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Drivers of CO_2 emissions in international aviation: the case of Japan

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Abstract

We estimated the CO_2 emissions produced by more than 40 000 international flights associated with Japan's two major airlines (Japan Airlines and All Nippon Airways), and identified the drivers for these CO_2 emissions using an index decomposition analysis conducted between 2005 and 2015. The results showed that introducing the more fuel-efficient Boeing 787 led to CO_2 emission reductions of 1.3 million tons by the two companies. However, these reductions were canceled out by the total number of flights and distances per passenger attributable to the airlines' operations. We conclude that the environmental and business strategy of introducing greener aircraft with better fuel efficiency was insufficient for mitigating aircraft emissions' effects on climate.

1. Introduction

The 2014 Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) stated that greenhouse gas (GHG) emissions generated by the international aviation industry accounted for approximately 6.52% of transport sector emissions, and that annual CO_2 emissions from aviation are rapidly increasing at a rate of 3% to 4% a year (IPCC 2014). Japan's transportation sector emitted 200 million tons of CO_2 in 2015, accounting for 20% of the nation's total CO_2 emissions (MLIT 2016b). Although CO_2 emissions from air transportation constitute a mere 5% of Japan's overall transport emissions, these values include only the CO_2 emissions associated with domestic flights, and thus exclude international flights (MLIT 2016b). Therefore, the CO_2 emissions from aviation reported by the Japanese government did not consider the CO_2 emissions associated with international flights. We must estimate the CO_2 emissions generated by both domestic and international flights when evaluating the CO_2 emissions associated with the airline industry.

The International Civil Aviation Organization (ICAO) introduced a global market-based measures (GMBM) program, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), to complement the global carbon reduction target (ICAO 2016b). During the first phase, from 2021 to 2026, airlines must reduce CO_2 emissions relative to the average baseline emissions for 2019 and 2020. Those exceeding the upper limit must buy an allowance (ICAO 2016b). During the second phase, from 2027 to 2035, all ICAO member states, except for developing countries and countries with low CO_2 emission levels, must also participate in this scheme (ICAO 2016b). Japan has been a participant since the first phase of its execution (ICAO 2016c). The scheme's upper limit for CO_2 emissions generated by international flights is designed to reduce CO_2 emissions and ensure that airlines operate in an environmentally friendly manner.

From the demand perspective, the World Tourism Organization (UNWTO) estimated that the tourism industry contributed 7% to *global* gross domestic product (GDP) in 2018, and that global tourism would continue to grow at an annual rate of 3% to 5% (UNWTO 2016). Studies have analyzed the environmental burdens associated with increasing tourism demands (Peeters and Dubois 2010, Gössling and Peeters 2015, Lenzen *et al* 2018). (Lenzen *et al* 2018) estimated the carbon footprint of global tourism and revealed that global demand was responsible for 8% of all greenhouse gas (GHG) emissions in 2013. The aviation industry was identified as one of the main contributors to the carbon footprint produced by tourism demand (Lenzen *et al* 2018).

Studies (Peeters and Dubois 2010, Gössling and Peeters 2015, Lenzen *et al* 2018) have confined themselves to addressing the important question of how airline companies can mitigate CO_2 emissions while maintaining current flight schedules and aircraft. (Schefczyk 1993) and Barros and Peypoch (2009) analyzed airlines' operational performance using data envelopment analysis (Farrell 1957, Charnes *et al* 1978). (Arjomandi and Seufert 2014) and (Liu *et al* 2017) analyzed airline performance using an environmental DEA approach and characterized CO_2 emissions as undesirable. (Liu *et al* 2017) analyzed the performance of 12 Chinese airlines from 2007 to 2013, finding that CO_2 emissions decreased by approximately 12% due to technological innovation.

Studies have also estimated CO_2 emissions generated by the passenger and freight transport sectors (Scholl *et al* 1996, Schipper *et al* 1997, Kveiborg and Fosgerau 2007, Eom *et al* 2012, Loo and Li 2012, Cristea *et al* 2013) and have examined the factors affecting CO_2 emission changes associated with these sectors (Lakshmanan and Han 1997, Mazzarino 2000, Kwon 2005, Lu *et al* 2007, Timilsina and Shrestha 2009, Papagiannaki and Diakoulaki 2009, Wang *et al* 2016, Andreoni and Galmarini 2012, Achour and Belloumi 2016, Fan and Lei 2016). (Andreoni and Galmarini 2012) identified the drivers of change in CO_2 emissions associated with aviation activities for both passenger and freight transportation in 27 European countries from 2001 to 2008, and found that the expansion of the aviation sector's market scale was the most important factor in the increase in CO_2 emissions (Andreoni and Galmarini 2012).

Andreoni and Galmarini (2012, p 596) stated about their study that, 'unfortunately, since Eurostat data are not disaggregated by the passenger and freight transports, the decomposition analysis presented in this paper cannot disaggregate between travelers and goods.' However, estimating CO_2 emissions—disaggregated between travelers and goods, according to origin—is the most important aspect of the methods intended to reduce CO_2 emissions produced by the aviation sector. The number of travelers is increasing. An upper limit on CO_2 emissions associated with international flights will be set in 2021. Thus, the aviation sector—particularly the airline industry—must participate in reduction activities targeted at international aviation.

Many studies have examined CO_2 emissions produced by the aviation sector and the operations of individual airlines. To the best of our knowledge, however, only a few studies (Miyoshi and Mason 2009, Baumeister 2017, Lee *et al* 2017) have estimated the CO_2 emissions generated by individual airlines or considered the effects of operational factors, such as the number of flights as a scale effect, or the number of passengers per flight as an efficiency effect.

This study focuses on Japan's two major airlines, Japan Airlines (JAL) and All Nippon Airways (ANA). First, we created a detailed database comprising direct flights in Japan's international passenger transport sector (departures and arrivals) in terms of the numbers of flights and aircraft in 2005, 2010, and 2015 at the company level. We estimated the amounts of direct and indirect CO_2 emissions associated with more than 40 thousand international flights in Japan. Second, we developed a new decomposition analysis framework to analyze the supply-and-demand factors for the CO_2 emissions associated with aviation. Finally, we discuss the major driving forces of increasing CO_2 emissions due to the aviation sector, and some methods of reducing them.

The remainder of this paper is organized as follows. Section 2 explains the study's methodology. Section 3 presents the study's data. Section 4 discusses the results, section 5 compares our results with existing studies, and section 6 summarizes our conclusions.

2. Methodology

This study estimates the CO_2 emissions associated with international flights between Japan and other countries, and analyzes the factors driving changes in them using an index decomposition method (Ang and Choi 1997, Ang *et al* 1998, 2003, Ang and Zhang 2000, Ang and Liu 2007). Index decomposition analysis has been widely used in environmental studies to discuss energy issues (Nag and Parikh 2000, Shrestha *et al* 2009, Malla 2009), greenhouse gas emissions (Torvanger 1991, Lise 2006, Bhattacharyya and Matsumura 2010, Hammond and Norman 2012), and toxicity (Shrestha and Timilsina 1998, Fujii *et al* 2017). (Fujii *et al* 2017) identified the main drivers of changes in toxicity emissions in US industrial sectors from demand and supply sides using an input–output structural decomposition method (Hoekstra and van den Bergh 2003, Nagashima 2018, Han *et al* 2019). This study develops a new decomposition analysis framework that considers both demand and supply factors in aviation emissions, following (Fujii *et al* 2017).

The amount of *direct* CO_2 emissions Q in year t associated with jet fuel combustion owing to international flights to a specific region i operated by airline company s is calculated as

$$
\begin{aligned}
Q_i^s(t) &= \frac{Q_i^s(t)}{f_i^s(t)} \times \frac{f_i^s(t)}{d_i^s(t)} \times \frac{d_i^s(t)}{P_i^s(t)} \times \frac{P_i^s(t)}{b_i^s(t)} \times b_i^s(t) \\
&= \frac{Q_i^s(t)}{f_i^s(t)} \times \frac{f_i^s(t)}{d_i^s(t)} \times b_i^s(t) \times \frac{d_i^s(t)}{P_i^s(t)} \times \frac{P_i^s(t)}{b_i^s(t)} \\
&= \underbrace{EI_i^s(t) \times FE_i^s(t) \times TN_i^s(t)}_{\textit{Supply factors}} \times \underbrace{DP_i^s(t) \times PF_i^s(t)}_{\textit{Demand factors}},
\end{aligned} \tag{1}
$$

where s is either JAL or ANA, and i indicates a region in which the company is operating (1 = North America; 2 = Europe; 3 = Asia and Oceania). Moreover, $EI_i^s(t)$ is CO_2 emission intensity (t-CO_2/L) at the region level, which indicates the CO_2 emissions per unit of aviation fuel consumption associated with international flights to region i. $FE_i^s(t) = \frac{f_i^s(t)}{d_i^s(t)}$ represents fuel efficiency (L/km), the amount of aviation fuel consumption ($f_i^s(t)$) per flight distance for region i ($d_i^s(t)$). We use the 'catalog-based' fuel efficiency (L/km) of aircraft models that fly between international airports in Japan and those the specific region, and estimate the annual total jet fuel combustion (L) for each air route by multiplying the catalog-based fuel efficiency by the cumulated round-trip flight distance for the air route over one year. The annual total aviation fuel combustion for each region i is estimated by summing up the jet fuel combustion over all air routes between international airports in Japan and those in the region. Finally, we define region-specific average fuel efficiency $FE_i^s(t)$ by dividing the annual total aviation fuel combustion for region i by the annual total of all cumulated round-trip flight distances for the air routes between international airports in Japan and those in the region. If the airline company introduces greener aircraft with better fuel efficiency (i.e. a lower value of $FE_i^s(t)$) for air routes to the region, then the aviation fuel combustion for the region will decrease.

Equation (1) also includes $DP_i^s(t) = \frac{d_i^s(t)}{P_i^s(t)}$, where $P_i^s(t)$ represents the number of passengers on international air routes to region i in year t, and $DP_i^s(t)$ represents the distance per passenger. For driving force $DP_i^s(t)$, we consider the physical flight service to passengers provided by the airline company. We further define $PF_i^s(t) = \frac{P_i^s(t)}{b_i^s(t)}$, where $b_i^s(t)$ represents the total number of flights on international air routes for region i operated by airline company s in year t. Accordingly, $PF_i^s(t)$ indicates the number of passengers per flight on air routes in region i. Airline companies try to increase passenger efficiency calculated by $PF_i^s(t)$.

Thus, the total CO_2 emissions for airline company s can be estimated by using the following five factors: emission intensity (EI), fuel efficiency (FE), total number of flights (TN), distance per passenger (DP), and passenger per flight (PF). The three factors of EI, FE, and TN, can be interpreted as supply factors in the sense that airline companies can determine them via the operation of their business. Conversely, the two factors of DP and PF can be interpreted as demand factors in the sense that consumers can determine them based on their preferences.

$$
Q^s(t) = \sum_i Q_i^s(t) = \sum_i EI_i^s(t)\, FE_i^s(t)\, TN^s(t)\, DP_i^s(t)\, PF_i^s(t) \tag{2}
$$

Equation (2) represents direct CO_2 emissions from fuel combustion by company s in year t. As the emission intensity for jet fuel combustion is fixed over time, the decomposition analysis framework for the change in aviation emissions between years 0 and t can be formulated by using the logarithmic mean Divisia index (LMDI) method (see Ang *et al* 1998) as follows:

$$
\begin{aligned}
\Delta Q_i^s &= Q_i^s(t) - Q_i^s(0) \\
&= \omega_i \ln \frac{FE_i^s(t)}{FE_i^s(0)} + \omega_i \ln \frac{TN_i^s(t)}{TN_i^s(0)} + \omega_i \ln \frac{DP_i^s(t)}{DP_i^s(0)} \\
&\quad + \omega_i \ln \frac{PF_i^s(t)}{PF_i^s(0)} \\
&= Q_{i,FE}^s + Q_{i,TN}^s + Q_{i,DP}^s + Q_{i,PF}^s,
\end{aligned} \tag{3}
$$

where $\omega_i = \frac{\Delta Q_i^s}{\Delta \ln Q_i^s} = \frac{Q_i^s(t) - Q_i^s(0)}{\ln Q_i^s(t) - \ln Q_i^s(0)}$. Here, $\omega_i = Q_i^s(t) = Q_i^s(0)$ if $Q_i^s(t)$ is equivalent to $Q_i^s(0)$. The four terms on the right-hand side of equation (3) represent the influences of the four drivers affecting the change in aviation CO_2 emissions among the airline company.

Equation (2) does not include CO_2 emissions associated with the refinement of jet fuel. We estimate refinery emissions as follows:

$$
R^s(t) = \sum_i \beta(t) f_i^s(t), \tag{4}
$$

where $\beta(t)$ is the CO_2 emissions intensity for the refinement of one liter of jet fuel. Summing the refined emissions of the aviation jet fuel for region i yields the refined emissions of airline company s.

One important consideration is that introducing new aircraft models with higher fuel efficiency helps reduce CO_2 emissions in flight, and helps increase the CO_2 emissions associated with the manufacturing of new aircraft purchased by the airline company. This study estimates the manufacturing emissions of airline company s in year t as follows:

$$
U^s(t) = \sum_k \sum_j \alpha_j(t)\, p_{jk}^s(t), \tag{5}
$$

where $\alpha_j(t)$ is the CO_2 emission intensity corresponding to the production of aircraft models at a purchaser's price of one million dollars, and $p_k^s(t)$ is the purchase price of aircraft model k produced by aircraft manufacturer j. Summing the CO_2 emissions of aircraft models k produced by Airbus ($j = 1$) and Boeing ($j = 2$) yields the manufacturing emissions of airline company s.

3. Data acquisition

We collected the following data on the international flights and aircraft models for JAL and ANA for 2005, 2010, and 2015:

(1) Number of international flights per week (JTB Corporation 2005, 2010, MLIT 2015)
(2) Aircraft models used in the international flights (JTB Corporation 2005, 2010, MLIT 2015a)
(3) Round-trip distance between each departure and arrival city (ICAO 2020)
(4) Fuel efficiency of each aircraft model (The Boeing Company 2020, ANA 2020)
(5) Emission intensity of jet fuel combustion (National Institute for Environmental Studies, Japan 2019)
(6) Embodied emission intensities of jet fuel refinery (Nansai 2019, Nansai *et al* 2020)
(7) Aircraft price (Airbus 2018, The Boeing Company 2020)

The database of fuel efficiency and timetable used in this study is provided in the supplementary files (available online at stacks.iop.org/ERL/15/104036/mmedia). We assume an equal aircraft sales price for JAL and ANA. The fuel efficiency of each aircraft model in L/km is calculated by dividing the catalog-based fuel capacity (L) by the catalog-based range of the aircraft (km). Since data on the *actual* fuel efficiency of aircraft models are unavailable, the catalog-based efficiency (L/Km) in our study is defined by dividing the fuel capacity of an aircraft by its achievable range in the case where the fuel is full and all seats are occupied. [1] In this study, we tried to evaluate/compare individual functions of each aircraft type under the assumption. Peeters *et al* (2005) and (Miyoshi and Mason 2009) considered the distance flown, and showed that the fuel intensity and the carbon emissions in g/km per passenger varied by ±20% to ±30% depending on flight range. Therefore, following the previous studies (Peeters *et al* 2005, Miyoshi and Mason 2009), the margin of error of the fuel combustion phase CO_2 emissions would range from ±20% to ±30%.[2] Examining the gap between actual and catalog-based fuel efficiency is left for a future study. The emission intensity of jet fuel combustion in flight is 2.46 (kg-CO_2/L; National Institute for Environmental Studies 2019). The Japanese carbon emission factor for jet kerosene is obtained from actual measurement (National Institute for Environmental Studies 2019). Using the database, we estimated the CO_2 emissions associated with the international flight activities of two Japanese airline companies (JAL and ANA) for 2005, 2010, and 2015. The companies own a combined total of 483 aircraft: 226 for JAL and 257 for ANA, accounting for 98% of the total number of aircraft in Japan in 2015 (JAL 2016, ANA 2016, MLIT 2019). Thus, Japan's airline market is dominated by these two companies. JAL went bankrupt in January 2010. Accordingly, we focus on Japan's two major airline companies, and the past decade has centered around JAL's bankruptcy.

Data on the number of flights are provided per week, and the timetable of each airline company is revised twice a year. Therefore, we convert the per-week values into annual values based on the assumption that the summer timetable from April to October has 30 weeks, and the winter timetable from November to March has 22.

The embodied CO_2 emission intensities of aircraft production, $\alpha_j(t)$, were estimated using the World Input–Output Database (WIOD; Timmer *et al* 2015, Corsatea *et al* 2019). Specifically, we focused on the 'other transport equipment' sector in France and the United States in the World Input–Output Tables in 2005, 2010, and 2014, and calculated the embodied CO_2 emission intensities of 56 sectors across 43 countries and regions as $\boldsymbol{\alpha}(t) = \mathbf{e}(t)(\mathbf{I} - \mathbf{A}(t))^{-1}$, where $\mathbf{e}(t)$ reflect the direct CO_2 emission intensities of the 56 sectors in the 43 countries and regions, $\mathbf{I}$ is the identity matrix, and $\mathbf{A}(t)$ is the intermediate input coefficient matrix based on the WIOD (e.g. Kagawa *et al* 2015). We used the vector elements of the 'other transport equipment' sector in France and the United States in $\boldsymbol{\alpha}(t)$ as the embodied CO_2 emission intensities (t-CO_2 per US dollars) of aircraft production in the two nations.

4. Results

4.1. Airline market

Before proceeding to the environmental analysis, it is worthwhile investigating the airline market in Japan. JAL and ANA dominate the market. As noted above, JAL and ANA own 483 aircraft combined. JAL's and ANA's sales of international passenger flights in 2005 were 690 and 230 billion yen, respectively (JAL 2005, ANA 2005), whereas their sales in 2015 were 448 and

[1]Following the previous article (Graver *et al* 2018), the passenger-based efficiency metric in passenger-kilometers per liter of fuel was defined as $passenger \times km/L = \left(\sum_i p_i \times d\right)/(100 \times f)$ where p_i is the mass of a passenger (i) and luggage, d is the distance flown, f is the total fuel consumption, the value of 100 denotes the standard mass for a passenger, and luggage of 100 kg is used (ICAO 2016d). It should be noted that if all N seats are occupied and N passengers have the same payload of $p_i = 100$kg, the passenger-based efficiency metric can be easily transformed as $\left(\sum_{i=1}^{N} p_i \times d\right)/(100 \times f) = (100 \times N \times d)/(100 \times f) = Nd/f$. Dividing the passenger-based efficiency metric by the number of passengers yields a reciprocal of the function-based efficiency metric used in this study. This study assumes that d is the achievable range in the case that fuel is full, all seats are occupied, and all passengers have a standard mass. It should be noted that aircraft fuel use is proportional to the total payload mass transported (Graver *et al* 2018).

[2]It should be noted that carbon emissions in g/km per passenger are 'linearly' affected by the margin of error of the fuel efficiency.

515 billion yen, respectively (JAL 2015, ANA 2015). The following figures are important: (1) total sales for the two airlines increased by 4.3% during the study period between 2005 and 2015; and (2) ANA's market share for international passenger flights increased from 25% to 53% during the study period, whereas JAL's decreased considerably from 75% to 47% due to its bankruptcy in January 2010. Here, market share is calculated by dividing the sales for international passenger flights of each airline company by the total sales for the two airlines.

4.2. CO_2 emissions in flight

The primary reason for the rapid decline in JAL's market share is the fact that the total number of flights decreased from 577 flights per week in 2005 to 457 flights per week in 2010 (see figure 1). The trend over this 10-year period decreased because of its bankruptcy in January 2010. Since then, the company has been working to improve its management. For example, unprofitable routes have been abandoned or had their numbers of flights decreased (JAL 2010). Conversely, over the same 10 years, ANA's flights increased from 225 per week in 2005 to 329 per week in 2010 (see figure 1). In 2010, ANA decided to increase its international flights due to a change in management policy (ANA 2010). This increase made up for the air routes abandoned by JAL in 2010.

It is important to consider how the changes in market shares for JAL and ANA have affected aviation emissions (i.e. CO_2 emissions associated with jet fuel combustion and production) in Japan. CO_2 emissions from their international flights decreased slightly by 0.2 Mt-CO_2 between 2005 and 2015, accounting for 1.5% of the aviation emissions in 2005 (see figure 2). We evaluated environmental efficiency at the sector level by dividing the total sales for the aviation sector in billion JPY and the CO_2 emissions for the aviation sector in Mt-CO_2. We found that the rapid change in Japan's aviation market contributed to a 9% increase in environmental efficiency during this decade, implying that the aviation sector in Japan has shown increased production rates with fewer CO_2 emissions since 2005, and has achieved the decoupling of total sales and energy-related CO_2 emissions.

Determining why this decoupling has been achieved in Japan's aviation sector of Japan requires looking at the changes in CO_2 emissions at the company level. The CO_2 emissions associated with international JAL flights decreased by approximately 4.03 Mt-CO_2 in 2015 relative to 2005 (see figure 2). This decrease is assumed to be the outcome of the reduction in the total number of flights caused by the bankruptcy. Conversely, the CO_2 emissions associated with international ANA flights increased by 3.84 Mt-CO_2 in 2015 relative to 2005 owing to the increase in the number of international flights since 2010 (see figure 2). The number of departures and arrivals at Narita International Airport increased. Additionally, Tokyo International Airport (i.e. Haneda International Airport), close to the Tokyo metropolitan area, opened its new international terminal in 2010; thus, facility factors provided tailwind for the increase in ANA's number of international flights.

We estimated the amount of CO_2 emissions due to the production of new aircraft for JAL and ANA between 2000 and 2015 (see figure 3) as 6940 Kt-CO_2 in equation (5). Both companies introduced new aircraft from 2006 to 2015. From 2000 to 2015, JAL introduced 54 new aircraft, and ANA introduced 63 aircraft. The two companies introduced 66 Boeing 787s, a new aircraft with higher fuel efficiency, between 2010 and 2015 (JAL 2016, ANA 2016). Therefore, the rate of increase in CO_2 emissions in the aircraft manufacturing phase is greater than the rate of emissions in the fuel combustion and consumption phases. Howe *et al* (2013) report that the CO_2 emissions associated with the manufacturing phase accounted for 0.1% of all life-cycle CO_2 emissions of an aircraft. 'Marginal' manufacturing emissions tend to be ignored in CO_2 mitigation policies in the aviation sector. However, as Scope 3 accounting insists (Greenhouse Gas Protocol 2011), calculations of CO_2 emissions associated with the airline business year by year should not discount the significance of managing production phase emissions.

4.3. Decomposition analysis

We assessed the contribution of each factor to the change in CO_2 emissions due to fuel combustion at the company level using decomposition analysis. We determined why Japan's aviation sector reduced its CO_2 emissions during the study period.

4.3.1. Fuel efficiency (FE) effect

Examining the fuel efficiency (FE) effect for JAL between 2005 and 2010 indicates that FE contributed to the decrease in CO_2 emissions in all regions (see figure 4). The Asia and Oceania regions saw a decrease in CO_2 emissions of approximately 0.81 Mt-CO_2 owing to the FE effect, which improved the fuel efficiency of aircraft between 2005 and 2010. Before its bankruptcy in January 2010, JAL's main aircraft was the jumbo jet as represented by the Boeing 747, which uses a large amount of fuel in each flight and has a poor fuel efficiency of 16.1 (L/km), resulting in higher CO_2 emissions. However, after its bankruptcy, JAL introduced fuel-efficient aircraft such as the Boeing 767 to decrease CO_2 emissions per flight. Moreover, the FE component in Europe was marginal during the five years between 2005 and 2010 (see figure 4).

Between 2010 and 2015, JAL introduced a new aircraft model, the Boeing 787, which is about 50% more fuel efficient (equal to 8.8 (L/km)) than conventional aircraft (e.g. Boeing 747) for North

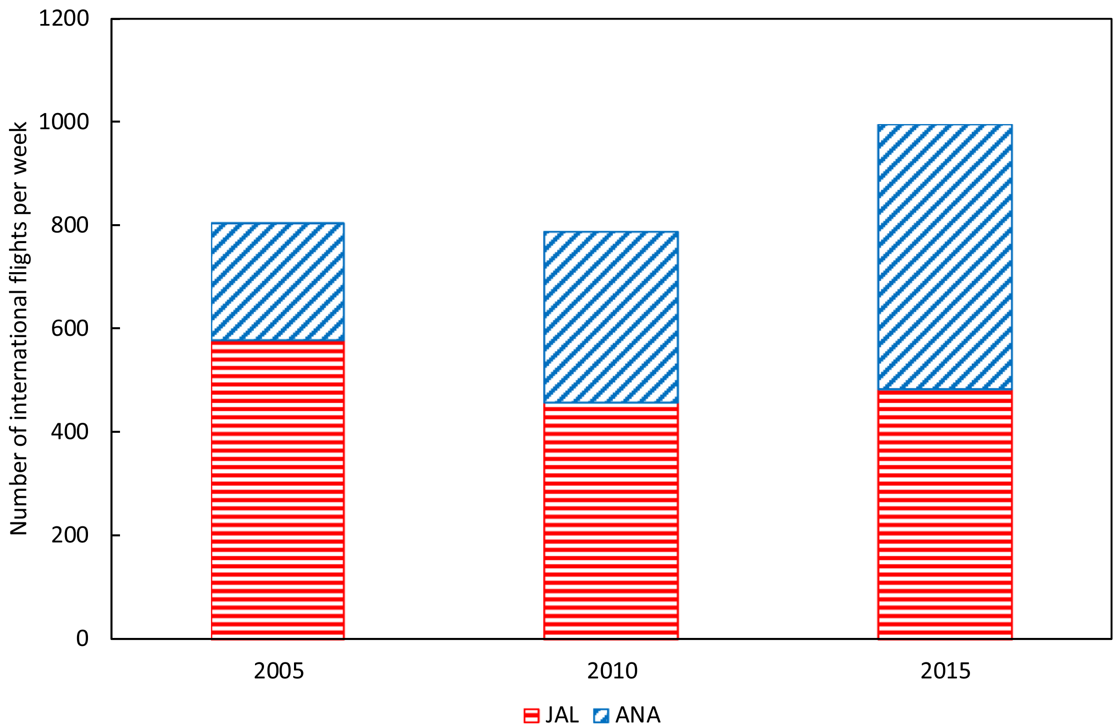

Figure 1. Total number of international flights per week.

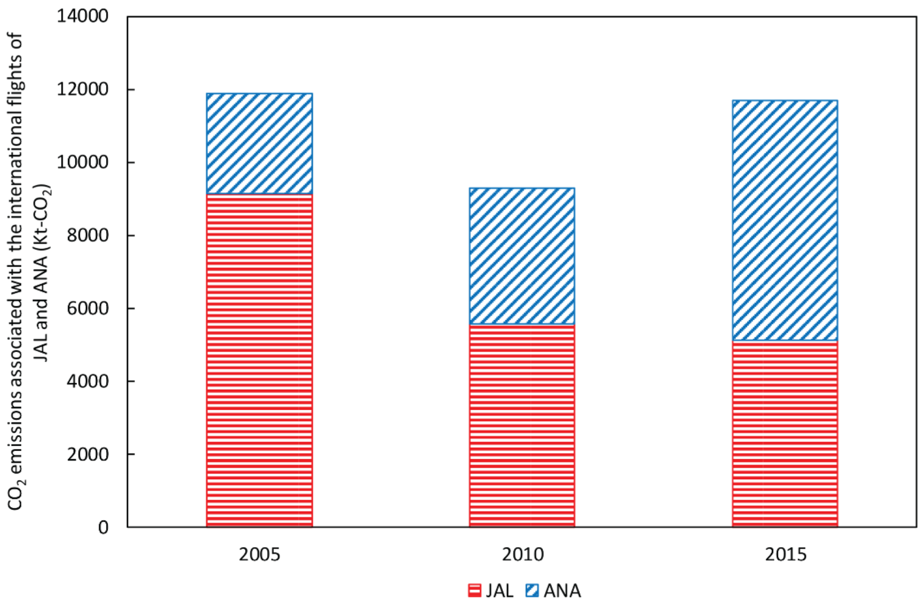

Figure 2. CO_2 emissions associated with fuel combustion and production attributed to JAL and ANA.

American and European flights. [3] These regions have long-distance routes, so the reduction in CO_2 emissions associated with international flights to North America and Europe from 2005 to 2010 (i.e. the effects of the Boeing 747) was significant, amounting to 0.82 Mt-CO_2 (see figure 5).

[3]Since the Boeing 787 has 246 seats and all 246 seats are occupied in this study, its payload is calculable as $246 \times 100 = 24600$kg. For the Boeing 787, the passenger-based efficiency metric can be estimated as $Nd/f = 246 \times 12020/126000 = 23.5(passenger \times km/L)$ where $d = 12020$(km) and $f = 126000$ (L) (see the supplementary data). Similarly, we can estimate the passenger-based efficiency metric of the Boeing 747 as 32.5 $(passenger \times km/L)$. It should be noted that the Boeing 787 is more fuel 'inefficient' than the Boeing 747 under the 'passenger-based' efficiency metric. In this study, we attempted to evaluate how the function-based fuel efficiency has affected the CO_2 emissions. Our results based on the 'function-based' fuel efficiency can be useful in considering how the Boeing Company can contribute to reducing the CO_2 emissions through the improved functions of each aircraft type.

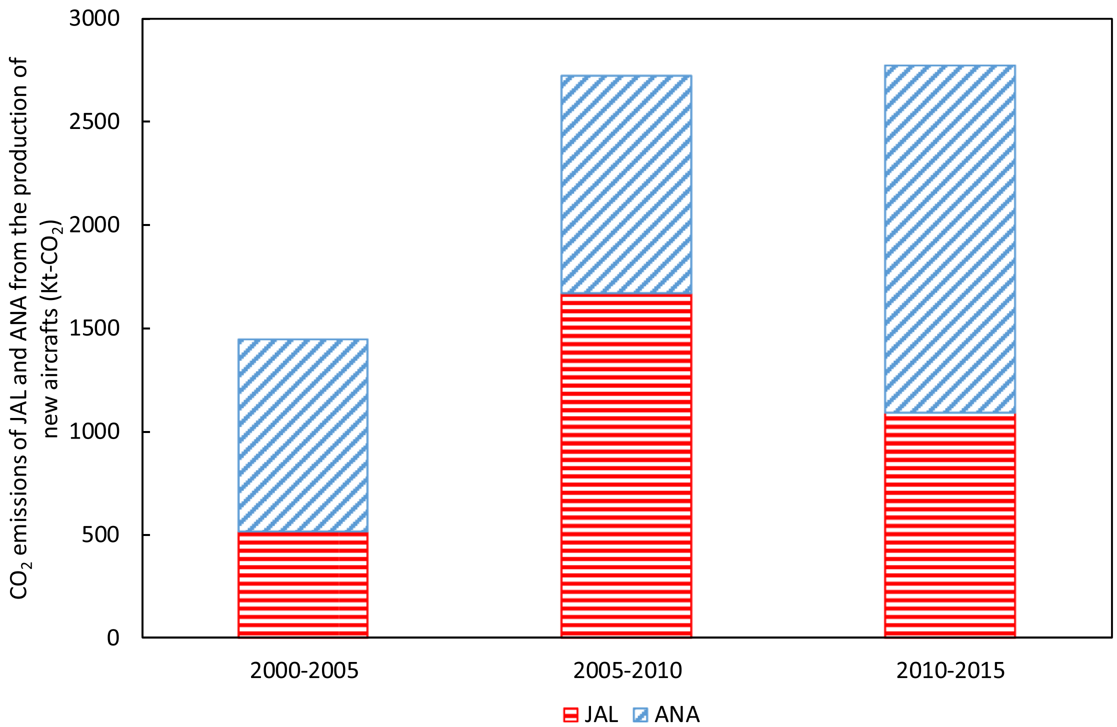

Figure 3. CO_2 emissions of JAL and ANA from production of new aircraft.

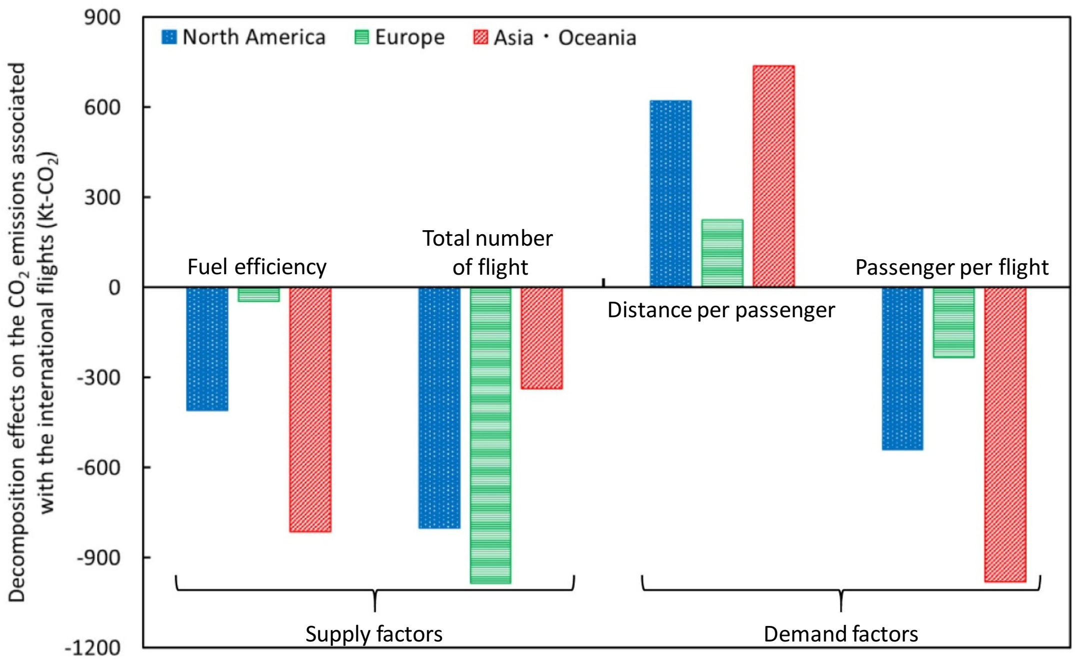

Figure 4. Decomposition effects of changes in CO_2 emissions associated with international JAL flights between 2005 and 2010.

The FE was a factor that contributed to ANA's decreases in CO_2 emissions in Asia, Oceania, and Europe as well as to the increase in North America between 2005 and 2010 (see figure 6). The increase of CO_2 emissions in North America reflects aircraft changes. In contrast to JAL, in 2010 ANA introduced larger aircraft (i.e. Boeing 777–300) than it used in 2005 (i.e. Boeing 777). These new aircraft had 20%

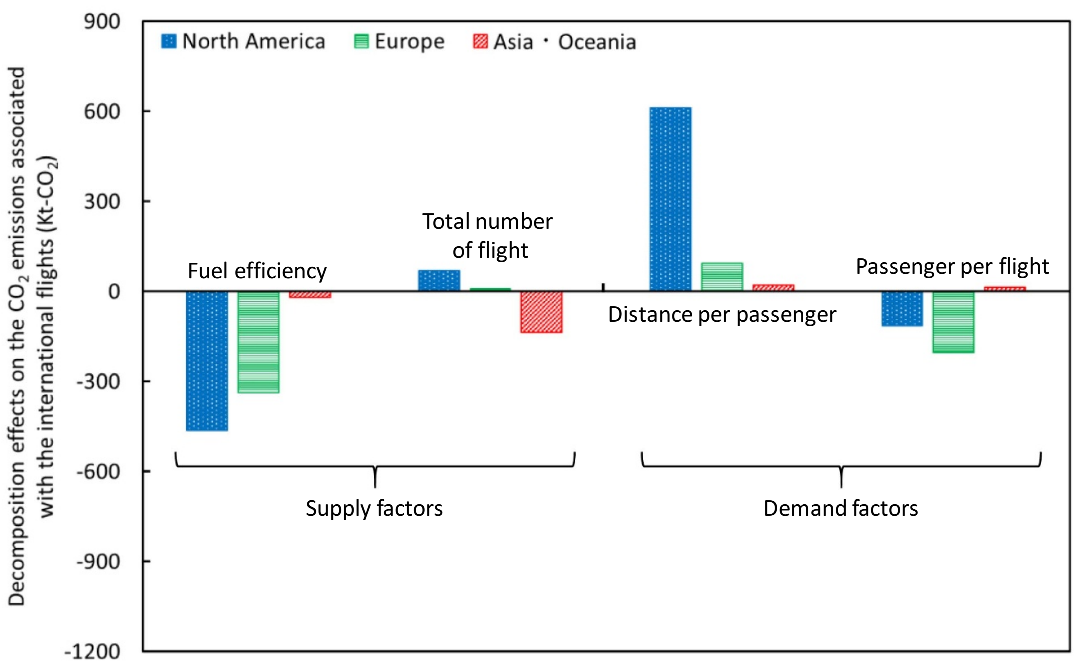

Figure 5. Decomposition effects of changes in CO_2 emissions associated with international JAL flights between 2010 and 2015.

poorer fuel efficiency, which increased CO_2 emissions.

Similarly, between 2010 and 2015, FE contributed to an increase in CO_2 emissions in Asia and Oceania, and to decreases in North America and Europe (see figure 7). The results for Asia, Oceania, and North America were the opposite of those for the 2005–2010 period (see figures 6 and 7). It is assumed that the reduction of CO_2 emissions in North America was due to the introduction of the Boeing 787, and the FE contributed to the increase in Asia. This new fuel-efficient aircraft was also introduced on these routes, but its fuel efficiency was worse than that of the Airbus 320, which was already being used. [4] However, during the study period, ANA decided to retire the Airbus 320, which had a higher fuel efficiency, because the Boeing 787 has many more seats and a greater flight range (ANA 2012).

4.3.2. Total number of flights (TN) effect

In this subsection, we assess the effects owing to the TN for JAL. TN is a factor that reduced CO_2 emissions in all regions between 2005 and 2010 (see figure 4). After the bankruptcy in 2010, JAL abandoned unprofitable routes or decreased their flights. Therefore, the total number of flights on international routes for all regions decreased in 2010 relative to 2005. This result shows that a reduction of CO_2 emissions for this period was brought about by the TN effect. Conversely, for ANA, TN helped increase CO_2 emissions in all regions between 2005 and 2010 (see figure 5). The total number of flights on international routes for all regions increased in 2010 relative to 2005, and CO_2 emissions thus also increased.

It is assumed that the increase in number of ANA's flights was caused by the decrease in the total number of JAL flights due to its 2010 bankruptcy. The number of JAL's flights decreased from 577 flights per week in 2005 to 457 flights per week in 2010, whereas the number of ANA's flights increased from 255 flights per week in 2005 to 329 flights per week in 2010. This change shows that ANA had to make up for the supply deficit caused by JAL's decrease. Therefore, the increase in ANA's total number of flights happened because ANA (a) maintained supply in the Japanese aviation industry and (b) changed its management policy and refocused on international flights.

The total number of JAL flights decreased significantly from 2005 to 2010 but increased by approximately 30 flights per week from 2010 to 2015. In 2015, JAL was still under monitoring, but they were able to increase their total number of flights gradually in accordance with the increasing demand. Similarly, for ANA, TN contributed to increases in all regions (see figure 7). Flights in all three regions increased by a factor of between 1.5 and 2, and the total number of flights increased by approximately 200 per week. Therefore, TN is the primary contributing factor in ANA's CO_2 emissions increases.

[4]The passenger-based efficiency metric of the Boeing 787 is 23.5 ($passenger \times km/L$), whereas that of the Airbus 320 is 38.7 ($passenger \times km/L$). It should be noted that the Boeing 787 is more fuel 'inefficient' than the Airbus 320 under the 'passenger-based' efficiency metric.

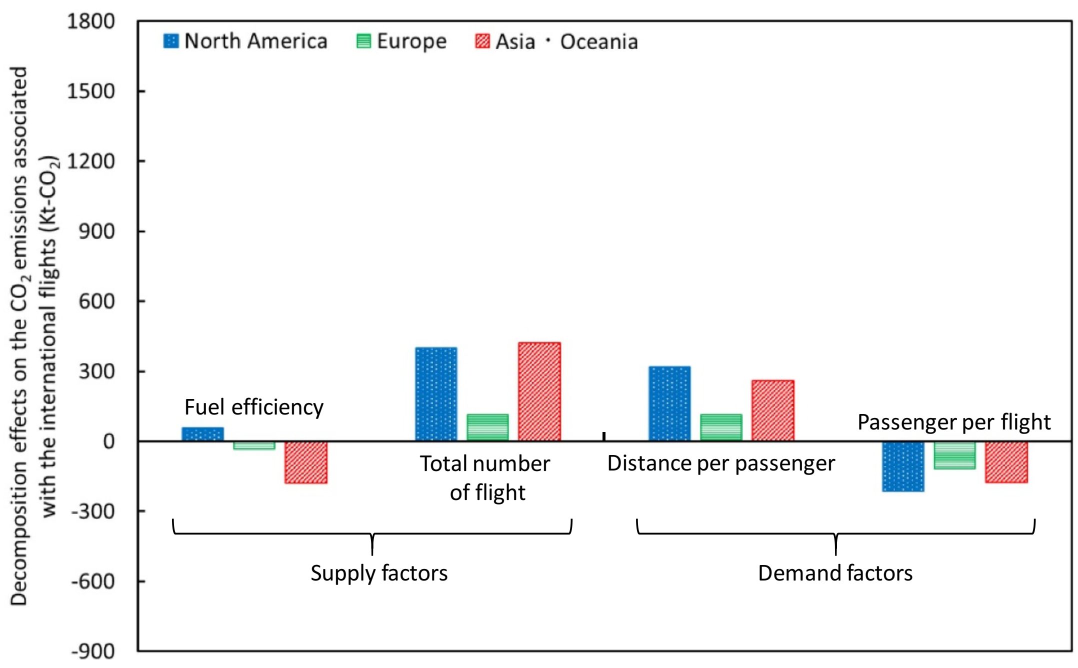

Figure 6. Decomposition effects of changes in CO_2 emissions associated with international ANA flights between 2005 and 2010.

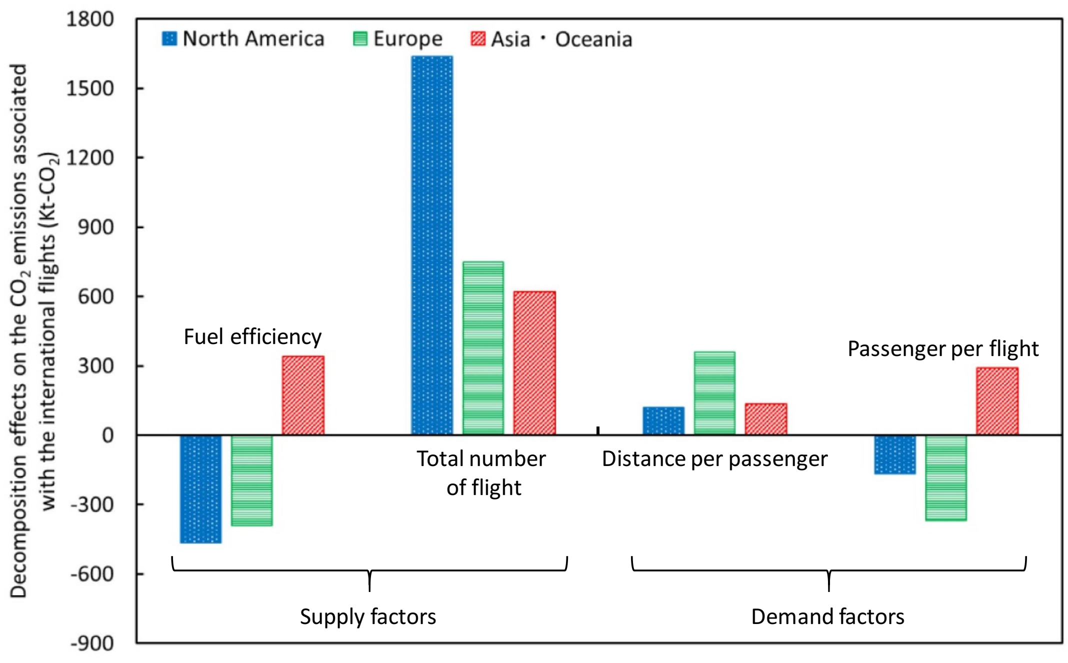

Figure 7. Decomposition effects of changes in CO_2 emissions associated with international ANA flights between 2010 and 2015.

4.3.3. Distance per passenger (DP) effect

The DP effect reflects the flight structure of the region. The distance shows the service provided by the airline company. If the DP effect is positive, the distance traveled in the region is longer; similarly, if the DP effect is negative, the distance in the region is shorter. For example, a positive DP effect indicates that long flights in the region increase.

The DP effect for JAL between 2005 and 2010 contributed to increases in CO_2 emissions in all regions (see figure 4). In North America, routes that did not exist in 2005 were added (MLIT 2015a). The primary reason for this positive effect was the route from Haneda to San Francisco, which is the longest in this region. The DP effect was also positive in Asia and Oceania. In this region, the number of flights along the Singapore and Denpasar routes, which are relatively long, decreased. However, the number of passengers decreased by approximately 3.5 million from 2005 to 2010. This decrease was greater than the decrease of long-haul routes. Therefore, the distance per passenger in Asia and Oceania increased. Accordingly, the effect owing to DP was positive.

The DP effect for JAL between 2010 and 2015 is a factor contributing to the increase in CO_2 emissions in all regions (see figure 5). The major reason for the positive effects in Asia, Oceania, and North America was the introduction of new long-distance routes. For example, the Jakarta and Singapore routes, both of which were relatively long, were added in Asia. In North America, a Boston route, which became one of the longest routes flown by JAL, was also added; thus, CO_2 emissions owing to the DP factor increased.

For ANA, DP contributed to increases in all regions between 2005 and 2010 (see figure 6). Like JAL, ANA added new long-distance routes. For example, Mumbai and Kuala Lumpur routes in Asia and a Chicago route in the United States were added, which contributed to a round-trip distance of more than 20 thousand kilometers in North America. Similarly, between 2010 and 2015, DP contributed to an increase in CO_2 emissions in Europe that was larger than that in any other region (see figure 7).

4.3.4. Passenger per flight (PF) effect

Finally, we assess the PF effect for JAL and ANA. Here, PF quantifies passenger efficiency in a particular region. The greater the PF effect, the better the airline's business performance.

The PF for JAL is a factor that contributes to a 49% decrease of CO_2 emissions in all regions between 2005 and 2010 (see figure 4). We found a remarkable CO_2 decrease of 27% in the Asia and Oceania routes (see figure 4). This reflects the abrupt decrease in JAL's passenger efficiency from 465 persons per flight to 331 persons per flight on the Asia and Oceania routes. In addition to several risk events such as the 2008 financial crisis and the 2009 swine flu pandemic, this inefficiency was clearly one of the causes of JAL's bankruptcy in 2010.

JAL's passenger efficiency on the Asia and Oceania routes rapidly improved between 2010 and 2015, leading to increases in CO_2 emissions on those routes. However, the efficiency of JAL's operations also clearly improved. Conversely, the North American route still contributed to the decrease in CO_2 emissions. On this route, flights increased by approximately 1000 flights in 2015 over 2010. However, the number of passengers on the North America route decreased by approximately 40 thousand.

For ANA, PF contributed to a 0.51 Mt-CO_2 decrease in CO_2 emissions in all regions between 2005 and 2010 (see figure 6). The decreases attributed to the PF factor is the largest among all factors for the period between 2005 and 2010. Conversely, between 2010 and 2015, PF contributed to a 0.29 Mt-CO_2 increase in Asia and Oceania and a decrease in North America and Europe (see figure 7). The Asia and Oceania route increased in this decade. The number of passengers on the Asia and Oceania route also increased by approximately 2 million. This increase indicates that demand on the Asia and Oceania route increased.

5. Comparison with relevant previous studies (Andreoni and Galmarini 2012, Yu *et al* 2020)

For a relevant study, (Andreoni and Galmarini 2012) decomposed CO_2 emissions from airline industry in the EU 27 countries and found that an expansion of the aviation market (i.e. an increase in the GDP share of the airline industry) contributed to the increasing CO_2 emissions. On the contrary, the present study reveals that an increase in the number of international flights operated by the Japanese airline companies contributed to an increase in CO_2 emissions. It is important to note that (Andreoni and Galmarini 2012) could not distinguish between passengers and freight transportation due to data constraints, however the present study uses detailed timetable data, which allows us to provide detailed CO_2 emissions inventory data by flight. Due to the different definitions on the aviation sector, it is difficult to compare the results of (Andreoni and Galmarini 2012) with those of this study.

(Yu *et al* 2020) estimated the 'direct' CO_2 emissions from 'domestic and international' flights operated by the Chinese aviation sector. According to the results from (Yu *et al* 2020), while the average yearly distance flown by Chinese airline companies increased during the study period during 1979 to 2017, its factor had a relatively small impact on increasing CO_2 emissions in the aviation industry—13%, on a yearly average. Meanwhile, this study defines a new factor of 'distance per passenger and flight' (i.e. physical flight service per passenger) and shows that the distance-per-passenger effect contributed to increasing CO_2 emissions in the aviation industry (JAL and ANA in this study) between 2005 and 2015 by 3.1% on a yearly average. Compared with the number of flights effect, accounting for 1.5% on a yearly average, we find that the distance per passenger effect had a relatively large impact of increasing CO_2 emissions in the aviation industry in Japan. Thus, this study provides a different angle of interpreting how distance matters in CO_2 emissions from the aviation industry.

Since previous studies estimated the aviation emissions by country and region, and decomposed the change in CO_2 emissions, they cannot evaluate the CO_2 emissions of individual airline companies. Therefore, from previous studies, it is difficult to propose a CO_2 emissions reduction policy at airline company level necessary for CORSIA, where emission limits are set for each airline company. It is important to note that the CO_2 emissions of each airline company are simultaneously affected by both supply-side factors such as practical flight operations, and demand-side factors such as passenger demand. In this study, we developed a new decomposition analysis framework to simultaneously analyze a tradeoff relationship between the supply-side factors and the demand-side factors.

6. Conclusion and policy implications

This study estimated the CO_2 emissions associated with international flights by JAL and ANA, and identified their drivers through an index decomposition analysis. The results show that changes in aircraft models and the total number of flights affected the CO_2 emissions attributable to the aviation industry most significantly. The introduction of the Boeing 787, the fuel efficiency of which is greater than that of conventional models, led to remarkable CO_2 emission reductions (of 2.8 Mt-CO_2) for both companies between 2005 and 2015.

Conversely, CO_2 emissions from both companies increased by 2.9 million tons from 2010 to 2015 due to an increase of TN, which was the strongest driving force. The Boeing 787 reduction effect was canceled out by the TN effect in the Japanese aviation industry. Although the supply factor is critical in the mitigation of carbon emissions generated by aviation, it is not practical to include this factor in policy discussions regarding CO_2 reduction given the increasing demand for aviation (see figure 1). Tokyo International Airport (Haneda Airport) has the capacity to increase its number of international flights. This airport is expected to handle a 1.7-fold increase in flights in 2021, the year of the Tokyo Olympic Games, relative to its 2015 number (MLIT 2017). This is expected to boost the number of international flights in Japan and the CO_2 emissions associated with them.

However, Japanese airline companies must mitigate their CO_2 emissions from international flights because the Japanese government is participating in CORSIA (ICAO 2016c). Importantly, we have also found that an environmental and business strategy of introducing greener aircraft with greater fuel efficiency, such as the Boeing 787, was not enough to reduce CO_2 emissions.

The FE's reduction effect due to the introduction of new aircraft increased CO_2 emissions in the manufacturing phase. We estimated the amount of CO_2 emissions generated by JAL and ANA from the production of new aircraft in equation (5) as 6940Kt-CO_2 between 2000 and 2015. These emissions were as large as the annual flying-phase emissions of the two companies. Therefore, airline companies need to evaluate in greater detail the life-cycle of CO_2 emissions beyond the flying phase, including in the production phase, to mitigate the CO_2 emissions produced by aviation activities.

Furthermore, the DP effect was the main factor in the increase of CO_2 emissions from 2005 to 2015, and accounted for 3.6 million tons of CO_2. During this decade, consumers preferred longer distances. To combat global warming, France introduced an eco-tax on airlines flying from French airports (Reuters 2019). The French government announced that it would 'add €1.50 ($1.68) to the cost of a plane ticket in economy class within the European Union (EU) and €3 to an economy ticket outside the EU. In business class, the levies will be €9 and €18 respectively' (Climate Home News 2019).

The French tax policy, based on seat classes, is not effective in reducing CO_2 emissions, because the eco-tax is imposed on consumers uniformly, regardless of flying distance. In 2018, the Swedish government introduced an air travel tax based on the flight's destination (Swedish Tax Agency 2018). For an eco-tax to reduce the CO_2 emissions attributable to both flying distance and aircraft type, it needs to be imposed based on aircraft type as well as flying distance, which would increase taxes on long-haul routes and less fuel-efficient aircraft.

The Japanese government has suggested improving aircraft and fostering greener operations by utilizing market mechanisms such as carbon emission trading, and by introducing bio-jet fuel to mitigate CO_2 emissions owing to international flights (MLIT 2015b). Furthermore, the International Air Transport Association (IATA) has also emphasized the importance of bio-jet fuel for CO_2 emission reduction (IATA 2018). Bio-jet fuel is commercialized in European countries and the United States. Additionally, the EU established the EU emissions trading system (EU-ETS) framework, which offsets CO_2 emissions from the combustion of bio-jet fuel (European Commission 2014). Studies by the National Aeronautics and Space Administration (NASA), as well as other research, predict that bio-jet fuel will lead to a reduction in CO_2 emissions from the aviation industry of approximately 50% to 70% (NASA 2017). This forecast will accelerate the use of biofuel in the aviation industry (Kousoulidou and Lonza 2016, Wise *et al* 2017, Yilmaz and Atmanli 2017, Staples *et al* 2018). Both JAL and ANA have invested in research and development of bio-jet fuel and conducted tests of flights powered by it (JAL 2009, ANA 2012). Thus, using bio-jet fuel will be crucial in reducing aviation emissions and enhancing passenger safety. Furthermore, it will be important to introduce a 'smart control system' to determine how to replace older aircraft with newer ones to meet airlines' long-term climate targets. Smart control systems can simulate the aviation emissions associated with the manufacturing/replacement and use phases given various driving factors, such as fuel efficiency, the number of flights, flight distance, and the number of passengers—all of which were considered in this study—as well as sales.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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