Vision SF50	Gulfstream Aerospace GV-SP (G550) CAEW
Gulfstream Aerospace GIV-X (G450)	Boeing 767-300ER
Bombardier BD-700-1A10 Global 6000	Raytheon Hawker 1000
Embraer EMB 500 Phenom 100	Boeing 767-200ER
Cessna 525B CitationJet CJ3+	Boeing 777-300(ER)
Cessna 525A CitationJet CJ2	Bombardier BD-100-1A10 Challenger 350
Gulfstream Aerospace G280	Airbus A340-500
Cessna 525 Citation M2	Tu-204-300
Canadair CL-600-2B16 Challenger 604	Cirrus Vision SF50 G2
Beechjet 400A	Dassault Falcon 2000DX
Hawker 400XP	Tu-214PU
Cessna 525 CitationJet	Boeing 737-300
Canadair CL-600-2B16 Challenger 605	Gulfstream Aerospace TP 102D (G550)
Gulfstream Aerospace GVI (G650)	Gulfstream Aerospace C-20G
Dassault Falcon 2000LX	Boeing 737-700
Gulfstream Aerospace G-IV-SP	Airbus A350-900
Bombardier Learjet 35A	ARJ100
Dassault Falcon 7X	Tu-214
Cessna 550 Citation Bravo	Bombardier Learjet 55B
Canadair CL-600-2B16 Challenger 650	Airbus ACJ330-200
Cessna 560 Citation Ultra	Boeing 777-200LR

Bombardier Learjet 75	Bombardier Learjet 25B
Cessna 550 Citation II	ERJ 170-200STD
Cessna 560 Citation V	Dassault Falcon 50-4
Cessna 525A CitationJet CJ2+	Dassault Falcon 20CF
Dassault Falcon 2000	Boeing 737-8(BBJ)
Honda HA-420 HondaJet	Boeing 777-300ER(BBJ)
Embraer Legacy 600	Fokker F100
Bombardier BD-700-1A11 Global 5000	Bombardier Learjet 24D
Raytheon Hawker 900XP	CRJ700 Srs 702
Cessna 525 CitationJet CJ1	Cirrus Vision SF50
Embraer EMB 545 Legacy 450	Boeing 767-300(ER)
Gulfstream Aerospace GVI (G650ER)	Boeing 787-9(BBJ)
Cessna 560 Citation Encore	Embraer ERJ 135BJ Legacy 650
Gulfstream Aerospace G200	Israel C-38A Astra SPX
Raytheon 390 Premier 1	Airbus A310-300
Embraer Legacy 650	Gulfstream Aerospace C-20H
Bombardier BD-700-2A12 Global 7500	Antonov An-148-100
Eclipse Aerospace EA500	Airbus A319-133CJ
Embraer Praetor 600	Grumman G-1159 Gulfstream II-TT
Gulfstream Aerospace G-IV	Cessna 680 Citation Sovereign
Bombardier Learjet 40	Bombardier Learjet 25
Dassault Falcon 900EX	Gulfstream Aerospace TP 102C (G-IV-SP)
Gulfstream Aerospace GV	Embraer Praetor 500
Dassault Falcon 50	Boeing 757-200(C-32A)
Embraer Praetor 500	Boeing 747-200(VC-25A)
Embraer EMB 550 Legacy 500	Boeing 737-79V BBJ
Challenger 850	Boeing 767-200(ER)
Gulfstream Aerospace GVII-G600	ACJ340-500
Bombardier Learjet 31A	Dassault Falcon 20EF
Bombardier BD-700-1A10 Global Express XRS	Boeing 767-400ER
Gulfstream Aerospace GVII-G500	Airbus ACJ220-100
Gulfstream Aerospace G150	Hawker 400XPR
Dassault Falcon 2000EX EASy	Dassault Falcon 200
Bombardier BD-700-1A10 Global Express	Boeing 777-300(ER)(BBJ)
Cessna 650 Citation III	Embraer EMB 505 Phenom 300E
Cessna 525 CitationJet CJ1+	Bombardier Learjet 40
Cessna 650 Citation VII	Tu-204-100
Cessna 501 Citation I/SP	Gulfstream Aerospace C-20B Gulfstream III
Cessna 680+ Citation Sovereign	Airbus ACJ340-600
Dassault Falcon 2000EX	Dassault Falcon 900EX EASy
Raytheon Hawker 850XP	Airbus A321-200
Dassault Falcon 900EX EASy	ARJ70

Dassault Falcon 8X	Boeing C-40B
Boeing 737-700(BBJ)	A330-200(MRTT)
Cessna 560 Citation Encore+	Boeing C-40C
Honda HA-420 HondaJet Elite	Boeing 777-200ER
Dassault Falcon 900B	Airbus CC-330
Dassault Falcon 50EX	Gulfstream Aerospace GV-SP (G550) Nahshon-Eitam
Airbus ACJ319-100	Boeing 777-200(LR)
Cessna 550 Citation S/II	Sukhoi SSJ 100/95LR
Canadair CL-600-2B16 Challenger 601-3A	Gulfstream Aerospace GV-SP (G550) Nahshon-Oron
Cirrus Vision SF50 G2	Il-96-300PU
Bombardier BD-700-1A10 Global 6500	Airbus Voyager KC3
Raytheon 390 Premier 1A	Embraer ERJ 135LR
Dassault Falcon 900LX	Bombardier Learjet 45
Dassault Falcon 900	Tu-214SR
Dassault Falcon 2000S	Airbus A321-251NX
Raytheon Hawker 750	Cessna 519 Citation Mustang
Israel IAI-1125A Astra SPX	Airbus A321-200NX
Bombardier Learjet 55	Yak-42D
Canadair CL-600-2B16 Challenger 601-3R	Boeing 787-8
Hawker Beechcraft 4000	Gulfstream Aerospace C-20A Gulfstream III
Boeing 757-200	Mitsubishi MU-300 Diamond I
Lineage 1000	Various Bombardier BD-100-1A10 Challenger 350 Airframes
Israel IAI-1126 Galaxy	Bombardier Learjet 35A
Airbus ACJ320-200	Bombardier BD-1001A10 Challenger 350
Cessna 500 Citation I	Boeing 727-100
Cessna 650 Citation VI	Dassault Falcon 20E-5
Bombardier Learjet 45XR	Dassault Falcon 20DF
Bombardier BD-700-1A11 Global 5500	Boeing 747-8
Cessna UC-35A-1 Citation Ultra	Challenger 870
Bombardier Learjet C-21A	Bombardier Learjet 24F
Bombardier Learjet 36A	Gulfstream Aerospace G280
Gulfstream Aerospace G-IV (G400)	Boeing 777-200(ER)
Dassault Falcon 10	MD-87
Bombardier Learjet 31	Boeing 737-7BC BBJ
Bombardier CRJ200LR	Gulfstream Aerospace GVIII-G800
Bombardier Learjet 70	Airbus ACJ321-200
Cessna 551 Citation II/SP	Embraer ERJ 145MP
Dassault Falcon 20F	Hawker Siddeley DH-125 Series 400A
Bombardier Learjet 60XR	Tu-154M
Dassault Falcon 900DX	Embraer ERJ 135B Legacy 650
Bombardier Learjet 35	Boeing 737-7JY BBJ

Airbus A320-200	Boeing 747-8KB
Israel IAI-1124 Westwind	Bombardier ND-100-1A10 Challenger 350
Dassault Falcon 20F-5	Bombardier Learjet 24E
Hawker Siddeley HS-125 Series 700A	Various Bombardier Airframes
Eclipse Aerospace EA550	Hawker Siddeley HS-125 Series 700B
Airbus A321-200NX(LR)	Gulfstream Aerospace
Dassault Falcon 20DC	Gulfstream Aerospace G-IV-SP
Dassault Falcon 20C-5	Embraer ERJ 145LU
Cessna UC-35D Citation Encore	Boeing 737-74U BBJ
Boeing 737-800(BBJ)	Embraer EMB 505 Phenom 300
Israel IAI-1125 Astra SP	Bombardier ND-100-1A10 Challenger 300
Israel IAI-1124A Westwind 2	Embraer EMB 505 Phenom 300
Airbus ACJ318-100	Gulfstream Aerospace GVI (G650ER)
Gulfstream Aerospace G-IV (G300)	Bombardier Learjet 24B
Gulfstream Aerospace C-37A	Bombardier BD-200-1A10 Challenger 300
Dassault Falcon 900C	Gulfstream Aerospace GVII-G600
Raytheon Hawker 800	Boeing 737-7GV BBJ
Challenger 800 (CRJ100)	Various Dassault Falcon 7X Airframes
Airbus A319-100	Bombardier BD-700-1A10 Global Express (Miscode)
Gulfstream Aerospace G100	Bombardier BD-700-1A10 Challenger 350
Beechjet 400	Raytheon 390 Premier I
Gulfstream Aerospace C-37B	Various Dassault Falcon 2000 Airframes
Cessna UC-35B Citation Encore	Boeing 737-800
Israel IAI-1125 Astra	Cessna Citation M3
Boeing 737-800	Various Dassault Falcon 2000LX Airframes
Bombardier Learjet 36	Boeing 737-8 BBJ
Gulfstream Aerospace G-1159A Gulfstream III	Embraer EMB-500 Phenom 100
ARJ85	Sukhoi SuperJet 100-95B
Raytheon Hawker 800XPi	Tu-214SUS
Gulfstream Aerospace GVIII-G700	Grumman G-1159 Gulfstream II-SP
Dassault Falcon 100	Various Bombardier BD-100-1A10 Challenger 350 Airframes
Airbus A330-200	Boeing 747SP
Dassault Falcon 20C	Gulfstream Aerospace G250
Gulfstream Aerospace GIV-X (G350)	Cessna 525A CitationJet CJ2
Bombardier Learjet 40XR	Bombardier BD-700-1A10 Global 5000
Bombardier Learjet 25D	Airbus A340-313X
Dassault Falcon 20E	Embraer EMB-505 Phenom 300
Canadair CL-600-1A11 Challenger 600S	Dassault Falcon 900EX EASy
Hawker 400XT	Dassault FA8X
Gulfstream Aerospace GV-SP (G500)	Embraer EMB 5005 Phenom 100
Challenger 800 (CRJ200)	Airbus A319-153N ACJ

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