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Greenhouse Gas Emission Estimations for 2016–2020 using the Sherlock Air Traffic Data Warehouse

John E. Melton, Susie Go, and Gregory G. Zilliac
Ames Research Center, Moffett Field, CA

Benjamin X. Zhang
Science and Technology Corporation, Mountain View, CA

August 2022

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National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, CA 94035-0000

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Nomenclature and Acronyms

ASDE-X	Airport Surface Detection Equipment, Model X (FAA)
ATM	Air Traffic Management
BTS	Bureau of Transportation Statistics
BWB	Blended Wing Body
EPFD	NASA Electrified Powertrain Flight Demonstrator
ERAM	En Route Automation Modernization (FAA)
FAA	Federal Aviation Administration
GHG	Greenhouse Gas
HADDS	Host-ATM Data Distribution System
IATA	International Air Transport Association
ICAO	International Civilian Aviation Organization
MPG	Statute Miles per U.S. Gallon
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PAX	Number of Passengers
SFD	NASA Sustainable Flight Demonstrator
SM	Statute Miles
STARS	Standard Terminal Automation Replacement System (FAA)
SWIM	System Wide Information Management (FAA)
TBFM	Time-Based Flow Management
TFM	Traffic Flow Management
TTBW	Transonic Truss Braced Wing
US+PR+VI	US + Puerto Rico + Virgin Islands
WX	Weather System (FAA)

Summary

Data and analyses are presented on the utilization of aircraft in the U.S. and the greenhouse gas emissions that they create. Commercial passenger and cargo aviation flight data, captured in the Sherlock data warehouse at NASA Ames over the five years from 2016 to 2020, is used to estimate the miles flown by major aircraft models. The estimates for aggregate annual number of flights are validated against data published by the Bureau of Transportation Statistics. The corresponding fuel usage is estimated using the International Civilian Aviation Organization (ICAO) fuel use tables and carbon dioxide emissions are calculated using a fuel-use multiplicative factor. A key conclusion of this analysis is that a small number of long-haul flights (with ranges greater than 2485 statute miles) create a disproportionately large fraction (30%) of annual total U.S. aviation-related carbon dioxide emissions, while a relatively large number of short flights (less than 311 statute miles) contribute a small net amount (less than 5%) of U.S. aviation-related carbon dioxide emissions. These U.S. results are consistent with a similar recent 2020 emissions study conducted by EUROCONTROL.

Introduction

On November 9, 2021, the Federal Aviation Administration (FAA) published the United States 2021 Aviation Climate Action Plan [1]. The stated goal of this government-wide plan is to achieve net-zero life cycle greenhouse gas (GHG) emissions from aviation in the United States[1] by 2050, and a dramatic reduction in aviation's contribution to climate change. Although aviation accounts for a relatively small portion of total GHG emissions (currently 1.9% of the total CO_2 emitted and 3.5% effective GHG when accounting for contrails), global aviation GHG emissions are projected to triple by 2050.

The FAA plan is a policy framework with government and industry goals and actions. In the near-term, the plan anticipates GHG reductions through aircraft efficiency improvements and greater use of sustainable drop-in jet fuels. In the far term, advanced technologies such as cryogenic hydrogen-fueled, electric, and electric-hybrid configurations are encouraged but are not expected to have an impact on GHG until after 2050. Paths to net zero GHG will require a major reworking of the nation's aviation and energy infrastructure at great cost. Eliminating fossil fuels from aviation by 2050 is an ambitious goal and the odds of success improve if decisions are made guided by science and data.

The original motivation for studying aircraft utilization and CO_2 emissions is a surprising result published by EUROCONTROL, the intergovernmental European air traffic, flight safety and support organization. Figure 1 is a recreation of a figure from a recent EUROCONTROL report [2] that showed that long-haul flights are disproportionately large contributors to European aviation GHG emissions.

[1] CO_2 emissions from (1) domestic aviation (i.e., flights departing and arriving within the United States and its territories) from U.S. and foreign operators, (2) international aviation (i.e., flights between two different ICAO Member States) from U.S. operators, and (3) airports located in the United States.

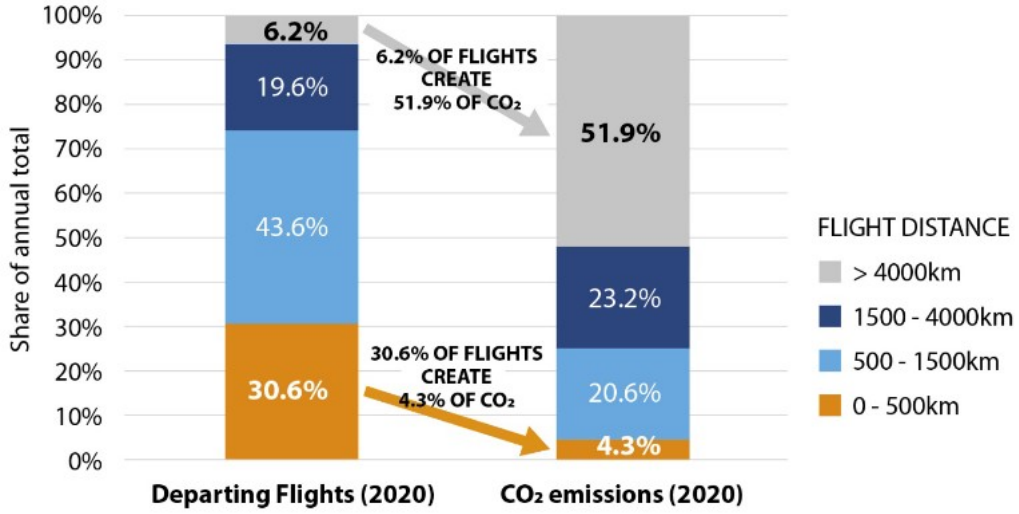

Figure **1**. European flight data and aviation emissions estimates for 2020 (adapted from [2]).

Presented in Figure 1 are the number of European departures in 2020 (left bar) and their corresponding CO_2 emissions contributions (right bar). The data for each bar is segregated into four distance bins (throughout this paper, the orange, light blue, dark blue, and grey figure colors represent short-, medium-, long-, and very long-haul flights, respectively). The chart shows that more than half of European aviation's CO_2 emissions were emitted by just 6.2% of the flights. The data also indicates that a full 31% of the flights, (with trip distances less than 500km), accounted for only 4% of the emissions. The EUROCONTROL authors rightly describe this situation as posing a strategic dilemma: while short-haul flights are those most likely to be successfully electrified, complete electrification of these flights using today's technology would reduce total emissions by no more than 4%. The EUROCONTROL authors conclude that increasing the supply of sustainable aviation fuels to cover just 10% of the long-haul flights would be more impactful on European aviation emissions reductions than the complete electrification of the entire short haul fleet.

The current study compares U.S. trends for departing flights with these European results and presents additional insights into the U.S. flights and emissions by using the flight data aggregated in the Sherlock data warehouse [3] along with ICAO fuel consumption models [4]. Additionally, the U.S. data in the Sherlock data warehouse is interrogated to study the impact of the COVID-19 pandemic on U.S. aviation during 2019 and 2020 and to compare those statistics with those reported by the Bureau of Transportation Statistics.

In the open literature, there are a couple of notable similar studies. Zeng and Rutherford [5] study the fuel use of commercial jet aircraft from 1960 to 2019. Their results show that although aircraft fuel efficiency has increased by a factor of two since 1960, aviation CO_2 emissions are continuing to increase. Quadros et al. [6] derive global civil aviation emissions estimates based on Automatic Dependent Surveillance–Broadcast (ADS-B) data coupled with a fuel use model to show that the majority of aviation fuel is consumed in North America, Europe and along the Pacific Rim. Seymour et al. [7] present a high-fidelity fuel use and CO_2 emission estimation methodology that is validated against airline fuel consumption reports for 133 aircraft models.

Data, Methods, and Procedures

In this section, the data sources used, methods, and processing and validation methodology are described.

Historical flight data

The Sherlock data warehouse [3] is developed and managed at the NASA Ames Research Center. Sherlock provides air traffic data in various formats and levels of fidelity that can be easily mined by aviation researchers. The Sherlock data warehouse is a rich collection of approximately 10 years of air traffic and weather data aggregated from numerous sources, including the FAA, NOAA, and the NWS as illustrated in Figure 2. The Sherlock infrastructure also provides machine learning functionality to aviation researchers both inside and outside of NASA.

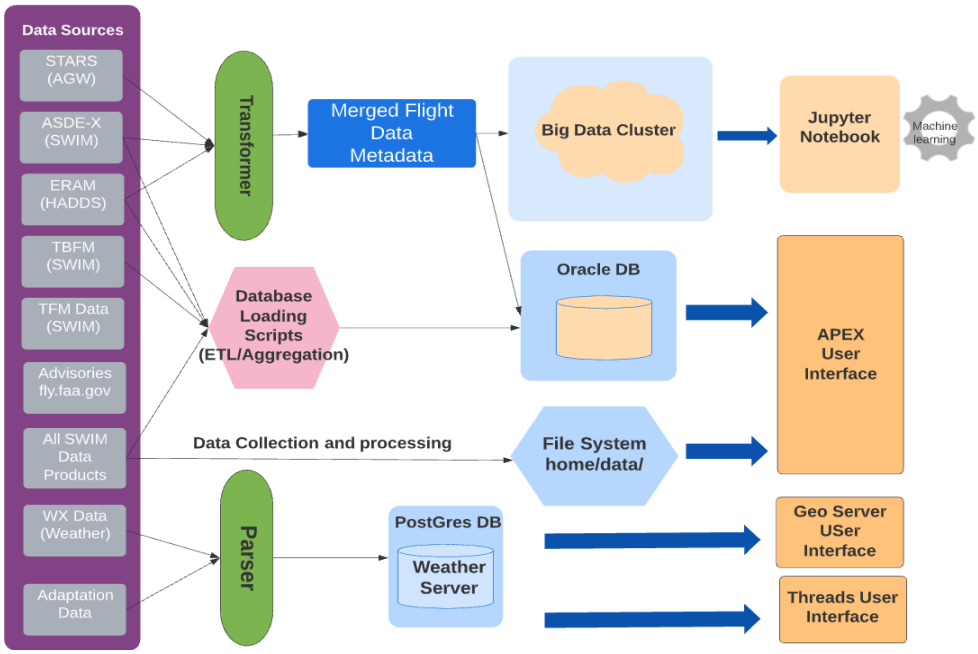

Figure 2. Sherlock data warehouse for historical flight and weather data (Source [3]).

Flight data from all aircraft types, including commercial passenger, cargo, military, helicopter, and general aviation vehicles is contained in the Sherlock data warehouse. This report describes processing of flight summary data solely contained in the “RD - flight summary” data store. Data items for each flight include such things as the type of aircraft (designated by its ICAO code), weight class, airline, and other flight-specific information (takeoff time, duration, origin and destination airports, etc.). Specialized Python scripts were created to filter out records from the Sherlock 2016–2020 datasets that 1) represent flights performed by military or general aviation aircraft, or 2) are missing key elements such as flight date, aircraft type, origin, or destination. This first stage of processing is designed to produce comprehensive yet streamlined annual subsets of U.S. domestic and international commercial air traffic (both passenger and cargo). Each flight in an annual subset was required to have a takeoff or landing at a recognized airport in the U.S., Puerto Rico, or Virgin Islands by a recognizable air carrier

and a recognizable aircraft type. In this report, a “domestic” flight is one with both arrival and departure airports within the U.S., Puerto Rico, or the Virgin Islands, while an “international” flight is one with either an arrival or a departure at/from a non-US+PR+VI airport.

Sherlock Data Augmentation and Emissions Estimation

The flight data in the Sherlock RD summary data store lacks some key information needed to directly compute CO_2 emissions, such as distance traveled, aircraft weights, seat and passenger counts, and fuel usage. To estimate the distance traveled, the geodesic (great circle) distance between the origin and destination airports for each flight is computed using airport latitudes and longitudes. The Sherlock flight data is further augmented with vehicle ID mappings between aircraft model, ICAO codes and available seats per aircraft collected from a wide variety of public sources (see Appendix A). Fuel consumption estimates for each flight are determined using linear interpolation (based on aircraft type and distance flown) of the detailed fuel consumption data tables provided in the ICAO emissions calculator report [4]. Figure 3 below shows the ICAO emissions calculation process and the inputs required to compute accurate fuel usage. Several detailed inputs and operational considerations such as passenger load factors, airline seat layouts, taxi distances, indirect routings, engine sub-models, mail and cargo, etc. are <u>not</u> accounted for in the fuel consumption estimates presented in this report, as this data was not generally available for each flight. Final carbon dioxide emissions are then calculated assuming 3.16 lb of CO_2 are created for each pound of fuel consumed.

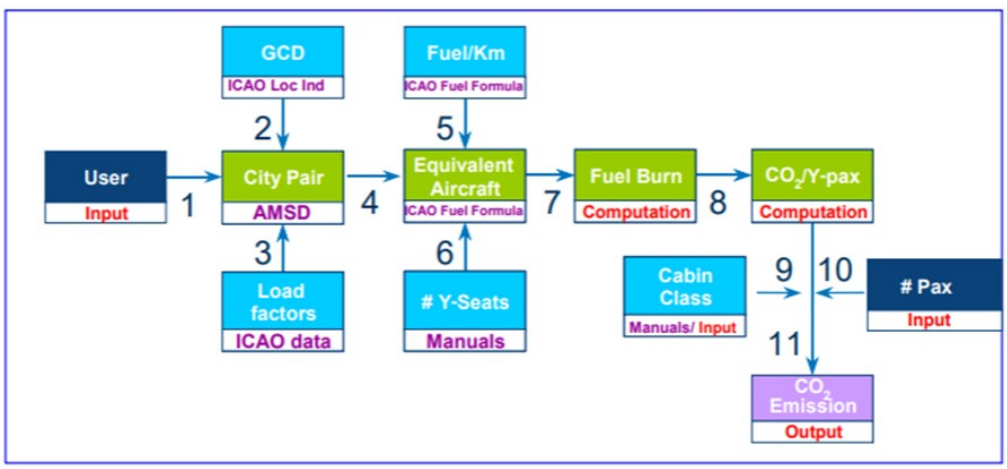

Figure **3**. ICAO emissions calculation (Source **[4]**).

Comparison with Bureau of Transportation Statistics for Passenger-only data

Five years of flight summary data from the Bureau of Transportation Statistics (BTS) [8] is used to validate the mined Sherlock flight data. The BTS data comparisons focused on passenger-only domestic and international flights. The BTS definition of a domestic flight is one with both a U.S. origin and U.S. destination, while the BTS definition of an international flight includes any flight with one non-U.S. airport and one U.S. airport. As seen in Table 1, the processed Sherlock flight data agrees well with the BTS flight data. There is one significant percentage difference in the 2020 international flights, where the Sherlock estimate is approximately 9% higher than the BTS value. We believe this increase in percentage difference is exacerbated by the large number of international flights cancellations during the COVID-19

pandemic, and we suspect that some of those cancellations were not correctly reflected in the RD data store.

Table 1. Comparison of the number of flights annually recorded by the BTS with that of the NASA Ames Sherlock flight data 2016–2020.

	BTS			Sherlock		
Year	Domestic	International	Total	Domestic	International	Total
2016	8,183,844	841,862	9,025,706	8,068,759	868,883	8,937,642
2017	8,176,047	845,794	9,021,841	7,834,343	852,845	8,687,188
2018	8,398,404	858,396	9,256,800	8,047,893	853,156	8,901,049
2019	8,594,869	868,848	9,463,717	8,325,305	843,750	9,169,055
2020	5,162,358	348,096	5,510,454	5,200,190	378,747	5,578,937

	(Sherlock – BTS) / BTS		
Year	Domestic	International	Total
2016	-1.4 %	3.2 %	-1.0 %
2017	-4.2 %	0.8 %	-3.7 %
2018	-4.2 %	-0.6 %	-3.8 %
2019	-3.1 %	-2.9 %	-3.1 %
2020	0.7 %	8.8 %	1.2 %

Figure 4 shows the detailed month-by-month comparisons of the domestic BTS and the Sherlock-derived passenger flight counts from 2018 through 2020, including the precipitous drop off in both domestic and international flights starting during the early months of 2020.

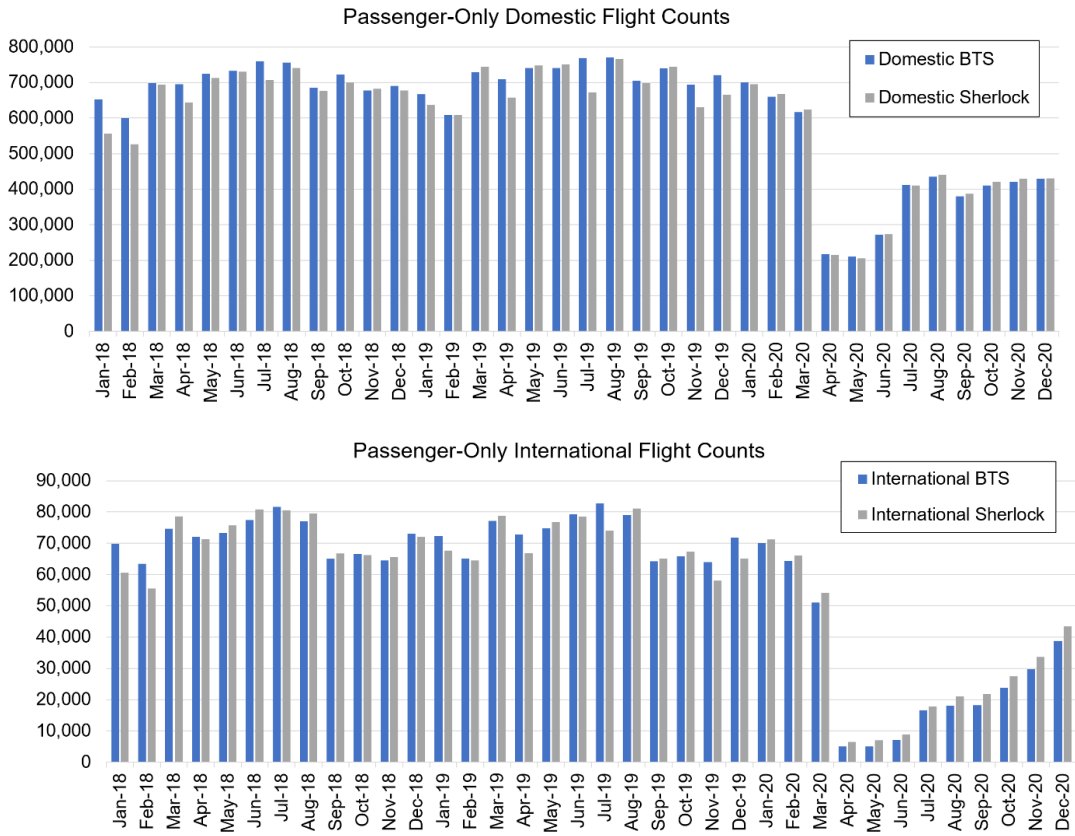

Figure 4. U.S. and foreign carrier monthly flight totals for flights originating at U.S. airports (January 2019 to July 2021).

Results

Emissions and Distance Results - Comparisons with 2020 EUROCONTROL data

The Sherlock data for 2016–2020 is next used to perform an emission and distance study for comparison with the EUROCONTROL results. To conform to the EUROCONTROL study, all departures of passenger and cargo flights from U.S. airports are identified and used for the emissions calculations using the simplified ICAO distance-based fuel calculations described earlier. Figure 5 shows the U.S. results from 2016 through 2020 using the same distance bins and coloring schema as the EUROCONTROL study.

Flight Distance in Statute Miles	Flight Distance in km
> 2485	> 4000
932 - 2485	1500 - 4000
311 - 932	500 - 1500
0 - 311	0 - 500

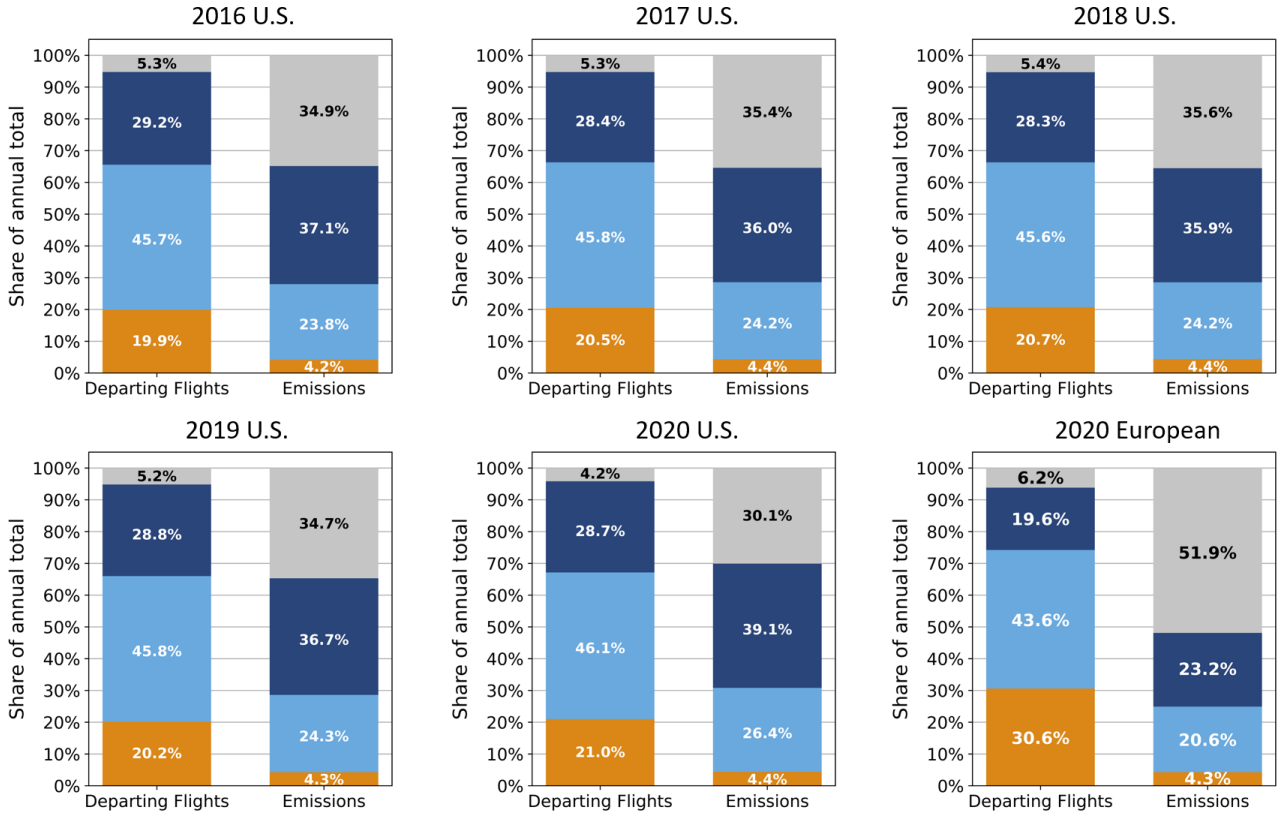

Figure 5. Comparison of 2016–2020 U.S. and European departure and emission data.

Figure 5 clearly shows the similarities and differences between the 2020 European and U.S. emissions results from 2016 through 2020. As in Europe, the majority of U.S. flights range between 500 and 4000 km (the light and dark blue layers), and the fractions of emissions produced by the shortest flights (orange layers) are very similar. Our calculations indicate that nearly one-third of the U.S. aviation CO_2 contribution comes from a relatively small number of long flights (grey layers), and a disproportionally small amount of CO_2 comes from a relatively large number of short flights (orange layers). Some differences include a smaller proportion of the longest U.S. flights compared to that from the EUROCONTROL data, with the emissions contribution scaling similarly. The other significant difference is that the largest portion of the U.S. emissions is produced by the longer flights under 4000 km (the dark blue layers), not the over 4000 km (grey layers) as in the EUROCONTROL data. The effects of the COVID-19 pandemic during 2020 are addressed in a later section of this memorandum.

Detailed Flight, Distance, Fuel Usage, and Available Seat-Miles for 2016–2020

Table 2 shows Sherlock-derived annual estimates for total passenger and cargo flights (US+PR+VI departures for recognized airlines), fuel consumed, total distance, and total available seat-miles from 2016 through 2020. Note that available seat-miles as used in this report is the simple product of the distance of a flight and the total number of passenger seats on the aircraft, regardless of actual passenger count.

Table 2. Annual statistics for U.S. departures of passenger and cargo flights.

Year	Total Flights (Millions)	Total Fuel (lb) (Billions)	Total Distance (sm) (Billions)	Total Available Seat-Miles (Billions)
2016	9.086	158.8	8.558	1,434
2017	8.876	154.4	8.287	1,404
2018	9.130	158.4	8.538	1,446
2019	9.440	163.2	8.846	1,494
2020	5.987	99.7	5.335	900

Figure 6 shows the 2020 histogram of number of flights by distance (similar charts for 2016 through 2019 can be found in Appendix B). The four distance bins are shown across the top of the chart for reference. Of note is the somewhat surprising consistency in both the mean and median flight distances from 2016 through 2020.

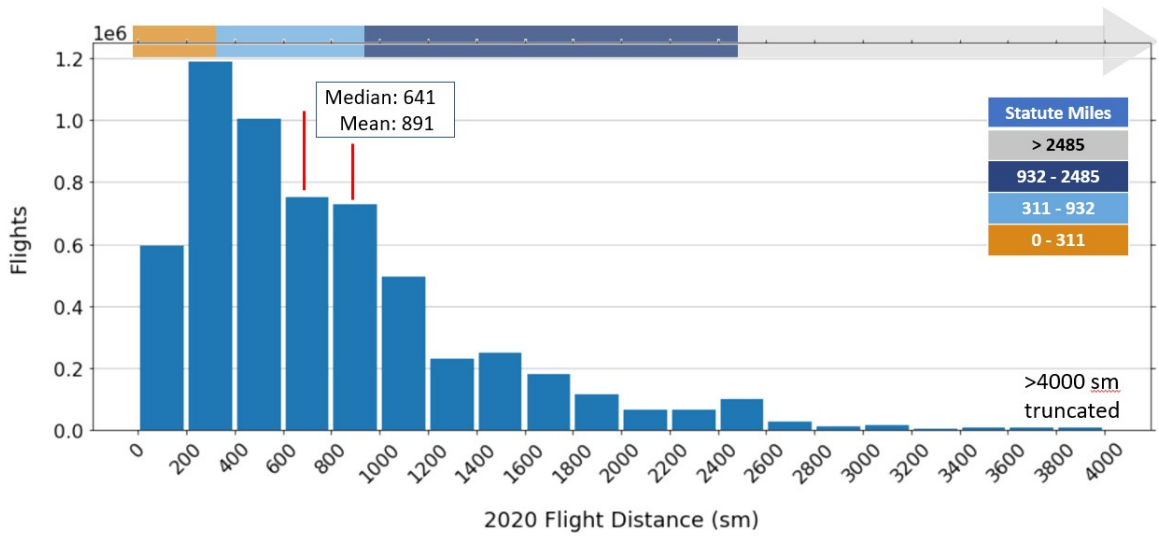

Figure 6. Histogram of number of flights flown in 2020 by distance, in 200-statute mile increments.

The histogram for number of flights in 2020 versus fuel used is presented in Figure 7 below (similar charts for 2016 through 2019 can be found in Appendix B). While the annual median fuel used per flight remains nearly constant from 2016 through 2020, a very slight reduction in annual mean fuel used per flight can be seen.

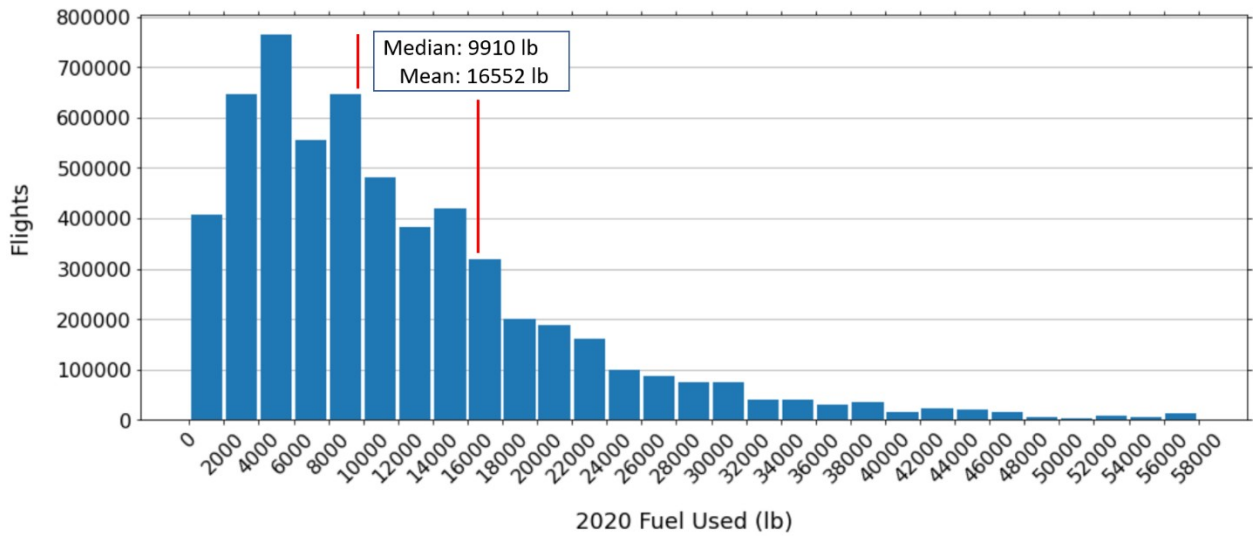

Figure 7. Histogram of number of flights flown in 2020 by fuel used.

The cumulative distribution of (great circle) distance flown annually during 2020 is shown in Figure 8 (similar charts for 2016 through 2019 can be found in Appendix B). The cumulative presentation can be used to determine the percentage of flights that are between any two distances. In Figure 8, the green box indicates that 80% of flight distances in 2020 were between approximately 200 and 1750 statute miles. The upper endpoint of this 80% distance box has contracted by 250 miles as compared with the 2016–2019 data. This is likely consistent with the disproportionate impact COVID-19 had on reductions in international travel.

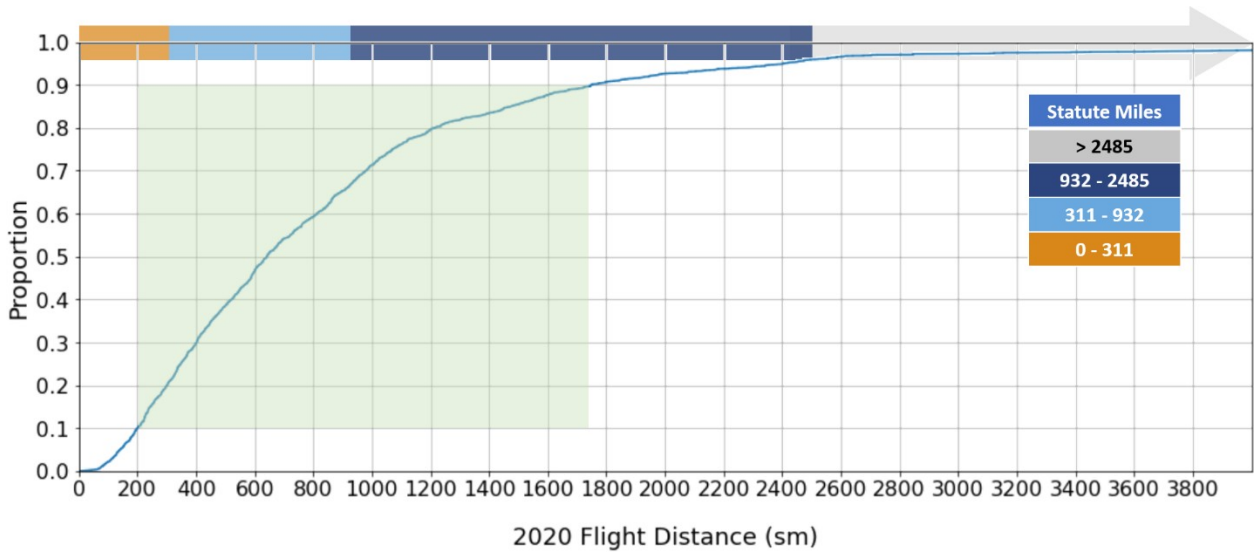

Figure 8. Cumulative distribution of number of flights flown in 2020 by distance.

The histogram illustrating 2020 fuel usage as a function of flight distance for all carriers including cargo flights, is shown in Figure 9 (similar charts for 2016 through 2019 can be found in Appendix B). As expected, flights between 250–1250 statute miles consumed a large amount of the total fuel used. The histogram shows two prominent spikes in fuel usage at the 800-1000 and 2400-2600 statute mile distances. These spikes are observed in the histograms for previous years as well, with the spike at the transcontinental 2400-2600 statute mile distance being more pronounced before the pandemic.

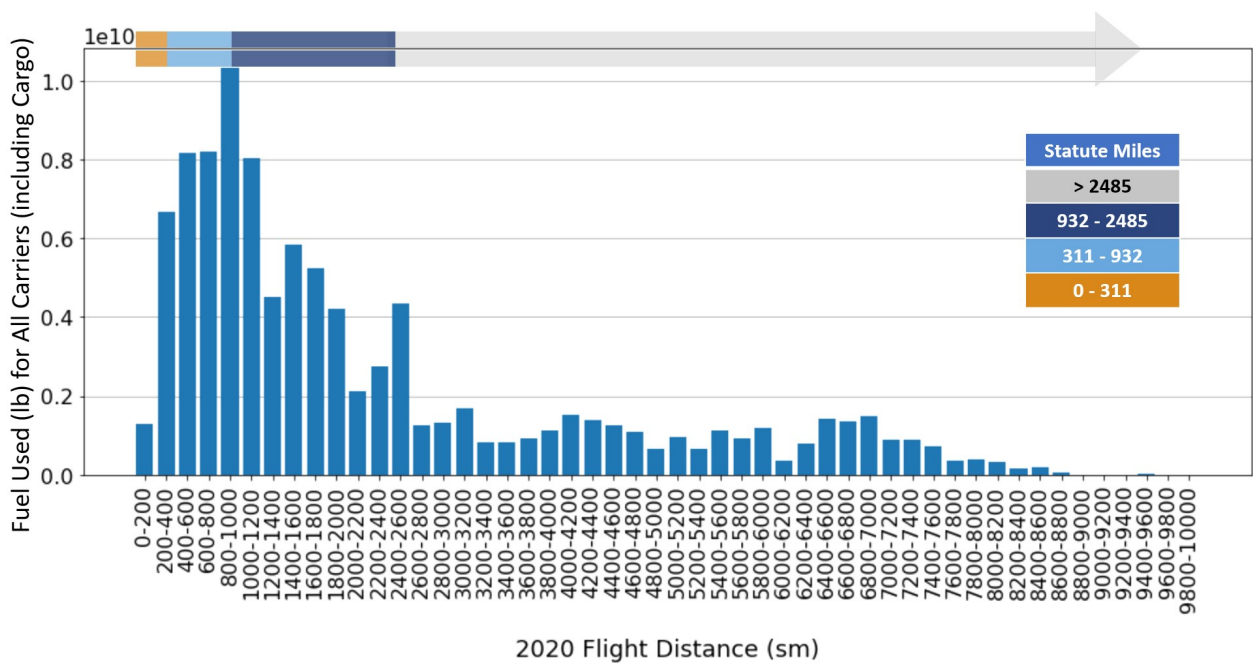

Figure 9. Histogram of fuel used in 2020 by distance in 200-statute mile increments.

Tabulated estimated fuel use statistics for the top 50 aircraft types, based on their 5-year estimated average fuel usage, are shown in Appendix C.

Five-Year Trends: 2016–2020

The next three charts (Figures 10–12) show five-year trends of the flight data when split by the four distance bins and averaged within each subset of data. The trend lines remain nearly constant between 2016 and 2020. Figure 10 shows the average distances flown within each distance bin. Figure 11 shows that the longest distances (grey line) use the most fuel per flight mile, but Figure 12 shows that when considering fuel efficiency as measured by available passenger seat-mile flown per gallon of fuel consumed, the long-distance flights (grey and dark blue) are superior.

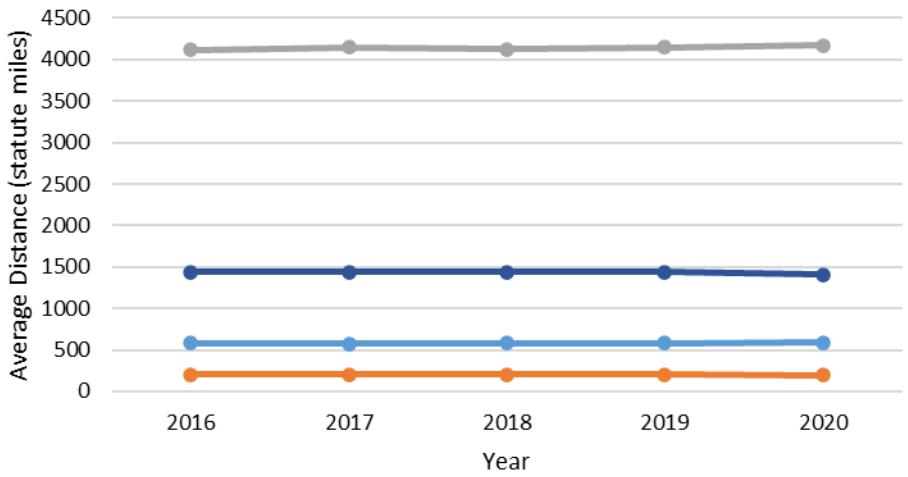

Figure 10. Average distance traveled within each distance bin, 2016–2020.

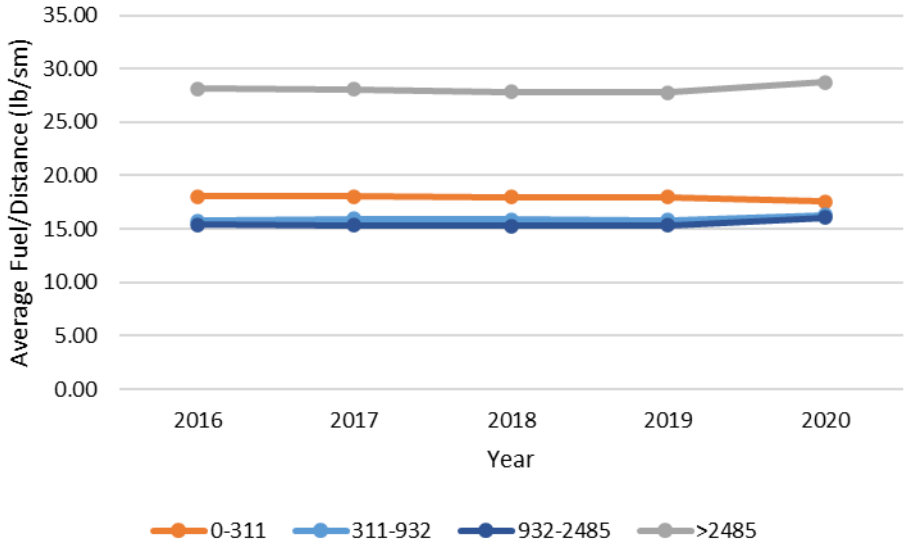

Figure 11. Average fuel used per statute mile flown within each distance bin, 2016–2020.

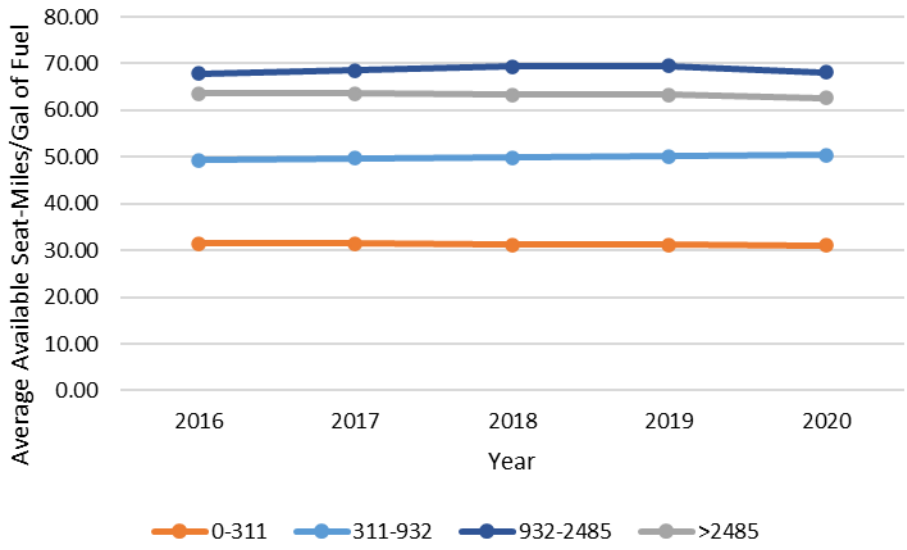

Figure 12. Average available seat-miles per gallon of fuel used, 2016–2020.

Figure 13 shows the cumulative percentage of total annual fuel used as a function of distance (in statute miles) between 2016 to 2020. The trends were very consistent from 2016 through 2019. The relatively larger percentage reduction in longer flights due to the COVID-19 pandemic is clearly seen by the deviation of the 2020 trend from that of the previous four years.

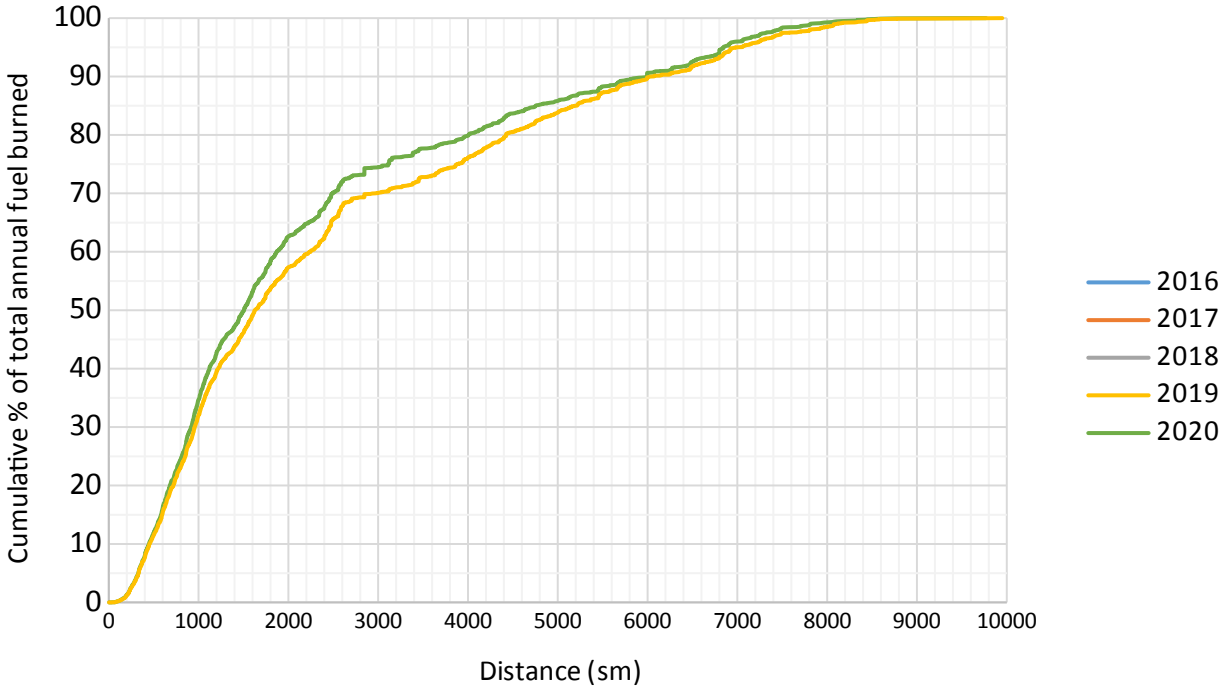

Figure 13. Cumulative percentage of total fuel used by distance traveled, 2016–2020.

Pandemic Impact on 2020 Flight Trends

The next four plots in Figure 14 show annual U.S. flight trends from 2016 to 2020 by number of flights, total distance traveled, total CO_2 emissions, and available seat-miles. All four charts reflect the reduction in air travel that occurred in 2020 because of the COVID-19 pandemic, illustrated by the sharp downturn in the solid lines. Interestingly, the proportions of flights per distance bin remain relatively stable across years, as seen by the dotted lines.

The percentage of short-haul flights is roughly 20% across all five years (orange dotted line), while the very long-haul flights make up less than 5% of all U.S. flights across all five years (grey dotted line). However, the relative contributions of CO_2 emissions are reversed: the short-haul flights contribute less than 5% of the total CO_2 emissions while the very long flights contribute 30-35% across all five years.

There is an upward trend for the medium and long-haul flights (light and dark blue dotted lines) in 2020, seen in every chart except the number of flights chart and a drop in percentage from the longest flights (grey dotted lines). This is likely due to relatively more international flights being cancelled in 2020 than domestic flights during the pandemic.

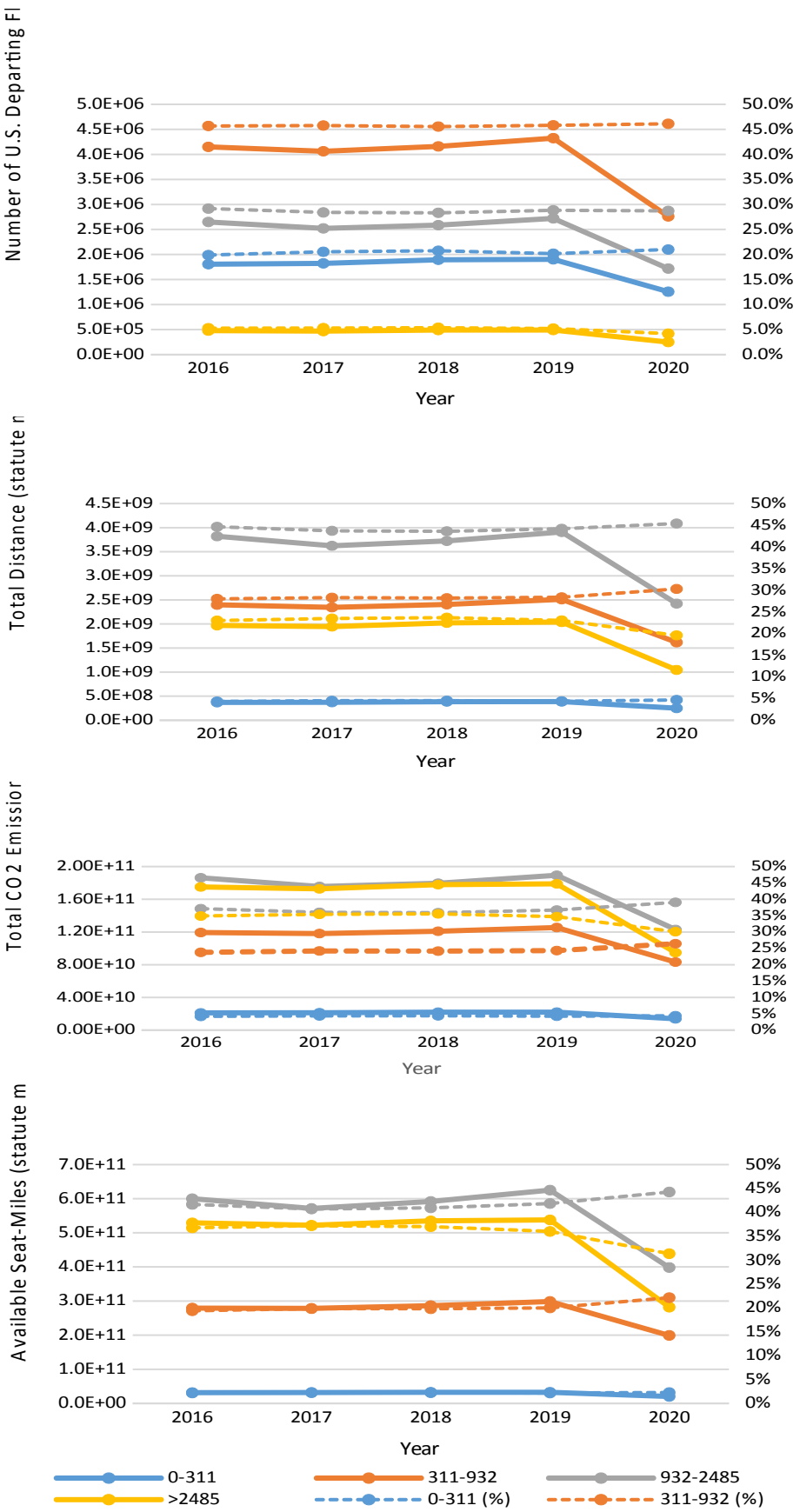

Figure 14. Five-year trends for total number of flights, total distance traveled, total CO_2 emissions, and available seat-miles per distance bin. The solid lines show the parameter values (left y-axis), and the dashed lines are the proportions of the annual totals (right y-axis).

Annual Flight Data Breakdown by Vehicle Types

Figure 15 breaks the 2020 flight data down by vehicle type, where a vehicle type includes an aircraft model and its related variants. Similar charts for 2016–2019 flight data are included in Appendix D. The ICAO code and its mapping to aircraft variants is provided in Appendix A. The figure shows the top 35 vehicle types, sorted in terms of total flights, distance, fuel consumption, and available seat-miles for a given year. These charts show the fuel used rather than CO_2 emissions. To convert to approximate pounds of CO_2, multiply the pounds of fuel used by a scaling factor of 3.16.

Because these charts are sorted by the top 35 vehicles per metric per year, the vehicle types change in each chart, as do their order. The 737-800s (B738) occur at the top of each list, but the other vehicle types move around depending on the metric. The Boeing 777-300ERs (B77W) rank number 29 in terms of number of flights flown, but ninth in terms of distance flown, sixth in terms of fuel used, and fourth in terms of available seat-miles. The Bombardier CRJ900s (CRJ9) rank fifth in terms of number of flights flown, 11th in terms of distance flown, 18th in terms of fuel used, and 17th in terms of available seat-miles.

Each vehicle bar is further split by the four distance bins that they flew, in order to understand more about the types of missions contributing to each metric for each vehicle type. For instance, the versatile Boeing 737-800 vehicles, while roughly evenly split between the number of medium- (light blue stack) and long- (dark blue stack) haul flights, have significantly larger contributions for the other three metrics, more than double, on the long-haul missions versus the medium-haul missions. The Boeing 777-300ER vehicle flies the very long-haul (grey stack) almost exclusively, as reflected by all four metrics. The CRJ900's medium-haul flights (light blue stack) contribute the greatest proportion of their fuel usage.

The pie charts show the relative percentages for each of the four distance bins for the different metrics. By flight count, the short-haul flights (orange slice) make up a significant portion of the total annual flights, roughly 30% of the total flights in 2020, but their contribution for all other metrics is relatively small, roughly 5% of the respective totals. In contrast, while the very long-haul flights (gray slice) make up the smallest proportion of total flights by count, roughly 4% of the total, they are among the largest contributor in all other metrics, from 20–35% of the totals, and specifically, contribute 30% of total fuel consumed. Although there are less than 30% of long-haul flights by count (dark blue slice), these missions are the largest contributor in all the other metrics: roughly 45% in terms of distance and available seat-miles, and 40% in terms of fuel usage.

Similar trends are seen in the 2016–2019 data provided in Appendix D. While large in terms of flight count (20% of total flights), the shortest flights consistently contributed less than 5% of total fuel used annually. In contrast, the long-haul flights flying between 932 and 2485 statute miles (dark blue slices) contribute the largest amount of total fuel used annually (36–37%).

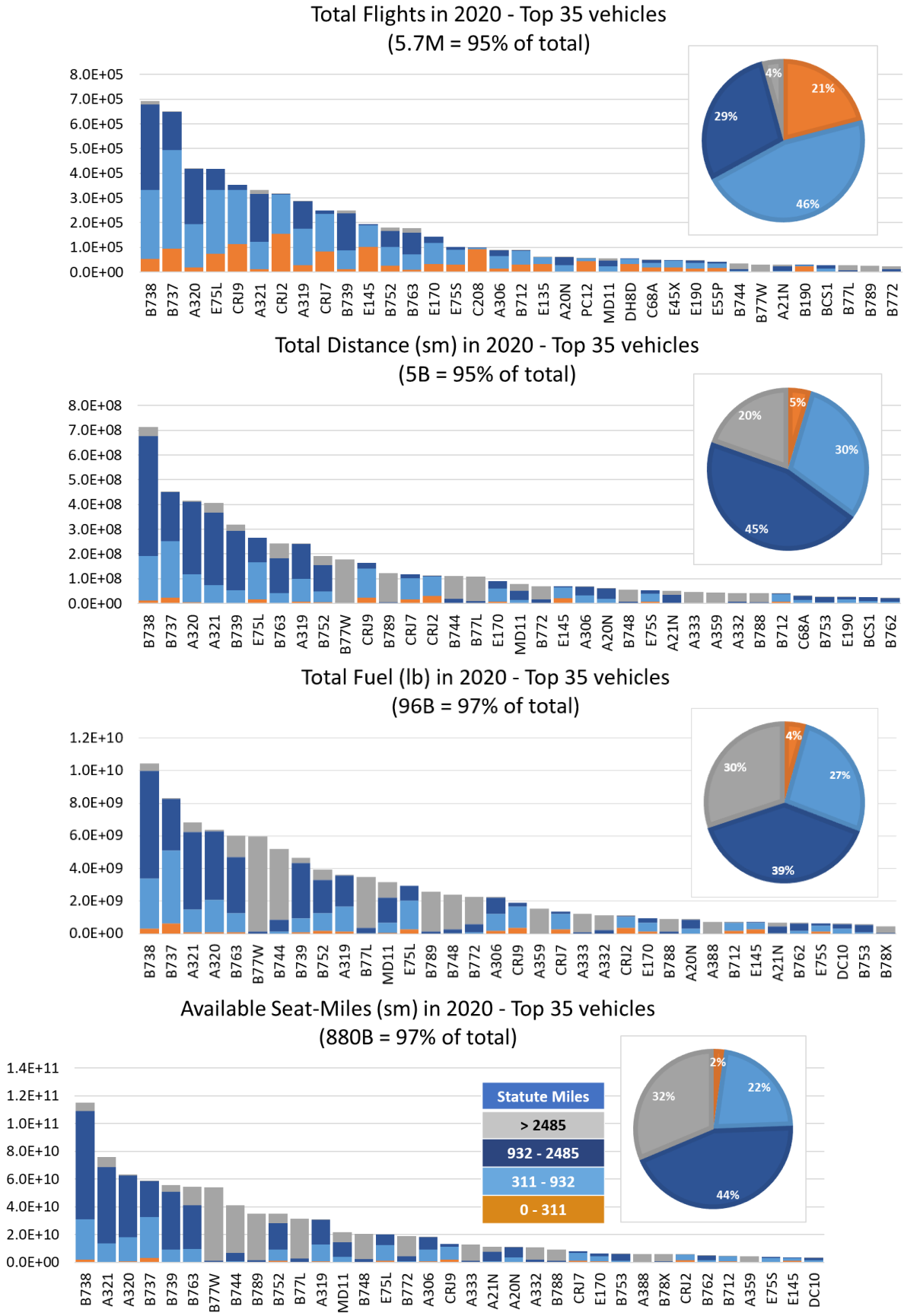

Figure 15. 2020 flight data for the top 35 vehicles by flight count, distance flown, fuel used and available seat-miles.

Aircraft Fuel Mileage

A familiar way to consider the efficiency of passenger aircraft is the statute miles travelled per U.S. gallon of fuel (MPG), viewed on a per available seat basis. Shown in Figures 16 and 17 are the MPG per available seat versus available seat statute miles for the most heavily utilized aircraft during 2019. The data points on the plot represent the fuel economy predicted for the average flight distance flown and the bars extending vertically from the data point span the range of fuel economy that the aircraft is capable of for flights between 300 statute miles and the plane's maximum range. So, for example, airplane models that are used near their peak fuel efficiency (on average) would have a bar extending below the associated data point (see Appendix A for the aircraft type, model codes and number of seats).

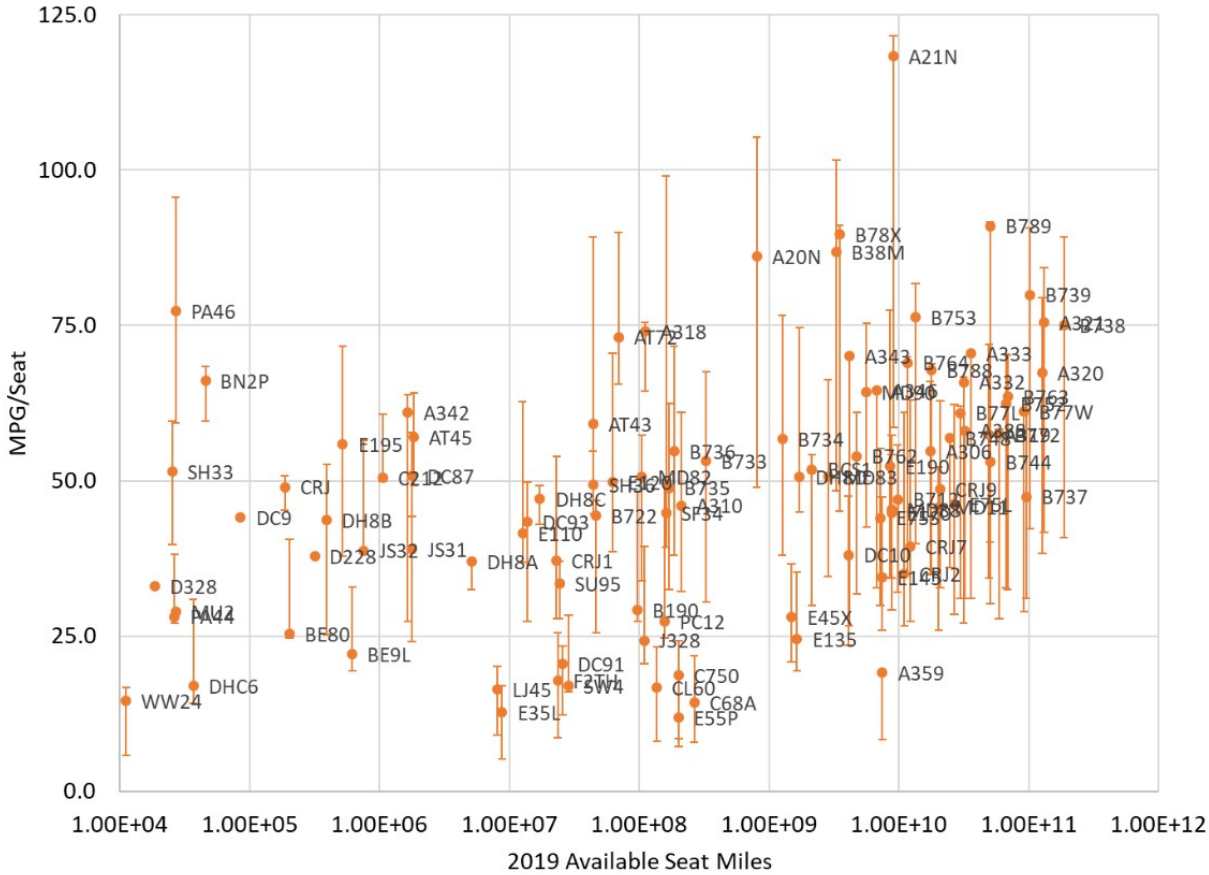

Figure 16. Aircraft fuel mileage per available seat-mile during 2019.

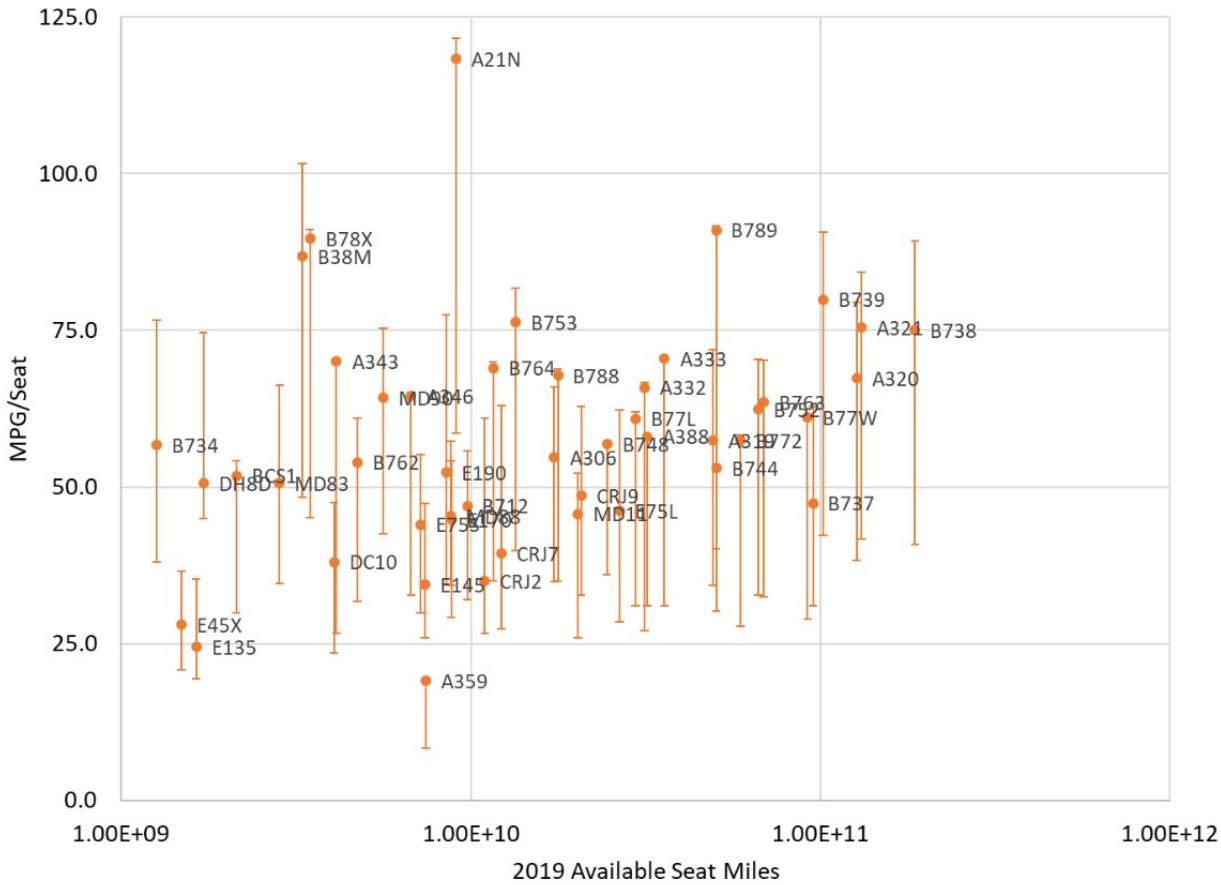

Figure 17. Expanded view of aircraft fuel mileage per available seat-mile in 2019.

Several major assumptions are made in these plots. Like the plots shown previously in this memorandum, the fuel usage is based on a simplified ICAO fuel use model [4] implemented with a load factor of one (i.e., a full aircraft). The number of seats for an aircraft model is highly variable between airlines and therefore the number of seats was assigned an average value taken from up to 22 different airline seating arrangements (see Appendix A for the seat count used). Typically, airline seat arrangements seat fewer passengers than the aircraft manufacture's advertised capacity for a given model and therefore the MPG/seat is less than optimal (i.e., the highest MPG/seat is obtained at maximum seat density). Finally, flight speed, cruise altitude, weather, air traffic, indirect routing, and the actual loading of a particular aircraft can have a significant impact on actual fuel usage. No accounting for these factors is included in this fuel mileage analysis, and the plotted values are subject to significant uncertainties.

Conclusions

This memorandum contains an analysis of U.S. flight departure patterns from 2016 to 2020 and their contribution to greenhouse gas emissions. A combination of publicly available aircraft, airport, and daily flight data from the Sherlock data warehouse maintained by NASA Ames Research Center was used for this analysis. The Sherlock flight data was validated against publicly available data on the BTS website and augmented with additional calculated parameters, including estimates for distance, fuel usage, and available seat-miles. No attempt was made to introduce the impact of actual passenger load factors, seating layouts, cargo, and other operational considerations on the fuel usage estimates. The fuel usage data for each flight

was computed used great circle distances and distance-binned fuel data developed by ICAO. CO_2 emissions were estimated using a multiplier applied to fuel used. This dataset provides alternative metrics that are useful for studying historical traffic patterns beyond simply counting the number of flights.

A comparison of 2020 U.S. passenger and cargo departures and emissions shows similar trends to the ones found by the 2020 EUROCONTROL data. Based on the number of U.S. departures in 2020:

- Long-haul flights (those traveling more than 2485 statute miles) create 30% of aviation related CO_2 emissions but make up only 4% of the total number of U.S. departures.
- Short-haul flights (those traveling less than 311 statute miles) make up 21% of the total number of U.S. departures yet create less than 5% of aviation-related CO_2 emissions.

The 2020 analysis was extended to cover U.S. departure flights between 2016 and 2019. Key findings from the five-year timeframe include:

- The annual CO_2 travel and emission trends were relatively consistent over the timeframe from 2016 to 2020.
- In 2020, the COVID-19 pandemic caused a significant reduction in total air traffic, with a proportionally larger reduction in long-haul flights caused by cancellation of relatively more international than domestic flights.
- The very long-haul flights (those traveling more than 2485 statute miles), while few in terms of number of flights (less than 5%), generate a large fraction (30–36%) of CO_2 emissions.
- The greatest portion of U.S. aviation CO_2 emissions (36–39%) are created by flights traveling 932 to 2485 statute miles. A reduction of 10% in fuel use in the vehicles flying these missions has the potential to result in a 4% emissions reduction. This is the same amount to which all the short-haul flights contribute annually.
- Flights ranging from 932 to 2485 statute miles also account for the greatest portion (40–44%) of U.S. available seat-miles.
- Flights between 500 and 2000 statute miles generated approximately 50% of total 2020 emissions.

The data generated for this memorandum can be mined in other ways to understand flight patterns such as seasonal variations and network connectivity, and to quantify the potential benefits of fleet substitution, flown both domestically and internationally, to support future sustainable aviation studies. The data presented in this report can also be used to assess the potential of new technologies (e.g., electric aircraft) on projected GHG emission trends. The results of this study should help inform future climate-related decision making by both governments and industry.

References

[1] Federal Aviation Administration. (2021) *United States 2021 Aviation Climate Action Plan* Washington, D.C. GPO https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf

[2] EUROCONTROL Data Snapshot #4 on CO_2 Emissions by Flight Distance https://www.EUROCONTROL.int/publication/EUROCONTROL-data-snapshot-co2-emissions-flight-distance published Feb 16, 2021.

[3] Arneson, H. M., "Sherlock Data Warehouse", Rept. ARC-E-DAA-TN58006, 2018. https://ntrs.nasa.gov/citations/20180004248

[4] ICAO Carbon Emissions Calculator Methodology, Version 11, June 2018. https://www.icao.int/environmental-protection/CarbonOffset/Documents/Methodology%20ICAO%20Carbon%20Calculator_v11-2018.pdf

[5] Zeng, X., S., Rutherford, D., "Fuel Burn of New Commercial Jet Aircraft: 1960 TO 2019," ICCT White Paper, 2020. https://theicct.org/sites/default/files/publications/Aircraft-fuel-burn-trends-sept2020.pdf

[6] Quadros, F. D. A., Snellen, M., Sun, J., Dedoussi, I. C., "Global Civil Aviation Emissions Estimates for 2017–2020 Using ADS-B Data" Journal of Aircraft, May 2022.

[7] Seymour, K., Held, M., Georges, G., Boulouchos, K., "Fuel Estimation in Air Transportation: Modeling Global Fuel Consumption for Commercial Aviation," Transport. Res. Part D: Transport Environ., 88 (2020), Article 102528.

[8] https://www.transtats.bts.gov/Data_Elements.aspx?Data=2 "Passengers: All Carriers – All Airports".

Appendix A: Aircraft Model and ICAO Codes

Table 3. Selected aircraft models, ICAO codes, IATA codes, and number of seats

ICAO Type	IATA Type	Model	No. of Seats (Average)	ICAO Type	IATA Type	Model	No. of Seats (Average)
A124	A4F	Antonov AN-124 Ruslan	0	B737	73G	Boeing 737-700 pax	130
A20N	320	Airbus A320 NEO (unverified)	183	B738	73H	Boeing 737 all pax models Boeing 737-800 pax Boeing 737-800 (winglets) pax	161
A21N	321	Airbus 321 NEO (unverified)	220	B739	739	Boeing 737-900 pax Boeing 737-900 (winglets) pax	174
A306	ABY	Airbus Industries A600-600 Freighter	0	B744	B74E	Boeing 747-400 pax Boeing 747-400 Combi Boeing 747-400 (Domestic) pax Boeing 747 all Combi models	368
A30B	AB3	Airbus A300B2, A300B4, and A300C4	240	B748	B74H	Boeing 747-8I Passenger Boeing 747-8F	366
A310	310	Airbus 310 pax	211	B752	722	Boeing 757-200 pax Boeing 757 all pax models Boeing 757-200 (winglets) pax Boeing 757-200 (winglets) pax Boeing 757 Mixed Configuration	184
A318	318	Airbus A318 Airbus A318 (sharklets)	116	B753	753	Boeing 757-300 pax	228
A319	319	Airbus A319 Airbus A319 (sharklets)	128	B762	762	Boeing 767-200 pax	220
A320	320	Airbus A320-100/200 Ceo Airbus A320-200 Ceo (Sharklets) Airbus A318/319/320/321 Airbus A320 Freighter	152	B763	76W	Boeing 767-300 pax Boeing 767 all pax models Boeing 767-300 (winglets) pax	225
A321	321	Airbus A321-100/200 Ceo	187	B764	764	Boeing 767-400 pax	253
A332	332	Airbus A330-200 Airbus A330-200 Freighter Airbus A330-200 Freighter	256	B772	772	Boeing 777-200 pax Boeing 777-200LR pax	270
A333	333	Airbus A330-300	280	B77L	77F	Boeing 777 Freighter	286
A342	342	Airbus A340-200	250	B77W	77W	Boeing 777 all pax models Boeing 777-300ER pax	302
A343	343	Airbus A340-300	295	B788	788	Boeing 787-8 pax Boeing 787-8 pax	220
A346	346	Airbus 340-600	380	B789	789	Boeing 787-9 pax (unverified)	290
A359	359	Airbus A350-900ULR (unverified)	100	B78X	78X	Boeing 787-10 (unverified)	300
A388	388	Airbus A380 pax	491	BCS1	221	Airbus A220-100	109
AT43	AT3	Aerospatiale/Alenia ATR 42-300 / 320	48	BE80	BE2	Beechcraft twin piston engines	6
AT45	AT5	Aerospatiale/Alenia ATR 42-500	48	BE9L	BET	Beechcraft light aircraft - twin turboprop engine	10
AT72	ATR	Aerospatiale/Alenia ATR 72	67	BN2P	BNI	Pilatus Britten-Norman BN-2A/B Is	10
B190	BEH	Beechcraft 1900D	19	C208	CNC	Cessna light aircraft - single turbop	0
B38M	7M8	Boeing 737 Max 8 (unverified)	173	C210	CN1	Cessna light aircraft - single piston	3
B712	717	Boeing 717	114	C212	CS2	CASA / IPTN 212 Aviocar	28
B722	722	Boeing 727, all pax models	170	C68A	CNJ	Cessna CitationLatitude (unverified)	9
B732	732	Boeing 737-200 PAX	115	C750	CNJ	Cessna Citation	10
B733	733	Boeing 737-300 pax	128	CL60	CCJ	Canadair Challenger	18
B734	734	Boeing 737-400	162	CRJ	CRJ	Canadair Regional Jet	90
B735	735	Boeing 737-500 pax	116	CRJ1	CR1	Canadair Regional Jet 100	50
B736	736	Boeing 737-600 pax	112	CRJ2	CR2	Canadair Regional Jet 200	50

ICAO Type	IATA Type	Model	No. of Seats (Average)		ICAO Type	IATA Type	Model	No. of Seats (Average)
CRJ7	CR7	Canadair Regional Jet 700 | Regional Jet 550	68		MD83	M83	McDonnell Douglas MD83	158
CRJ9	CR9	Canadair Regional Jet 900	81		MD88	M88	McDonnell Douglas MD88	158
CVLT	CV5	Convair CV-580 pax	0		MD90	M90	McDonnell Douglas MD90	166
D228	D28	Fairchild Dornier Do.228	19		MU2	MU2	Mitsubishi Mu-2	10
D328	D38	Fairchild Dornier Do.328	30		P68	PN6	Partenavia P.68	5
DC10	D10	Douglas DC-10 pax	280		PA44	PAT	Piper light aircraft - twin turboprop e	3
DC87	D8Y	Douglas DC-8-71 / 72 / 73 Freighters	0		PA46	PAG	Piper PA-46	6
DC9	DC9	Douglas DC-9 all pax models	115		PC12	PL2	Pilatus PC-12	10
DC91	D91	Douglas DC-9-10 pax	50		S76	S76	Sikorsky S-76	14
DC93	D93	Douglas DC-9-30 pax	115		SF34	SF3	Saab SF340	34
DH8A	DH1	De Havilland Canada DHC-8-100 Dash 8 /	39		SH33	SH3	Shorts SD.330	30
DH8B	DH2	De Havilland Canada DHC-8-200 Dash 8 /	39		SH36	SH6	Shorts SD.360	36
DH8C	DH3	De Havilland Canada DHC-8-300 Dash 8 /	53		SU95	SU9	Sukhoi Superjet 100-95	98
DH8D	DH4	De Havilland DHC-8-400 Dash 8Q	76		SW4	SWM	Fairchild (Swearingen) SA26 / SA226 / SA227 Metro / Merlin / Expediter	9
DHC6	DHT	De Havilland Canada DHC-6 Twin Otter	9		WW24	WWP	Israel Aircraft Industries 1124 Westwind	10
E110	EMB	Embraer EMB.110 Bandeirnate	18					
E120	EM2	Embraer 120 Brasilla	30					
E135	ERD	Embraer RJ140	37					
E145	ER4	Embraer RJ145 Amazon	50					
E170	E70	Embraer 170	72					
E190	E90	Embraer 190	100					
E195	E95	Embraer 195	116					
E35L	ER3	Embraer Legacy 600 / Legacy 650	14					
E45X	ERD	Embraer RJ145 (unverified)	37					
E55P	E55	Embraer Phenom 300 (unverified)	8					
E75L	E75	Embraer 175 (long wing)	75					
E75S	E75	Embraer ERJ 170-100	78					
F2TH	DF2	Dassault (Breguet Mystere) Falcon 10 / 100 / 20 / 200 / 2000	14					
IL76	IL7	Ilyushin IL76	0					
J328	FRJ	Fairchild Dornier 328JET	33					
JS31	J31	British Aerospace Jetstream 31	19					
JS32	J32	British Aerospace Jetstream 32	20					
LJ45	LRJ	Gates Learjet	10					
MD11	M11	McDonnell Douglas MD11 pax McDonnell Douglas MD11 Freighter McDonnell Douglas MD11 Mixed Configuration	279					
MD82	M82	McDonnell Douglas MD82	155					

Appendix B: 2016–2019 Flights, Fuel, and Emissions Data

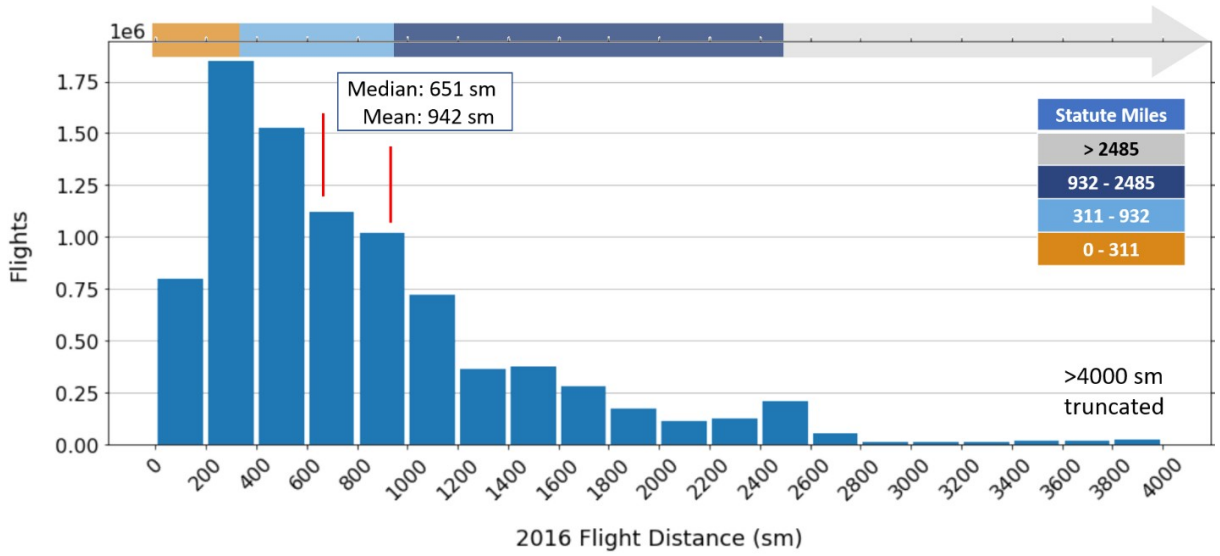

Figure 18a. Histogram of number of flights flown in 2016 by distance, in 200-statute mile increments.

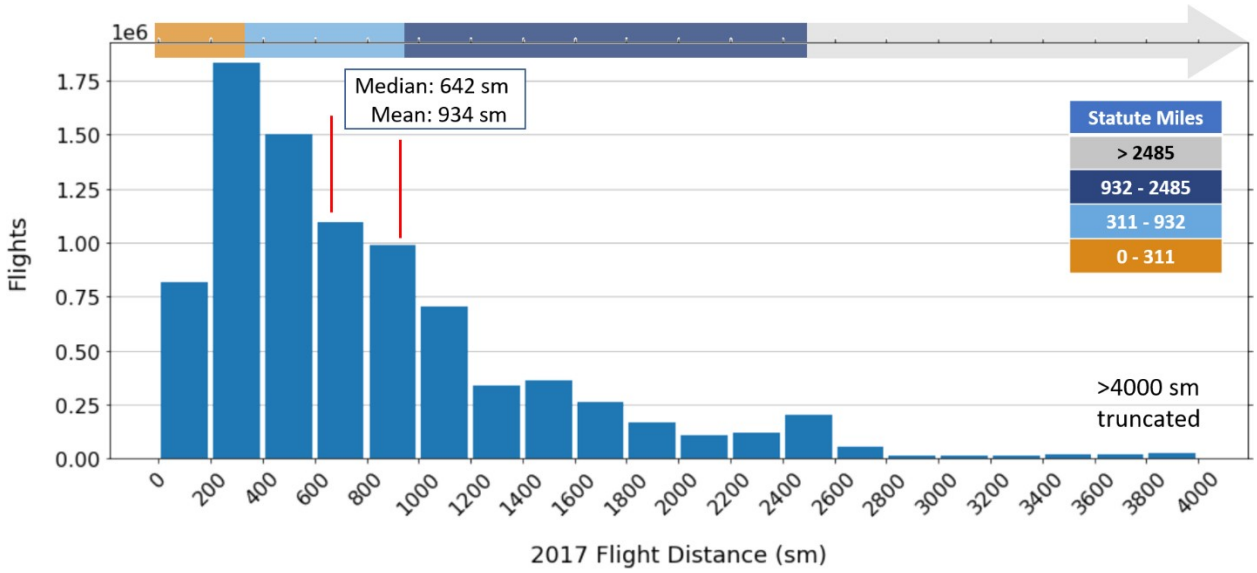

Figure 18b. Histogram of number of flights flown in 2017 by distance, in 200-statute mile increments.

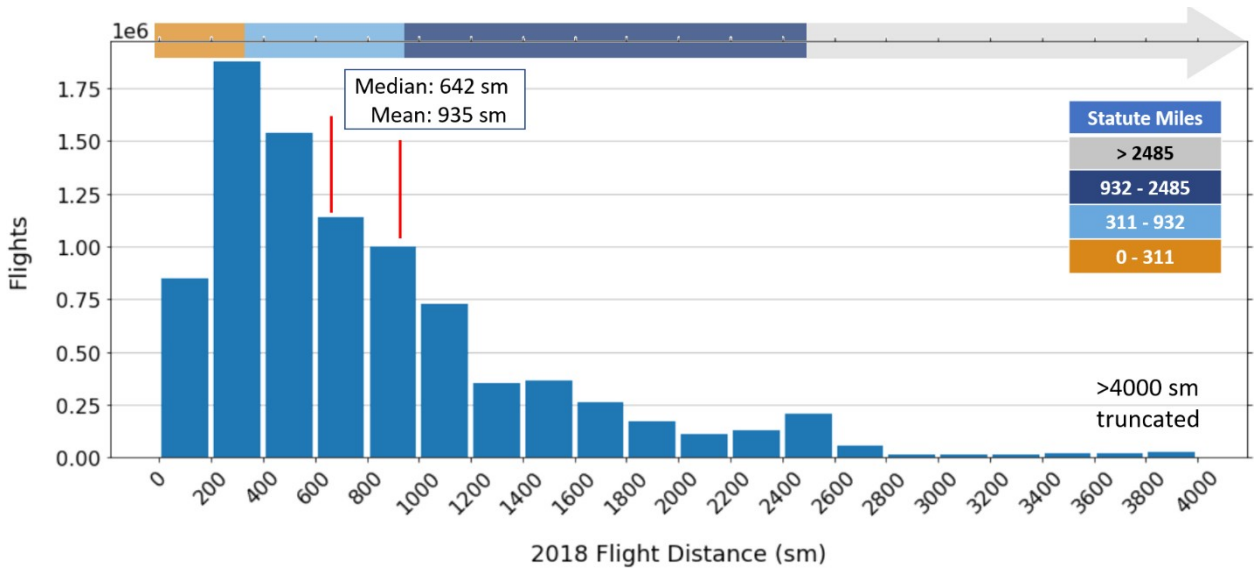

Figure 18c. Histogram of number of flights flown in 2018 by distance, in 200-statute mile increments.

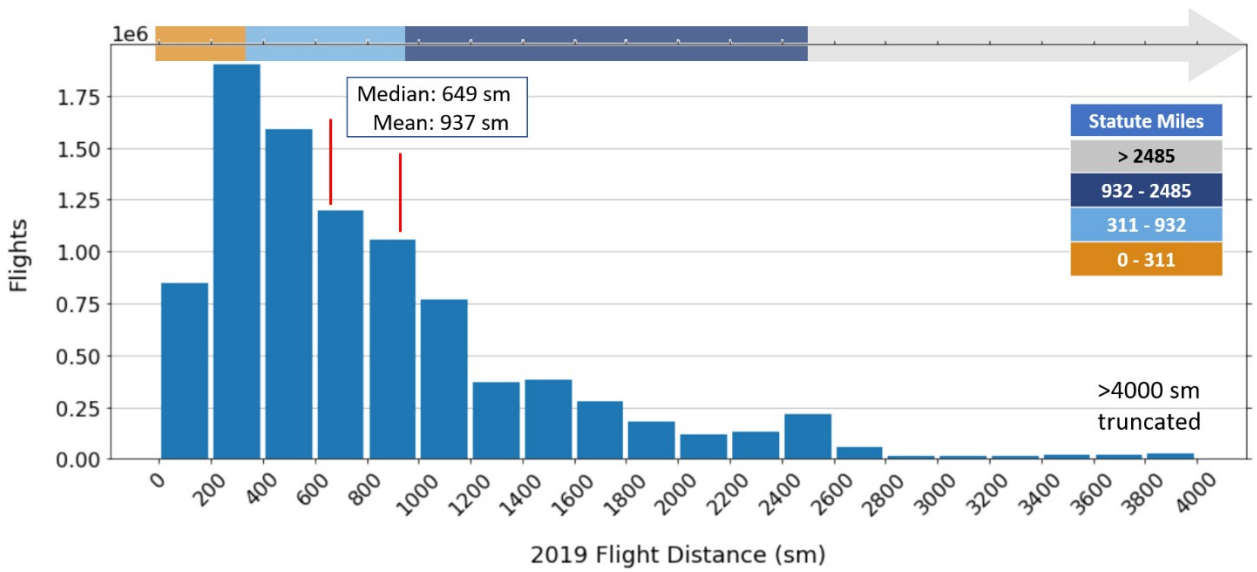

Figure 18d. Histogram of number of flights flown in 2019 by distance, in 200-statute mile increments.

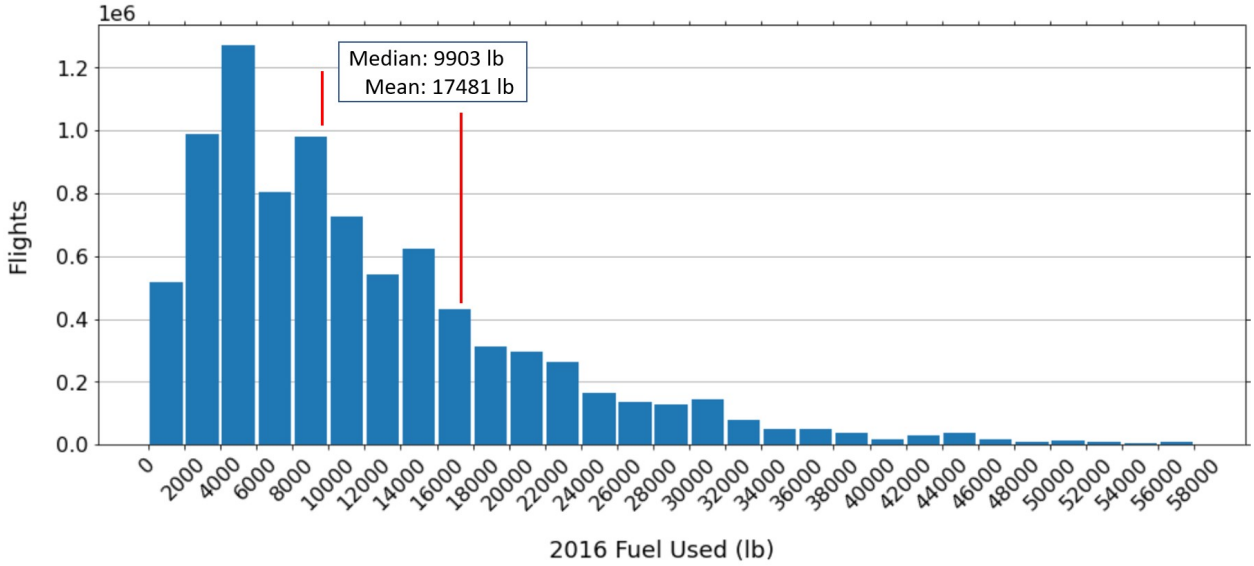

Figure 19a. Histogram of number of flights flown in 2016 by fuel used.

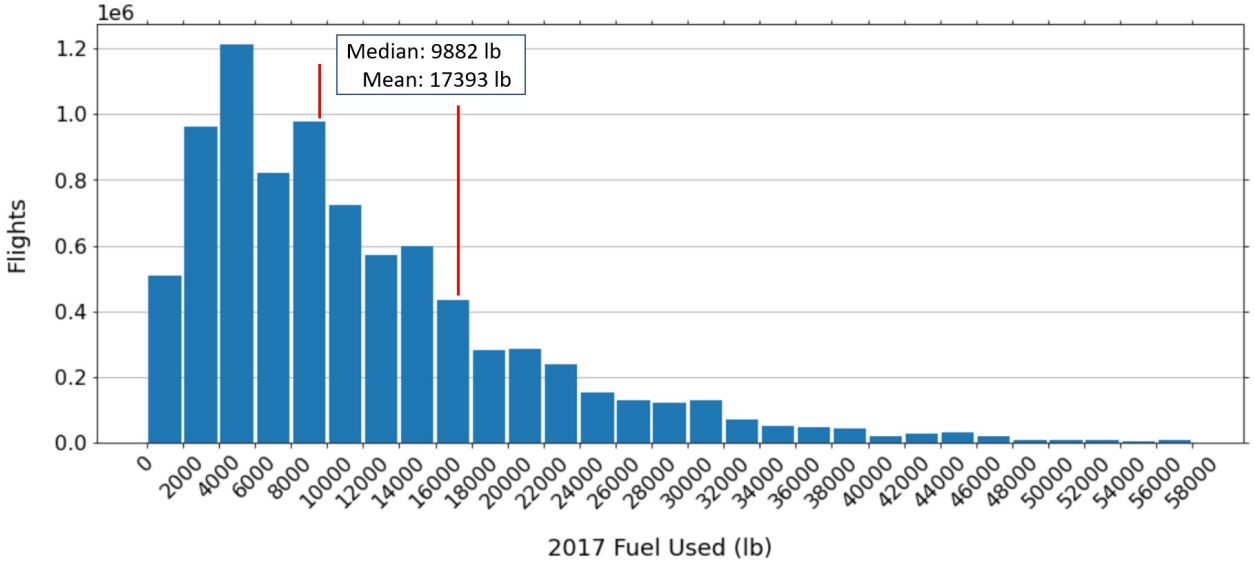

Figure 19b. Histogram of number of flights flown in 2017 by fuel used.

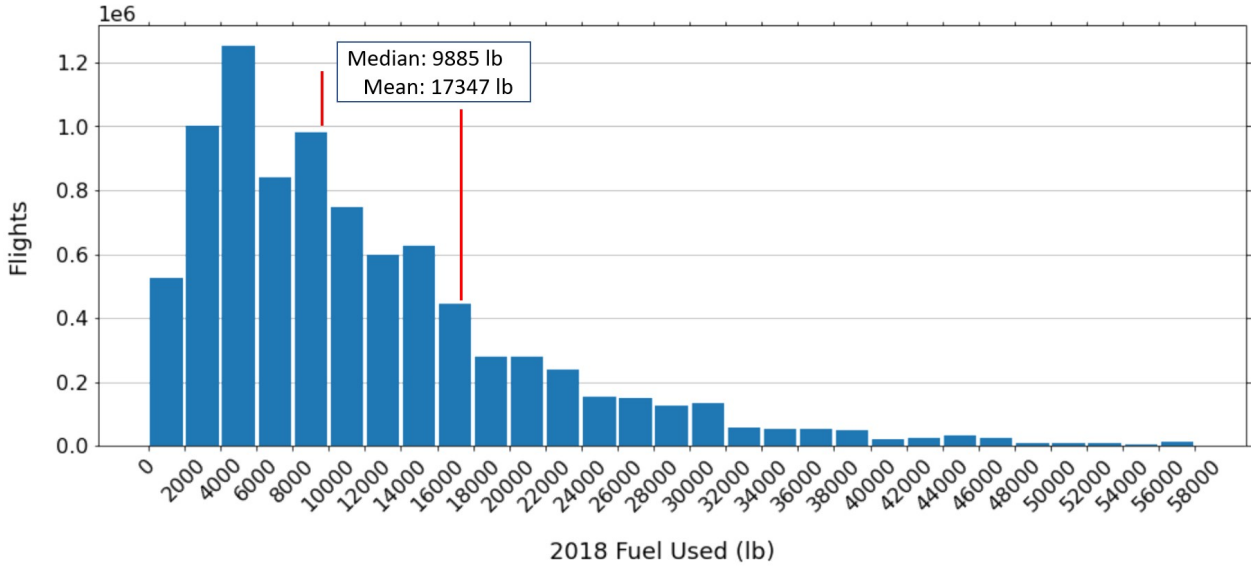

Figure 19c. Histogram of number of flights flown in 2018 by fuel used.

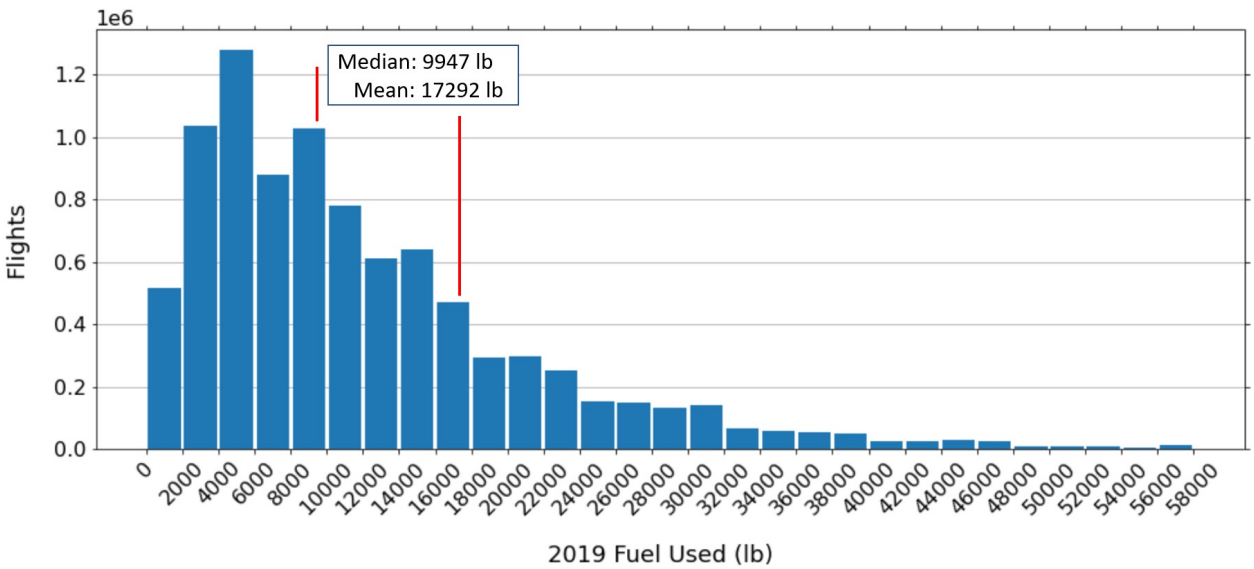

Figure 19d. Histogram of number of flights flown in 2019 by fuel used.

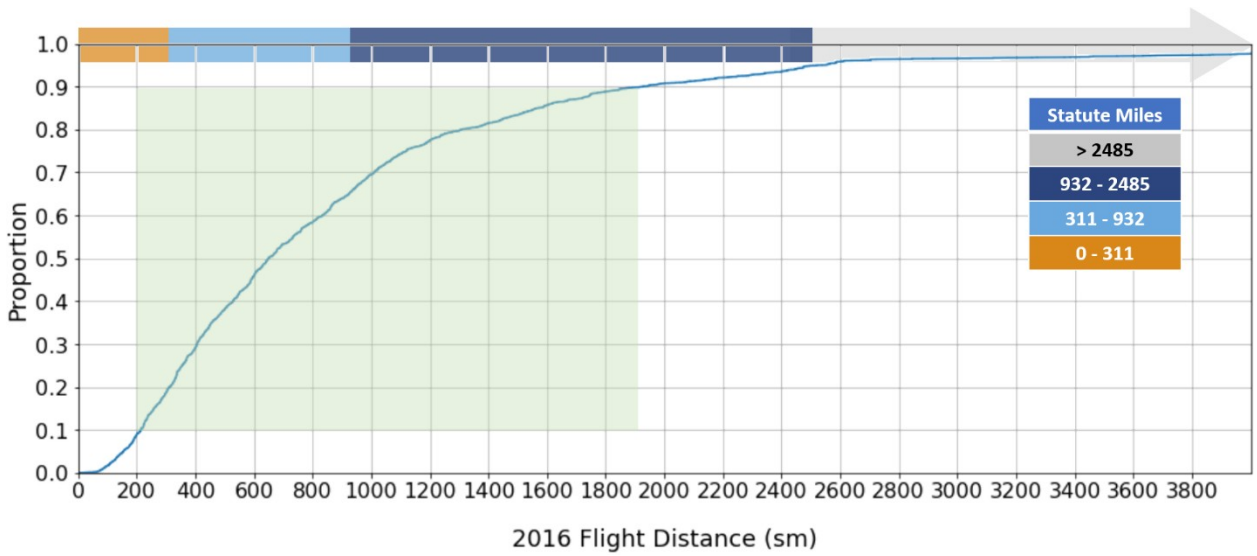

Figure 20a. Cumulative distribution of number of flights flown in 2016 by distance.

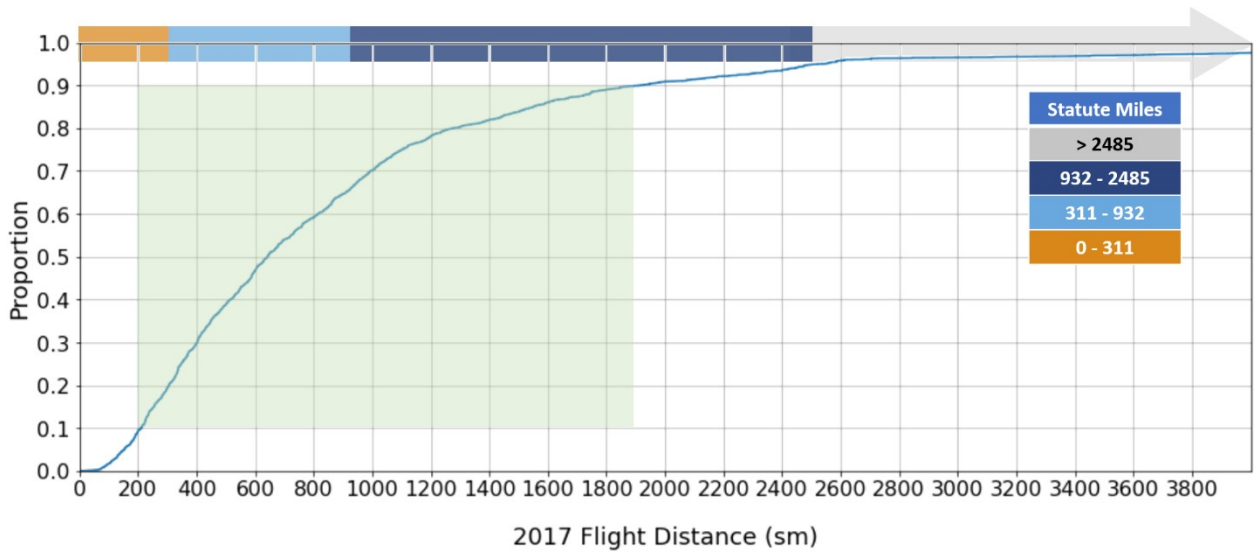

Figure 20b. Cumulative distribution of number of flights flown in 2017 by distance.

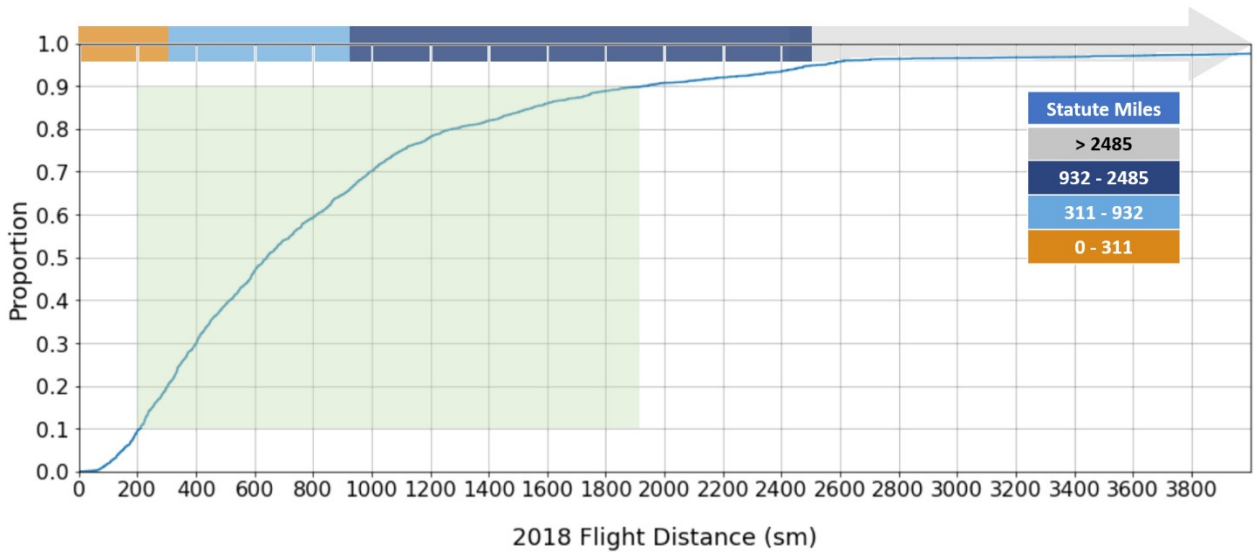

Figure 20c. Cumulative distribution of number of flights flown in 2018 by distance.

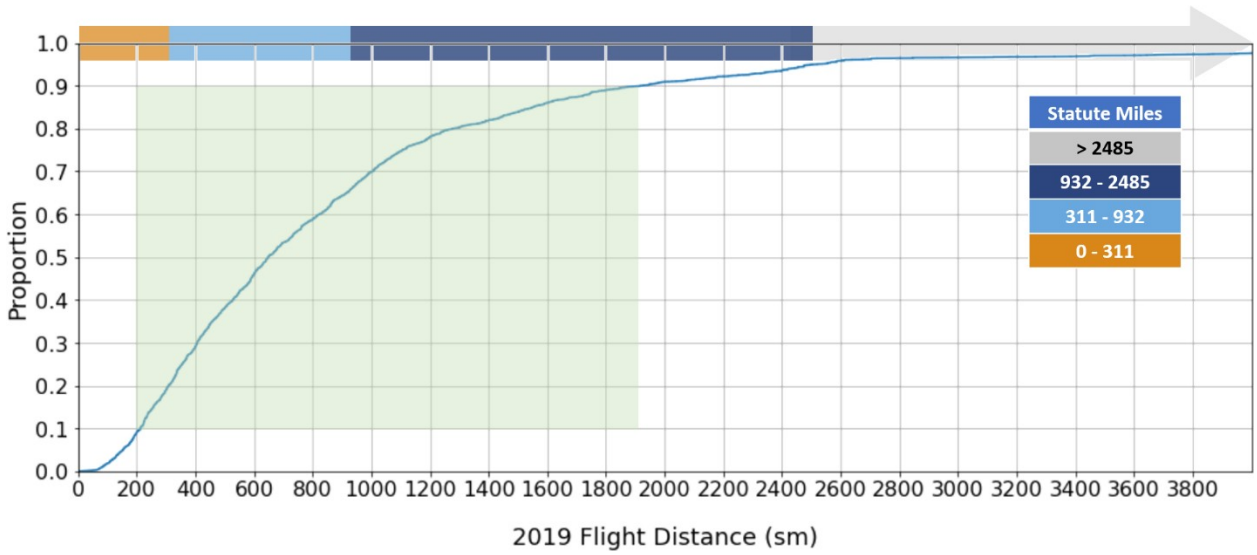

Figure 20d. Cumulative distribution of number of flights flown in 2019 by distance.

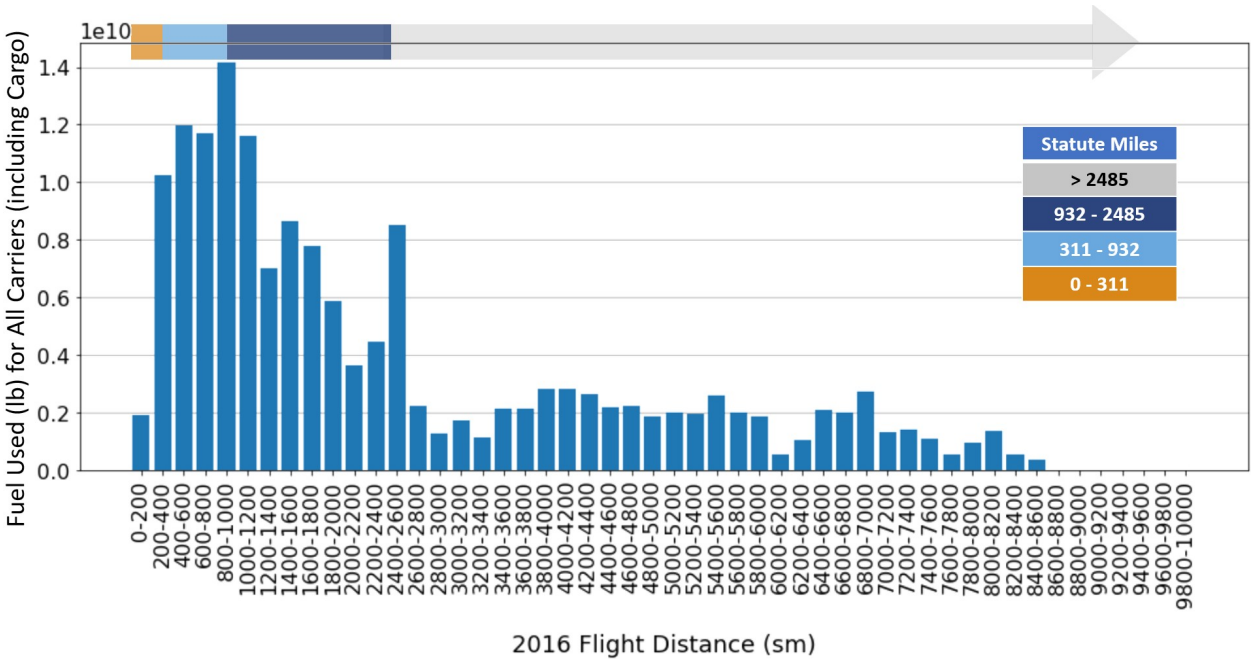

Figure 21a. Histogram of fuel used in 2016 by distance in 200-statute mile increments.

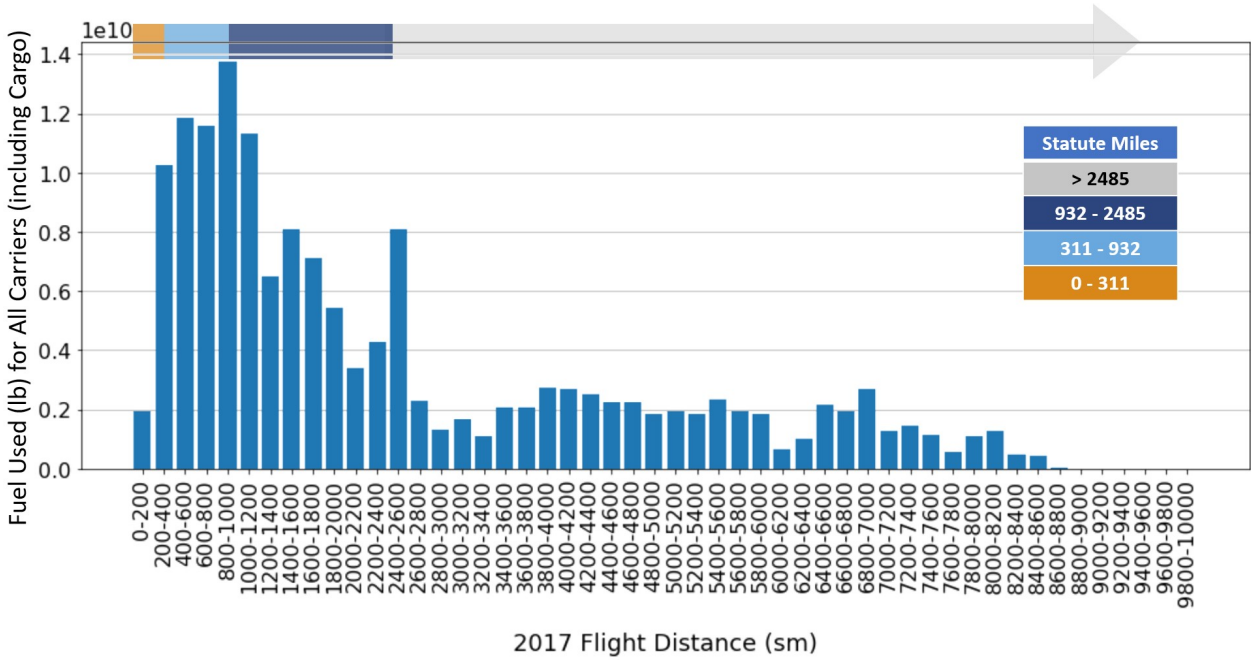

Figure 21b. Histogram of fuel used in 2017 by distance in 200-statute mile increments.

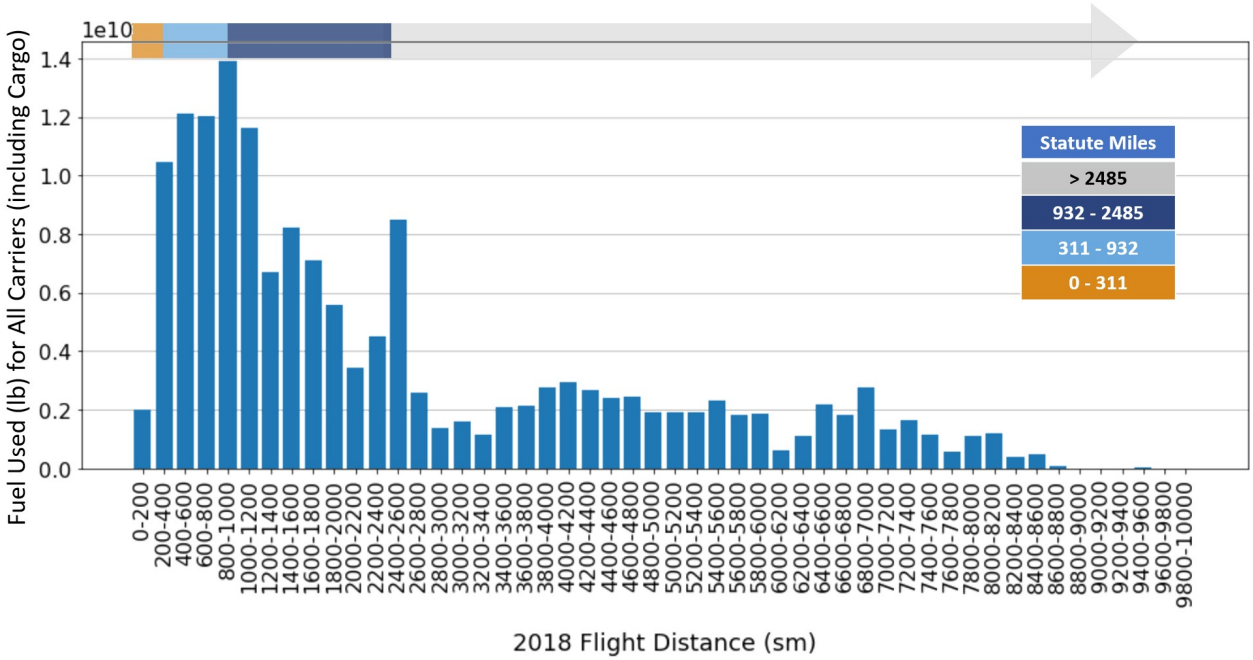

Figure 21c. Histogram of fuel used in 2018 by distance in 200-statute mile increments.

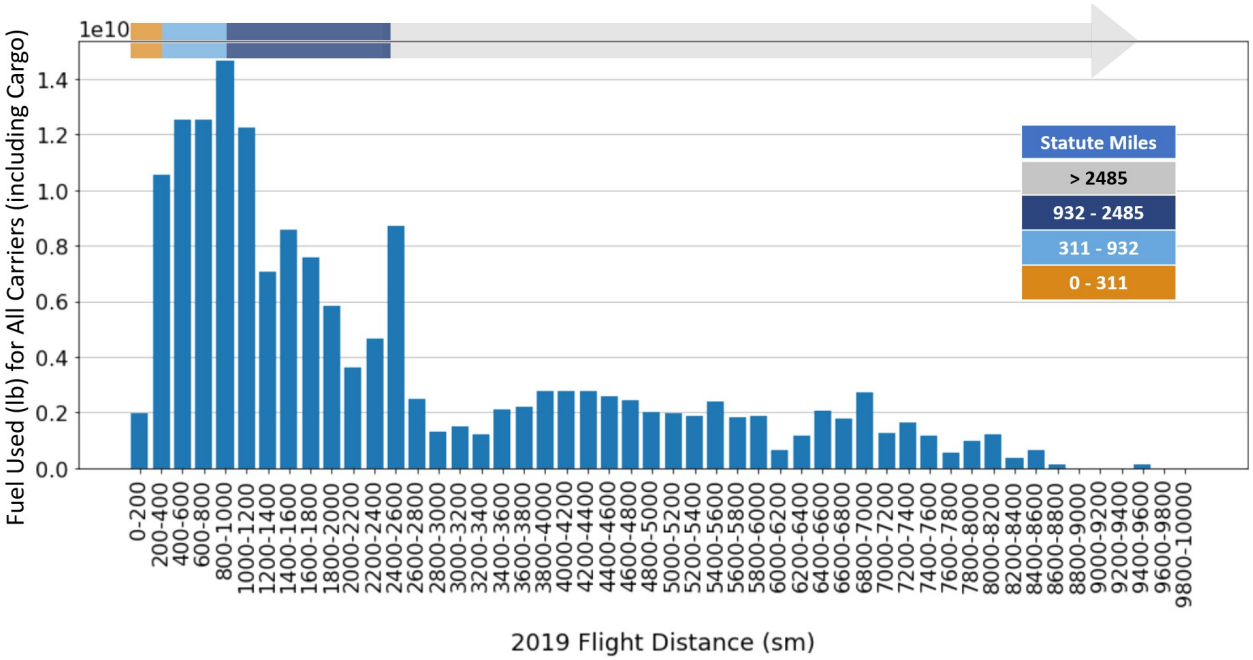

Figure 21d. Histogram of fuel used in 2019 by distance in 200-statute mile increments.

Appendix C: Top 50 Aircraft Based on 5-Year Average Fuel Used

Table 4. Top 50 aircraft based on estimated average annual fuel used (millions of lb) between 2016–2020.

ICAO ID	2016	2017	2018	2019	2020	5-year Avg
B738	15191.5	15606.4	16352.2	16631.0	10460.6	14848.3
B737	14049.2	13653.3	13582.6	13434.4	8259.9	12595.8
A320	12102.1	11276.0	11601.5	12615.0	6355.3	10789.9
B77W	9101.0	9946.6	10160.8	10067.0	5951.7	9045.4
A321	7323.0	8506.7	10266.0	11611.0	6829.4	8907.2
B739	6522.0	6848.9	7571.8	8535.5	4659.2	6827.4
B744	8037.1	7239.6	6785.0	6357.5	5184.6	6720.7
B763	6978.1	6579.3	6727.0	7237.2	5989.6	6702.2
B752	7805.0	6964.2	6914.9	7126.2	3950.1	6552.0
B772	6892.7	6499.9	6647.4	6892.6	2256.6	5837.8
A319	5924.9	5543.2	5510.1	5727.9	3590.8	5259.3
A388	4245.1	3942.9	3776.8	3685.2	703.0	3270.5
MD11	3310.3	3142.2	3137.9	2959.5	3167.6	3143.4
B77L	2863.0	2975.4	2966.6	3249.7	3460.0	3102.9
A333	3125.6	3282.2	3380.9	3397.2	1240.6	2885.3
A332	3331.4	3335.0	3274.5	3190.7	1113.4	2848.9
E75L	967.1	2719.0	3227.4	3857.4	2954.9	2745.1
B748	2763.9	2608.5	2683.0	2881.6	2411.6	2669.7
CRJ9	2758.0	2679.0	2671.6	2845.4	1899.8	2570.7
B789	1166.7	1987.3	2909.2	3700.9	2592.3	2471.2
CRJ7	2544.8	2401.2	2337.9	2079.3	1344.6	2141.5
A306	2134.0	2027.0	2104.8	2119.0	2219.5	2120.8
CRJ2	2570.0	2194.5	2112.0	2095.2	1081.4	2010.6
MD88	2580.3	2392.7	2010.1	1292.2	255.6	1706.1
B788	1988.9	1927.3	1850.4	1750.5	903.7	1684.1
E170	2659.2	1037.7	1117.9	1313.5	959.2	1417.4
A359	219.7	657.9	1865.6	2604.4	1536.3	1376.7
E145	1678.3	1502.0	1427.5	1436.3	688.4	1346.5
B712	1431.8	1457.8	1445.9	1390.8	697.3	1284.6
B753	1248.0	1167.6	1105.4	1177.1	564.5	1052.5
B764	1166.5	1108.1	1182.2	1124.0	294.7	975.1
DC10	1508.4	1122.2	929.4	714.2	575.0	969.8
E190	1180.4	1122.9	1108.9	1086.3	336.4	966.9
MD83	1631.3	1280.6	877.1	374.8	16.4	836
E75S	297.8	1040.2	1085.8	1090.7	625.2	827.9
MD90	1269.4	1149.2	892.6	585.0	101.0	799.4
A346	1102.6	933.7	699.0	699.4	113.1	709.5
B733	2059.8	1042.4	22.6	41.2	53.8	643.9

B762	630.2	642.1	606.3	587.8	646.9	622.6
A343	815.8	583.1	510.3	393.7	124.9	485.5
A21N			231.3	513.5	664.2	469.6
E45X	529.4	364.0	360.1	355.0	171.3	355.9
A20N			4.6	62.5	859.8	308.9
DH8D	375.0	324.9	280.0	226.9	140.2	269.4
E135	141.8	70.3	312.5	446.6	202.7	234.7
B78X			3.5	259.0	436.3	232.9
B38M		15.9	623.3	254.0	1.0	223.5
MD82	699.7	250.0	125.0	13.9	0.4	217.8
BCS1			3.3	275.3	367.0	215.1
B734	384.3	228.3	175.2	148.7	97.2	206.7

Appendix D: Top 35 Aircraft per Year, 2016–2019

Figures 22–25 show the top 35 aircraft per year, from 2016–2019, based on total estimated fuel used. Each figure shows the vehicle type sorted by total flights flown, total distance traveled (statute miles), total estimated fuel used (pounds), and total available seat-miles (statute miles). The bar and pie charts show the contributions by distance bin (in statute miles): 0–311 (orange), 311–932 (light blue), 932–2485 (dark blue), and > 2485 (grey).

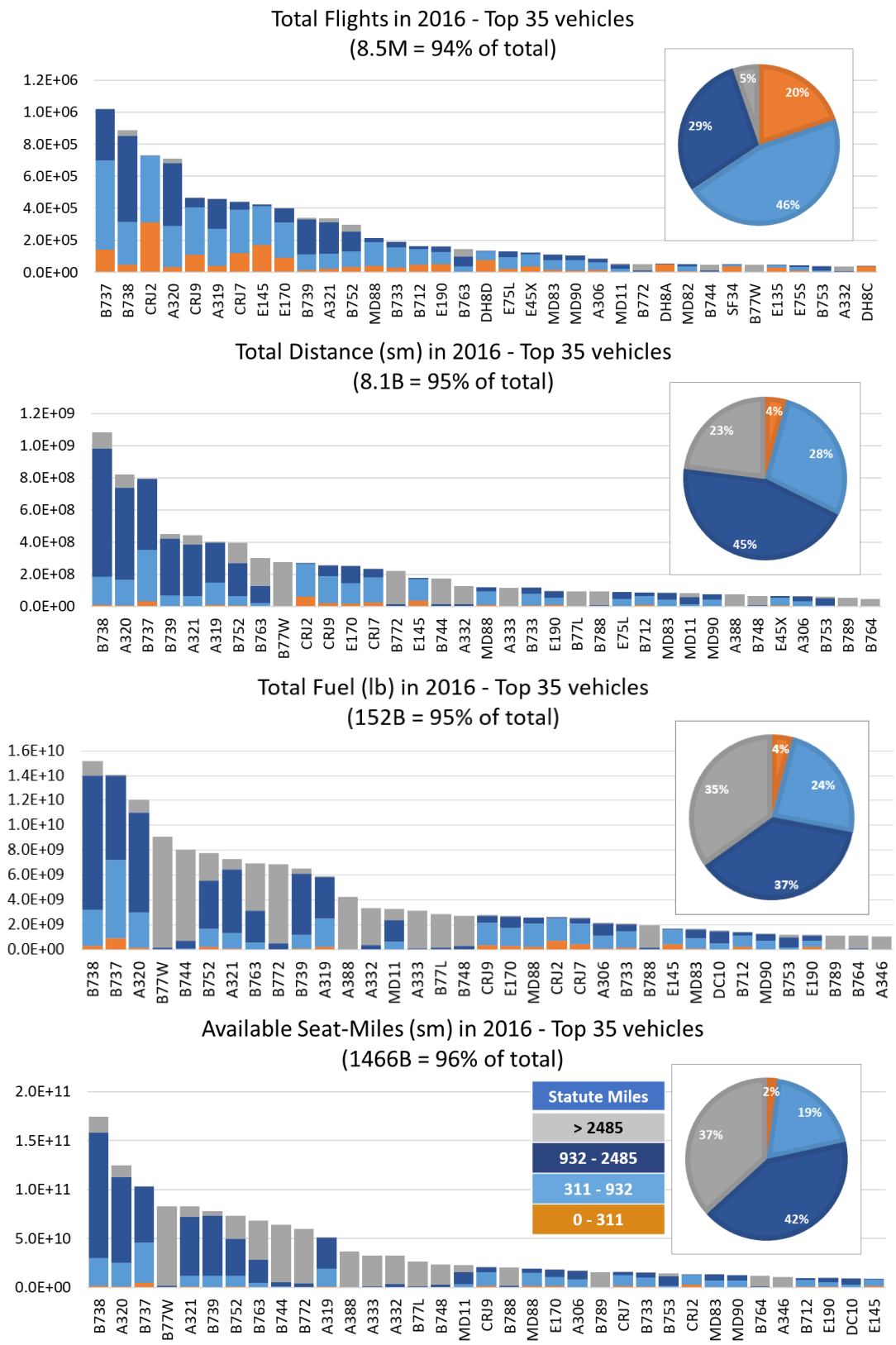

Figure 22. 2016 U.S. flight data for the top 35 vehicles by flight count, distance flown, fuel used and available seat-miles.

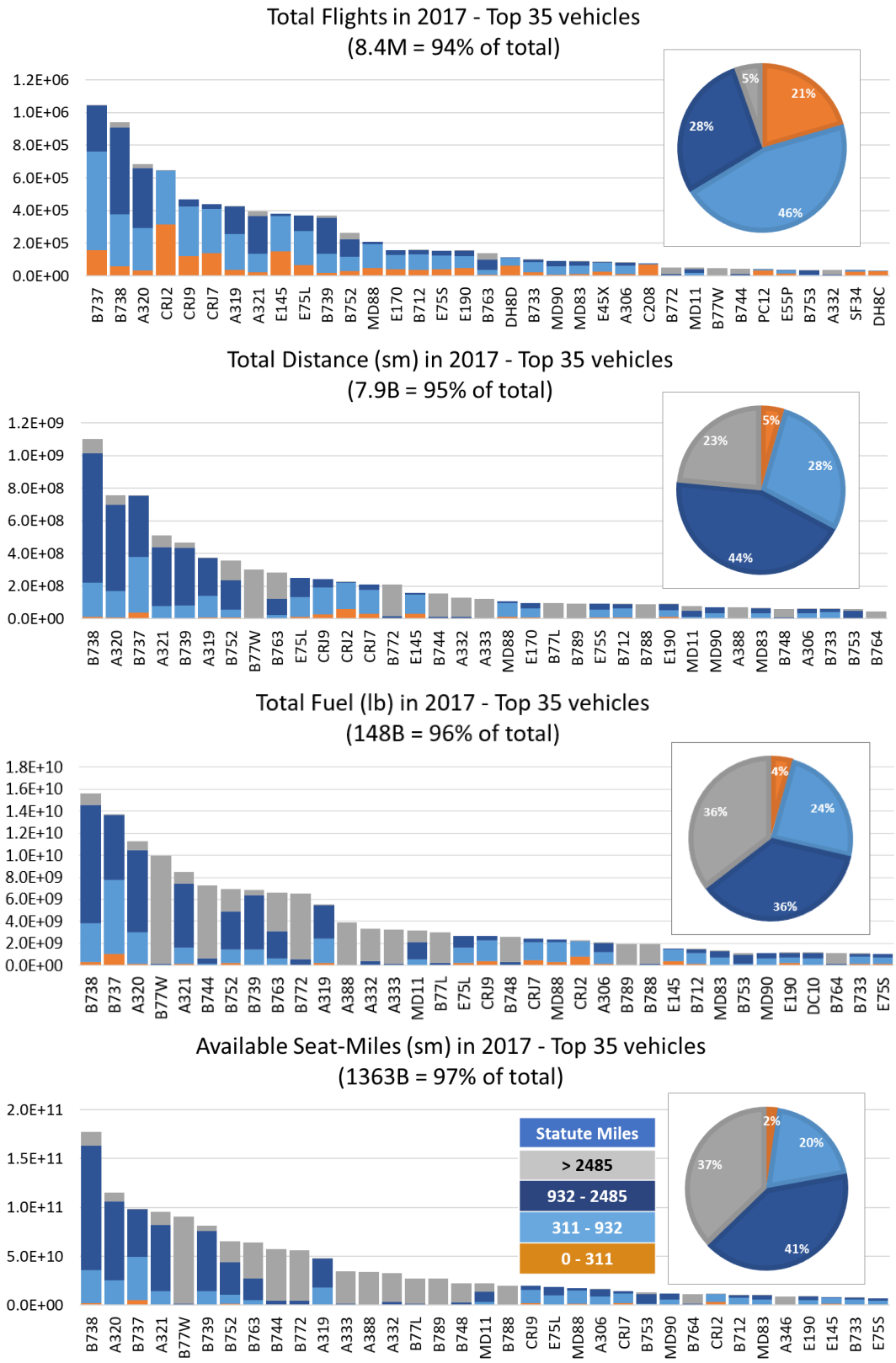

Figure 23. 2017 U.S. flight data for the top 35 vehicles by flight count, distance flown, fuel used and available seat-miles.

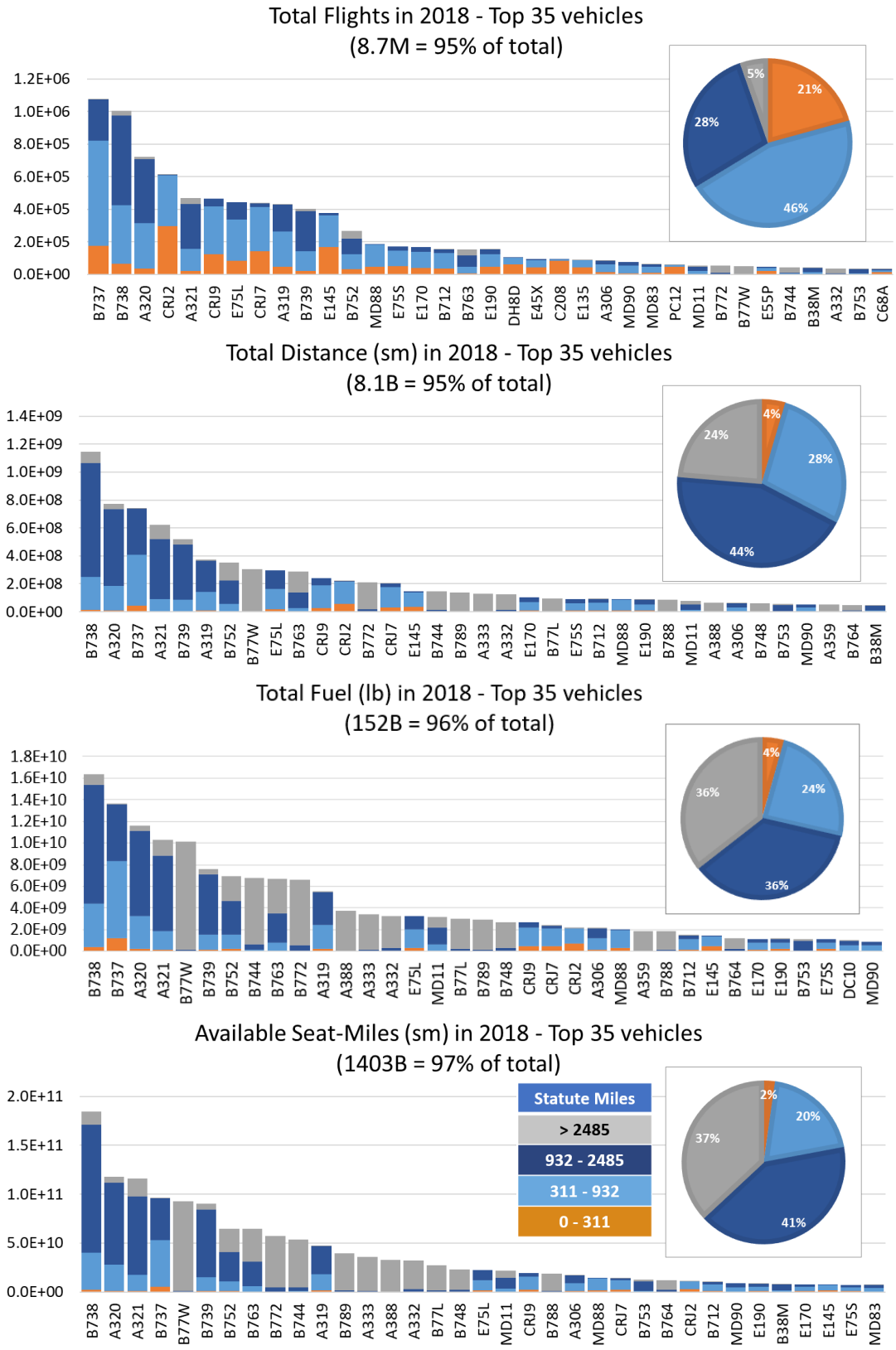

Figure 24. 2018 U.S. flight data for the top 35 vehicles by flight count, distance flown, fuel used and available seat-miles.

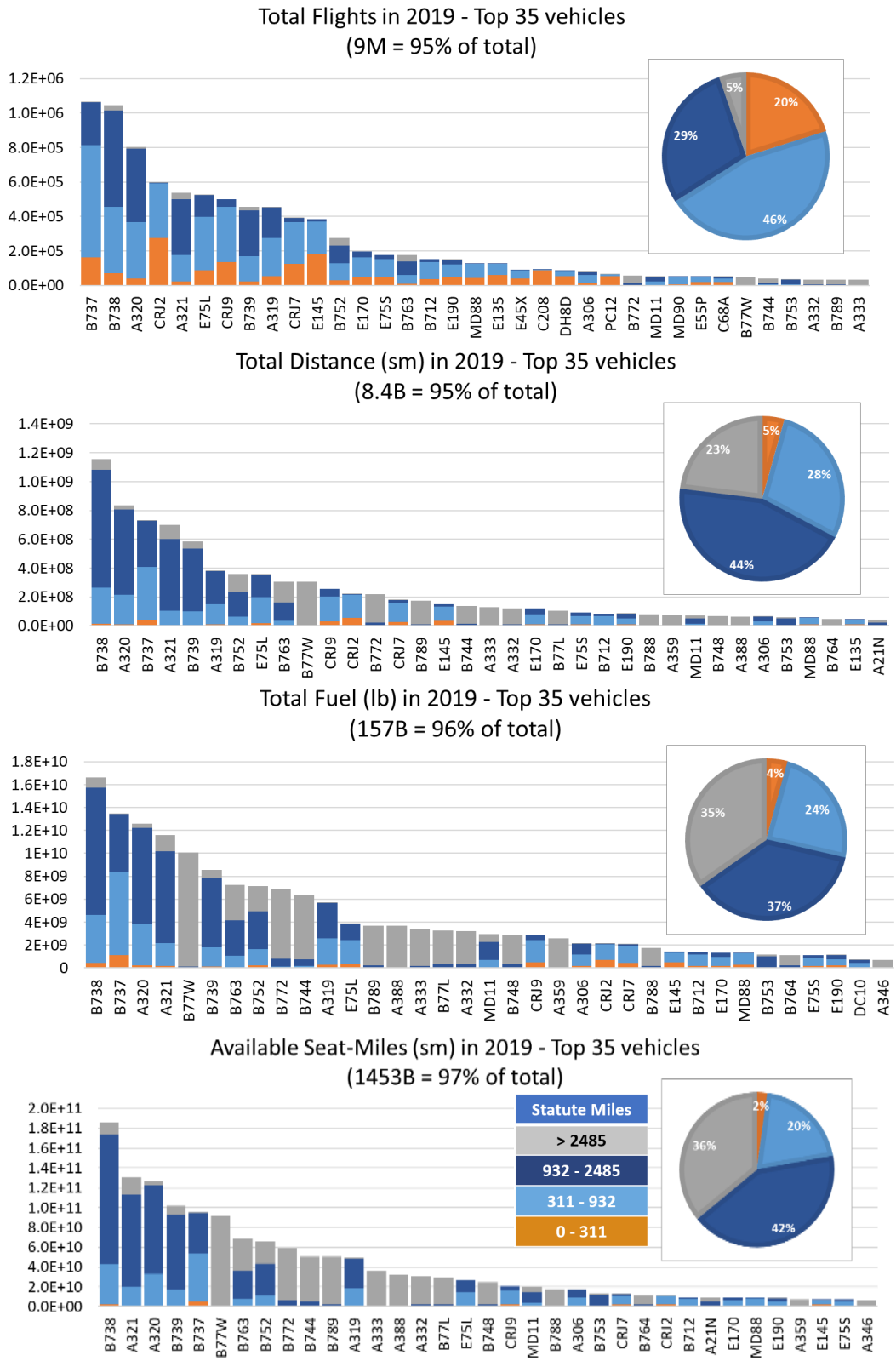

Figure 25. 2019 U.S. flight data for the top 35 vehicles by flight count, distance flown, fuel used and available seat-miles.