Carbon dioxide emissions from international air transport of people and freight: New Zealand as a case study

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Keywords: international aviation emissions, carbon dioxide emissions, greenhouse gas emissions, New Zealand air transport, aeroplane passenger emissions, air freight emissions, aircraft emission factors

Abstract
International aviation accounts for over 2% of global emissions, but was not subject to Kyoto Protocol liabilities, and was not directly addressed by the Paris Agreement. Calculating emissions associated with individual countries is complicated, with data that is publicly available and free to access often being difficult to obtain. In this paper, a case study is presented where commercially sensitive fuel uplift is used to calculate New Zealand specific emissions factors of 0.81 kg CO2 per tonne km (CO2 per t-km) for short-haul and 0.79 kg CO2 per t-km for long-haul international aviation. This was used to estimate international aviation CO2 emissions associated with New Zealand in 2017 to be 8.4 Mt CO2 in total (2 significant figures, rounded down), with international visitor travel to and from New Zealand accounting for 4.3 Mt CO2, New Zealand residents’ international travel for 2.6 Mt CO2, exports for 0.72 Mt CO2, and imports for 0.89 Mt CO2 (all 2 significant figures, rounded up). Results show the fleet of aeroplanes which serviced New Zealand between 2007 and 2017 has become, on average, less efficient due to changes in operational factors such as seating density.

1. Introduction
Earth’s climate is impacted by greenhouse gas emissions from human activities such as the burning of fossil fuels for the international transport of people and goods. However, quantifying international transport emissions is much more difficult than might be initially assumed due to the commercially sensitive nature of some of the required data and other factors (Winther et al 2016). If aviation were a country rather than a transport mode, it would be one of the ten highest CO2 emitting countries, accounting for over 2% of global emissions (ICAO 2016). Despite this significant contribution to global emissions, international aviation greenhouse gas emissions were not liable under the Kyoto Protocol (Eggleston et al 2006). The Paris Agreement similarly side-stepped international transport emissions (UNFCCC 2016). The issue of apportioning responsibility to individual countries for international transport emissions is vexed, and calculating emissions associated with individual countries is complicated. Currently there are few international transport alternatives to fossil fuels available for water-locked countries, so global ambitions to limit climate change rely on quantification of emissions which is further complicated by the lack of available data. New Zealand is an isolated country, and depends heavily on aviation for transport of passengers and goods.

The ultimate goal of the present research was to quantify the contribution to CO2 emissions from international air transport to and from an individual country, using New Zealand as a case study. In this paper, we present a method which can be applied to other nations or regions.

1.1. Background
There is no accepted method of assigning responsibility for international transport emissions, though many have been proposed (Miljøstyrelsen Miljøministeriet 2003, Larsson et al 2018, Graver et al 2019). The International Civil Aviation Organization (ICAO) requires member states to report on fuel use (ICAO 2018),
with the intention of quantifying global international aviation though not all states report complete data (ICAO, pers. comm., 20 Dec. 2018). While some airlines currently release emissions estimates, there is no system to verify the accuracy of these because data specifically about fuel use in aviation are not readily available. The approach of the present research is to account for all emissions which can be directly associated with a country, using various sources of fuel data so that comparisons can be made between both confidential and freely available fuel data. This method of accounting for an entire country’s aviation emissions if used on a regional or national level would overestimate global emissions, giving twice the global total, because it counts all flights arriving in or leaving a country in the total aviation emissions for that country.

The Auckland International Airport fuel uplift data (i.e., fuel sold data, obtained from Air BP, pers. comm., 25 Jan. 2019) acquired during the present research was used to calculate emissions factors in kg CO₂ per t-km, as these are more versatile than emissions factors accounting solely for passengers, as the latter do not enable any accounting for mail and freight carried on aeroplanes along with passengers. Emissions calculated from aircraft movement numbers and fuel burn per trip require more complete data to get a comprehensive estimate of total emissions. We calculated emissions factors from representative, though not necessarily exhaustive data, which gives a reliable estimate of totals, and as they are calculated by tonne-kilometre, can be used to differentiate between passengers and freight.

1.2. Impact and outlook of international aviation
Globally, aviation accounts for 2% of CO₂ emissions, and international aviation alone 1.3% (ICAO 2016), and with non-CO₂ greenhouse effects included is estimated to be 4.9% of global anthropogenic totals (Lee et al 2010). If aviation continued to grow at the rates predicted in 2018, it was estimated by Staples et al (2018) that aviation’s share of global emissions could increase to 4.6%–20.2% of global CO₂ emissions by the middle of the 21st century, though this proportion is amplified by predicted emission decreases from other carbon intensive activities. In 2020 prior to the COVID-19 global pandemic, ICAO’s Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) started, with the goal of carbon neutral growth from 2020 on. However, the fuel efficiency goals in CORSIA were not being met as of 2019 (IEA 2019), and the Intergovernmental Panel on Climate Change (IPCC) warned that aviation’s carbon intensity needed to reduce by 56% from 2014 levels to meet a 1.5 degree global warming goal, along with a 6.72 EJ uptake of biofuel by 2060 (Rogelj et al 2018). The problems facing international aviation are further complicated by its economic importance, particularly to a country as isolated as New Zealand, where tourism in 2017 directly and indirectly contributed to 10.1% of GDP through job creation, international visitor travel and tourist spending (Statistics New Zealand 2018a), and in 2018/2019, 20.4% of New Zealand’s total export earnings was from international tourism expenditure (Statistics New Zealand 2019). While globally COVID-19-related travel restrictions and disruptions had reduced daily average emissions from domestic and international aviation by 60% from 1 January to 30 April 2020 (Le Quéré et al 2020), it is not known what, if any, long-term changes will result. This paper provides a useful case study for future comparisons of COVID-19 impacts.

1.3. Aviation’s importance to New Zealand
New Zealand is made up of islands and has been heavily reliant on air transport, especially for the movement of people, because it is very isolated with the nearest large international ports in Australia more than 2,000 km away leaving few alternative means of international transport. Ninety-six percent of all passenger travel in and out of the country in 2017 was by aeroplane, with 3.4% travelling by cruise ship (Statistics New Zealand 2018b) which was a significant increase since the 2007 cruise ships emissions research of Howitt et al (2010). In 2017 international tourism was the largest contributor to GDP when considered as an export, ahead of the dairy industry (Statistics New Zealand 2018a). The economic importance of international visitors to New Zealand increases the reliance on international air travel. Air freight has been essential to trade for New Zealand, as transport of goods by ship over long distances is time consuming. Therefore, goods which are time sensitive or perishable are often carried by aeroplane. These typically have a high value-to-mass ratio (Howitt et al 2011); imported and exported goods comprise 0.3% of cargo by mass, but 17% by value (Ministry of Transport 2016). The rest of the cargo travels by maritime transport (Fitzgerald et al 2011, Howitt et al 2011).

2. Methods
2.1. Overview
The method used in the present research is adapted from Smith and Rodger (2009) and Howitt et al (2011). Howitt et al (2011) established a method for deriving country specific CO₂ emissions factors using fuel uplift and aircraft movements for a representative airport, giving emissions factors which can be used to calculate both traveller and freight emissions. These emissions factors were then applied to the method outlined in Smith and
Rodger (2009), where total emissions due to aviation are calculated by identifying top countries by traveller volume for both international visitors arriving in New Zealand, and New Zealanders travelling internationally, as well as freight imported and exported by air, to which the emissions factors can be applied. The differences between the method used by Howitt et al (2011), and here are: (1) the top countries for travellers by volume and freight by mass had some variations between 2007 and 2017, as some of those used in Howitt et al (2011) no longer represented the top countries in 2017; (2) average load factor increased, from 79% in Howitt et al (2011) to 83% in the present research; and (3) the seat capacity of aeroplane models was taken from numbers given by airlines, whereas in Howitt et al (2011) the seat capacity used was that given by the manufacturer. The change in seat capacity method is examined in section 4.1 of this paper, as it is considered a key change that could influence the overall change in emissions factors, as well as the comparability between Howitt et al (2011) and the present research.

Emissions factors were calculated by tonne-kilometre rather than by passenger-kilometre due to the frequent co-occurrence of passenger transport and freight transported globally (Feng et al 2015), and in New Zealand in particular, where most freight is transported in the belly-hold of passenger aircraft (Howitt et al 2011). Additionally, emissions factors in tonne-kilometres can be used to give the emissions of the entire plane, the passengers, or freight, whereas emissions factors by passenger-kilometre estimate only the passenger portion of the flight, and can skew the perceived efficiency of air passenger transport. Passenger emissions factors are often weighted by the mass of the passengers relative to the mass of the freight carried, implying that any efficiency in passenger transport can be improved by increasing the mass of freight carried on a given flight (Baumeister 2017, Graver and Rutherford 2018). This is only a relevant suggestion where there is sufficient demand or necessity for an increase in freight transported by air, as diverting international freight from maritime transport to aviation would increase both the financial and carbon cost of freight unnecessarily.

The term ‘passenger’ is used here to refer to a person on board an aircraft who is not crew working onboard that aircraft. The industry term ‘revenue passenger’ is the closest equivalent, however that term does not include children who do not occupy their own seat or airline employees or relations who have air travel benefits as part of their employment. Hence, our term ‘passenger’ includes both revenue and non-revenue passengers (ICAO 2013). ‘Traveller’ and ‘visitor’ are used here to refer to a person visiting one country from another, for any purpose, not restricted to tourism. ‘Flight leg’ is used here to mean a known non-stop trip between an airport pair, and ‘journey’ to be a passengers’ entire trip between city pair, i.e., a journey from Auckland to London is made up of at least two flight legs, as there were no non-stop flights operating from Auckland to London as of 2017.

The two sources of industry data used in the present research are the Auckland International Airport branch of Air BP, and Airways. Air BP are a subsidiary of British Petroleum dealing with aircraft fuel in particular, and manage the Joint User Hydrant Installation, which delivers fuel to aeroplanes at Auckland International Airport. Airways, formerly a division of the Ministry of Transport, is a state-owned enterprise that provided air traffic control to all commercial New Zealand airports in 2017.

2.2. Methods of calculating operating emissions of aircraft

The two broad methods of calculating emissions from aircraft are: (1) separating flights into landing and take-off (LTO) and cruise phases (Ministry of Transport 2017, Cox et al 2018, Lo et al 2020), or (2) using emissions factors (Smith and Rodger 2009, Howitt et al 2011, DBEIS 2017, Feng et al 2015). Using a LTO and cruise method relies on a database, such as the EMEP/EEA dataset (Winther et al 2016, hereafter cited as EMEP/EEA data). This provides more detailed information by flight stage, allowing for greater accuracy in estimating flights for which the only known information is model and distance.

Emissions factors for aviation are not commonly calculated in peer reviewed literature, with Baumeister (2017), and Larsson et al (2018) being two of the few recent examples. The methods and aims in the peer reviewed literature on this subject often varies. Examples of this can been seen in those papers; Baumeister (2017) ascertained emissions from different airlines flying a few select routes, and analysed the factors influencing their efficiency, whereas Larsson et al (2018) calculated a single global average emissions factor as a function of time, looking at general changes to the efficiency of flying.

Grey literature is the source of annually updated emissions factors, such as the UK Department for Business, Energy and Industrial Strategy (DBEIS), formerly released by the Department for the Environment, Food and Rural Affairs (DEFRA), which releases updated emissions factors annually, or more recently the International Council on Clean Transport (Graver et al 2019). DBEIS (2017) calculates a range of United Kingdom (UK) specific factors. Using these for a specific country, in the case of the globally derived factor, or for a different country, increases any uncertainty already present in the calculation, as there are key differences in input factors, as shown in section 2.6.
2.3. Data sources

Two key datasets were used in the calculation of New Zealand specific emissions factors, with another two used to estimate total aviation emissions. The year covered in this paper is 2017. Some additional calculations are carried out here for 2007, contained in section 4.1.

The first dataset contained average fuel uplift for aircraft refuelling at Auckland International Airport on outbound international flights (Air BP, pers. comm., 25 Jan. 2019). The fuel uplift data covers 2017 from January to the end of June for 28 destination cities across 13 aircraft models. Each aircraft model had fuel uplift data for between one and 13 destinations. Aircraft which fly to Auckland, but did not frequently refuel there during this time period were not included in this data (Air BP, pers. comm., 29 Jan. 2019); this is further discussed in section 2.5.

The second dataset contained all flights arriving in or departing from Auckland Airport in 2017, by time and aircraft type. All aircraft departures from Auckland were excluded from calculations due to inconsistency in coverage of arrival airport, and flights were assumed to be round trip to the international airport from which they had arrived. Due to the temporal limitation in the Auckland fuel uplift data, only flights arriving in Auckland between 1 January 2017 and 30 June 2017 were included in calculations. Flights in this dataset were airport to airport movements providing consistency with the fuel uplift data (Airways, pers. comm., 23 Jan. 2019).

The third and fourth datasets are both publicly available from Statistics New Zealand and contain all passenger movements, by country of departure and arrival, and Harmonised System (HS) data containing all imports and exports by mass for every country of trade (Statistics New Zealand n.d.). The passenger data was categorised into visitor arrivals to New Zealand, and New Zealand resident departures. The HS data used here is the ten-digit HS code (HS10) level of data; the HS was developed by the World Customs Organisation, and is the international standard. Traveller data was differentiated by travel purpose for each country by Statistics New Zealand. However to provide full inclusion of all aviation emissions, only the aggregated total all purpose' column was used, see Supplementary Information. Trade data was broken down by airport, and all airports in a single country were then grouped by country. Top countries by mass for both import and export were then selected. Given there were a small number of key countries making up trade by mass and passengers by volume, 90% of the total mass was considered representative of the total mass, and for travellers 90% of total traveller number was considered representative of the total number of travellers, rather than including every country to which passengers travelled and goods were transported. The HS10 trade dataset was also used in calculating the emissions factors, summed and divided by the total number of travellers to arrive in or depart from New Zealand to obtain a per passenger figure for freight carried.

In addition to the fuel uplift data from Auckland International Airport, two publicly available fuel databases were used in this paper, the ICAO Fuel Consumption table given in Appendix C of the Carbon Calculator methodology (ICAO 2017), and the EMEP/EEA Master Emissions Calculator (Winther et al 2016). While these are not the only fuel databases the authors are aware of, they were the only free and publicly available fuel databases to be found at the time of the primary research undertaken by the authors. Thus, the comparison made here between the empirical Auckland International Airport fuel uplift data provided by Air BP and these datasets could be of use to others.

2.4. Equations

The following equations were adapted from Howitt et al (2011), with changes made only to equation (3), as this was used to calculate both passenger and freight emissions; Howitt et al (2011) used the same method, but the equivalent equation in Howitt et al (2011) is written only in terms of freight emissions.

Equation (1) was used to calculate the mean CO$_2$ emissions factor for each of the aeroplane models represented in the fuel uplift data. Equation (1) was applied separately for city pairs which represented short and long-haul journeys. This resulted in a mean short and long-haul CO$_2$ emissions factor for each aeroplane model being calculated.

\[
EF_{CO_2,\text{uplift}} = \frac{\sum_{n=1}^{m_{\text{total}}} \left( \frac{m_{\text{fuel}} \times EF_{CO_2,\text{fuel}}}{\Delta_t \times N_{\text{total}} \times LF \times (m_p + m_f)} \right)}{n}
\]

Where:
- $EF_{CO_2,\text{uplift}}$ is the emissions factor for each of the given fuel uplifts (kg CO$_2$ per t-km);
- $a$ (subscript) denotes a particular aeroplane model;
- $i$ (subscript) denotes a city pair of origin and destination airports;
- $n$ denotes the total number of city pairs of origin and destination airports;
- $m_{\text{fuel}}$ is the fuel uplift (kg);
- $EF_{CO_2,\text{fuel}}$ is the CO$_2$ emissions generated from the combustion of $m_{\text{fuel}}$ (kg CO$_2$ per kg fuel);
is the distance travelled by an aircraft between a city pair of origin and destination airports (km); 
\( N_{\text{max}} \) is the passenger capacity of the aeroplane (number of passengers); 
\( LF \) is the passenger load factor, presented as a fraction of \( N_{\text{max}} \) of the aeroplane; 
\( m_p \) is the average mass of a passenger (tonne (t) per passenger); 
\( m_f \) is the average mass of freight carried per passenger (t per passenger);

Equation (2) was used to weight the mean CO\(_2\) emissions factors for each model of aeroplane with respect to the proportions of the total journeys undertaken by each model. This was also applied separately for short-haul and long-haul journeys to obtain a weighted mean CO\(_2\) emissions factor for both distance brackets.

\[
EF_{\text{CO}_2i} = \sum_{a=1}^{p} EF_{\text{CO}_2, uplifti|a} \times X_a
\]  

Where:
\( j \) (subscript) denotes the mean emissions factor for short-haul or long-haul;
\( a \) (subscript) denotes a particular aeroplane model;
\( p \) denotes the total number of aeroplane models;
\( EF_{\text{CO}_2, uplifti|a} \) is the emissions factor for each of the given fuel uplifts (kg CO\(_2\) per t-km);
\( X_a \) is the proportion of the total aeroplane movement numbers for aeroplane model \( a \).

To calculate the total emissions from New Zealand’s combined passenger and freight aviation, equation (3), below, was used.

\[
E_{\text{CO}_2} = \sum_{i=1}^{n} (m_p + m_f) \times p_i \times d_i \times 1.09 \times EF_{\text{CO}_2j} \times 2
\]  

Where:
\( E_{\text{CO}_2} \) is the total emissions of CO\(_2\) (kg);
\( i \) (subscript) denotes a city pair of origin and destination airports;
\( m_p \) is the average mass of a passenger (tonne (t) per passenger);
\( m_f \) is the average mass of freight carried per passenger (t per passenger);
\( p_i \) is the number of passengers travelling between a city pair of origin and destination airports;
\( d_i \) is the distance travelled by an aircraft between a city pair of origin and destination airports (km); 
1.09 is the correction factor for indirect flights and circling at airports;
\( EF_{\text{CO}_2j} \) is the emission factor for CO\(_2\) (kg CO\(_2\)/t-km), and whether the short or long-haul value is used depends on \( d_i \);
2 is a round trip.

2.5. Missing fuel data

The fuel uplift data did not include data for all flights by three aircraft types, the A330-200, A330-300, and A380 (see section 4), or short-haul flights for a fourth type, the B787-800, and long-haul flights for a fifth, the B747-400. While the B747-400 also flew short-haul flights to New Zealand, and the B787-800 also flew long-haul flights to New Zealand, there was fuel uplift data for these flights in the Auckland Airport fuel uplift data. The flights with missing fuel uplift data collectively made up 13% of short-haul and 24% of long-haul flights, as those models did not typically refuel before departing again (Air BP, pers. comm., 29 Jan. 2019). Alternative sources of fuel data were considered necessary to account for these missing flights. Short-haul flights for some aircraft types would be possible to fly return without refuelling. However, there is no data available on this, and the degree to which this would affect fuel consumption is unknown. Thus, fuel data was taken for the most common routes of these aircraft types with no accounting for extra fuel uplift to fly return. Three methods were considered to account for the missing fuel consumption of these aircraft. Firstly, emissions factors were calculated with the total data, leaving these aircraft types out entirely, which we have called the ‘Auckland fuel only’ method. Secondly, fuel estimates from the EMEP/EEA database for specific aircraft on specific routes and distances for legs frequently flown per aircraft type were included in the emissions factors calculation, which we have called the ‘EMEP/EEA fuel patch’ method. Thirdly, fuel estimates were included, as for method two, but using the ICAO (2017) emissions estimates; we have called this the ‘ICAO fuel patch’ method. This approximate fuel uplift was included in the calculations of average emissions factors, otherwise following the method outlined in sections 2.1 and 2.4, and comparisons of results from each method is made in section 3.1. Not all missing fuel uplift was able to be obtained from these two datasets, as they did not provide fuel estimates for some flights in our data which were considered to be outside the possible flight range by the datasets. Where this was the case, these flights were omitted from calculations. Including the aircraft for which fuel uplift data was missing in calculations accounts for 95% of all international flights.
2.6. Calculation of emissions factors

The method for calculating emissions factors in this paper is based on that of Howitt et al (2011), with some modifications, which will be discussed in this section. A combination of the EMEP/EEA Tier 2 and 3 method was used, as some fuel data for flights was available by aircraft type, differentiated by distance. However, as it did not cover every aircraft or leg flown to or from New Zealand, there was no way to account for missing flights without producing an average emissions factor.

The use of fuel uplift data presents one of the significant differences in the present study to the majority of the existing peer reviewed literature, as it is commercially sensitive data, and therefore not typically available. The data obtained for 2017 provided average fuel uplifts for routes departing Auckland International Airport, but had five missing aircraft models. These models were confirmed to be absent from the fuel uplift data as they did not commonly refuel in New Zealand (Air BP, pers. comm., 29 Jan. 2019). The fuel burn of these aircraft for their travel leg of greatest distance was approximated as outlined in section 2.5.

There were five flights to Pacific Islands which had at least twice the fuel uplift as trips by the same aircraft when the fuel uplift was weighted by distance. In the case of these Pacific flights, it was assumed that this extra fuel uplift was so that a roundtrip flight could be made without refuelling, either because it was more economic for the airline to carry extra fuel, or there was limited availability of aviation fuel due to the remoteness of the islands. These fuel uplift outliers were excluded from all calculations, as they were deemed unrepresentative of the fuel used for a one-way flight by that aircraft.

Flight distance was calculated by applying a correction factor of 1.09 to the great circle distance between airports to allow for circling (EUROCONTROL 1992, Penner et al 1999, Howitt et al 2011), though it should be acknowledged that this is a conservative overestimate for New Zealand (Howitt et al 2011). Distances between airports were calculated using the WGS-84 Ellipsoid (NIMA 2000), using airport latitudes and longitudes from the Global Airport Database, an online database of airport coordinates for 9,300 airports (Partow 2003).

Passenger load was assumed to be 83%, as this was the yearly average across international flights performed by Air New Zealand (2018a), and an update of that used by Howitt et al (2011). ICAO would be a more comprehensive source for specific flight leg load factors, but as discussed in section 4.4, their data was deemed unusable due to lack of coverage. A conversion factor of 3.157 kg CO₂ per kg fuel was used to calculate CO₂ from the combustion of aviation fuel (ICAO 2009, Jardine 2009).

The assumed mass of the average passenger plus luggage was taken to be 100 kg (ICAO 2009, DBEIS 2017). The weight of the seats and other on-board infrastructure necessary to operate a commercial aircraft is not attributed to passengers, as it is considered critical to the aircraft flying, and does not change with the load factor of the aircraft.

Mass of air freight taken on board per passenger was calculated by assuming all freight to be carried as belly-cargo on passenger flights, and to be evenly distributed with passenger load, i.e., every passenger ‘carried’ a certain amount of freight with them. The total number of passenger movements into and out of all international airports in New Zealand was taken from Statistics New Zealand (n.d.), and was 12,585,244, and import and export mass was 105,538,547 kg and 111,487,313 kg respectively for 2017, giving an average of 17.2 kg per passenger. This is less than in 2007 (Howitt et al 2011) which assumed 24 kg of freight per passenger, as mass of air cargo for New Zealand has only increased by 5% between 2007 and 2017, while passenger numbers have increased by 45% over the same time. This freight per passenger of 17.2 kg was added to the 100 kg average allowed per passenger (including luggage) in ICAO (2009), so every passenger effectively weighed 117.2 kg.

Seating capacity has a substantial effect on the efficiency of a flight. DBEIS (2017) give average seating capacity figures from the UK Civil Aviation Authority for aeroplanes flying to and from the UK. Newer model aeroplanes have average seating capacities on their respective corporate websites, along with some specifications of older aeroplane models (Boeing n.d.; Airbus n.d.). Additionally, the seating capacities of airlines flying into New Zealand was collected so as to compare real world capacity against manufacturer reported capacity, taken from airlines which flew to and from New Zealand most frequently (Skyscanner n.d.), of which at the start of 2019 there were 21 (Air China n.d.; Air New Zealand n.d.; All Nippon Airways n.d.n.d.; American Airlines n.d.; British Airways n.d.; Cathay Pacific n.d.; China Airlines n.d.; China Eastern n.d.; China Southern Air n.d.; Emirates n.d.; Korean Air n.d.; Malaysia Airlines n.d.; Philippine Airlines n.d.; Singapore Airlines n.d.; Thai Airways n.d.; Tianjin Airlines n.d.; Qantas n.d.; Qatar Airways n.d.; United Airlines n.d.; Virgin Atlantic Airways n.d.; Virgin Australia n.d.), and an average was taken across each aircraft model. Available seats as given by the airlines were generally lower than those in DBEIS (2017) or manufacturer specifications, see table 1, though it should be noted that airline and manufacturer seating figures were collected in January/February 2019 and assumed to be representative of 2017. Table 2 demonstrates the effect this can have on emissions factors, keeping everything else constant, which compounds when emissions factors are used to calculate total emissions. To establish which of these gave the most accurate representation for New Zealand, the total number of seats available was calculated for each dataset and flight numbers per aircraft model, with the total number of travellers through Auckland Airport and Christchurch Airport, New Zealand’s two largest, in 2017 being
11,685,019. Using DBEIS (2017) figures, the number of available seats was 21,639,660, giving a load factor of 54%. With the averaged airline seats, the total available seats was 14,908,799, and a load factor of 78%, whereas the manufacturer seat numbers totalled 15,825,708, with a load factor of 74%. As the load factor given by the average seating taken from airline figures was the closest to the assumed industry average of 83%, this was taken to be the most representative average seat capacity.

The Auckland Airport fuel uplift data gave average uplift for common flight legs flown by particular aircraft. From the Airways dataset, it could be seen that the Auckland Airport fuel uplift data did not cover every flight leg flown by an aircraft. For the legs for which fuel uplift were given, those data were taken as representative fuel uplift for the aircraft across all flight legs, even if some legs were missing fuel uplift data. For the legs that Airways data indicated flights had occurred, but for which no fuel uplift data were available for all short-haul, or for all long-haul, or for all flight legs, then representative fuel use was added from the ICAO and EMEP/EEA databases for that aircraft.

As shown in equation (1), each aircraft has an average emissions factor across known flight legs. The average emissions factor per aircraft was taken as the numerical mean across flights, where $m_{fuel}$ is the fuel uplift (kg) from either the Auckland Airport fuel uplift dataset, or the ICAO or EMEP/EEA database, as explained above.

### 2.7. Calculation of total aviation emissions

All passengers and freight were assumed to travel through a representative airport for the country of origin and departure, as this is how the data is disaggregated by Statistics New Zealand. Countries were divided into short-haul (<3700 km) and long-haul (>3700 km), and into New Zealand residents travelling internationally, international visitors travelling to New Zealand, imports, and exports. Countries of arrival or destination were selected as the top 21 for international visitors and top 30 for New Zealand residents out of a total of 247 and 246 countries, respectively. This covered 90% and 92% of all travellers. For freight, the top 20 and 25 countries for exports and imports out of 205 were selected, which both accounted for 90% by mass. The method of applying emissions factors to visitor numbers is adapted from Smith and Rodger (2009), originally taken from DEFRA (2007), and falls under the Tier 1 method in the EMEP/EEA guidebook (Winther et al 2016). For all of these
Table 2. Emissions factors for 2017 using average seating capacities from different listed sources, for comparison purposes. Note that the emissions factors for 2017 used to calculate the final results from this research are those given in the second column, i.e., those using airlines’ average seat capacity and a load factor of 83%.

|                          | DBEIS (2017) seat capacity and load factor of 83% | Airlines’ average seat capacity (21 airlines, January/February 2019) and load factor of 83% | Manufacturer capacity, 2007, with 2019 where no 2007 information (see section 4.1) and load factor of 79% | Manufacturer seat capacity (January/February 2019) and load factor of 79% |
|--------------------------|--------------------------------------------------|-------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Short-haul (kg CO₂ per t-km) | 0.66                                             | 0.81                                                                                      | 0.84                                                                                                                  | 0.78                                                                      |
| Long-haul (kg CO₂ per t-km)   | 0.61                                              | 0.79                                                                                      | 0.76                                                                                                                  | 0.79                                                                      |
datasets, ~10% of data was too time-consuming to include, as this was the difference between 20–30 inputs versus >100. For exports and imports, the Howitt et al (2011) weighted average approach was used to scale for the missing mass. The uncertainty associated with these omissions is discussed in section 4.4.

Flight leg distances were calculated as for the emissions factors (section 2.6). Flights which would require two or more legs, e.g., London to Auckland, which requires a stopover, were treated as a single flight, as stopover countries vary for long-haul flights by operator and route. Freight and passenger emissions were calculated separately, as there are some differences in the distribution of important trade countries compared to tourist countries.

3. Results

3.1. Overview: accounting for missing fuel data

Including fuel burn for the aircraft which did not refuel in Auckland using the EMEP/EEA patch method or the ICAO patch method increases total emissions by up to 0.4 Mt CO₂ or 5%; estimates were obtained of 8.2 Mt CO₂ (2 significant figures, rounded down) using Auckland fuel uplift only (i.e., excluding the aircraft which did not refuel in Auckland), 8.5 Mt CO₂ (2 significant figures rounded up) for the EMEP/EEA patch method, and 8.6 Mt CO₂ (2 significant figures, rounded up) for the ICAO patch method, with most of the variation due to passenger aviation, as shown in figure 1. Both the ICAO (2017) and EMEP/EEA data (Winther et al 2016) have differences when compared to known Auckland fuel uplift, shown in figure 2, but the EMEP/EEA fuel only and Auckland fuel only methods have total emissions results that are closest to each other. Estimates of total emissions excluding the aircraft which did not refuel in Auckland were 8.2 Mt CO₂ (2 significant figures, rounded down) using only the Auckland fuel uplift, 8.3 Mt CO₂ (2 significant figures, rounded up) using only the EMEP/EEA fuel data, and 9.2 Mt CO₂ (2 significant figures, rounded up) using only the ICAO fuel data. From the fuel uplift dataset, comparisons were made with estimated fuel burn from the ICAO (2017) and EMEP/EEA datasets for the flights where both distance and fuel uplift were in the Auckland fuel uplift dataset. When taken as an average across all aircraft models, EMEP/EEA data underestimates fuel by 5.4%, whereas ICAO (2017) overestimates fuel by 8.1%. All aircraft for which fuel uplift is missing are wide body, and when wide body fuel figures were compared across data sources, EMEP/EEA underestimated by 0.13% while the ICAO (2017) figures overestimated by 12%. Lack of coverage was an issue for both databases, with ICAO (2017) not having fuel information for three long-haul flight legs, and EMEP/EEA for nine long-haul flight legs, as they were considered outside the possible range for various aircraft by the databases. It should be noted that both databases had fuel figures for the flights discussed in section 2.5, thus there is no lack of coverage for these flights, and
supplementing fuel uplift with data for these flights results in full coverage for all major aircraft models in the fleet servicing New Zealand. EMEP/EEA was assumed to be a more accurate source of fuel statistics than ICAO (2017), and it is these figures which are used throughout these calculations for aircraft models where empirical fuel uplift data was not available.

3.2. Emissions factors

The emissions factors obtained in this paper are 0.81 kg CO₂ per tonne-kilometre (kg CO₂ per t-km) for short-haul and 0.79 kg CO₂ per t-km for long-haul flights in 2017. These figures were calculated from Auckland, New Zealand specific fuel uplift and flight movement data and EMEP/EEA fuel data where there was no fuel uplift data. The majority of short-haul flights were due to two aircraft types. The average efficiencies of these models are therefore going to disproportionately weight the overall short-haul emissions factors. There was no dominant aircraft type for long-haul.

Short-haul flights were dominated by the A320 and B737-800 (see section 4). Of the aircraft flying short-haul in 2017, on average the B737-300 has the lowest fuel consumption, however the Auckland fuel uplift data only contained fuel uplift data for one of these trips for this aircraft, so it is unclear whether this is true of all routes flown by the B737-300, and it only flew 0.1% of flights, so had no real impact on efficiency. The aircraft with the lowest fuel consumption and an above average number of data points for short-haul flights are the B787-900 and the B737-800 implying there are fleet improvements which could reduce short-haul CO₂ emissions.

For long-haul flights, there are aircraft with lower fuel consumption than the combined average (the A320, B777, B777-300 and B787-900) and the B767 the highest, with a difference of more than 0.4 kg CO₂ per t-km between them, however, apart from the B767, the aircraft efficiency of the long-haul models is relatively similar.

In general, the range of emissions factors across aircraft types flying short-haul in 2017 is much larger than in 2007, as shown in figure 3. Most aircraft present in the 2007 short-haul fleet are flying in a less efficient manner in 2017, and some of the aircraft that have more recently been introduced to the fleet are also less efficient than some of those they have replaced. Newer additions to the fleet dominate long-haul flights in 2017; though the range of emissions factors is smaller than for the short-haul fleet in 2017, the average emissions factor across the fleet has still increased as all but one aircraft (the A320) has an average emissions factor above the 2007 average, as shown in figure 4.

The data used in the calculations of emissions factors are averaged, and therefore general. This makes it difficult to pinpoint the factors leading to the 2017 long-haul and short-haul emissions factors being similar to each other (but not identical at the two significant figure level). Examination of the average emissions across each aircraft in the fleet, as explained above, gives some insights. Another factor, the impact of distances flown, is...
explored further in section 4.5. The average distance flown for both short- and long-haul flight legs in and out of New Zealand are longer than for the UK, for example, and will also be higher than for many of the other countries in the world given how isolated New Zealand is compared to other countries. One of the major stalling points of any aviation research is limited availability of data. For a limited number of routes in April 2014, Baumeister (2017) was able to collect information on utilised space on an aircraft for passengers, the number of seats occupied on a flight, and the amount of freight carried compared to passengers, and thus produce a much more detailed assessment of factors impacting efficiency. While there was insufficient data available to do the same with the present research, it is safe to assume that these factors would all provide some explanation as to the emissions factors calculated here. We believe this is a reasonable assumption because the space utilised on an aircraft, and hence proportion of mass relative to the mass of the aeroplane itself, is a critical factor in determining efficiency.

3.3. CO₂ from New Zealand passenger and freight aviation

Using the emissions factors presented in section 3.2, total passenger emissions for New Zealand were estimated to be 4.3 Mt CO₂ (2 significant figures, rounded up) for international visitors travelling return to New Zealand, and 2.6 Mt CO₂ (2 significant figures, rounded up) for New Zealand residents travelling return internationally.
Air exports totalled 0.72 Mt CO₂ (2 significant figures, rounded up), and imports totalled 0.89 Mt CO₂ (2 significant figures, rounded up), giving a total for all air transport to and from New Zealand in 2017 of 8.4 Mt CO₂ (2 significant figures, rounded down).

Passenger and freight emissions were primarily due to air travel between New Zealand and a few key countries. For passenger aviation in 2017, Australia, China, the UK, and the United States of America (USA) were the four largest countries by cumulative emissions for both country of residence for passengers travelling to New Zealand, and as destinations for New Zealand residents. By region, aside from Oceania, which was primarily dominated by Australia, Asia had the largest share of emissions both for international and New Zealand residents, with China constituting the majority. The dominance of China in traveller statistics could be due to its economic importance to New Zealand, as China was a primary trading partner with New Zealand in 2017, and accounted for the majority of air cargo emissions, both for exports and imports. Imports transported by air freight to New Zealand came mostly from China and Australia, followed by a cohort of western European countries. Exports transported by air freight were more diverse, with the USA having the second greatest share of emissions by country after China, followed by Australia, Hong Kong, Japan and the UK. Less cargo by mass was exported to China than imported, and this, combined with the distribution of exports going to nearer countries — mostly Asia and the USA — than imports had resulted in lower total emissions due to exports. New Zealand’s air trade alone totalled 1.6 Mt CO₂ in 2017. The majority of emissions due to air freight already came from countries which are geographically close to New Zealand, though this is relative given New Zealand’s isolation.

3.4. Emissions estimates using fuel databases
Using the same methods as sections 3.2 and 3.3 total emissions were calculated using fuel burn solely from the EMEP/EEA and ICAO (2017) databases. While the analysis in section 3.1 showed that a straight average taken across fuel burn varied by small amounts relative to the fuel burn for figures taken from the EMEP/EEA database, when these same figures where weighted by aircraft flying to and from New Zealand, the magnitude of the underestimation of fuel is amplified. This is primarily due to many of the longest long-haul flights not being considered to be within the range of aircraft, and so no fuel burn was able to be calculated using the database. As discussed further in section 4.4, the longer flights have a non-linear fuel burn to distance ratio, as aeroplanes burn disproportionately more fuel per unit distance when flown beyond a certain range (Winther et al 2016). Here the missing flights were often very near the limit of what the range of the aeroplane is, and so flight legs for which fuel burn was higher than usual are missing from the EMEP/EEA calculations. This would likely be less of a problem for most other countries as New Zealand has many flights which are well outside the average long-haul flight length. The emissions factors calculated from EMEP/EEA fuel burn were 0.77 kg CO₂ per t-km for short-haul flights, and 0.78 kg CO₂ per t-km from long-haul. The short-haul emissions factor is an underestimation, as noted above, by 5%. The long-haul emissions factor varies from that in section 3.2 by −1%, which is in keeping with the total average variation from fuel uplift as in section 3.1 as not all long-haul aircraft are wide-body. Emissions calculations taken from ICAO (2017) fuel burn are over-estimated when compared to known Auckland fuel uplift. The ICAO (2017) fuel burn gave emissions factors of 0.90 kg CO₂ per t-km for short-haul and 0.85 kg CO₂ per t-km for long-haul. The magnitude of the over-estimation using ICAO (2017) fuel burn is the same as earlier found in section 3.1, even when looking at short- and long-haul individually. Here a comparison between only wide-body aircraft gave a discrepancy 12% for short- and long-haul. When these emissions factors are used to calculate total emissions, 8.3 Mt CO₂ (2 significant figures, rounded up) and 9.2 Mt CO₂ (2 significant figures, rounded up) are obtained using the EEA/EMEP and ICAO fuel databases, respectively, with use of the Auckland fuel uplift yielding 8.2 Mt CO₂ (2 significant figures, rounded down). The breakdown across passenger and freight for these totals is given in figure 2. As noted above, both databases lacked information for some of the flights included in the Auckland Airport fuel uplift, so while neither is an entirely accurate representation for New Zealand, they would be suitable substitutes for countries which had shorter average long-haul flight distances, as discussed further in section 4.2.

4. Discussion

4.1. Comparisons with New Zealand aviation research
Smith and Rodger (2009) and Howitt et al (2011) were New Zealand focused and therefore are the most relevant literature with which to make comparisons. International aviation research for other countries is discussed in section 4.2.

The comparison between Howitt et al (2011) and the present research is shown in figures 3 and 4 with emissions factors for each aircraft identified in the New Zealand fleet shown for both 2007 and 2017. Howitt et al (2011) used the Smith and Rodger (2009) method, but replaced the DEFRA emissions factors with those calculated in Howitt et al (2011) to estimate passenger aviation’s carbon footprint for 2007 at 4.3 Mt CO₂ in total,
with 2.9 Mt CO₂ and 1.4 Mt CO₂ attributed to international visitors and New Zealand residents, respectively. For 2007, Howitt et al. (2011) derived a short-haul emissions factor of 0.82 kg CO₂ per t-km and a long-haul emissions factor of 0.69 kg CO₂ per t-km. The short-haul emissions factor calculated in the present research shows a small change to that of Howitt et al. (2011) on average, though there are significant differences in individual aircraft efficiency and large changes in fleet composition, as shown in figure 1. The long-haul figure represents a significant decrease in efficiency, again along with large changes in individual aircraft efficiency and fleet compositional changes (figure 2). Both of these results counter the accepted idea that aviation is becoming more efficient by between 1%–2% per annum (Penner et al. 1999, Larsson et al. 2018).

Outside of fuel uplift and passenger load, the variable with the largest impact is average seating capacity. Table 1 shows the difference between seating capacity used in this research compared to Howitt et al. (2011). In both 2007 and 2017, A320s were flying short-haul and long-haul flights, but the (previously unpublished) seating capacity assumed for this model by Howitt et al. (2011) presented in table 1 was lower than the airline average used here. The other models flying long-haul in both years have greater seating capacities in the estimate used by Howitt et al. (2011).

To examine the effect of seating density more definitively between Howitt et al. (2011) and the present research, emissions factors for 2017 were also calculated using the same load factor of 79%, and seating capacities as Howitt et al. (2011) (see table 1), with manufacturer seat numbers filling in gaps where aircraft models had changed. The result of this is emissions factors of 0.84 kg CO₂ per t-km for short-haul, and 0.76 kg CO₂ per t-km for long-haul flights in 2017. This shows that both the short-haul and long-haul emissions factors would have increased, in the scenario where load factor and seat capacity remained constant, from 0.82 kg CO₂ per t-km in Howitt et al. (2011), to 0.84 kg CO₂ per t-km for short-haul, and from 0.69 kg CO₂ per t-km in Howitt et al. (2011), to 0.76 kg CO₂ per t-km. There are two main changes influencing these results: firstly, the manufacturer seating capacity used in these calculations is significantly different to the airline averages used in the above calculations, see table 1, and the second is the different load factors.

Long-haul emissions factors would have increased by 10%. The smaller increase (2%) that would have occurred for in short-haul emissions factors is primarily due to the increase in efficiency of the B737–800, which was 23% of short-haul flights in 2007, and 37% in 2017, as this outweighed the introduction of larger aircraft flying short-haul. The increase in long-haul emissions factors is due to the introduction of the A330–200, and the B777–200 being significantly less efficient when compared to 2007, as these two models have the highest average emissions per passenger-kilometre in the fleet servicing New Zealand, while jointly making up 35% of all flights.

Using these modified emissions factors to calculate total emissions gives an alternative total of 8.3 Mt CO₂. The traveller total is 6.7 Mt CO₂, with 4.2 Mt CO₂ from international visitors travelling to New Zealand, and 2.5 Mt CO₂ from New Zealand residents travelling internationally, and a freight total of 1.6 Mt CO₂, with 0.70 Mt CO₂ from exports, and 0.87 Mt CO₂ from imports (table 3). Howitt et al. (2011) and final results figures are also shown in table 3; when the modified emissions figures result are compared with Howitt et al. (2011), it can be seen that there has been an increase in the amount of CO₂ from international visitors of 45%, and a 79% increase from New Zealand residents’ CO₂ emissions, with a combined increase of 56%, and when the final results are compared with Howitt et al. (2011), the increases were 48%, 86%, and 60% respectively. Between 2007 and 2017 passenger–kilometres travelled by international visitors and New Zealand residents increased by 42% and 60% respectively, with a combined increase of 46%. Thus, emissions have increased more than passenger–kilometres. The increase in the number of passengers was 53% for international visitors and 50% for New Zealand travellers, with a combined increase of 52%. Although the percentage increase in passenger numbers for international and New Zealand travellers is similar, the short–haul and long–haul distances travelled have increased in different ways. This is important because the short–haul emissions factor is almost unchanged from 2007 to 2017, whereas the long–haul emissions factor has increased. Specifically, for international visitors the percentage of travel classified as long–haul was 53% in both 2007 and 2017, whereas for New Zealand travellers the percentage of travel classified as long–haul increased from 30% to 37%. However, although the proportion of international visitor travel classified as long–haul was 53% in both 2007 and 2017, the mean distance travelled by each passenger decreased by 8.0%. This drop in the mean distance was due to the large increase in passenger numbers from long–haul destinations that are closer to New Zealand (+246% for China and +60% for the USA) and a decrease in passenger numbers from locations further from New Zealand (−14% for the UK), For New Zealand travellers, passenger numbers for the three main long–haul destinations of China, the UK, and the USA all increased, by 109%, 28%, and 121%, respectively. For short–haul destinations, Australia dominates both international visitor origin and New Zealand traveller destination, and passenger numbers increased by 56% and 25%, respectively.

The figures from Smith and Rodger are not directly comparable to either the present research, or to Howitt et al. (2011), as there are significant differences between the flight information used to calculate the emissions factors between the UK and New Zealand, and the UK emissions factors are known to be unrepresentative of New Zealand. Despite this, the passenger statistics changes are relevant, and these are analysed below.
Table 3. Comparison between 2007 (Howitt et al. 2011), and 2017 when emissions factors are calculated with the same aircraft load factor and using manufacturer seat capacity method as Howitt et al (2011) (‘modified emissions factors’), and the final 2017 results of the current research as described in sections 3.2 and 3.3.

|                          | International visitors to New Zealand | New Zealand residents travelling internationally | Exports | Imports |
|--------------------------|---------------------------------------|-----------------------------------------------|---------|---------|
| 2007, Howitt et al (2011) | 2,243,467 travellers                   | 1,721,721 travellers                           | 94,273  | 96,061  |
|                          | Quantity (top 21 countries/regions (international visitors), top 30 countries (NZ residents), top 20 countries (exports and imports), Statistics New Zealand (n.d.)) |                                   |         |         |
|                          | Quantity multiplied by distance (Top countries, unpublished) | 1.9 × 10^{10} passenger-km | 0.99 × 10^{10} passenger-km | 6.8 × 10^8 tonne-km | 8.9 × 10^8 tonne-km |
|                          | CO\textsubscript{2} emissions (Mt CO\textsubscript{2}) (No scaling for international visitors and NZ residents, scaled up from top 20 countries for exports and imports) | 2.9 | 1.4 | 0.53 | 0.67 |
| 2017, present research with modified emissions factors | 3,433,744 travellers                   | 2,581,220 travellers                           | 100,610 | 95,411 |
|                          | Quantity (top 21 countries for international visitors, top 30 countries for NZ travellers, top 25 countries for imports and top 20 countries for exports, Statistics New Zealand (n.d.)) |                                   |         |         |
|                          | Quantity multiplied by distance (Top countries only) | 2.7 × 10^{10} passenger-km | 1.6 × 10^{10} passenger-km | 8.0 × 10^8 tonne-km | 9.8 × 10^8 tonne-km |
|                          | CO\textsubscript{2} emissions (Mt CO\textsubscript{2}) (No scaling for international visitors and NZ residents, scaled up from top 20 countries for exports, and top 25 countries for imports) | 4.2 | 2.5 | 0.70 | 0.87 |
| 2017, present research, final results | 3,433,744 travellers                   | 2,581,220 travellers                           | 100,610 | 95,411 |
|                          | Quantity (top 21 countries for international visitors, top 30 countries for NZ travellers, top 25 countries for imports and top 20 countries for exports, Statistics New Zealand (n.d.)) |                                   |         |         |
|                          | Quantity multiplied by distance (Top countries only) | 2.7 × 10^{10} passenger-km | 1.6 × 10^{10} passenger-km | 8.0 × 10^8 tonne-km | 9.8 × 10^8 tonne-km |
|                          | CO\textsubscript{2} emissions (Mt CO\textsubscript{2}) (No scaling for international visitors and NZ residents, scaled up from top 20 countries for exports, and top 25 countries for imports) | 4.3 | 2.6 | 0.72 | 0.89 |
Since 2005, the year that Smith and Rodger (2009) examined, traveller numbers for international visitors to New Zealand have increased from 2,365,529 for the top 21 countries in 2005 to 3,433,744 for the top 21 countries in 2017, or 45%. Traveller numbers for New Zealand residents increased from 1,871,801 for the top 30 countries in 2005 to 2,581,220 for the top 30 countries in 2017, or 38%. Passenger-kilometres travelled by international visitors have increased from $1.9 \times 10^{10}$ km to $2.7 \times 10^{10}$ km, and for New Zealand residents from $0.9 \times 10^{10}$ km to $1.6 \times 10^{10}$ km, or by 42% and 78% respectively between 2005 and 2017. However, there are difficulties comparing the Smith and Rodger (2009) emissions estimates with the emissions estimates both in this paper and Howitt et al (2011), because the Smith and Rodger (2009) paper used UK emissions factors whereas Howitt et al (2011) and in this paper we have derived New Zealand based emissions factors. Smith and Rodger (2009) used DEFRA (2007) emissions factors of 130 g CO₂ per p-km for short-haul and 105 g CO₂ per p-km for long-haul. The total emissions calculated in Smith and Rodger (2009) are therefore not able to be compared with this paper and Howitt et al (2011) due to the differences in emissions factors used. The emissions calculated in Smith and Rodger (2009) appear significantly larger, and therefore unrealistically lessen the apparent magnitude of growth in total emissions when direct comparisons are attempted.

4.2. Comparisons with international research

Given the dearth of aviation emissions research carried out globally, there were few up-to-date international publications to make comparisons with. To the best of the authors’ knowledge, DBEIS is the only source of annually updated emissions factors, and calculating country specific emissions factors in peer-reviewed literature is uncommon. In DBEIS (2017) emissions factors for mixed passenger flights with belly-hold freight are given as 1.0 kg CO₂ per t-km for short-haul and 0.7 kg CO₂ per t-km for long-haul. Given the geographic differences between New Zealand and the UK, some disunity between the figures is unsurprising, though there are some possible explanations. Firstly, as noted in table 1, the average seating used in the UK emissions factors is generally higher than those used in the present research, with the sole exception of the B737-300. While a greater seating density per aircraft would necessitate greater overall fuel uplift, Graver and Rutherford (2018) found that seating density had a large impact on passenger based efficiency. Secondly, the distance travelled per aircraft leg has impacts for the efficiency of the flight. An important consideration is the relative average distance between short-haul and long-haul in New Zealand and the rest of the world. Including only airport-to-airport movements, for the UK the average distance of a short-haul international flight is 1,366 km, and long-haul is 6,823 km (DBEIS 2017). Across all international flights to and from New Zealand present in the dataset from Airways, the average New Zealand flight legs distance were 2,495 km for short-haul, and 10,205 km for long-haul. Of the 28 destinations covered in the fuel uplift, 12 were short-haul, with an average distance of 2,565 km. The average UK long-haul flight was 6,823 km (DBEIS 2017), much closer to the optimally efficient long-haul flight length of between 4,000 km and 5,000 km (Wit and Dings 2002). The average New Zealand short-haul flight is more than 80% longer than the average UK short-haul flight. Although the New Zealand short-haul emissions factor is lower than the DBEIS (2017) short-haul emissions factor, the New Zealand short- and long-haul emissions factors are both larger than the DBEIS long-haul factor, implying that the average flight in each of these categories are sub-optimal in terms of emissions. Short-haul flights are impacted by the greater proportion of LTO emissions to distance flown compared to long-haul, and long-haul flights by the extra fuel carried to enable the aeroplanes to fly lengthy distances.

Larsson et al (2018) derived a single emissions factor for global passenger aviation, averaging all flights, across short-haul and long-haul, for every year between 1990 and 2014, with the CO₂ factor being 158 g per passenger km (g per p-km) in 1990, dropping to 100 g CO₂ per p-km in 2014. These figures are calculated using global totals, which are unlikely to be representative of a country like New Zealand. This is because the average flight distances for short- and long-haul are skewed for New Zealand; globally the average flight length in 2007 was 2,400 km, almost the same distance as the average short-haul New Zealand flight in 2017. This implies that a short-haul flight to or from New Zealand is more efficient than the average global flight of the same length, while New Zealand’s long-haul flights are typically longer than the international average.

Kito et al (2020) compared the Japanese aircraft fleet between 2005 and 2015, and found that emissions factors had decreased overall, though total emissions had increased due to growth in the number of flights. However, when examining the changes in the aircraft in the fleet in the years studied, some similar changes were found to have occurred in that fleet as we have concluded from the present New Zealand-focussed research. Kito et al (2020) observed that the introduction of the B787 had improved fleet efficiency, as these had largely replaced aircraft which were less efficient, such as the B747 and B767. However, some of the more efficient aircraft, such as the A320, had also been replaced, including with the B787. While the B787 is more efficient than the B747 for example, it is not more efficient than the A320, so some of these changes had negative consequences. Similar substitution changes have also been observed for the New Zealand fleet, see figures 3 and 4.
4.3. Impact of seating density changes

There is a marked difference across aircraft floorplans when an increasing number of classes are introduced, as individual seats in premium economy, business, and first class take up more space than an economy seat (ICAO 2017), up to seven times the floor space in the case of first class in a wide body aeroplane (World Bank 2013). Due to the general lack of historical fleet information outside of quantities of aircraft model in use in a given year, it is unclear whether a greater proportion of aeroplanes now use more space housing business and first class passengers. Fleet statistics for aeroplanes capable of flying short-haul and long-haul routes were taken from Air New Zealand’s in-flight magazines at six monthly intervals where possible for the years 2007–2018 (Air New Zealand 2007–2018), and the average number of seats per plane across the fleet increased from 222 in 2007 to 265 in 2018, while total numbers of aircraft in the fleet was 47 in both years. Seating density has a large impact on efficiency (Baumeister 2017, Graver and Rutherford 2018), and so an increase in the number of seats on a given aeroplane model, assuming the load factor remains constant, should have a positive effect on emissions factors.

4.4. Uncertainty, limitations and data availability

Flight leg data from Airways lists aircraft by ICAO code, which provides less specificity than equivalent International Air Transport Association (IATA) codes, particularly with freight sub-models of aircraft. The ICAO codes do not distinguish between passenger, military, freighter or private flights. Aircraft models that could be identified as serving any purpose other than scheduled passenger transport were excluded, however freighter models which could not be distinguished from passenger flights may remain. Howitt et al (2011) found there was no source available at the time of their research to determine either the number of dedicated freighters servicing New Zealand, or what quantity of overall freight mass they transported. ICAO was identified as a possible source of this information for the present research, as they have granular data for all airlines and countries, but due to incomplete coverage this did not prove a viable source of data. Due to the lack of new information on freight-only flights at the time of this research we assume most freight is carried in the belly-hold of passenger aircraft, as in Howitt et al (2011).

The use of emissions factors has an associated uncertainty, as it generalises the fleet servicing New Zealand, and the routes and distances flown. Calculating emissions factors from known aircraft legs and applying them to longer routes has been assumed to be an underestimation, particularly for New Zealand, as it is remote, and fuel burn increases non-linearly relative to distance travelled past a certain distance. However Baumeister (2017) has results to show that single leg trips are not necessarily more efficient than multi-leg trips between the same departure and arrival pair, so it is unclear whether this is in fact an underestimate.

The simplification of using a single representative airport is an underestimation, though this is more significant for some countries than others, e.g., long-haul flights to Europe travel through either Asia, the Middle East, or North America, and always have at least two flight legs when departing New Zealand. First, there are multiple main airports that receive direct flights to New Zealand, and secondly, the passenger or freight’s ultimate place of arrival or destination may be outside of their designated port. In both cases, this method has a small uncertainty concerning arrivals to New Zealand, and any extra distance travelled is comparatively small, though for departures from New Zealand the uncertainty could be much larger. This is particularly relevant as the method presented here is by destination and arrival, and not flight leg.

Using an alternative source of fuel data for aircraft which do not refuel in New Zealand has some uncertainty, though the variation in fuel across all wide body aircraft fuel is small, as discussed in section 3.1. The EMEP/EEA data is a better approximation than ICAO data when compared to the fuel uplift in this paper, and so was chosen as the more accurate source for calculations. The figures calculated here include both departures and arrivals to provide coverage of all air transport associated with New Zealand, as well as any difference between incoming and outgoing aviation. However, if applied to all countries this would result in double counting.

All flights were assumed to be a single leg trip from airport of departure to that of arrival. It is unclear whether this has any effect of the uncertainty of the GHG total, as Baumeister (2017) found that some multi-leg trips could be more efficient than a non-stop flight between the same airports. This goes against common logic that a single flight should be more efficient than the same trip divided into multiple legs, as take-off and landing are the more fuel intensive sections of a flight, while the cruise phase uses a smaller relative amount of fuel, therefore a single leg should have more time spent in the more efficient cruise phase, and only have one each of take-off and landing.

The uncertainty of the omission of countries is simple to calculate, with the lower bound assuming Australia was the country of departure or arrival, with the United Kingdom as the upper bound, and this gives an underestimate by between 0.26 Mt CO₂ and 2.1 Mt CO₂ for passenger travel, and 0.042 Mt CO₂ to 0.34 Mt CO₂ for freight, with an overall underestimate of between 0.30 Mt CO₂ and 2.5 Mt CO₂. Following the Howitt et al (2011) method, emissions for passenger travel were not scaled, so the lower and upper bounds directly represent
the underestimate associated with those emissions, which were 6.9 Mt CO$_2$ in total. Howitt et al (2011) scaled freight emissions and this was also done in the current work, so the lower and upper bounds represent the underestimate associated with the unscaled emissions which were 1.4 Mt CO$_2$ in total (not the scaled value of 1.6 Mt CO$_2$).

We were unable to quantitatively assess the uncertainty for these calculations, as sufficient data was not available. Additionally, some choices necessitated by the available data, such as assuming all trips to be a single leg have an unknown effect on the uncertainty, and there is insufficient research in this field to be able to assess this.

4.5. Efficiency of long-haul air travel

Long-haul air travel associated with New Zealand appears less efficient than long-haul air travel associated the UK, as DBEIS (2017) reported a long-haul emissions factors of 0.7 kg CO$_2$ per t-km. The 16 long-haul destinations in the fuel uplift data from Auckland International Airport had an average distance of 9,499 km, meaning all New Zealand specific long-haul emissions factors should be lower as long-haul is typically more efficient per kilometre, due to larger passenger loads and a greater distance spent in cruise compared to LTO.

However, there is a point of diminishing returns for how efficient a flight can be in terms of distance. Wit and Dings (2002) pinpoint the most efficient distance for long-haul flights to be 4,000 km to 5,000 km, and Park and O’Kelly (2014) show that the most efficient distance range was 1000 nautical miles to 2500 nautical miles (1852 km to 4630 km), and that (their figure 3) for flight-stage distances of 5000 to 6500 nautical miles (9,260 km to 12,308 km) aeroplanes begin to significantly increase in fuel burn per km by more than approximately 20 to 70% compared to the most efficient range distance, though this does not include data on some of the long range aircraft which have become more ubiquitous in recent years. Additionally, some of the longer haul flights stopping in New Zealand cover ranges that are considered outside the viable flight range by aircraft model in the EMEP/EEA database (Winther et al 2016), as the database uses data for European flight routes, covering shorter distances on average. This means the degree to which fuel use increases in relation to distance as shown in Park and O’Kelly (2014) is only partially represented, as the data in their study is taken from the EMEP/EEA database.

5. Conclusion

It is commonly reported that aeroplane fuel efficiency is increasing (DIRD 2017, Cox et al 2018) but the results of this paper have not found this to be the case for flights into and out of New Zealand, as we found that emissions factors for short-haul had remained relatively constant since 2007, at 0.81 kg CO$_2$ per t-km, while the long-haul emissions factor had increased by 14% since 2007 to 0.79 kg CO$_2$ per t-km in 2017. When applied to passenger volumes and freighted mass, CO$_2$ emissions associated with international aviation to and from New Zealand totalled 8.4 Mt CO$_2$ (2 significant figures, rounded down), with 4.3 Mt CO$_2$ (2 significant figures, rounded up) due to international visitors to New Zealand, 2.6 Mt CO$_2$ (2 significant figures, rounded up) due to New Zealand residents travelling overseas, and 0.72 Mt CO$_2$ (2 significant figures, rounded up) and 0.89 Mt CO$_2$ (2 significant figures, rounded up) due to exports and imports respectively. While aeroplane models may be improving in efficiency relative to earlier iterations of the same model, when considered in the context of how and to where they are flown, this is not borne out in total emissions estimates. Long-haul air transport associated with New Zealand has become less efficient between 2007 and 2017, partially due to models in use during both 2007 and 2017, on average, being operated in a way that is less efficient per tonne-kilometre, as well as the increased dominance of less efficient aircraft making up a larger proportion of flights. The biggest change in long-haul emissions factors was for the B767 which emitted, on average, 0.45 kg CO$_2$ per t-km less in 2007 on long-haul flights than in 2017. This is despite an increase in passenger load, which should increase fuel efficiency (Baumeister 2017, Graver and Rutherford 2018). As shown in figures 3 and 4, a greater number of aircraft models are flying to and from New Zealand in 2017 versus 2007 with a broader range of aircraft specific efficiencies. This broadening has increased long-haul emissions factors significantly, as three of four existing aircraft (B767, B777-200, B747) are being operated in ways that are less efficient than in 2007, and aircraft introduced to the fleet in this time are mostly comparatively inefficient.

Acknowledgments

The authors thank Air BP and Airways for providing data for this research. Emirates, ICAO, and the New Zealand Ministry of Transport are also thanked for valuable assistance in answering questions. The University of Otago Department of Physics 2018 Summer Research Bursary scheme provided financial support for A.P.T.’s involvement in this research. David Duval from the University of Winnipeg provided helpful insights into aviation industry practices. Thank you to Susanne Becken from Griffith University for her very helpful reading.
of the manuscript. Two anonymous reviewers provided extremely constructive feedback, for which the authors are grateful.

Data availability statement
The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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