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Carbon dioxide emissions from international air freight

Oliver J. A. Howitt, Michael A. Carruthers, Inga J. Smith, and Craig J. Rodger*

Department of Physics, University of Otago, P.O. Box 56, Dunedin 9054, New Zealand

* Corresponding author

Tel.: +64 3 479 7755

Fax: +64 3 479 0964

E-mail address: inga@physics.otago.ac.nz

Abstract

Greenhouse gas emissions from international air transport were excluded from reduction targets under the Kyoto Protocol, partly because of difficulties with quantifying and apportioning such emissions. Although there has been a great deal of recent research into calculating emissions from aeroplane operations globally, publicly available emissions factors for air freight emissions are scarce. This paper presents a methodology to calculate the amount of fuel burnt and the resulting CO_2 emissions from New Zealand's internationally air freighted imports and exports in 2007. This methodology could be applied to other nations and/or regions. Using data on fuel uplift, air freight and air craft movements, and assumptions on mean passenger loadings and the mass of passengers and air freight, CO_2 emissions factors of 0.82 kg CO_2 per t-km and 0.69 kg CO_2 per t-km for short-haul and long-haul journeys, respectively, were calculated. The total amount of fuel consumed for the international air transport of New Zealand's imports and exports was calculated to be 0.21 Mt and 0.17 Mt respectively, with corresponding CO_2 emissions of 0.67 Mt and 0.53 Mt.

Keywords

International air freight, carbon dioxide emissions, greenhouse gas emissions, New Zealand trade, aeroplane passenger emissions, aeroplane emission factors.

1. Introduction

1.1. Aim of the present research

This paper presents a methodology for calculating international air freight CO_2 emissions factors for a particular nation or region and the total CO_2 emissions associated with the nation's or region's international air freight. New Zealand is used as a case-study in the present research for which emissions factors and total emissions are calculated, based on the 2007 calendar year. This case study will be useful for other researchers and policy analysts performing similar studies at national or regional levels as well as helping guide New Zealand policy on international transport emissions.

Currently, there is no internationally accepted methodology for apportioning international aviation emissions (Wood et al., 2010). There is little peer-reviewed literature available for calculating the CO_2 emissions from international air freight. A core issue surrounding the accurate quantification of international aviation emissions lies in the commercially-sensitive nature of accurate, activity-based data on fuel use by international aeroplanes. Agencies such as the UK Department for Environment, Food and Rural Affairs (DEFRA) have used other input data, such as specific fuel-oil consumption rates, to calculate CO_2 emissions factors (DEFRA, 2008), which have subsequently been used in aviation emissions studies (e.g., Andersen et al., 2010; Saunders and Hayes, 2007). The alternative to activity-based quantification of aviation emissions is bunker fuel sales statistics, but these lead to discrepancies which were discussed in the global context by Owen et al. (2010), and in the New Zealand context by Smith and Rodger (2009).

The present research obtained commercially-sensitive fuel uplifts for aeroplanes refuelling in New Zealand to derive CO_2 emissions factors for air freight. These were combined with a dataset containing all of New Zealand's imports and exports transported by air freight to quantify the CO_2 emissions associated with their international transport.

Due to the commercially-sensitive nature of the data needed, calculating air freight CO_2 emissions factors as was done in the present research is rare. The international aviation sector is heavily reliant on aeroplanes built by only two manufacturers, who also produce the dominant aircraft used to fly into and out of New Zealand. There is a high rotation of the global aeroplane fleet, meaning that the aeroplanes which service New Zealand also operate in other regions around the world. For these reasons, the emissions factors derived in the present research are likely to be applicable to other nations; however, more research is required to verify this. Comparisons with the few publicly available emissions factors for air freight are discussed.

1.2. Global aviation fuel burn and carbon dioxide emissions

The global aviation industry consumed approximately 200-250 Mt of kerosene per year in the mid-2000s (Kim et al., 2007; Nygren et al., 2009; Lee et al., 2010), resulting in the emission of 733 million tonnes (Mt) of CO_2 in the year 2005 (Lee et al., 2009). This contribution represents approximately 3% of the total CO_2 emissions from the combustion of fossil fuels and is slightly less than Germany's national contribution in 2005, the 6th largest contribution by a country (International Energy Agency, 2010). Aviation accounted for 12% of the CO_2 emissions from the global transport sector in the year 2000, the third largest contributor after road and maritime transport (Lee et al., 2009).

The contribution of the aviation sector to global radiative forcing takes into account historical emissions and, therefore, provides a more accurate representation of the sector's contribution to anthropogenic climate change than considering CO_2 emissions alone (Penner et al., 1999). In 2005, the radiative forcing due to aviation was estimated to be between 23 and 87 mW/m^2 (excluding cirrus cloud enhancement, 90% likelihood range with a best estimate value of 55 mW/m^2), equivalent to 1.3 - 10% (3.5% best estimate) of the total anthropogenic radiative forcing (Lee et al., 2010). This contribution is especially significant when considering that the sector has only been commercially active since about the 1950s, whereas some other CO_2-producing sectors have been active for over one hundred years (e.g., the coal industry). While radiative forcing provides a more accurate representation of historical emissions, it is a difficult metric to use in estimating future impacts.

1.3. Aviation emissions and international policy

Under the Kyoto Protocol, Annex I countries are only liable for domestic aviation emissions that are included in a country's National Greenhouse Gas Inventory, whilst international aviation emissions are only required to be reported (Eggleston et al., 2006). Under Article 2.2 of the Kyoto Protocol, Annex I parties "shall pursue limitation or reduction" of greenhouse gas emissions by working through the International Civil Aviation Organization (ICAO) (United Nations, 1998).

It is uncertain whether global climate change agreements will include international aviation emissions in the foreseeable future. The introduction of the aviation sector into the European Union Emissions Trading Scheme (EU ETS) in 2012 will be the first international policy measure to use binding targets that aim to reduce CO_2 emissions from aviation (Anger and Köhler, 2010). Accurate quantification should always precede policy decisions, and it is in this regard that the present research will be informative.

1.4. Radiative forcing and metrics

Quantifying the non-CO_2 climate effects that emissions have on radiative forcing is an area of active research (Sausen et al., 2005; Forster et al., 2006; Forster et al., 2007; Lee et al., 2009, 2010; Fuglestvedt, 2010; Wuebbles et al., 2010). Aviation emissions cause both positive and negative changes to radiative forcing in the atmosphere. There is currently no internationally standardised approach for accounting for the non-CO_2 effects of aviation emissions. It is for this reason that no radiative forcing metric is applied to the calculations carried out in the present research.

1.5. Estimates of national emissions from air freight

Discussions on the regional- or product-level determination of CO_2 emissions from aviation have increased in the literature recently, particularly as part of life cycle assessments and the sector being introduced into the EU ETS in 2012. However, there are few peer-reviewed papers that calculate the CO_2 emissions associated with a single country's imports and/or exports from air freight, with Andersen et al. (2010) and Cadarso et al. (2010) being two rare examples. In both of those papers, the calculation of air freight emissions was not the focus of the paper and neither developed a unique air freight emissions factor. This highlights the need for more research to be done in developing emissions factors for air freight.

1.6. Aviation and New Zealand

New Zealand is a geographically isolated island nation, and is therefore dependent on air and maritime transport for all international movement of people and goods. For the year ended June 2007, air freight accounted for only 0.56% and 0.45% of New Zealand's imports and exports, respectively, by mass (Statistics New Zealand, 2007a). However, for the same year, air freight accounted for 21% and 15% of New Zealand's imports and exports, respectively, by value (Statistics New Zealand, 2007a). This indicates that high value, low mass goods are traded internationally by air freight, with lower value, heavier items shipped by sea. Air freight is also the preferred mode of transport for time-sensitive goods (Sankaran, 2000).

Air freight can either be transported in dedicated freighters or in the lower holds of passenger aeroplanes ("belly-hold", as it is referred to herein). New Zealand air freight is mostly transported in the belly-holds of scheduled passenger services (Ministry of Economic Development, 2005; Air New Zealand, pers. comm., 19 November 2010).

2. Methodology

2.1. Overview

The present research utilises a general methodology of multiplying the mass-distance of commodities transported by international airfreight by CO_2 emissions factors. The authors are not aware of any other peer-review sources that outline how this methodology is specifically applied in a global, national or regional context. Previous air freight emissions factors that have been derived are found in non-peer reviewed sources. There are many inputs that are used in calculating both the mass-distance of commodities and emissions factors, some of which vary widely between sources. The present research details one approach to calculating the mass-distance of commodities transported by international air freight and air freight emissions factors. Many of the important inputs and their varying quantities found in the literature are discussed, aiding other researchers carrying out similar calculations in the future.

The 2007 calendar year was chosen as the reference year to be consistent with international transport emissions research by other authors (Buhaug et al., 2009) as well as the authors of the present research (Howitt et al., 2010; Fitzgerald et al., 2011a; Fitzgerald et al., 2011b).

CO_2 emissions factors were derived based on commercially-sensitive fuel uplift data from internationally-bound aeroplanes departing Auckland, New Zealand's largest international airport. "Fuel uplift" is an aviation industry term for the total amount of fuel taken onboard the aeroplane before its departure (see sections 2.3 and 2.4). A comprehensive dataset which included all of New Zealand's air freighted imports and exports in 2007 was used to identify the mass of goods and the two airports which each good was transported between. From this, the amount of air freight tonne-kilometres in 2007 could be determined. The CO_2 emissions factor derived from New Zealand data was then applied to calculate the total CO_2 emissions associated with New Zealand's air freight.

2.2. Equations

Eq. 1 was used to calculate the mean CO_2 emissions factor for each of the aeroplane models represented in the fuel uplift data. Eq. 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.

$$EF_{(CO_2,uplift)_a} = \frac{\sum_{c=1}^{r}\left(\frac{m_{fuel_c} \times EF_{CO_2,fuel}}{d_c \times N_{\max a} \times LF \times (m_p + m_f)}\right)}{r} \quad \text{(Eq. 1)}$$

Where:

a (subscript) denotes a particular aeroplane model.

c (subscript) denotes a particular city pair of origin and destination airports.

r denotes the total number of city pairs of origin and destination airports.

$EF_{(CO_2,uplift)_a}$ is the emissions factor for each of the given fuel uplifts (kg CO_2 per t-km);

m_{fuel} is the fuel uplift (kg);

$EF_{CO_2,fuel}$ is the CO_2 emissions generated from the combustion of m_{fuel} (kg CO_2 per kg fuel);

d_c is the distance flown between the origin and destination airports (km);

N_{max_a} is the passenger capacity of the aeroplane (number of passengers);

LF is the passenger load factor, presented as a fraction of N_{max_a} of the aeroplane;

m_p is the average mass per passenger plus their luggage (t per passenger);

m_f is the average mass of freight carried per passenger (t per passenger).

Eq. 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- and long-haul journeys to obtain a weighted mean CO_2 emissions factor for both distance brackets.

$$EF_{CO_2\,j} = \sum_{a=1}^{p} EF_{(CO_2,uplift)_a} \times X_a \quad \text{(Eq. 2)}$$

Where:

j (subscript) denotes the product journey.

$EF_{CO_2,j}$ is the emissions factor for either a short-haul or long-haul journey (kg CO_2 per t-km).

a (subscript) denotes a particular aeroplane model.

p denotes the total number of aeroplane models.

$EF_{(CO_2,uplift)_a}$ 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*.

Eq. 3 was used to calculate the total CO_2 emissions from New Zealand's international air freight.

$$E_{CO_2} = \sum_{j=1}^{n} m_j \times d_j \times 1.09 \times EF_{CO_2,j} \qquad \text{(Eq. 3)}$$

Where:

E_{CO_2} is the total emissions of CO_2 (kg);

m_j is the mass of air freighted cargo on each journey (tonnes (t));

d_j is the distance travelled by an aeroplane on each journey (km);

1.09 is the correction factor for indirect flights and circling at airports (see section 2.4);

$EF_{CO_2,j}$ is the emissions factor for either a short-haul or long-haul journey (kg CO_2 per t-km).

2.3. Data Sources

Three main datasets were used in the present research to calculate the CO_2 emissions from New Zealand's international air freight. The central dataset contained all of New Zealand's imports and exports in 2007 which were transported by air freight. This dataset was obtained from Statistics New Zealand in the form of Harmonised System (HS) data, specifically the ten-digit HS code (HS10) level of data. The Harmonised System (HS) was originally developed by the World Customs Organization (WCO) as a way of internationally standardising global merchandise (Statistics New Zealand, n.d.). In this dataset, individual air freight journeys could not be separated out from the data, but the total mass of HS10 goods traded between two airports was represented accurately. Therefore, the dataset provided the required mass component of Eq. 3, as well as providing the origin and destination airport pairs from which the air freight distance could be calculated.

The second dataset contained typical fuel uplifts for six different aeroplane models flying from Auckland to 31 different overseas airports. In total, 53 aeroplane's uplifts were represented by the data with each of the six aeroplane models having between 5 and 14 fuel uplifts each. Fuel uplift details the total amount of fuel taken onboard an aeroplane before its departure. Such commercially-sensitive data are usually difficult for researchers to obtain because fuel use is where airlines can gain a competitive advantage

(Air BP, pers. comm., 20 July 2009). In addition, confidential data were obtained from other sources on fuel use on particular journeys by two different airlines. The confidential data were not used in the calculations, but were used to verify that the "typical" values in the commercially-sensitive dataset were representative.

The third dataset contained aeroplane movements from Auckland, Wellington and Christchurch international airports over two one-week periods in 2007 (March and September), obtained from the New Zealand Ministry of Transport. Aeroplane schedules at a given airport are kept reasonably constant within the two major seasons that the international aviation industry observes: northern hemisphere winter and summer (Ministry of Transport, pers. comm., 12 August 2009). The two one-week periods of aeroplane movements included in the dataset were representative of each of those two seasons. This dataset was used to weight each of the aeroplane-specific CO_2 emissions factors derived from the fuel uplift data with respect to each aeroplane's relative utilisation in New Zealand in 2007.

2.4. Calculation of air freight emissions factors

The proportion of air freight transported by dedicated freighters and belly-hold could not be determined from the HS10 dataset due to Customs New Zealand and Statistics New Zealand not recording which mode air freight is transported by (Statistics New Zealand, pers. comm., 19 November 2010). The methodology of the current research considers all of New Zealand's air freight to be transported as belly-hold cargo, and this is represented by the formulation of Eq. 1. This assumption will be discussed in section 2.6.

The following paragraphs discuss each of the variables in Eq. 1 for calculating the CO_2 emissions factor for each fuel uplift, followed by how these emissions factors were weighted to get an overall short- and long-haul CO_2 emissions factor for New Zealand's air freight.

The fuel uplift for each aeroplane's journey was provided directly from the data obtained. Generally, aeroplanes carry only the amount of fuel required to get them from their point of departure to destination, plus a given amount of extra fuel as a safety margin. This is because carrying any additional fuel unnecessarily increases the mass of the aeroplane, increasing the amount of fuel required during the flight. Aeroplanes bound for an international destination from Auckland airport would generally refuel before departure, unless there was the unusual problem of there being a lack of supply (Auckland Airport, pers. comm., 20 July 2009).

If it is assumed that aeroplanes hold a constant amount of additional fuel as a safety margin, then the fuel uplift should be equivalent to the amount of fuel consumed on each journey. However, when the fuel uplifts were weighted by the distance travelled for each of the six aeroplane models, six of the 53 aeroplane uplifts were noticeable outliers as their fuel uplift per km was approximately twice as large as the smallest values for the same aeroplane model. These six fuel uplifts each represented journeys from Auckland to an airport in a small Pacific Island country or territory; Norfolk Island, Noumea, Tonga, Rarotonga and Papeete. There are three plausible explanations which could lead airlines to uplift more fuel than what is required for only the one-way journey to these locations: due to their small size, these airports have no, or a limited supply of, aviation fuel; the fuel at these locations is more expensive than at Auckland, making it more economical to uplift fuel for the return journey also; and/or they may have to carry an additional amount of fuel to reach a different Pacific Island airport in case of emergency. These six outliers were therefore excluded from the calculation of CO_2 emissions factors due to their fuel uplifts not representing the fuel consumed during the one-way leg.

The CO_2 emissions factor for the combustion of aviation fuel used in the present research was 3.157 kg CO_2 per kg fuel (ICAO, 2009a; Jardine, 2009).

The distance each aeroplane travelled between a New Zealand airport and the given overseas airport was determined from the airport pair’s latitudes and longitudes and the Great Circle Distance between the two (see section 2.5). There is currently no internationally standardised methodology for accounting for the deviation of actual flights from Great Circle Distances. Penner et al. (1999) state an average factor of 1.09, citing EUROCONTROL (1992). ICAO endorse three discrete correction factors which depend on the distance of the flight (ICAO, 2009a), which has subsequently been adopted by the Australian Department of Infrastructure, Transport, Regional Development and Local Government for official reporting purposes (Department of Infrastructure, Transport, Regional Development and Local Government, 2010). The Civil Air Navigation Services Organisation (CANSO) report a 92% - 94% global average Air Traffic Management (ATM) efficiency in 2007 (CANSO, 2008), which correspond to correction factors of 1.087 – 1.064, respectively. EUROCONTROL (2010) state an average route extension from the Great Circle Path of 5.8% (corresponding to a factor of 1.058) in Europe in 2007. The present research has adopted the recommendation from the Ministry for the Environment of using the factor of 1.09 from Penner et al. (1999), which is recognised to represent a conservative (over)estimate for New Zealand (Ministry for the Environment, 2011).

The passenger capacity of each of the six aeroplane models were obtained from their respective manufacturer’s websites (Boeing, 2009; Airbus S.A.S., 2010). If there was more than one version of aeroplane per model operating to and from New Zealand (e.g., B737-300, B737-700 and B737-800), an average passenger capacity for the model was obtained from weighting each version's capacity relative to the New Zealand aeroplane movement datasets.

All aeroplane journeys were assumed to have a passenger load factor of 79%. Passenger load factor represents the percentage of the passenger capacity which is occupied and this average value was based on load factors presented in Air New Zealand's 2008 Annual Financial Report (Air New Zealand, 2008). This load factor lies between the values used by DEFRA (2008) for short-haul (81%) and long-haul (78%) and is the same as the average passenger load factor in 2007 in the US (79%) reported by Hileman et al. (2008). It is also compares well with the 80% passenger load factor given by the Singapore Airlines and Qantas annual reports for the 2007-2008 period (Singapore Airlines, 2008; Qantas, 2008).

Each passenger, including luggage, was assumed to have a mass of 100 kg. This is the average passenger mass recommended by ICAO (ICAO, 2009b) and is the same assumption used in ICAO (2009a), DEFRA (2008) and Ross (2009). A 2003 study of New Zealand domestic airline passengers' masses quantified a mean mass of 88.2 kg per passenger, including carry-on luggage (NFO New Zealand, 2003). Due to that study excluding the mass of non carry-on luggage, it was not able to be incorporated into the present research. However, an average mass of around 88 kg per passenger does leave a plausible mean mass of 12 kg of non-carry-on luggage per passenger.

Both ICAO (2009a) and DEFRA (2008) add a certain amount of mass per passenger (50 kg and approximately 200 kg, respectively) to account for passenger facilities onboard, such as seats and galleys, when accounting for air freight. However, in the methodology adopted in the present research it was decided not to include a mass factor for the passenger facilities on the aeroplane. This is because most of New Zealand's international cargo is transported as belly-hold on scheduled passenger services, and so the mass of seats and galleys were considered to be an essential part of the operation of the service. In a similar way, the additional mass embedded in the freight facilities of the belly-hold, such as containers and machinery, was not taken into account.

The mass of air freighted cargo onboard each aeroplane was assumed to be 24 kg per passenger. This was calculated by assuming that all air freight was transported as belly-hold on scheduled passenger services. The total mass of New Zealand's air freight in the 2007 calendar year was calculated from the HS10 dataset to be 206,547 tonnes. The total number of international arrivals and departures in 2007 from Auckland, Wellington and Christchurch International Airports was 8.668 million passengers (Statistics New Zealand, 2007b). Therefore the 2007 mean amount of air freight per passenger was calculated as 24 kg per passenger (2 s.f.). Jardine (2009) notes that publicly available industry data on freight loads are rare, but states that freight factors are typically 15-30% for wide-bodied aeroplanes, and the value of 24% (24 kg freight per 100 kg passenger) found in the current research lies within this range.

Data on aeroplane movements over two representative one-week periods in 2007 provided a break-down of the models of aeroplane which fly short- and/or long-haul routes to and from New Zealand. There is currently no internationally standardised definition for short- and long-haul air travel. DEFRA (2008) defines a cut-off between short- and long-haul flights at 3700 km and Jardine (2005) defines the cut-off to be at 3500 km. The present research uses the DEFRA (2008) definition for short- and long-haul aeroplane journeys. The relative proportions of each aeroplane model to the total journeys made by short- or long-haul journeys in New Zealand were calculated and were used to represent the weighting of each aeroplane model (X_a in Eq. 2).

From the inputs discussed in this section, Equations 1 and 2 were used to calculate the CO_2 emissions factor for air freight for short- and long-haul journeys.

2.5. Calculation of New Zealand's air freight emissions

Auckland (AKL), Christchurch (CHC), and Wellington (WLG) international airports account for almost all of the air freight that is imported to and exported from New Zealand (Statistics New Zealand, 2008). These three airports accounted for 99.999% of all imports and 99.99% of all exports by gross mass in the 2007 HS10 dataset. Therefore, it was decided that the calculation of CO_2 emissions from air freight would use AKL, CHC and WLG as the New Zealand origin/destination airports, with the remaining New Zealand airports being ignored, as their contribution to the final result was considered to be negligible.

In total, the HS10 dataset contained 1,868 airports which were the previous departure point for imports and 1,118 airports which were the next destination for exports in the year 2007. It was decided that it would be more manageable to use the representative airports in the origin or destination countries or territories rather than the detailed listing of airports. There were 205 countries or territories of origin for both imports and exports in the year 2007. Of these 205 countries or territories, it was calculated that 20 countries or territories accounted for over 92% of the imports and exports in terms of gross mass (shown by Figures 1 and 2, respectively). Mass, rather than value or volume, was used in the present research as it provides a more accurate representation of the energy required for transportation. The top 20 countries or territories of imports and exports by gross mass were used in the present research as the basis for calculating CO_2 emissions for air freight for the year 2007. The remaining 185 countries or territories were assigned the weighted mean distance and CO_2 emissions factor from the calculations from the top 20 countries or territories.

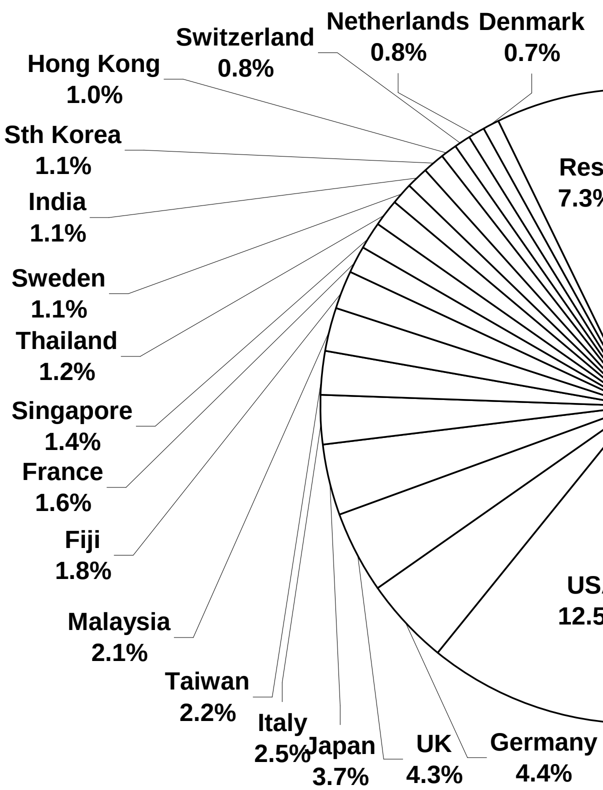

Figure 1; Proportions of the total gross mass of New Zealand's air freighted imports in 2007 from the top 20 countries or territories. The total mass is 104,243 tonnes.

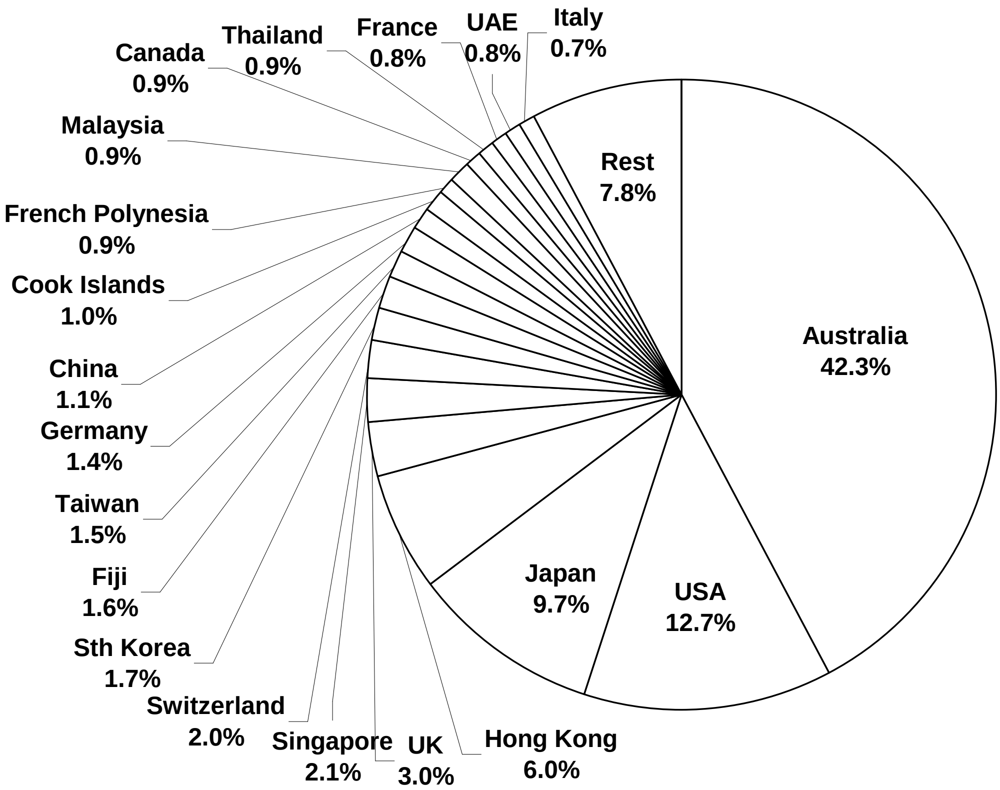

Figure 2; Proportions of the total gross mass of New Zealand's air freighted exports in 2007 to the top 20 countries or territories. The total mass is 102,303 tonnes.

Figures 1 and 2 show that the four most dominant international trading partners by mass for air freight in New Zealand in 2007 were Australia, USA, Japan and China, together accounting for approximately two-thirds of imports and exports.

The representative airport for each country or territory was chosen by the combination of three factors: the passenger volume of each airport, accessibility of New Zealand airlines to each airport and the geographical location of each airport. Airports with a larger passenger volume were favoured over airports with smaller passenger volumes. Passenger volumes were used because of the fact that international air freight carried as belly-hold on passenger flights accounts for nearly five times more tonne-kilometres than air freight carried on international dedicated long-haul cargo services (DEFRA, 2008), and accounts for an even higher proportion in New Zealand (Air New Zealand, pers. comm., 19 November 2010). Representative airports also had to be accessible to airlines that service New Zealand; therefore some airports with a lower passenger volume were chosen over the countries' busiest international airports because they were the entry point for airlines that service New Zealand. The representative airport for each country or territory had to also be one of the closest to New Zealand, therefore making it the most likely entry point for airlines servicing New Zealand. This is justified in the context of the present research as the aim is to quantify the emissions associated with international transport, which are not liable under the Kyoto Protocol. The emissions associated with any domestic air freight journeys undertaken after the goods enter the overseas country of destination for exports and New Zealand for imports are currently liable under the Kyoto Protocol and should be accounted for in national greenhouse gas inventories already. As an example of these selection criteria, the representative airport for the USA in the present research was Los Angeles International Airport (LAX), while the busiest international passenger airport in the USA is John F. Kennedy International Airport (JFK) (US Department of Transportation, 2006). LAX was chosen because it is closer to New Zealand and more accessible to the airlines which service New Zealand.

By making use of the three New Zealand international airports and the 20 representative overseas airports, journey distances were calculated between each appropriate airport pair for each commodity imported or exported by air freight in the year 2007. Distances between each of the airport pairs were calculated using the WGS-84 method. To determine these distances, the latitude and longitude coordinates of the airport pairs were required. These data were obtained from the Global Airport Database, an online database that provided latitude and longitude coordinates for 9,300 airports worldwide (Partow, 2003). This was used in the absence of a publicly available database of this information from regulatory or industry bodies, such as ICAO.

The derived short- or long-haul CO_2 emissions factor was assigned to each of the 20 countries or territories and the CO_2 emissions for each imported or exported good's journey was calculated by using Eq. 3. Using the total mass and mass-distance of air freighted imports and exports from the top 20 overseas countries or territories, a weighted average distance was calculated and applied to the remaining 185 countries or territories. Similarly, from the total CO_2 emissions and mass-distance of the top 20 countries or territories a weighted mean CO_2 emissions factor could be calculated and applied to the remaining countries or territories.

The total CO_2 emissions was converted back into the mass of fuel consumed by using the conversion factor of 3.157 kg CO_2 per kg of aviation fuel burnt. The gross energy content of the fuel burn was calculated from the conversion factor of 46.23 MJ per kg of aviation fuel (Ministry of Economic Development, 2009).

2.6. Uncertainties

An assumption was made in the present research that all air freight was transported as belly-hold on scheduled passenger services. This is a simplification due to some unknown fraction of air freight being transported by dedicated air-freighters. In 2007 there were at least five airlines which included dedicated freight services in and out of New Zealand (Air New Zealand, pers. comm., 19 November 2010). However, by mass, these services only accounted for approximately 5% of New Zealand's air freight in the same year (Air New Zealand, pers. comm., 19 November 2010). Therefore, it was considered that the belly-hold assumption provided a very good first-order approximation for the calculation of CO_2 emissions from New Zealand's air freight.

The dominant uncertainty in the calculation of the total emissions from New Zealand's air freight was the distance between the origin and destination of the goods (d_j in Eq. 3). Due to the methodology of the present research, air freighted imports or exports which included one or more stopover would have their total distance, and therefore CO_2 emissions, underestimated.

The distance, and CO_2 emissions, for air freighted imports or exports originating from or destined to an overseas airport which was not the representative airport chosen for the country or territory, would be underestimated. This is because the closest major overseas airport to New Zealand was chosen.

The present research used the mean distance and emissions factor from the top 20 countries or territories by mass to calculate the CO_2 emissions from the remaining 185 countries or territories, representing about 7.5% of the total mass of goods. These approximations would be inaccurate if the mean distance and emissions factor from the top 20 countries were not representative of the remaining countries.

Due to one country's export being another country's import, if the methodology of the present research was applied to all the countries that traded with New Zealand then the total calculated emissions would be twice the real total due to double-counting. Note that the emissions from the aviation sector included in the EU ETS could also be double-counted if other countries took a similar approach. Dividing up these emissions internationally is a policy issue rather than a science issue, and therefore is not explored in this paper.

3. Results

3.1. New Zealand aeroplane movements

The geographical location of New Zealand results in the average distance needed to fly between New Zealand and an overseas destination being considerably larger than for many other countries. As a result of this, of the top 20 countries or territories for imports and exports, only Australia, Fiji and the Cook Islands were short-haul international journeys. These countries combined accounted for 34% and 49% of the gross mass of air freighted imports and exports, respectively, from the top 20 countries. Therefore, 66% and 51% of the gross mass of New Zealand's air freighted exports and imports, respectively, from the top 20 countries travel long-haul distances.

The analysis of the two representative one-week periods of international aeroplane movements to and from three New Zealand airports in 2007 is shown by Figure 3 for short-haul journeys and by Figure 4 for long-haul journeys.

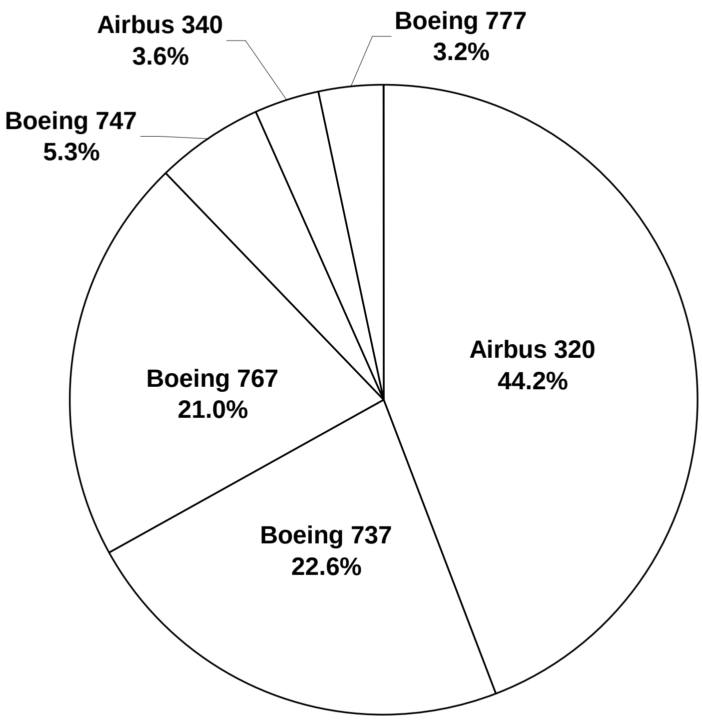

Figure 3; Proportions of international short-haul aeroplane movements from six aeroplane models in New Zealand in 2007. The total number of movements represented in the two weeks covered by the dataset was 561.

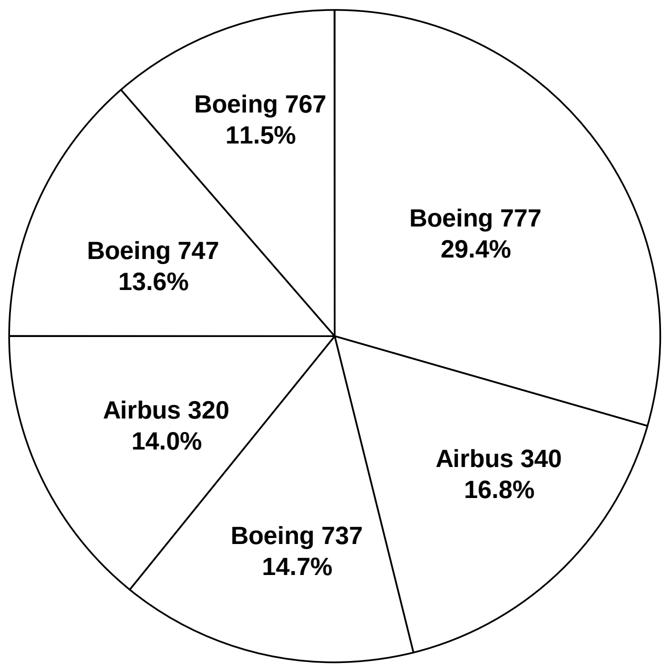

Figure 4; Proportions of international long-haul aeroplane movements from six aeroplane models in New Zealand in 2007. The total number of movements represented in the two weeks covered by the dataset was 470.

Figures 3 and 4 show that the Airbus 320 and Boeing 777 undertook the greatest share of New Zealand international short- and long- haul journeys, respectively. The proportion of journeys shown by Figures 3 and 4 were used in Eq. 2 to calculate the New Zealand-specific emissions factor.

3.2 Air Freight CO_2 emissions factors

The present research calculated CO_2 emissions factors for international air freight to be 0.82 kg CO_2 per tonne-kilometre (kg CO_2 per t-km) for short-haul journeys and 0.69 kg CO_2 per t-km for long-haul journeys, based on New Zealand fuel uplift data. Table 1 shows the air freight emissions factors calculated in the present research compared with other emissions factors from various sources.

Table 1; Air freight emissions factors calculated in the present research and from other sources.

Source	**Emissions Factor ($kg\ CO_2$ per t-km)**		**Comments**
	1	**2**	
This research	0.82	0.69	1) Short-haul; 2) Long-haul. Specific to the aeroplane fleet flying to and from New Zealand in 2007. Based on fuel uplift data.
Defra (2008)	1.32	0.61	1) Short-haul; 2) Long-haul. Based on the UK's aeroplane fleet and uses specific fuel-oil consumption rates.
Cadarso et al. (2010)	0.54		Value taken from an online calculator which does not disclose its methodology.
Buhaug et al. (2009)	0.435-0.474	1.1-1.8	Calculations based on particular freighter aeroplanes: 1) Boeing 747 F; 2) Ilyushin IL 76T.
Facanha and Horvath (2006)	0.66		Calculated for Boeing 747's and average utilisation factors (value converted from 68% of 1410 g CO_2 per ton-mile, where 68% was used to exclude other life-cycle components in the original value)
Hileman et al. (2008)	1.0		2007 US Fleet-wide average, calculated based on data from the US Department of Transportation, Bureau of Transportation Statistics (value converted from 66 kg-km/MJ)

The DEFRA (2008) methodology has been applied in many studies worldwide, including being used in air freight life-cycle analyses (e.g., Saunders and Hayes, 2007). With respect to the emissions factors derived in DEFRA (2008), the emissions factors calculated in the present research are 38% lower and 13% higher for short-haul and long-haul air freight journeys, respectively. These differences arise from the different calculation methodologies and the different characteristics of the aviation industry in New Zealand and in the UK.

Although the air freight emissions factors calculated in the present research were specific to the fleet of aeroplanes which serviced New Zealand in 2007, they could be used in future studies in other regions and for different time periods; however more research is required to verify this.

In addition to this, the emissions factors derived in the present research could be applied equally to passengers and be used to calculate the CO_2 emissions resulting from passenger flights. This is because both passengers and air freight were treated on an equal mass basis and the cargo was treated as if it was in the belly-hold of scheduled passenger services. Since each passenger was assumed to weigh 100 kg (including luggage), the CO_2 emissions factors for passengers are equal to 82 g CO_2 per passenger-km (g CO_2 per p-km) and 69 g CO_2 per p-km for short- and long-haul flights, respectively.

3.3 CO_2 Emissions from New Zealand's air freight

International air freight between New Zealand and the top 20 countries or territories for imports and exports were calculated to travel a weighted mean distance of 8504 km and 6695 km, respectively (not including the factor of 1.09 for circling/indirect routes). Due to the greater mass-distance travelled by long-haul journeys compared to short-haul, the weighted mean emissions factors for the top 20 countries or territories were close to that for long-haul journeys at 0.70 kg CO_2 per t-km and 0.71 kg CO_2 per t-km for imports and exports, respectively. These are the mean values which were used for all distances, d_j, and emissions factors, $EF_{CO_2,j}$, in Eq. 3 for the remaining 185 countries or territories.

Through this research, 0.67 Mt and 0.53 Mt of CO_2 emissions were estimated to have been generated by air freighted imports and exports, respectively, to and from New Zealand in the year 2007. A summary of the results for the fuel consumption and CO_2 emissions is shown in Table 2.

Table 2; Results for the calculation of the amount of fuel consumed and CO_2 emissions from New Zealand's international air freight in 2007. Values to 2 s.f.

	Aviation Fuel Consumed (Million L)	**Aviation Fuel Consumed (Mt)**	**Aviation Fuel Gross Energy (PJ)**	**CO_2 Emissions (Mt)**
Imports	260	0.21	9.7	0.67
Exports	200	0.17	7.7	0.53
Total	460	0.38	17.4	1.2

Imports contributed 56% to the overall CO_2 emissions and fuel consumption, and exports the remaining 44%.

A breakdown of the top 10 countries or territories for CO_2 emissions from New Zealand's imports and exports in 2007 is shown by Figures 5 and 6, respectively. Due to the direct conversion of aviation fuel to CO_2 emissions, Figures 5 and 6 are identical (with a different total) for the fuel consumed per country.

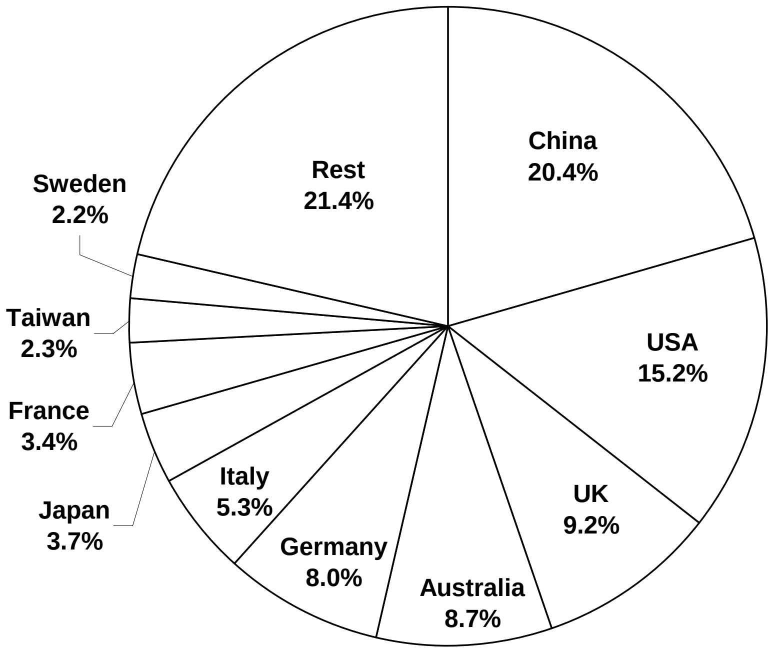

Figure 5; Top 10 countries for the CO_2 emissions generated from the air freight of New Zealand's imports in 2007. The total CO_2 emissions are 0.67 Mt.

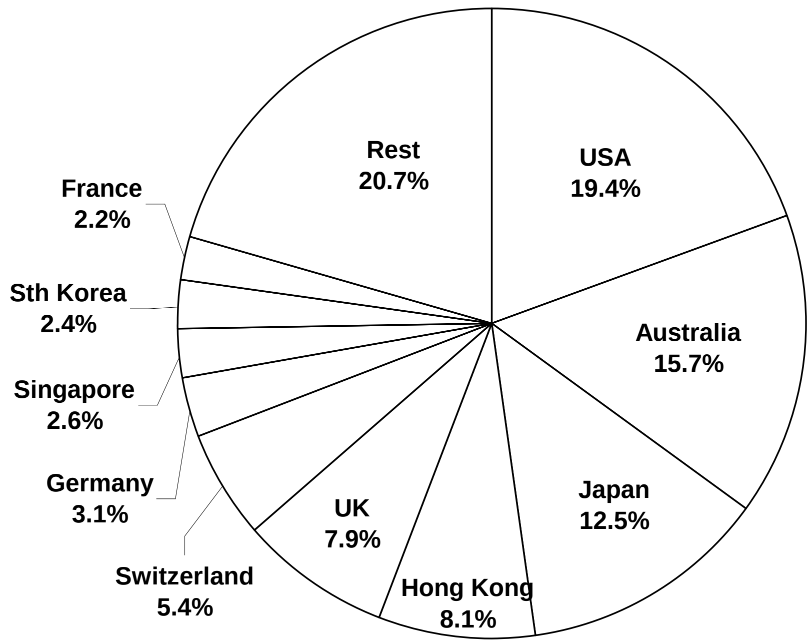

Figure 6; Top 10 countries for the CO_2 emissions generated from the air freight of New Zealand's exports in 2007. The total CO_2 emissions are 0.53 Mt.

Tables 3 and 4 show the breakdown of CO_2 emissions generated by commodity for imports and exports, respectively. Note that the breakdown is based on the chapter titles (HS2) of each of the commodities and each value of CO_2 emissions can be converted into fuel consumed by dividing by the conversion factor of 3.157 kg CO_2 per kg of aviation fuel.

Table 3; CO_2 emissions generated from the top 10 air freighted import commodities to New Zealand in 2007. Values rounded to 3 s.f., but percentages calculated based on unrounded values.

Chapter Title	**Description**	**CO_2 (tonnes)**	**%**
84	Boilers, Machinery and Mechanical Appliances	142,000	21.0%
85	Electrical Machinery	91,600	13.6%
49	Books, Newspapers, Manuscripts & Plans	46,900	6.9%
61	Knitted Apparel	28,600	4.2%
39	Plastics	26,800	4.0%
62	Non-Knitted Apparel	25,800	3.8%
90	Surgical and Medical Instruments	25,500	3.8%
30	Pharmaceutical Products	23,400	3.5%
87	Vehicle Accessories	18,600	2.8%
33	Essential Oils and Cosmetics	18,100	2.7%
Rest		228,000	33.8%
TOTAL		**675,000**	**100.0%**

Table 4; CO_2 emissions generated from the top 10 air freighted export commodities from New Zealand in 2007. Values rounded to 3 s.f., but percentages calculated based on unrounded values.

Chapter Title	**Description**	**CO_2 (tonnes)**	**%**
03	Fish, Crustaceans and Molluscs	102,000	19.3%
02	Meat	61,800	11.7%
07	Vegetables	50,600	9.6%
08	Fruit and Nuts	40,900	7.7%
84	Boilers, Machinery and Mechanical Appliances	36,600	6.9%
04	Dairy Produce	28,600	5.4%
85	Electrical Machinery	22,400	4.2%
06	Live Trees and Plants	21,500	4.1%
90	Surgical and Medical Instruments	20,500	3.9%
39	Plastics	13,800	2.6%
Rest		130,000	24.6%
TOTAL		**529,000**	**100.0%**

As shown by Table 3, mechanical appliances, electrical machinery and books, newspapers, manuscripts and plans were the three largest contributors to CO_2 emissions from imports, contributing over 40% of the total. For exports, five of the top six contributors were food products, together contributing to over half of the total CO_2 emissions. Mechanical appliances and electrical machinery often have a high value-to-mass ratio and books, newspapers, manuscripts and plans, and food products are often time-sensitive, perhaps explaining the choice of air freight over maritime transportation.

3.4 Intercomparison of CO_2 emissions from international transport modes to and from New Zealand

The CO_2 emissions calculated in the current research can be compared to the emissions from international maritime transportation and international aviation passenger transport.

Fitzgerald et al. (2011a) calculated the CO_2 emissions from the international maritime transportation of New Zealand's imports and exports in 2007 to be 2.9 Mt and 4.8 Mt of CO_2, respectively, totalling 7.7 Mt. Therefore, including the results from the present research, the international transport of New Zealand's imports and exports in 2007 generated approximately 8.9 Mt of CO_2 in total, of which 3.6 Mt and 5.3 Mt was from imports and exports, respectively (air freight comprising 13%, 19%, and 10%, of the three totals, respectively). Maritime transportation accounted for 99.5% of the total mass of New Zealand's imports and exports in 2007 (i.e. 200 times more mass than air freight), but only 87% of the CO_2 emissions. This difference is predominantly because of the relative CO_2 efficiencies of the two modes of transportation; the mean emissions factor in Fitzgerald et al. (2011a) was 17 g CO_2 per t-km for maritime transportation, compared to 820 g CO_2 per t-km and 690 g CO_2 per t-km for short- and long-haul air freight, respectively, in the present research.

Smith and Rodger (2009) calculated the CO_2 emissions for tourists travelling to and from New Zealand, and for New Zealand residents travelling overseas and returning, by air in 2005. In order to compare with the present research, it was necessary to gather additional data on the number of tourists entering New Zealand in the year 2007, as well as updating the emissions factors used by the model to utilise the emissions factors derived in the present research. As outlined in section 3.2, the emissions factors derived in the present research are applicable to passengers also and were calculated to be 82 g CO_2 per p-km and 69 g CO_2 per p-km for short- and long-haul flights, respectively. The updated data were entered into the Smith and Rodger (2009) model, which calculated the total emissions to be 4.3 Mt CO_2 emissions for the year 2007 (2.9 Mt from international visitors and 1.4 Mt from New Zealand residents). Combined with the results from the present research, the international aviation transportation of people and goods to and from New Zealand in 2007 produced 5.5 Mt CO_2 emissions, 22% of which was from international air freight.

4. Conclusion

The climate impacts of international aviation due to the emissions of CO_2 are currently not liable under any global agreements. An increase in research into the CO_2 emissions from aviation in recent years has been due to interest in quantifying air transport's climate impacts, as well as increased use of product life-cycle assessments and the impending addition of the aviation sector into the EU ETS. However, there is minimal peer-reviewed literature on air freight CO_2 emissions factors and the CO_2 emissions from a single country. The present research calculated CO_2 emissions factors and the total emissions from one country's air freighted imports and exports, based on New Zealand in the year 2007.

Fuel uplift data, which are usually difficult for researchers to obtain due to commercial sensitivity, were used in the present research to calculate CO_2 emissions factors for air freight. The New Zealand international aviation industry transports most of its air freight as belly-hold in aeroplanes carrying out scheduled passenger services. New Zealand's air freighted imports and exports travelled from and to 205 countries or territories in 2007; however 20 countries and territories together accounted for over 92% of the total mass of imports and exports. These 20 countries or territories were used as the basis for calculating the total CO_2 emissions from New Zealand's air freight in 2007.

International air freight emissions factors of 0.82 kg CO_2 per t-km for short-haul journeys and 0.69 kg CO_2 per t-km for long-haul journeys were derived in the current research from New Zealand fuel uplift data, air freight and aeroplane movements data, and assumptions on mean passenger loadings and the mass of passengers and air freight. These emissions factors were applied to all New Zealand's air freighted imports and exports for the year 2007, from which it was calculated that a total of 460 million litres or 0.38 Mt of fuel was used. This fuel use resulted in the emission of 1.2 Mt of CO_2. Of these totals, 44% was attributable to air freighted exports and 56% to air freighted imports.

The high level of rotation of aeroplanes on international routes, and the relatively long life of aeroplanes, means that the New Zealand-specific emissions factors should be relevant to research in other countries and regions. Further, this paper lays out a methodology for researchers who wish to carry out a similar regional analysis, including highlighting potential uncertainties and data access barriers.

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