WORKING PAPER 2019-16

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

CO_2 emissions from commercial aviation, 2018

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Date: September 2019

Keywords: aviation; aircraft; fuel efficiency; carbon dioxide

SUMMARY

Greenhouse gas emissions from commercial aviation are rapidly increasing, as is interest among fliers in reducing their carbon footprints. Under a business-as-usual trajectory, the United Nations' International Civil Aviation Organization (ICAO) expects aviation emissions to roughly triple by 2050, at which time aircraft might account for 25% of the global carbon budget.

Although ICAO and the International Air Transport Association (IATA) publish annual summary statistics of aircraft operations and economics, respectively, relatively little data is available about fuel burn, fuel efficiency, and carbon emissions at the regional and national levels. Policymakers cannot determine the precise amount of carbon emissions associated with flights departing from individual countries, nor can they distinguish the proportion of emissions from passenger-and-freight and all-freight operations, or from domestic and international flights.

To better understand carbon emissions associated with commercial aviation, this paper develops a bottom-up, global aviation CO_2 inventory for calendar year 2018. Using historical data from OAG Aviation Worldwide Limited, national governments, international agencies, and the Piano aircraft emissions modelling software, this paper details a global, transparent, and geographically allocated CO_2 inventory for commercial aviation. Our estimates of total global carbon emissions, and the operations estimated in this study in terms of revenue passenger kilometers (RPKs) and freight tonne kilometers (FTKs), agree well with aggregate industry estimates.

Nearly 39 million flights from 2018 were analyzed, and 38 million of these were flown by passenger aircraft. Total CO_2 emissions from all commercial operations, including passenger movement, belly freight, and dedicated freight, totaled 918 million metric tons (MMT) in 2018. That is 2.4% of global CO_2 emissions from fossil fuel use and a 32% increase over the past five years. Further, this emissions growth rate is 70% higher than assumed under current ICAO projections.

The data shows that passenger transport accounted for 747 MMT, or 81%, of total emissions from commercial aviation in 2018. Globally, two-thirds of all flights were domestic, and these accounted for approximately one-third of global RPKs and 40% of global passenger transport-related CO_2 emissions. On a national level, flights departing airports in the United States and its territories emitted almost one-quarter (24%) of global passenger transport-related CO_2, and two-thirds of those emissions came from domestic flights. The top five countries for passenger aviation-related carbon emissions were rounded out by China, the United Kingdom, Japan, and Germany. CO_2 emissions from aviation were distributed unequally across nations; less developed countries that contain half of the world's population accounted for only 10% of all emissions.

This paper also apportions 2018 emissions by aircraft class and stage length. Passenger movement in narrowbody aircraft was linked to 43% of aviation CO_2, and passenger emissions were roughly equally divided between short-, medium-, and long-haul operations. The carbon intensity of flights averaged between 75 and 95 grams (g) of CO_2 per RPK, rising to almost 160 g CO_2/RPK for regional flights less than 500 kilometers.

BACKGROUND

Greenhouse gas emissions from commercial aviation are rapidly increasing. If the global aviation sector were treated as a nation, it would have been

Acknowledgments: *We thank Sola Zheng for her assistance in preparing the data file and graphics associated with this paper, and Dale Hall, Jennifer Callahan, Joe Schultz, Annie Petsonk, and Bill Hemmings for providing constructive feedback on an initial draft. This work was conducted with generous support from the Aspen Global Change Institute.*

the sixth-largest source of carbon dioxide (CO_2) emissions from energy consumption in 2015, emitting more than Germany (Air Transport Action Group [ATAG], 2019; Olivier, Janssens-Maenhout, Muntean, & Peters, 2016). The International Civil Aviation Organization (ICAO), the United Nations organization with authority over global aviation, expects CO_2 emissions from international aviation to approximately triple by 2050 if current trends hold (ICAO, 2019a). If other sectors decarbonize in line with the Paris Agreement's climate ambitions, aviation could account for one-quarter of the global carbon budget by mid-century (Pidcock & Yeo, 2016).

In 2009, the International Air Transport Association (IATA), the global trade association for cargo and passenger air carriers, set three goals for reducing CO_2 emissions from aviation: (1) an average improvement in fuel efficiency of 1.5% per year from 2009 to 2020; (2) a limit on net aviation CO_2 emissions after 2020 (i.e., carbon-neutral growth); and (3) a 50% reduction in net aviation CO_2 emissions by 2050, relative to 2005 levels (IATA, 2018a). According to industry estimates, global CO_2 emissions from the airline industry were 862 million metric tonnes (MMT) in 2017, and fuel efficiency has improved by 2.3% per year since 2009 (ATAG, 2019).[1] For 2018, IATA (2019) estimated 905 MMT of CO_2 from global aviation, an increase of 5.2% from its 2017 estimate of 860 MMT of CO_2.

The values that groups like IATA and ATAG provide annually only give the public a single data point with respect to fuel burn, fuel efficiency, and carbon emissions. ICAO (2019b) provides RPK and FTK data by country and geographic region, and breaks down global scheduled services into domestic and international operations. What remains largely unavailable, though, is additional texture about the data, including details of emissions based on where flights originate, emissions from domestic versus international travel, and the proportion of emissions from passenger-and-freight and all-freight operations. To help, this paper details ICCT's compilation of a new data set and uses that data to analyze the geographic distribution of CO_2 emissions from commercial aviation. It also relates emissions to operational variables like aircraft class and stage length.

METHODOLOGY

Multiple publicly available data sources were acquired and merged to quantify commercial fuel consumption using Piano 5, an aircraft performance and design software from Lissys Ltd.[2] The data obtained concerned airline operations, airports, and demand, as detailed below. From that we modeled fuel burn and estimated CO_2 emissions, and then validated the results.

AIRLINE OPERATIONS DATABASE

Global airline operations data for calendar year 2018 was sourced from OAG Aviation Worldwide Limited (OAG). The OAG dataset contained the following variables for passenger and cargo airlines: air carrier, departure airport, arrival airport, aircraft type, and departures (number of flights). Operations data for cargo carriers DHL, FedEx, and UPS was not available from OAG due to restrictions put in place by the companies. To compensate, we utilized alternate data sources to identify the fuel burn associated with these carriers' operations (Deutsche Post DHL Group, 2019; U.S. Department of Transportation [DOT], 2019). All of these sources were combined to create our new Airline Operations Database.

General and military aviation, which likely accounted for 10% or less of all aviation CO_2 in 2018, are both beyond the scope of this work.[3] The non-CO_2 climate impacts of commercial aviation linked to emissions of nitrogen oxides, black carbon, and aviation-induced cloudiness were likewise not quantified.[4]

GLOBAL AIRPORTS DATABASE

We created a Global Airports Database, a database with geographic information for all of the airports included in the Airline Operations Database. For each airport, the city, country/territory, latitude, and longitude were recorded from Great Circle Mapper.[5] Based on the country/territory information, each airport was assigned to one of ICAO's statistical regions and subregions. (See Appendix A for more information on the countries and territories in each ICAO statistical region and subregion.)

DEMAND ESTIMATION

We quantified the revenue passenger kilometers (RPKs) for every airline-aircraft-route combination using the number of departures from the Airline Operations Database; the flight distance, itself calculated using airport latitudes and longitudes from the Global Airports Database; the number of seats for the particular airline-aircraft combination; and the passenger load factor associated with the airline or ICAO route group.

Total mass transported, in revenue tonne kilometers (RTKs), was quantified for both passenger and cargo

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[1] Measured in terms of revenue tonne kilometers (RTKs) transported per liter of fuel. Compounded annually, RTKs have increased by 6.4% since 2009, while fuel use has increased by 4% over the same time period. See ATAG (2019).

[2] http://www.lissys.demon.co.uk/index2.html.

[3] General aviation, which includes business jets and smaller turboprop aircraft, is estimated to account for about 2% of total aviation CO_2 (GAMA & IBAC, n.d.). Data on military jet fuel use is very sparse. According to one estimate by Qinetiq, in 2002, military aircraft accounted for 61 MMT CO_2, or 11% of global jet fuel use at the time and 6.7% of 2018 commercial jet fuel use (Eyers et al., 2004).

[4] Though considerable uncertainty persists, the non-CO_2 climate impacts of aviation, as measured by their contribution to historical radiative forcing, are believed to be comparable to those of CO_2 alone. See Lee et al. (2009).

[5] http://www.gcmap.com

operations. For passenger aircraft, RPKs were converted to RTKs by assuming 100 kg per passenger with luggage (ICAO, 2019c) and incorporating the ICAO passenger-to-freight factor. (See Appendix B for details of both passenger load and passenger-to-freight factors.) Airline-specific data were utilized, if available, to estimate the average passenger and cargo distribution of payload (ICAO, 2019d). For cargo aircraft, either publicly available average payload data was used, or average payload was estimated by using available capacity and a global average weight load factor of 49% (IATA, 2018b), in conjunction with calculated flight distance. RTKs from cargo carriers not included in the Airline Operations Database were quantified from the other sources mentioned previously.

FUEL BURN MODELING AND CO$_2$ ESTIMATION

Each air carrier and aircraft combination (e.g., United Airlines Boeing 777-300ER) in the Airline Operations Database was matched to an aircraft in Piano 5. In cases where the specific aircraft type was not included in Piano 5, it was linked to a surrogate aircraft. Default Piano values for operational parameters such as engine thrust, drag, fuel flow, available flight levels, and speed were used because of the lack of airline- and aircraft-specific data. Cruise speeds were set to allow for a 99% maximum specific air range, which is believed to approximate actual airline operations.

Taxi times were set to 25 minutes, as estimated from block and air-time data of United States air carriers in 2018 (U.S. DOT, 2019).[6] Fuel reserve values to account for weather, congestion, diversions, and other unforeseen events were based on United States Federal Aviation Administration Operations Specification B043 (2014). Changes in aircraft weight due to varying seat configurations were incorporated by adjusting the default number of seats in Piano, using 50 kilograms (kg) per seat (ICAO, 2017). The number of seats per aircraft type for each airline was determined based on airline websites or other public data sources. If no information was found for a specific air carrier and aircraft type combination, then the Piano default for number of seats was used.

The departure and arrival airports in the Airline Operations Database were matched to the geographic information in the Global Airports Database. The latitude and longitude for the departure and arrival airports of each route were used to calculate great-circle distance (GCD), or the shortest distance linking two points on the surface of a sphere. Aircraft will typically fly as close as possible to GCD between airports in order to minimize travel time and fuel use. However, to account for variability in actual flight paths due to weather conditions, the GCD of each route was adjusted using ICAO correction factors of 50 km to 125 km, based on GCD (ICAO, 2017).

Payload for each passenger air carrier and aircraft combination was estimated by the number of aircraft seats, the passenger load factor, and the passenger-to-freight factor. Passenger-to-freight factor is the proportion of aircraft payload that is allocated to passenger transport. Passenger payload was calculated by multiplying the number of aircraft seats by the passenger load factor and the industry average of 100 kg for passenger mass and checked baggage (ICAO, 2019c).

As a default, ICAO passenger load and passenger-to-freight factors were used for each route (ICAO, 2017). If an air carrier's passenger load factor and/or freight carriage data for 2018 were not available from data purchased from ICAO (2019d), from publicly available data (e.g., U.S. DOT), or from data published by the airline, then the ICAO subregional average passenger load and passenger-to-freight factors were used. For freighter aircraft, if freight carriage data was not available from data purchased from ICAO or published by an airline, then the industry average freight load factor of 49% of available capacity was used.

For each combination of route, air carrier, and aircraft type, fuel burn was modeled in Piano 5, using an air carrier and aircraft type-specific Piano aircraft file; the ICAO correction factor-adjusted GCD, itself calculated using the latitude and longitude of the departure and arrival airports; and the payload calculated as described above. To determine the total yearly fuel consumption, the modeled fuel burn was multiplied by the number of departures in the Airline Operations Database. Fuel burn from cargo carriers not included in the Airline Operations Database were identified from other sources mentioned previously.

For passenger aircraft, fuel burn was apportioned to passenger and freight carriage using the following three equations.

Equation [1]

$$\textit{Total Passenger Fuel Use}\ [kg] = \left(\frac{\textit{Total Passenger Weight}\ [kg]}{\textit{Total Weight}\ [kg]}\right)(\textit{Total Fuel Use}\ [kg])$$

Equation [2]

$$\textit{Total Passenger Weight}\ [kg] = (\textit{Number of Aircraft Seats})(50\ kg) + (\textit{Number of Passengers})(100kg)$$

Equation [3]

$$\textit{Total Weight}\ [kg] = \textit{Total Passenger Weight}\ [kg] + \textit{Total Freight Weight}\ [kg]$$

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[6] This value is similar to the 26 minutes of taxi time ICAO defined in its landing and takeoff cycle, derived from operations data from the 1970s. See ICAO (2011).

It is assumed that total fuel use is proportional to payload mass. Carbon emissions were estimated using the accepted constant of 3.16 tonnes of CO_2 emitted from the consumption of one tonne of aviation fuel.

VALIDATION

Previous studies (Graver & Rutherford, 2018a and 2018b; Intergovernmental Panel on Climate Change [IPCC], 1999a) established that aircraft performance models tend to underestimate real-world fuel consumption. To develop correction factors by aircraft type, fuel burn per RPK was modeled for U.S. passenger airlines in Piano and validated by operations and fuel burn data reported by U.S. carriers to the U.S. DOT.[7] Modeled fuel burn per RPK was adjusted upward by correction factors for individual aircraft types. These ranged from 1.02 to 1.20 by aircraft class, and averaged 9% across all classes. If a specific aircraft type in the Airline Operations Database was not operated by a U.S. passenger airline, then the fuel burn correction factor for a comparable aircraft was used.

In addition, data from the Civil Aviation Administration of China (2019) and Japan's Ministry of Land, Infrastructure, Transport and Tourism (2019) was used to validate the results for these two nations. If aviation fuel consumption was reported as a volume (i.e., in gallons or liters), a density of 0.8 kg per liter was used (ICAO, 2019c). Alternative jet fuels, which accounted for only 0.002% of global jet fuel use in 2018 (Hupe, 2019), were not included in this analysis.

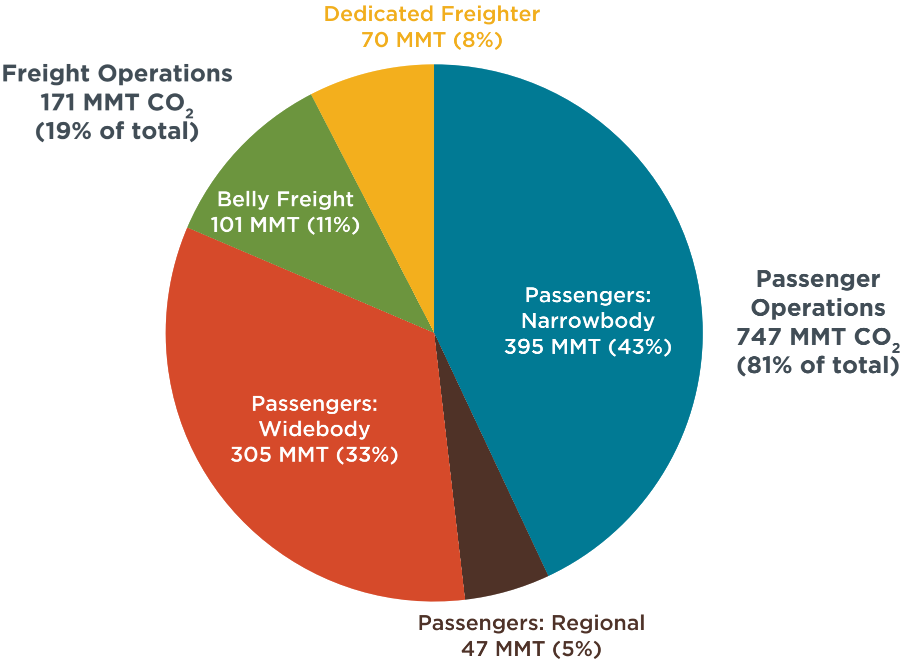

Figure 1. CO_2 emissions in 2018 by operations and aircraft class

DATA ANALYSIS

TOTAL GLOBAL OPERATIONS

Nearly 39 million flights were included in the Airline Operations Database for 2018, and of these, 38 million were flown by passenger aircraft. The global operations modeled in this study agreed well with industry estimates. Our estimate of the total passenger demand by global passenger airlines was 8,503 billion RPKs, about 2% higher than IATA's published value of 8,330 billion RPKs. The total cargo demand transported was estimated as 260 billion freight tonne kilometers (FTKs), within 1% of IATA's published value of 262 billion FTKs.

TOTAL GLOBAL CO_2 EMISSIONS

We estimate that global aviation operations for both passenger and cargo carriage emitted 918 MMT of CO_2 in 2018, about 2% higher than IATA's published value. This equals 2.4% of the estimated 37.9 gigatonnes of CO_2 emitted globally from fossil fuel use that year (Crippa et al., 2019). Using industry's values, CO_2 emissions from commercial flights have increased 32% over the past five years from the 694 MMT emitted in 2013 (IATA, 2015). The implied annual compound growth rate of emissions, 5.7%, is 70% higher than those used to develop ICAO's projections that CO_2 emissions from international aviation will triple under business as usual by 2050 (ICAO, 2019a).[8]

As shown in Figure 1, passenger transport accounted for 747 MMT, or 81%, of commercial aviation carbon emissions in 2018. Passenger movement in narrowbody aircraft was linked to 43% of aviation CO_2, followed by widebody jets (33%), and regional aircraft (5%). The remaining 19% of total aviation emissions, 171 MMT, were driven by freight carriage and divided between "belly" freight carriage on passenger jets (11%) and dedicated freighter operations (8%).

Given that passenger transport emitted four times as much CO_2

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[7] Previous ICCT studies compared the relative, not absolute, fuel consumption of airlines, and did not apply fuel burn correction factors to modeled Piano values. This is because doing so was not expected to influence the relative rankings of carriers. However, these correction factors were required for this paper, as absolute fuel burn and CO_2 emissions were assessed.

[8] ICAO projects a 2.2 to 3.1-fold increase in CO_2 emissions from international aviation from 2015 to 2045, or a 2.7% to 3.9% annual compound growth rate, depending upon assumptions about fuel-efficiency gains. A simple average of the compound growth rates implies a 3.3% annual increase and a 2.8-fold increase in emissions from 2018 to 2050.

than freight transport in commercial aviation, the focus of the rest of this paper is on passenger transport and aircraft. Future work can refine the data on cargo carriage, and recall from above that analysis of such activity is somewhat impeded by data availability constraints applied by carriers.

Table 1. CO_2 emissions from passenger transport in 2018, by operations

Operations	Departures		RPKs		CO_2	
	Million	% of total	billions	% of total	[MMT]	% of total
Domestic	25	67	3,115	37	296	40
International	13	33	5,388	63	451	60
Total	**38**	**100**	**8,503**	**100**	**747**	**100**

CO_2 FROM PASSENGER TRANSPORT

Globally, two-thirds of all flights in 2018 were domestic, as shown in Table 1. These account for approximately one-third of global RPKs and 40% of global passenger transport-related CO_2 emissions. Domestic operations accounted for a large majority of departures in a number of countries, including Brazil (92%), the United States (91%), China (91%), Indonesia (89%), and Australia (86%). These are all countries with large total area. Conversely, nearly all flights from the United Arab Emirates, a comparatively smaller country, are international operations. Of the 230 nations and territories included in the Airline Operations Database, a total of 83 had domestic flights account for 1% or less of total departures.

Since the Airline Operations Database includes the departure and arrival airports for every commercial passenger flight, the carbon emissions from passenger air transport can be allocated to specific regions and

Table 2. CO_2 emissions and carbon intensity from passenger transport in 2018, by regional route group

Rank	Route Group (Not directional specific)	CO_2 [MMT]	% of Total CO_2	RPKs (billions)	% of Total RPKs	Carbon Intensity [g CO_2/RPK]
1	Intra-Asia/Pacific	186	25	2,173	26	86
2	Intra-North America	136	18	1,425	17	96
3	Intra-Europe	103	14	1,189	14	86
4	Europe ↔ North America	50.0	6.7	597	7.0	84
5	Asia/Pacific ↔ Europe	43.4	5.8	523	6.1	83
6	Asia/Pacific ↔ North America	38.7	5.2	459	5.4	84
7	Asia/Pacific ↔ Middle East	33.5	4.5	388	4.6	86
8	Intra-Latin America/Caribbean	29.1	3.9	303	3.6	96
9	Europe ↔ Middle East	25.1	3.4	291	3.4	86
10	Latin America/Caribbean ↔ North America	23.4	3.1	290	3.4	81
11	Europe ↔ Latin America/Caribbean	21.1	2.8	259	3.1	81
12	Africa ↔ Europe	16.5	2.2	197	2.3	84
13	Intra-Middle East	9.18	1.2	79.0	0.9	116
14	Middle East ↔ North America	8.84	1.2	98.8	1.2	89
15	Intra-Africa	8.62	1.2	72.6	0.9	119
16	Africa ↔ Middle East	7.75	1.0	84.8	1.0	91
17	Africa ↔ Asia/Pacific	2.73	0.4	30.0	0.4	91
18	Africa ↔ North America	1.90	0.3	19.4	0.2	98
19	Asia/Pacific ↔ Latin America/Caribbean	0.91	0.1	10.2	0.1	89
20	Latin America/Caribbean ↔ Middle East	0.79	0.1	8.29	0.1	96
21	Africa ↔ Latin America/Caribbean	0.46	0.1	4.73	0.1	97
Total		**747**	**100**	**8,503**	**100**	**88**

countries by the departure airport.[9] Table 2 lists all 21 route groups, using ICAO-defined regions. Note that ICAO further breaks the regions into subregions. For example, the Asia/Pacific region is made up of Central and South West Asia, North Asia, and Pacific South East Asia.

Flights within the Asia/Pacific region emitted the largest share of passenger transport-related CO_2 at 25% of the global total. This region contains four out of the 10 nations with the most aviation RPKs in Table 3 (China, Japan, India, and Australia). Intra-North America flights—U.S. domestic, Canada domestic, and transborder flights—emitted nearly 18% of global passenger CO_2 emissions. Collectively, the 28 current members of the European Union accounted for 142 MMT CO_2 from passenger transport in 2018, or 19% of the global total. Intra-Europe operations, which includes flights to and from non-EU member states, accounted for nearly 14% of global passenger CO_2 emissions. Intra-EU flights, which includes the United Kingdom, emitted an estimated 67 MMT of CO_2, or 9% of global passenger CO_2 emissions.

Table 3. CO_2 emissions from passenger transport in 2018 – top 10 departure countries

Rank	Departure country	Operations	CO_2 [MMT]	% of Total CO_2	RPKs (billions)	% of Total RPKs
1	**United States**[a]	Domestic	126	17	1,328	16
		International	56.1	7.4	650	7.6
		Total	**182**	**24**	**1,976**	**23**
2	**China**[b]	Domestic	65.9	8.8	781	9.2
		International	29.0	3.9	361	4.2
		Total	**94.9**	**13**	**1,142**	**13**
3	**United Kingdom**[c]	Domestic	1.51	0.2	12.0	0.2
		International	28.3	3.8	328	3.9
		Total	**29.8**	**4.0**	**350**	**4.1**
4	**Japan**	Domestic	9.41	1.2	95.5	1.1
		International	14.0	1.9	172	2.0
		Total	**23.4**	**3.1**	**267**	**3.1**
5	**Germany**	Domestic	1.53	0.2	12.4	0.1
		International	20.7	2.8	235	2.8
		Total	**22.2**	**3.0**	**247**	**2.9**
6	**United Arab Emirates**	Domestic	<0.01	<0.1	<0.01	<0.1
		International	21.1	2.8	233	2.7
		Total	**21.1**	**2.8**	**233**	**2.7**
7	**India**	Domestic	10.8	1.4	125	1.5
		International	8.60	1.2	109	1.3
		Total	**19.4**	**2.6**	**234**	**2.8**
8	**France**[d]	Domestic	4.53	0.6	48.9	0.6
		International	14.7	2.0	172	2.0
		Total	**19.2**	**2.6**	**221**	**2.6**
10	**Australia**[e]	Domestic	6.65	0.9	76.3	0.9
		International	12.3	1.7	144	1.7
		Total	**19.0**	**2.5**	**220**	**2.6**
10	**Spain**	Domestic	2.88	0.4	28.9	0.3
		International	15.6	2.1	203	2.4
		Total	**18.5**	**2.5**	**232**	**2.7**
Rest of the World			**298**	**40**	**3,381**	**40**
Total			**747**	**100**	**8,503**	**100**

[a] Includes American Samoa, Guam, Johnston Island, Kingman's Reef, Midway, Palmyra, Puerto Rico, Saipan (Mariana Islands), Wake Island, Virgin Islands
[b] Includes Hong Kong SAR and Macau SAR. Emissions and activity from flights between mainland China, Hong Kong SAR, and Macau SAR are included in the domestic total.
[c] Includes Anguilla, Bermuda, British Virgin Islands, Cayman Islands, Falkland Islands (Malvinas), Gibraltar, Guernsey, Isle of Man, Montserrat, St. Helena and Ascension, Turks and Caicos Islands
[d] Includes French Guiana, French Polynesia, Guadeloupe, Martinique, Mayotte, New Caledonia, Reunion Island, St. Pierre and Miquelon, Wallis and Futuna Islands
[e] Includes Christmas Island, Coco Islands, Norfolk Island

Table 2 also lists the carbon intensity of flights, defined as grams (g) of CO_2 emitted per RPK after correcting for fuel apportioned to belly freight carriage, by market. On average, global aircraft emitted 88 g of CO_2/RPK in 2018. The least-efficient route groups were flights within the Middle East and within Africa. These emitted more than 30% more CO_2 to transport one passenger one kilometer than the average worldwide. This is due primarily to the use of older, fuel-inefficient aircraft

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[9] The question of how international aviation emissions could be allocated to individual countries has been a topic of international discussion under the UNFCCC's Subsidiary Body for Scientific and Technical Advice (SBSTA) since 1995. In 1997, SBSTA outlined five options for attributing international aviation emissions to countries for future refinement: (1) no allocation; (2) allocation by fuel sales; (3) allocation by where a plane is registered; (4) allocation by country of departure or destination of an aircraft; or (5) allocation by country of departure or destination of payload (passengers or cargo). See UNFCC SBSTA (1997); IPCC (1999b); and Murphy (2018). The attribution issue remains unsettled. This paper, which assumes no fuel tankering (i.e., excess fuel carriage to take advantage of differences in fuel prices across airports), applies option (4) to the country of departure of an aircraft.

and low passenger load factors in these markets.

Table 3 lists the 10 countries with the highest carbon emissions from passenger transport by departure. Overall, these countries and their territories accounted for 60% of both CO_2 and RPKs from global commercial aviation passenger transport.

In 2018, flights departing an airport in the United States and its territories supplied nearly 23% of global RPKs, while emitting 24% of global passenger transport-related CO_2. Domestic airline operations, where both the departure and arrival airports were located in a U.S. state or territory, accounted for 16% of global RPKs and 17% of global passenger CO_2 emissions. Flights that departed China, Hong Kong, and Macau in 2018 accounted for 9% of both demand and CO_2 from global commercial aviation passenger transport. Air travel within mainland China emitted 62 MMT of CO_2 and supplied 733 billion RPKs, both 8% of global totals.

Figure 2 shows the distribution of CO_2 emissions from passenger aviation in 2018 across World Bank-defined income brackets: high income (Organisation for Economic Co-operation and Development countries); upper middle income (e.g., China); lower middle income (e.g., India); and low income (e.g., Uganda). High-income countries were responsible for 62% of CO_2 emitted from passenger aircraft in 2018, followed by upper middle (28%), lower middle income (9%), and low income (1%). This means that overall, less developed countries that contain half of the world's population accounted for only 10% of all passenger transport-related aviation CO_2.

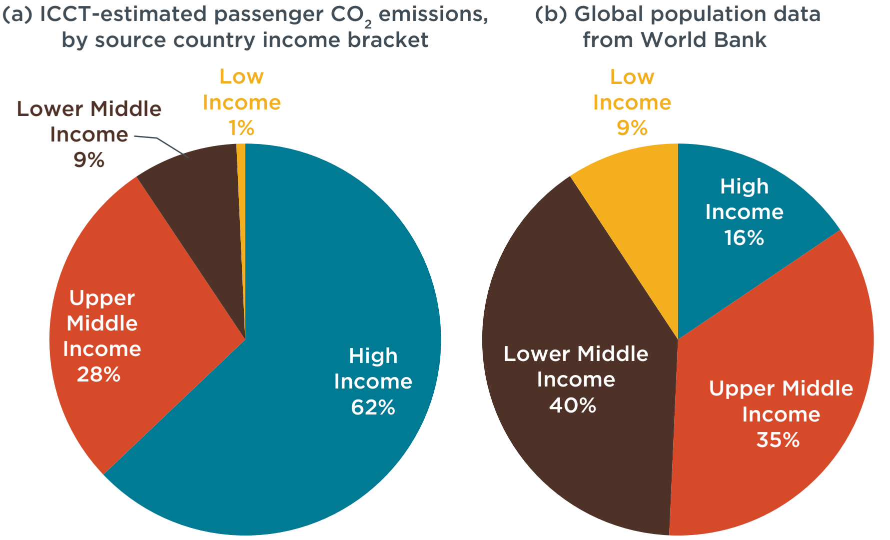

Figure 2. CO_2 emissions from passenger aviation operations and total population in 2018, by country income bracket (United Nations, 2019; World Bank, 2019)

Table 4. CO_2 emissions and intensity from passenger transport in 2018, by aircraft class

Aircraft Class	Departures		RPKs		Avg Distance [km]	CO_2		Carbon Intensity [g CO_2/RPK]
	Million	% of total	billions	% of total		[MMT]	% of total	
Regional	9.77	26	303	4	632	47	6	156
Narrowbody	25.1	66	4,629	54	1,330	395	53	85
Widebody	3.10	8	3,570	42	4,700	305	41	85
Total	**38**	**100**	**8,503**	**100**	**1,425**	**747**	**100**	**88**

CO_2 EMISSIONS AND INTENSITY BY AIRCRAFT TYPE AND STAGE LENGTH

Further analysis was conducted to determine the total CO_2 and average carbon intensity for each aircraft type included in the Airline Operations Database. Table 4 analyzes flight operations by aircraft class—regional (turboprops and regional jets), narrowbody, and widebody. Two-thirds of all passenger flights were operated on narrowbody aircraft in 2018, accounting for 54% of all RPKs and 53% of passenger CO_2 emissions excluding freight. On average, narrowbodies and widebodies had the same carbon intensity, with regional aircraft emitting 84% more CO_2 per RPK.

On average, transporting one passenger emitted 88 g CO_2/km of flight distance, or 125 kg of carbon over the average flight distance of 1,425 km. An average narrowbody flight of 1,330 km emitted 113 kg of CO_2 per passenger. An average widebody aircraft flight of 4,700 km emitted 400 kg of CO_2 per passenger. Round trips between two airports would emit twice as much CO_2 over the full itinerary.

Figure 3 shows the percentage distribution of passenger aircraft CO_2 emissions (the blue bars) and carbon intensity by stage length (the orange line) in 500 km increments. Approximately one-third of passenger CO_2 emissions occurred on short-haul flights of less than 1,500 km. An additional one-third occurred on medium-haul flights of between 1,500 km and 4,000 km, and the remaining third on long-haul flights greater than 4,000 km.[10] Regional flights less than 500 km, roughly the distance where aircraft compete directly with other modes of passenger transport, accounted for about 5% of total passenger CO_2 emissions.

The carbon intensity of medium- and long-haul flights varies between 75 and 95 g CO_2/RPK, with a minimum at about 3,000 km and a slight upward slope as flight length increases.[11] On short-haul flights, the average carbon intensity is roughly 110 g CO_2/RPK, or about 35% higher than the medium-haul average. On regional flights of 500 km or less, the carbon intensity of flying roughly doubles, to 155 g of CO_2/RPK. This is because the extra fuel used for takeoff becomes relatively large compared to the more fuel-efficient cruise segment, and also because of the use of less fuel-efficient regional jets on the shortest flights.

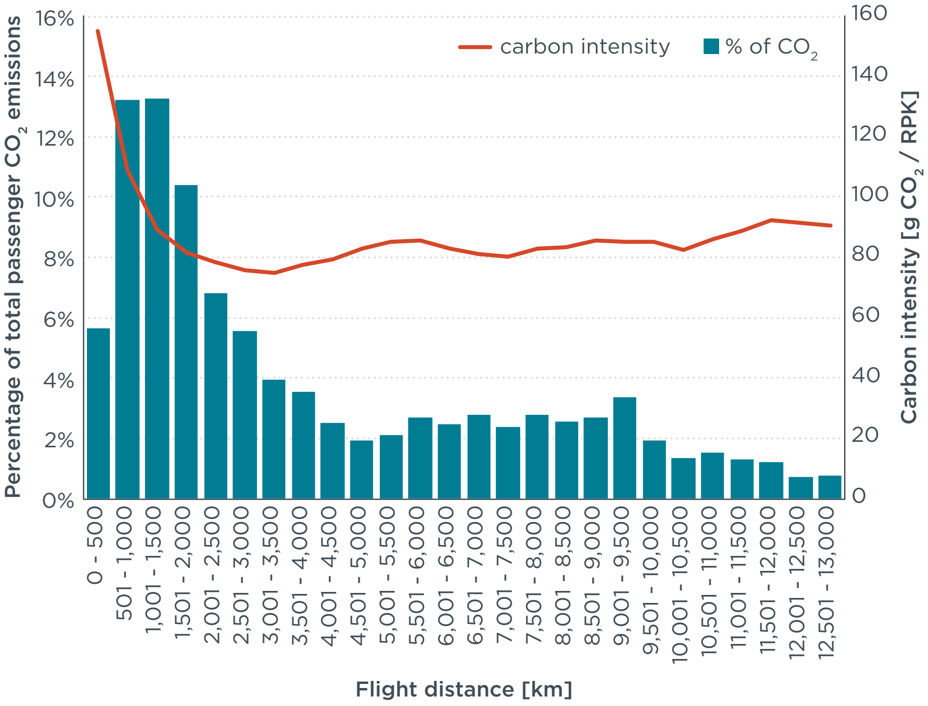

Figure 3. Share of passenger CO_2 emissions and carbon intensity in 2018, by stage length.

CONCLUSIONS AND NEXT STEPS

This paper provided an up-to-date, bottom-up, and transparent global CO_2 inventory for commercial aviation. Multiple public data sources were acquired and merged to quantify the amount of fuel burned and, therefore, CO_2 emitted, using an aircraft performance and design software. Both the airline operations estimated in this study and the estimates of total global carbon emissions agreed well with highly aggregated industry estimates.

This data set is provided at a time when the climate impact of air transport is coming under increasing scrutiny. Airlines and governments are beginning to take heed, but existing policies such the ICAO's CO_2 standard for new aircraft and its Carbon Offsetting and Reduction Scheme for International Aviation are not expected to reduce aircraft emissions significantly (Graver & Rutherford, 2018c; Pavlenko, 2018). Additionally, the ICAO has yet to codify a 2050 climate goal in the way the International Maritime Organization (IMO), its sister agency governing international shipping, already has for oceangoing vessels (Rutherford, 2018). Further action, supported by the best available science on aviation emissions' impacts and data about where those emissions are originating from, is needed.

The ICCT aims to update this work annually to provide global, national, and regional policymakers with the data needed to develop strategies that will reduce carbon emissions from commercial aviation while still accommodating future passenger and freight demand. We envision several avenues for refinement of this data. One, we will identify better data sources to improve the analysis of air freight, in particular to support allocation of air freight to regions and countries. Two, we will pursue expanded work on model validation, particularly for domestic operations, using international, national, and airline-level data. Three, data on projected emissions over time based upon annual, updated inventories may be integrated into future reports.

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[10] EUROCONTROL's distance definitions for short-, medium-, and long-haul flights were used. See https://www.eurocontrol.int/sites/default/files/2019-07/challenges-of-growth-2018-annex1_0.pdf.

[11] This phenomenon, known colloquially as "burning fuel to carry fuel," occurs because longer flights are disproportionately heavy at takeoff due to the extra fuel needed to travel long distances.

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APPENDIX A: ICAO Statistical Regions and Subregions

Africa Region, North Africa Subregion

Algeria, Egypt, Libya, Morocco, Tunisia, Western Sahara

Africa Region, Sub Saharan Africa Subregion

Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Mozambique, Namibia, Niger, Nigeria, Reunion Island, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Togo, Uganda, United Republic of Tanzania, Zambia, Zimbabwe

Asia/Pacific Region, Central and South West Asia

Afghanistan, Bangladesh, Bhutan, China, India, Kazakhstan, Kyrgyzstan, Macau SAR, Mongolia, Myanmar, Nepal, Pakistan, Sri Lanka, Tajikistan, Turkmenistan, Uzbekistan

Asia/Pacific Region, North Asia

Democratic People's Republic of Korea, Hong Kong SAR, Japan, Republic of Korea, Chinese Taipei

Asia/Pacific Region, Pacific South East Asia

American Samoa, Australia, Brunei Darussalam, Cambodia, Coco Islands, Cook Islands, Fiji, French Polynesia, Guam, Indonesia, Johnston Island, Kingman's Reef, Kiribati, Lao People's Democratic Republic, Malaysia, Maldives, Marshall Islands, Federated States of Micronesia, Midway, Nauru, New Caledonia, New Zealand, Niue Islands, Norfolk Island, Palau, Palmyra, Papua New Guinea, Philippines, Saipan (Mariana Islands), Samoa, Singapore, Solomon Islands, Thailand, Timor-Leste, Tonga, Tuvalu, Vanuatu, Vietnam, Wake Island, Wallis and Futuna Islands

Europe Region, Europe Subregion

Albania, Andorra, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Faroe Islands, Finland, France, Georgia, Germany, Gibraltar, Greece, Greenland, The Holy See, Hungary, Iceland, Ireland, Isle of Man, Italy, Kosovo, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Republic of Moldova, Monaco, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Russian Federation, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom

Latin America/Caribbean Region, Central America/Caribbean Subregion

Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bonaire, British Virgin Islands, Cayman Islands, Costa Rica, Cuba, Curacao, Dominica, Dominican Republic, El Salvador, Grenada, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Puerto Rico, Sint Maarten, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Islands, U.S. Virgin Islands

Latin America/Caribbean Region, South America Subregion

Argentina, Plurinational State of Bolivia, Brazil, Chile, Colombia, Easter Island, Ecuador, Falkland Islands, French Guiana, Guyana, Paraguay, Peru, St. Helena and Ascension, Suriname, Uruguay, Bolivarian Republic of Venezuela

Middle East Region, Middle East Subregion

Bahrain, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Under Palestinian Authority, United Arab Emirates, Yemen

North America Region, North America Subregion

Bermuda, Canada, St. Pierre and Miquelon, United States

APPENDIX B: Passenger Aircraft Load Factors by Route Group (ICAO, 2017)

Route Group (Not directional specific)	Passenger Load Factor	Passenger-to-Freight Factor*
North Africa - Central and South West Asia	72.90%	83.90%
North Africa - North Asia	72.90%	83.90%
North Africa - Pacific South East Asia	72.90%	83.90%
Sub Saharan Africa - Central and South West Asia	72.90%	83.90%
Sub Saharan Africa - North Asia	72.90%	83.90%
Sub Saharan Africa - Pacific South East Asia	72.90%	83.90%
North Africa - Middle East	71.10%	83.09%
Sub Saharan Africa - Middle East	71.10%	83.09%
North Africa - North America	77.28%	90.74%
Sub Saharan Africa - North America	77.28%	90.74%
North Africa - Central America/Caribbean	79.21%	84.41%
Sub Saharan Africa - Central America/Caribbean	79.21%	84.41%
Middle East - Central America/Caribbean	79.21%	84.41%
North Africa - South America	60.20%	84.41%
Sub Saharan Africa - South America	60.20%	84.41%
Middle East - South America	60.20%	84.41%
Central America/Caribbean - Europe	83.00%	86.96%
Central America/Caribbean - North America	81.05%	92.96%
Central America/Caribbean - South America	77.10%	89.68%
Central Asia - Europe	82.08%	63.49%
Central Asia - Middle East	76.40%	81.26%
Central Asia - North America	82.85%	62.28%
Central and South West Asia - North Asia	73.50%	79.99%
Central and South West Asia - Pacific South East Asia	76.96%	80.65%
Europe - Middle East	74.38%	77.17%
Europe - North Africa	75.08%	82.16%
Europe - North America	82.16%	79.63%
Europe - North Asia	80.50%	63.49%
Europe - Pacific South East Asia	79.50%	63.49%
Europe - South America	82.20%	77.10%
Europe - South West Asia	81.10%	63.49%
Europe - Sub Saharan Africa	76.00%	82.16%
Intra-North Africa	60.35%	84.41%
Intra-Sub Saharan Africa	60.35%	84.41%
North Africa - Sub Saharan Africa	60.35%	84.41%
Intra-Central America/Caribbean	66.92%	94.90%
Intra-Central and South West Asia	75.60%	79.99%

Route Group (Not directional specific)	Passenger Load Factor	Passenger-to-Freight Factor
Intra-Europe	80.89%	96.23%
Intra-Middle East	71.13%	84.41%
Intra-North America	81.78%	93.34%
Intra-North Asia	76.50%	79.99%
Intra-Pacific South East Asia	76.05%	79.99%
Intra-South America	77.40%	82.64%
Central America/Caribbean - North Asia	72.50%	84.63%
Central America/Caribbean - Pacific South East Asia	72.50%	84.63%
Middle East - North America	77.91%	79.56%
Middle East - North Asia	77.50%	81.26%
Middle East - Pacific South East Asia	77.50%	81.26%
Middle East - South West Asia	77.90%	81.26%
North America - North Asia	80.44%	66.34%
North America - Pacific South East Asia	77.50%	84.44%
North America - South America	79.66%	77.50%
North America - South West Asia	80.61%	62.28%
North Asia - Pacific South East Asia	77.58%	79.99%

*Passenger-to-freight factor is the proportion of aircraft payload that is allocated to passenger transport.
Note: For some route groups, the Central and South West Asia region has been separated into two subregions (e.g., Central Asia - Europe, Europe - South West Asia).