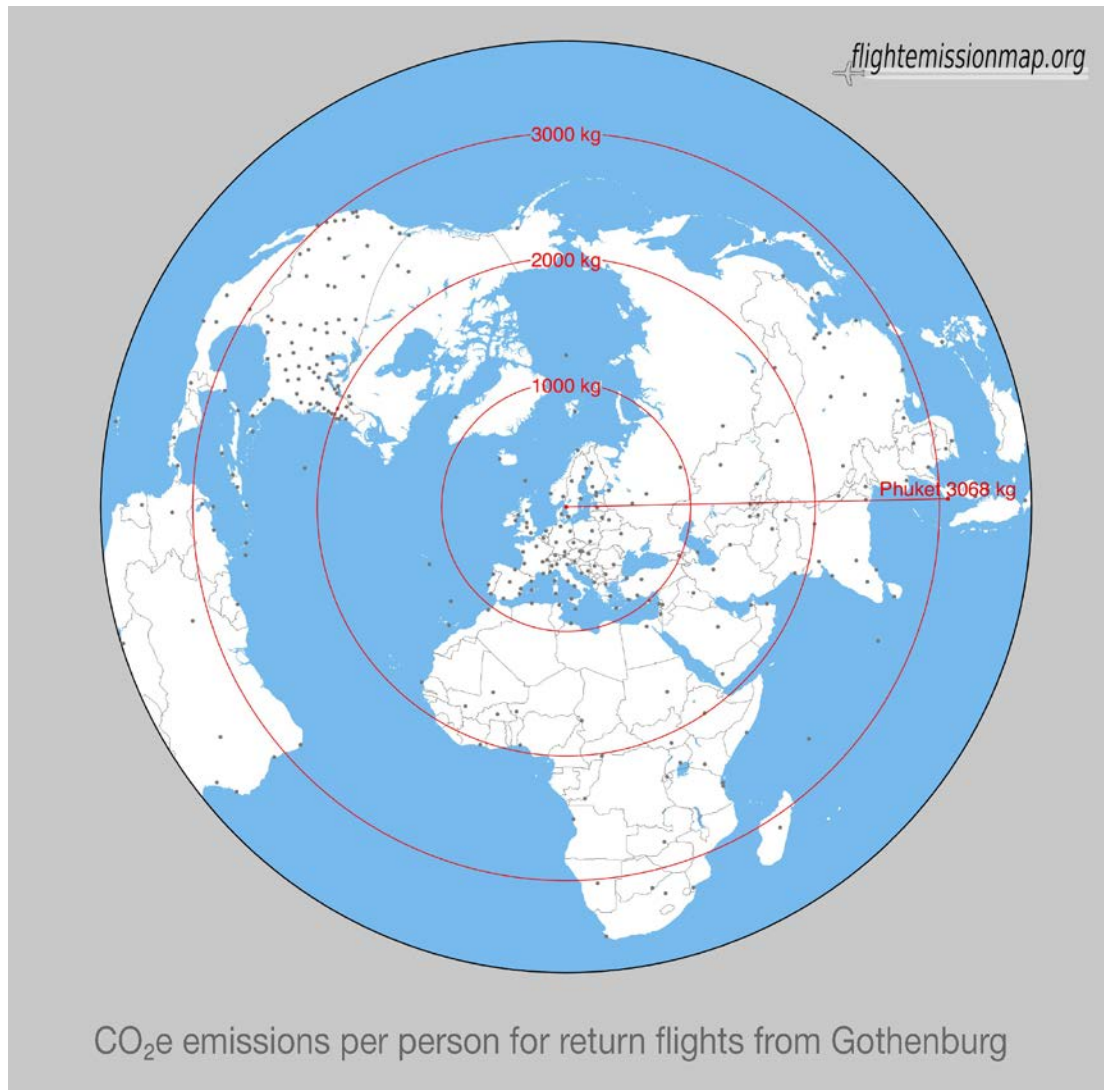




CHALMERS



Climate footprint from Swedish residents' air travel

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Summary

Greenhouse gas emissions from air travel are substantial for high-income countries like Sweden. The established accounting methodology for aviation, which is used for reporting to the UNFCCC, is based on how much fuel aircrafts take on in each country (termed bunker fuels). We have developed a supplementary indicator that includes emissions from the entire trip to the final destination as well as the non-CO₂ effects from aviation. In this report we have analysed the trends between 1990 and 2017.

The number of trips per person has increased dramatically. Domestic air travel has not increased but international trips have doubled from 0.5 trips per person and year in 1990 to 1.0 trips per person in 2017, an annual increase of 2.9 %.

The average distance to the final destination has not increased much during the period since the number of both short and long trips have increased. The average distance is about 2700 km for a one-way trip, which is similar to the distance between Stockholm and Madrid.

Emissions per passenger km have decreased by 1.9 % per year on average. In 2017, emissions from air travel were 90 grams CO₂ per passenger km, and if the non-CO₂ effects are included, these emissions are estimated at 170 grams CO₂eq. Even if there is a great deal of uncertainty concerning non-CO₂ effects, there is no doubt that such effects exist and that they are not insignificant. We assess that the most reasonable position to take is to be in line with the IPCC report (AR5) and include these effects. We use the most well-established scientific estimate which is, measured in GWP100, that the overall climate impact is approximately 1.9 times higher than the impact of CO₂ emissions alone (including the effects of contrails and cirrus clouds for example).

True emissions per passenger km obviously vary depending on the distance and aircraft type, etc., but using the same emissions factor for all travel gives a fairly good estimate for most flights. Although long distance trips typically have lower CO₂ emissions per passenger km, a larger share of the trip is at a higher altitude and thus causes more non-CO₂ emissions per passenger km. The opposite is true for short distance trips where CO₂ emissions per passenger km are typically higher due to the energy-demanding ascent but where only a small, or non-existent, share of the flight is at altitudes where the non-CO₂ emissions principally arise. As such, these two effects cancel each other out and the resulting CO₂eq per passenger km are similar, regardless of the distance.

The 170 grams CO₂eq can be compared with the emissions from long-distance travel by car, which is about 50 grams per passenger km, based on the average number of persons (3) in each car on long-distance trips.

The total emissions from air travel by Swedish citizens was 10 million tonnes CO₂eq in 2017, an increase of 47 % since 1990. Emissions from domestic aviation are

decreasing and now account for only 7 %, while emissions from international trips have increased and now account for 93 % of the air travel emissions. This increase in emissions occurred during the 1990s. After 2000, emissions have remained on the same level due to the emissions decrease per passenger km having been on par with the increase in passenger km.

The greenhouse gas emissions from Swedish inhabitants' air travel is now about equivalent to Sweden's emissions from car use. Sweden's annual emissions from air travel are now about 1.1 tonnes CO₂eq per inhabitant, which is about five times higher than the global average.

Front page: The image on the front page shows GHG emissions including non-CO₂ emissions for return trips from Gothenburg. It is based on emissions of 170 g CO₂eq per passenger km. The image was produced by Björn von Sydow, Chalmers University of Technology. An interactive version of this map can be found at www.flightemissionmap.org.

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1 Introduction

The climate summit in Paris in 2015 established the global goal of keeping the temperature increase well below 2°C compared with pre-industrial levels. To have a reasonable chance of achieving this goal will require proactive climate efforts in principle in all sectors in all countries. In 2010, global aviation was responsible for 2.6 % of all energy-related CO₂ emissions (IPCC, 2014, p. 603 och 646) and emissions from aviation have increased by 40 % between 1990 and 2010 (IPCC, 2014). In addition to emissions of CO₂, a climate impact of almost a similar size arises from non-CO₂ effects which are a result of e.g. emissions of nitrogen oxides, contrails and cirrus clouds at high altitudes (see also Section 2) (Azar & Johansson, 2012; Lee et al., 2010). There is uncertainty about how large these non-CO₂ effects are, but when the best scientific estimates are used, total greenhouse gas emissions from aviation are roughly 4–5 % of total global emissions.

Greenhouse gas emissions from global aviation continue to rise, because air travel volumes are increasing faster than advances in technological and organizational efficiencies (Larsson, Kamb, Nässén, & Åkerman, 2018). For example, the number of passengers increased globally by 60 % between 2008 and 2017 (ICAO, 2018a). The number of air passengers is expected to rise by 4 % per year over the next twenty years according to the International Air Transport Association (IATA, 2015a) and the International Civil Aviation Organization (ICAO). If this happens, and if land-based emissions follow an emissions path that is in line with the 2°C goal, emissions from international aviation will eventually be responsible for more than 20 % of global CO₂ emissions in 2050 (M. Cames, Graichen, Siemons, & Cook, 2015).

In order to reduce the risk of aviation jeopardising the global climate goals, stronger instruments ought to be considered. On 1 April 2018, Sweden introduced a flight tax and the aviation industry has developed a roadmap with the aim of making domestic aviation fossil-free by 2030 (Swedish Air Transport Society, 2018). The Swedish Government also has an ongoing enquiry into how the use of biofuel can be promoted (Regeringen, 2018). Since a large portion of global air travel is international, about 65 % of fuel consumption is used for international aviation (ICAO, 2016a), and because of the global nature of the aviation industry, there is a need for international policy instruments. Since 2012, aviation in the European Union (including domestic flights) is part of the EU's emissions trading system (EU, 2017). The ICAO decided in 2016 to introduce a system called “Carbon Offsetting and Reduction Scheme for International Aviation” (CORSIA), which stipulates that airlines are obliged to compensate for their emissions increases after 2020 by purchasing credits from projects that reduce emissions outside the aviation sector (ICAO, 2016b). Even if CORSIA were to function perfectly, it would still only partially compensate for the anticipated increase in greenhouse gas emissions since non-CO₂ effects are not included. Furthermore, the additionality of carbon offsetting projects is often challenged (Anderson & Bernauer, 2016; Becken & Mackey, 2017). Additionality means that the emissions reduction would not have occurred if the investment from

the carbon offsetting project had not been made (Hyams & Fawcett, 2013). A study showed that 87 % of 5,500 evaluated projects were not additional and did not deliver the emissions reduction they were certified for (Martin Cames et al., 2016).

For further reading about existing and potential instruments within the aviation sector, we refer the reader to our previous research (Larsson, Elofsson, Sterner, & Åkerman, 2019; Åkerman, Larsson, & Elofsson, 2016), the environmental objectives inquiry (Miljömålsberedningen, 2016, pp. 395-402) and a report from the Stockholm Environmental Institute (Axelsson, Bell, & West, 2018).

The monitoring system for emissions from aviation currently in place is the result of international negotiations. Countries can either make calculations based on how much fuel is taken on (bunker fuels) or use model calculations with varying levels of detail (IPCC, 2006). Sweden calculates its CO₂ emissions using the Tier 2 method which is based on the quantity of fuel sold and includes some modelling. It is these figures (broken down into domestic and international aviation) that are reported to the UN (Naturvårdsverket, 2018b). Emissions from domestic aviation are included in Sweden's reporting of national greenhouse gas emissions to the UN Framework Convention on Climate Change (UNFCCC), but emissions from international aviation (and shipping) are not allocated to any country. Under the Kyoto Protocol, emissions from international aviation (and shipping) are instead reported separately to the UNFCCC (IPCC, 2006; Wood, Bows, & Anderson, 2010). For domestic air travel, this monitoring system results in a relatively comprehensive and reasonable picture, but for international travel the bunker fuels metric is problematic in a number of different ways:

- The metric includes only emissions from Sweden to the first transit airport. This means that the climate impact of many long-distance trips by air are not included in Sweden's statistics. Thus, this system does not give a good picture of the emissions from air travel by a country's own inhabitants.
- This form of allocation means that countries with large transit airports (e.g. the Netherlands) are allocated high emissions while other countries get low emissions (e.g. Sweden). Since transit airports are important sources of income for countries, this metric does not function as an incentive to encourage these countries to reduce emissions.
- When a country gets more direct flights to destinations in other countries, the bunker fuels metric normally indicates increasing emissions even though absolute global emissions in practice decrease because there will be fewer detours and fewer take-offs due to stopovers.
- The system covers only CO₂ emissions and not the other climate impacts of aviation (see Section 2).

These problems mean that the bunker fuels metric as the sole metric reported to the UN does not provide a good enough picture of the scale of the climate impact of aviation. By comparison, Luxembourg reports no emissions from international

aviation, while the Netherlands reports 65 % higher aviation emissions per person than Sweden, and this in spite of similar GDP levels for these three countries (UNFCCC, 2018).

The purpose of this report is to elaborate on the supplementary indicator that was developed in 2016 and which reflects the total greenhouse gas emissions¹ from the Swedish population's air travel (Kamb, Larsson, Nässén, & Åkerman, 2016; Larsson et al., 2018), and to apply this to the period 1990–2017. A Swedish version of this report was published in 2018 (Kamb, Larsson, & Åkerman, 2018). This work is important in that it contributes to a better understanding of the total impact on the climate of air travel and how it evolves over time. This type of monitoring is also relevant as a complement to the bunker fuels metric for monitoring the effects of various instruments of control. Monitoring systems that are sensitive to the effects of instruments of control are essential for being able to follow progress over time (Gössling, Cohen, & Hares, 2016; Kander, Jiborn, Moran, & Wiedmann, 2015). The bunker fuels metric for domestic flights is well suited for monitoring the effects of an increase in the use of biofuels. The supplementary indicator for the population's total aviation emissions is well suited for monitoring policy instruments such as promoting the choice of closer destinations and choosing a mode of transport that causes less emissions than air travel².

The work behind this report has been financed by the Swedish Environmental Protection Agency. A number of organizations have contributed to this work in various ways. Swedavia has generously shared data from its extensive customer survey, which Avinor in Norway and Copenhagen airports in Denmark have also done. We have also received constructive comments from many research colleagues, including Jonas Åkerman, Christian Azar, Daniel Johansson, Anna Elofsson, Jonas Nässén and Björn von Sydow.

2 Non-CO₂ effects

When it comes to the climate impact of aviation, there are several effects in addition to CO₂ emissions. These effects mainly occur during flights at altitudes above roughly 8000 meters (Köhler et al., 2008; Rädcl & Shine, 2008). These effects include emissions of nitrogen oxides and the contrails forms when warm aircraft emissions high in water content encounter the surrounding cold air and form ice crystals (Azar & Johansson, 2012; Boucher et al., 2013; ICAO, 2013; IPCC, 2014; Lee et al., 2010). Under certain conditions, these contrails persist and remain in the atmosphere for several hours, in other cases they disappear within a few minutes. In addition, aviation emissions can increase in the formation of high cirrus clouds, in part due to persisting vapor contrails developing into cirrus clouds that have an effect for a day or so (Lee et al., 2010). These climatic effects are short-lived compared with CO₂ which affects the climate for thousands of years (Joos et al., 2013), but on the other hand, they are thousands of times more powerful during the time that they last. Uncertainty in

estimating the climate impact of contrails has been reduced over time, while uncertainty in estimating the climate impact of aviation-induced cirrus clouds continues to be great (Kärcher, 2018).

Furthermore, emissions of aerosols, primarily soot and sulphate, have climate impacts. The effect of aerosols is very uncertain and different studies have generated different results depending on their model's assumptions ranging from for example a cooling effect of 46 mW/m^2 (Chen & Gettelman, 2016; Gettelman & Chen, 2013) to a warming effect of 90 mW/m^2 (Zhou & Penner, 2014). The uncertainty in these models is still great because the results are highly dependent on the assumptions about the role of aerosols in cloud processes (Chen & Gettelman, 2016). There is also a great lack of observations of the effects on cloud formation of emissions of aerosols, making it challenging to reduce this scientific uncertainty (Kärcher, 2018).

Thus, there is uncertainty about how great these various non- CO_2 effects are and there is also great variation in the scientific understanding of the various mechanisms involved. We do not offer any evaluation of our own of current status of the science in this area but rely on the overall assessment made by the UN Panel on Climate Change (IPCC) (Boucher et al., 2013). The IPCC concludes that not insignificant non- CO_2 effects exist and point to the fact that persistent contrails during 2011 contributed $+0.01 \text{ W/m}^2$ (medium confidence) to warming through radiative forcing³.

Furthermore, the combination of contrails and clouds from contrails is deemed to contribute an effective radiative forcing⁴ of $+0.05 \text{ W/m}^2$ (low confidence). (Boucher et al., 2013; Myhre et al., 2013)

Even if there is a great deal of uncertainty concerning non- CO_2 effects, there is no doubt that such effects exist and that they are not insignificant. According to the IPCC report (Boucher et al., 2013), they are probably positive, but there are more recent studies pointing to the fact that they can be positive and greater than stated by the IPCC, while there are a few recent studies pointing to the fact that they can be negative, i.e. have a cooling effect. The current status of the science is very unclear, but we assess that the most reasonable position to take is to be in line with the IPCC report (AR5) and include these effects. To do this, an appropriate measure needs to be selected that takes account of the different time horizons of CO_2 and non- CO_2 emissions. The IPCC provides no recommendation here for aviation emissions. Within the UN system, generally GWP100⁵ is used for the gases included in the negotiations⁶ (UNFCCC, 2014). We use the most well-established scientific estimate which is, measured in GWP100, that the overall climate impact is approximately 1.9 times higher than the impact of CO_2 emissions alone (including the effects of contrails and cirrus clouds for example) (Lee et al., 2010). This emission weighing factor also lies close what Azar and Johansson (2012) have assessed and it is in line with the recommendation from an assessment of a large number of different scientific analyses (Jungbluth, 2013). This estimate is also consistent with what both the Swedish Environmental Protection Agency (2018a) and the Swedish Transport Agency state

(2018a), as well as the UK government's guidelines for corporate reporting of greenhouse gas emissions (Hill, Watson, & James, 2016).

How great the non-CO₂ effect is for a specific flight varies greatly depending on e.g. weather conditions and may be both higher or lower than the emission weighing factor of 1.9. The factor of 1.9 is probably an overestimation for shorter trips (Fichter, Marquart, Sausen, & Lee, 2005; Trafikanalys, 2016), but also an underestimation for longer trips. That 1.9 is an overestimation for domestic air travel is partly due to the fact that the aircrafts do not reach, or spend only a very small percentage of the flight time, at a sufficiently high altitude, and in part due to the fact that the domestic air travel many turboprop aircraft are used, that do not get up to a sufficient altitude for these effects to arise. Österström (2016) estimated that an emission weighing factor for domestic aviation that is almost half as high as the global average is reasonable. Österström (2016) assumes an average emission weighing factor of 1.7 and a factor of 1.3 for domestic aviation. These figures were used in the inquiry into a Swedish airport tax (SOU 2016:83). In this report, 1.9 is used for international flights, which is the most well-established scientific estimate (Lee et al 2010), while 1.4 is used for domestic flights.

Non-CO₂ effects can be reduced by changing the flight path, but this is a complex issue as it can simultaneously lead to increases in CO₂ emissions. The issue of strategies to reduce non-CO₂ effects lies outside the terms of reference of this report.

3 Method and data for Sweden 1990–2017

In developing an alternative to the bunker fuels' statistic, a number of methodological criteria need to be taken into account. Based on an analysis of the different allocation alternatives, we have chosen to use the population perspective. Furthermore, we have excluded upstream emissions, such as emissions from the production of fuel. For more details on the overall choice of method, we refer the reader to our journal article (Larsson et al., 2018).

Our method is described below, where emissions of greenhouse gases are calculated by multiplying the number of international trips made by a country's inhabitants [passengers] by the average distance per trip [km] and the average emissions per passenger km [kg CO₂eq/pkm] for each year. For more details about the calculations, download the Excel file *Beräkningar - Klimatpåverkan från svenska befolkningens flygresor 1990 – 2017* (Calculations – Climate impact from air travel by Sweden's population)⁷.

3.1 Number of trips

In order to calculate the number of trips made by a nation's population, you need passenger statistics from all airports in the country. However, this set of statistics covers both the country's inhabitants as well as foreign citizens, so in order to only count the trips made by the country's inhabitant, these passenger statistics must be

adjusted. In addition, if it is likely that the country's inhabitants use airports in other countries as their departure airport for an international flight, the same statistics are needed from these airports.

In Sweden, there are statistics covering the total numbers of arriving and departing international and domestic passengers to and from Swedish airports (Trafikanalys, 2018; Transportstyrelsen, 2016). The share of passengers who are resident in Sweden is based on Swedavia's passenger survey⁸ (Swedavia, 2016, 2018b) and responses are scaled to represent the number of departing passengers.

Many Swedish inhabitants live relatively close to Kastrup Airport in Denmark or Gardemoen Airport in Norway and use these airports as their principal international airport⁹. In order to include these journeys¹⁰ data from Kastrup Airport (Copenhagen airport, 2018) and Gardemoen airport (Avinor, 2018) were used.

3.2 Average distance

To calculate the average distance of an international trip, you need to know where the trip begins and its final destination, not just the first destination abroad. Consider an international trip with multiple stopovers, e.g. Kiruna – Stockholm – London – New York – Los Angeles. In this report, the trip from Stockholm to Los Angeles is the relevant one and the basis for calculating the average distance.

Calculations of average distance are based primarily on data from Swedavia. Data from Swedavia is available for 2010–2017 and is based in part on total passenger statistics from Swedavia's airports (Swedavia, 2018c) and part on the passenger surveys based on 140,000 interviews conducted annually at Swedavia's airports (Swedavia, 2018a). In order to capture trends since 1990, we also used passenger survey data from the Resurs AB/Swedish Agency for Economic and Regional Growth for 1990 and 1991 (Resurs AB, 2014). Since comparisons between data from Swedavia and Resurs AB indicate an overestimation of the average distance in the data from Resurs AB, a downward adjustment of the average distance for 1990 and 1991 was made by 3.7 %.

Each data set contains the departure airport for international travel and the final destination. The Google Maps API, via the Google Sheets Add-On *Geocode*¹¹, was used to find the coordinates of each airport and final destination. The distance between each pair was then calculated via the great-circle distance¹², which is the shortest distance between the two points¹³. Additional distance due to stopovers is not taken into account, which results in a small underestimation.

Based on the Swedish Agency for Economic and Regional Growth/Resurs AB's data, the average distance was then calculated based on the number of passengers to each destination. The average distance based on Swedavia's data was calculated in two stages: first for Swedish residents' direct trips and then for transit trips:

Direct trips – the average distance for direct trips from the Swedish airports was calculated based on passenger statistics weighted by the proportion of Swedish residents. The distance was also adjusted to deduct transferring passengers. The passenger statistics include all passengers travelling via Swedavia's airports (total statistics) and the percentage who are Swedish residents, and in addition the percentage transferring have been deducted from the passenger survey figures. In this manner, travel patterns that are unique to Swedish resident passengers are estimated.

Transit trips – the average distance for Swedish resident passengers who have stopovers has been assessed solely with data from Swedavia's passenger survey, where the departure airport and the actual final destination have been collected.

After calculating an average distance for direct trips, and one for transit trips, a weighted average distance can be calculated for all international trips based on the percentage who have at least one stopover on the way. This figure is based on Swedavia's passenger survey. For the years when this data was not collected, a linear adjustment has been made.

3.3 Emissions per passenger km

The calculation of emissions per passenger km for international trips is based on a global average. Since we have found that the average emissions from aircraft that depart from Swedish airports are lower, we have chosen to adjust the global figures by 6 % for the whole period (based on the average difference between global emissions and Swedish international flights for the period 1998–2015).

In order to calculate the average global emissions per passenger km, you need statistics on global fuel consumption and passenger km travelled, as well as statistics on freight tonnages to allocate the emissions between freight and passengers. The global average is based on data for global fuel consumption within aviation from the International Energy Agency (IEA, 2018). Data for passenger km and freight was retrieved from the ICAO and IATA. To adjust the figures down, we used the bunker fuels statistics for international aviation that the Swedish Environmental Protection Agency (2018d) publishes and statistics on passenger km from the Swedish Transport Agency (2018b). Appendix A describes the calculation of emissions per passenger km in detail.

3.4 Emissions from domestic trips

The stages described above are used to calculate emissions from the Swedish population's international flights. For domestic trips, the starting point is the bunker fuel metric which is reported to the UNFCCC (Naturvårdsverket, 2018c). To calculate the emissions from foreign residents, Swedavia's passenger survey is used again (Swedavia, 2016, 2018b). In order to also include here the climate impacts due to emissions at high altitude domestic emissions are adjusted with an emission weighing factor of 1.4 (read more in Section 2).

4 Results: the Swedish population's flights 1990–2017

The most important results are presented below. The changes in the data and method have been applied retrospectively in the time series which has resulted in slightly lower figures compared to the report published in 2016 – both the average distance and emissions per passenger km are now slightly lower. For more detailed results, download the Excel file *Beräkningar - Klimatpåverkan från svenska befolkningens flygresor 1990 – 2017* (Calculations – Climate impact from air travel by Sweden's population)¹⁴.

4.1 Number of trips

To begin with, the number of flights taken for both Swedish and foreign residents is described here. From 1990 to 2017, the number of arriving and departing foreign passengers has increased from 9 million to 31 million (Trafikanalys, 2018; Transportstyrelsen, 2016), which is an increase of 240 %. On the other hand, for domestic flights the number of departing and arriving passengers has remained more or less unchanged during the period and has been stable at around 7 million one-way trips (Trafikanalys, 2018; Transportstyrelsen, 2016),

What is relevant from the population perspective however is the number of flights taken by the Swedish population. During this period, the percentage of passengers who are Swedish residence has decreased. For example at Stockholm Arlanda Airport (which accounts for two thirds of international passengers), the proportion of passengers who are Swedish residents has fallen from an average of 66 % in the years 2001–2005 to an average of 54 % in the years 2013–2017 (Swedavia, 2018b). Figure 1 shows the number of international and domestic return flights by Swedish residents per year. When foreign residents have been excluded, the increase for Swedish residents' international trips shows an increase of 160 % between the years 1990–2017, which represents an average annual growth of 3.5 %. Of the 10.2 million international return trips completed by Swedish residents during 2017, 1.4 million had Kastrup in Denmark as their departure airport for the international flight and 0.2 million were from Gardemoen in Norway.

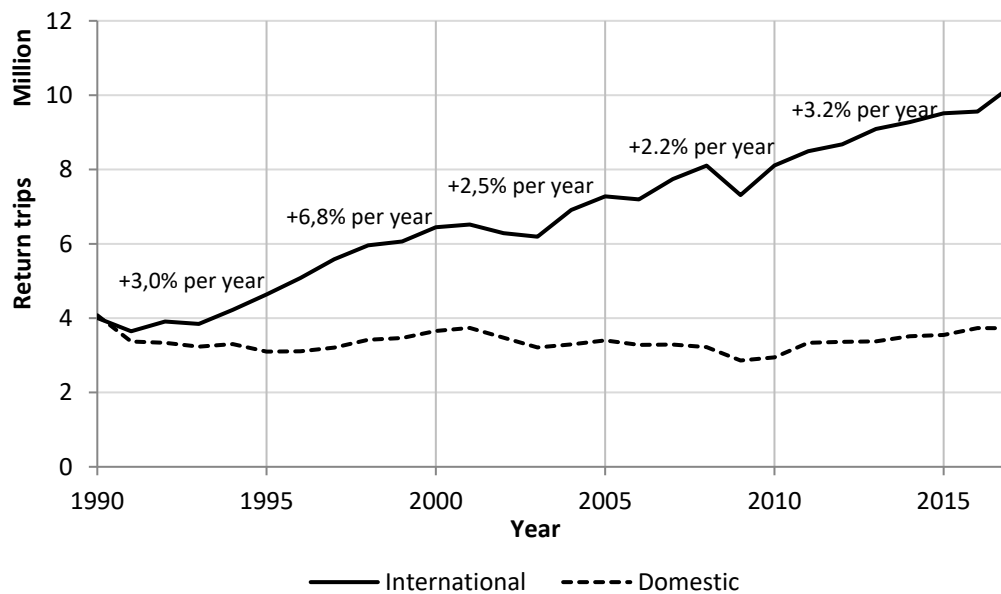


Figure 1 Total number of international and domestic return flights by Swedish residents. The percentages illustrate the average annual increase in each five-year period for international trips.

Three clear dips can be seen in Figure 1. The first was in the early 1990s, when there was a recession in Sweden which may very well explain the stagnation in the number of flights. The other clearer dip was in the early 2000s, which could be linked to the terrorist attacks of 11 September 2001 and the outbreak of the SARS epidemic. The effect on global air traffic of these attacks is well documented (Ito & Lee, 2005), and the same applies to the SARS epidemic (Lee et al., 2009). The third dip was in 2009, which was during the global financial crisis, which also impacted Sweden. Furthermore, a steep increase is seen in the period 1993–2000, very likely to be connected to the deregulation of the aviation industry and the creation of a market within the EU (Scharpenseel, 2001).

Since the population of Sweden has increased, the increase per person is slightly lower. Calculated per capita, Figure 2 below shows that Swedish residents made approximately 0.5 international return trips per person in 1990, which increased to 1.0 trips per person by 2017. This is an increase of 120 % and an annual increase of 2.9 % per person per year. If the same method is applied to domestic flights, where the number of trips has been more or less stable over this 27-year period, Swedish residents made 0.4 domestic return trips per person in 2017. Thus 1.4 return trips, domestic and international together, were made per capita. In a similar study from Denmark, residents of Denmark made slightly more return trips per capita: about 1.8 domestic and international trips (Christensen, 2016).

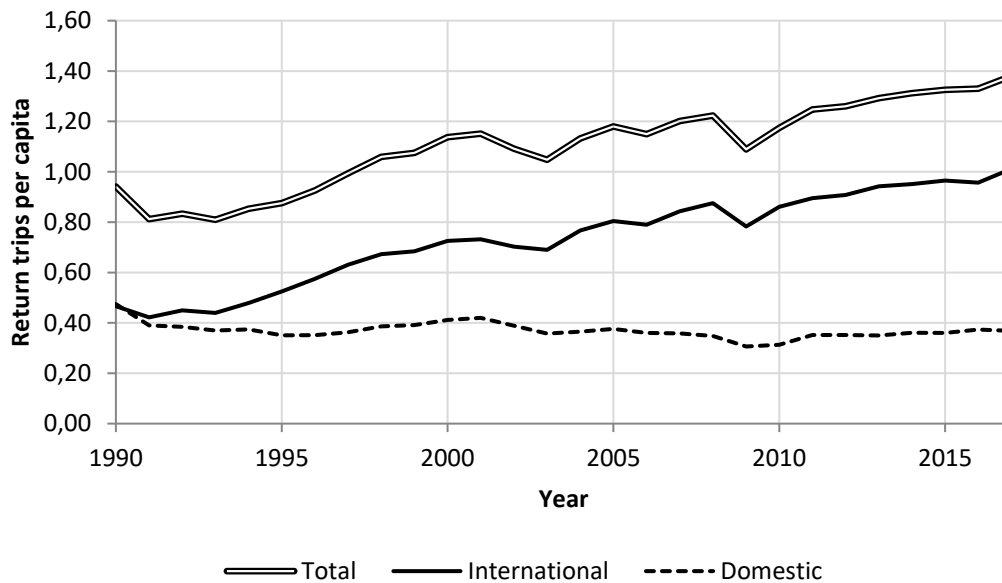


Figure 2 Number of return trips per capita. International, domestic and total.

4.2 Average distance

The average distance for international trips has not increased significantly between 1990 and 2017 (see Figure 3). It has remained at between 2,600 and 2,900 km during the period, with a peak in 2010, when the proportion who travelled to Asia was higher than in the subsequent years. By way of comparison, the distance for a one-way flight between Stockholm and Madrid is approximately 2,600 km, while a one-way flight from Stockholm to New York is approximately 6,300 km.

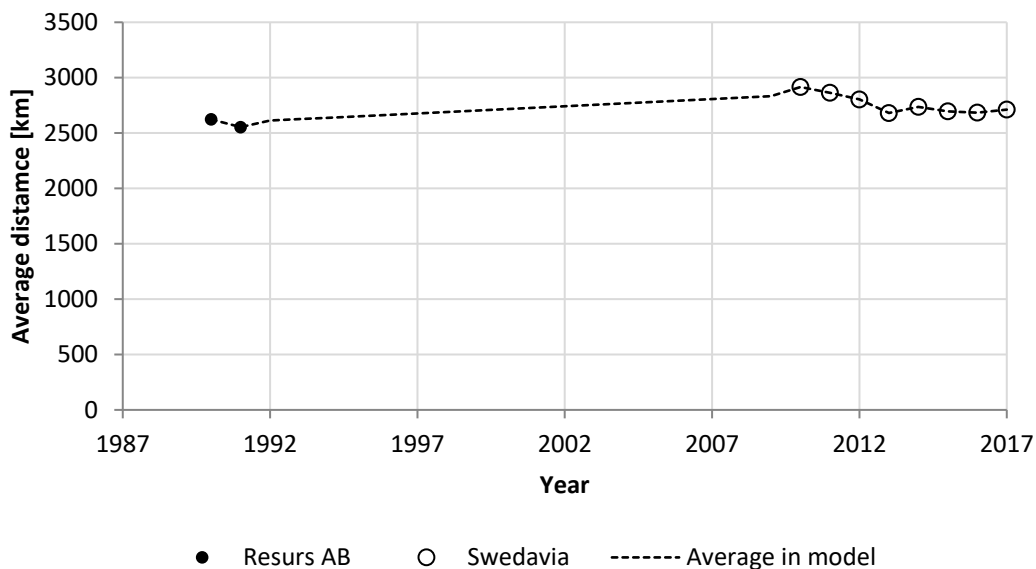


Figure 3 Average distance of the Swedish population's international air travel.

Figure 3 shows the average distance calculated using data from the Resurs AB (1990–1991), Swedavia (2010–2017), and the linear adjustment between them. In 2017, the average distance for direct trips is estimated at 2,100 km and for transit trips at 4,800

km. Of all the trips made by residents of Sweden, 77 % were direct trips and 23 % transit trips, which gives the weighted average distance as 2,700 km in 2017.

4.3 Number of passenger km

The number of passenger km can be calculated based on the number of trips and average distance¹⁵. Figure 4 shows the number of passenger km from Swedish residents' domestic and international travel and the total for both. From 1990 to 2017, the number of passenger km for the Swedish population increased from 25 to 59 billion passenger km, an increase of 142 % and an average increase of 3.3 % per year.

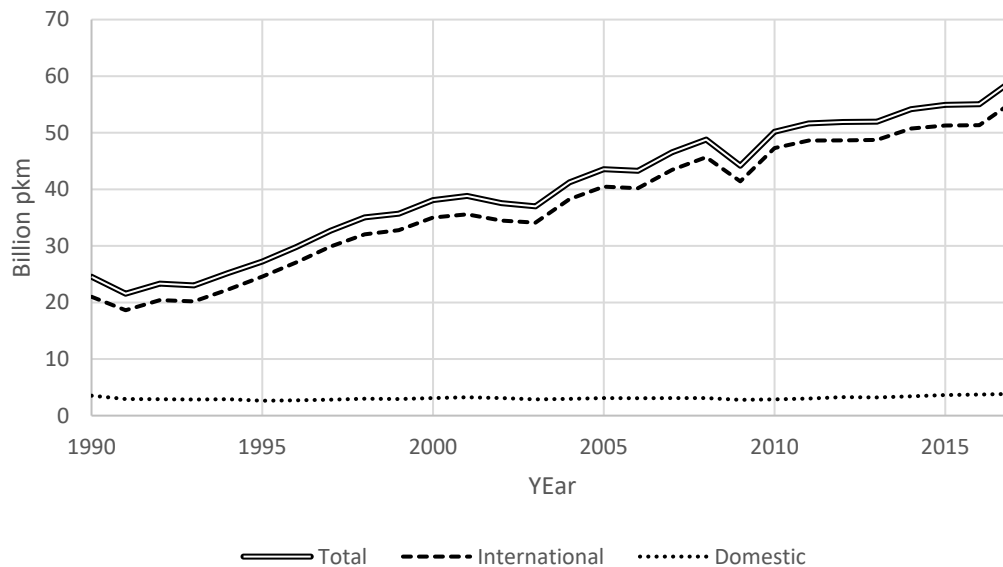


Figure 4 Number of passenger km for the Swedish population's international and domestic trips and in total.

4.4 Emissions per passenger km

Carbon dioxide emissions from international air travel have fallen from 150 grams per passenger km in 1990 to 90 grams in 2017, which is a decrease of 40 % and an annual reduction of 1.9 % (see Figure 5)¹⁶. According to our calculations, emissions from domestic aviation were 120 g CO₂ per passenger km 2017. These reductions are due to technological development, that the cabin factor has been improved, and that there have been changes in air traffic control.

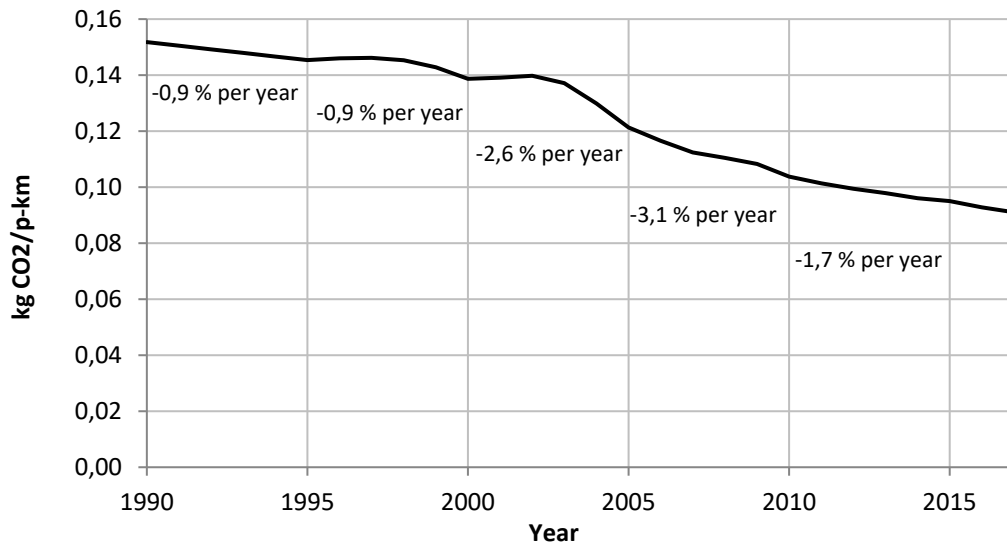


Figure 5 Emissions in kg of CO₂ per passenger km. The percentages illustrate the average annual change in each five-year period.

With an emission weighing factor of 1.9 to include non-CO₂ effects, emissions rise to 170 g CO₂ equivalents per passenger km for international flights in 2017. For domestic flights, with an emission weighing factor of 1.4, the emissions are thus 170 g CO₂ equivalents per passenger km. The figure of 170 g can be compared with the emissions from the average car in the Swedish vehicle fleet which is approximately 154 g CO₂ per km (Trafikverket, 2018), which corresponds to just over 50 grams per person since on average there are three people in a motor vehicle on trips of over 300 km (Larsson & Kamb, 2018, page 6). Figure 6 is produced to illustrate what 170 g CO₂ equivalents per passenger km means.

True emissions per passenger km obviously vary depending on the distance and aircraft type, etc., but using the same emissions factor for all travel gives a fairly good estimate for most flights. Although long distance trips typically have lower CO₂ emissions per passenger km, a larger share of the trip is at a higher altitude and thus causes more non-CO₂ emissions per passenger km. The opposite is true for short distance trips where CO₂ emissions per passenger km are typically higher due to the energy-demanding ascent but where only a small, or non-existent, share of the flight is at altitudes where the non-CO₂ emissions principally arise. As such, these two effects cancel each other out and the resulting CO₂eq per passenger km are similar, regardless of the distance.

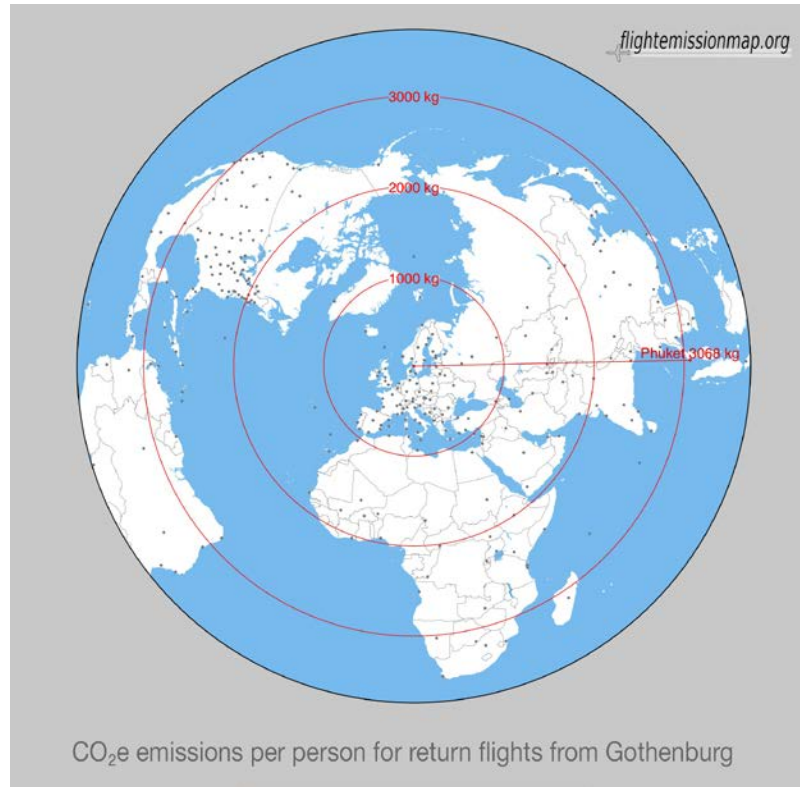


Figure 6 Emissions including non- CO₂ effects for return trips between Gothenburg and different destinations. The figure is based on 170 g CO₂ equivalents per passenger km.

To validate our results, which for CO₂ emissions were 90 g per passenger km in 2017, we have compared them with other sources (see Table 1). Some of these sources have emissions figures for years other than 2017, so in order to obtain comparable figures we have adjusted these figures down by an efficiency factor of -1.9 % per year up to 2017 (based on the results of this study). Furthermore, one source includes upstream emissions, i.e. emissions from the production of the fuel, which have also been adjusted downward. When the figures have been adjusted, they are relatively well in line with each other. ICCT's figures are somewhat lower, but they include only transatlantic trips which are longer than the average. The ICAO offers no global means, but instead calculates emissions for each specific trip and even allocates different proportions of the emissions to economy and business class. This results in a relatively large range depending on the length of the journey, destination and travel class. The ICAO's figures here are based on a selection of seven longer and shorter trips from Sweden (Larsson & Kamb, 2018).

Table 1 Comparison of different emissions factors for air travel, 2017.

| Source | g CO ₂ per passenger km | g CO ₂ eq per passenger km (including non-CO ₂ emissions) |
|---|---------------------------------------|---|
| International emissions (Kamb & Larsson 2019) | 90 | 170 |
| Domestic emissions (Kamb & Larsson 2019) | 120 | 170 |
| ICCT Transatlantic ranking (Graver & Rutherford, 2018) | 74 | 140 |
| ICAO Emissions Calculator – International Economy ^{d)} (ICAO, 2018b) | 43-110 | 82-210 |
| ICAO Emissions Calculator - International Business ^{d)} (ICAO, 2018b) | 86-110 | 160-210 |
| SAS international (SAS, 2019) | 90 | 170 |
| Intra-EU aviation (European Environment Agency, 2012) | 98 | 190 |
| Danish study ^{f)} (Christensen, 2016) | 85 | 160 |
| Norwegian study ^{g)} (Aamaas & Peters, 2017) | 93 | 180 |

a) Only emissions from combustion. Sources with a different base year than 2017 have been adjusted with an efficiency factor of -1.9 % per year until 2017.

b) Multiplied by 1,9 for international and 1,4 for domestic flights (see section 2).

c) Only transatlantic flights. Longer flights on average result in lower CO₂ emissions than shorter flights. The non-CO₂ emissions of +90 % is however most likely an underestimate in this case.

d) ICAO calculates the emissions for each specific flight and allocates the emissions between business and economy. www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx The numbers presented here is based on a selection of five long and short distance flights from Sweden (Larsson & Kamb, 2018).

e) The source stated emissions of 110 g CO₂ per passenger km for 2011.

f) The source stated emissions of 97 g CO₂ per passenger km for 2010 (own calculation based on Christensen (2016), for trips of 1500–4000 km).

g) The source stated emissions of 140 g CO₂ per passenger km for 2009, which also includes upstream emissions. The original data was adjusted with -20 % to discount the upstream emissions (see e.g. Moretti, Moro, Edwards, Rocco, and Colombo (2017) or Edwards, Larivé, Rickeard, and Weindorf (2014)). For trips longer than 800km.

4.5 Emissions from the Swedish population's air travel

The results show that in 2017, greenhouse gas emissions from the Swedish population's air travel, both domestic and international, was 10 million tonnes CO₂equivalents (Mt CO₂eq)¹⁷. In comparing the size of these emissions to other emissions, it should be noted that they roughly correspond to the emissions from the Swedish population's total passenger vehicle trips.¹⁸ Of these emissions, business travel accounts for approximately 1/5 and private travel for approximately 4/5¹⁹.

These emissions can also be compared with a global average per person. Emissions amounted to approximately 1.1 tonnes CO₂ equivalents per Swedish resident in 2017. The corresponding global average is about 0.2 tonnes per capita²⁰. Consequently, emissions from air travel for the average Swedish resident are five times higher than the global average.

Our results (based on country of residence) of 10 million tonnes CO₂ equivalents can be compared with the bunker fuels metric. This can be compared with the bunker fuels metric which showed a total of 3.1 Mt CO₂, of which 2.6 Mt comes from international and 0.5 Mt from domestic trips (Naturvårdsverket, 2018c, 2018d). The difference is largely explained by the fact that our indicator covers emissions all the way to the final destination, i.e. even after stopovers, and the non-CO₂ effects. The trend over time and the division between domestic and international travel can be seen in Figure 7.

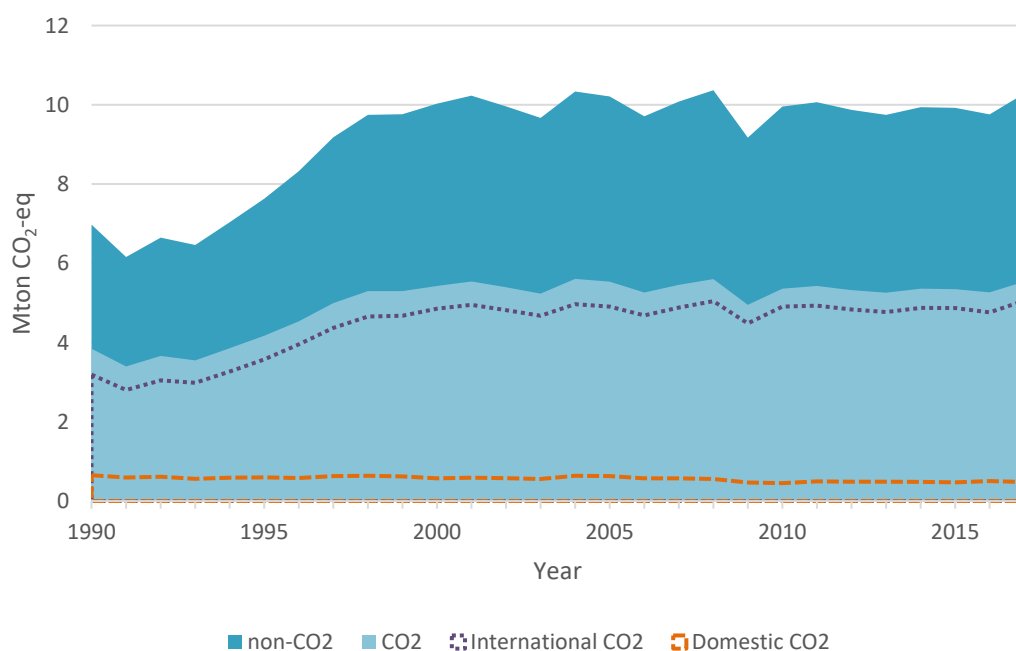


Figure 7 Emissions from the Swedish population's air travel 1990-2017. The light blue bar shows the total emissions of CO₂ including both domestic and international travel, and the dark blue bar shows the non-CO₂

effects. The dashed orange line shows the CO₂ emissions from domestic trips and the dotted purple line shows the CO₂ emissions from international trips.

Emissions from the Swedish population's air travel have increased by 47 % since 1990, which corresponds to an average annual increase of 1.5 %. The differences between domestic and international travel are very great. Emissions from domestic flights have fallen by 26 % whereas emissions from international flights have increased by 58 % since 1990. For 2017, domestic trips account for 7 % of emissions while international trips account for 93 %.

The big increase in emissions took place after the recession in the early 1990s. Between 1993 and 1998, the number of international trips increased very strongly (see Figure 1), which was probably associated with reduced prices following deregulation of the aviation industry and the creation of a European aviation market (Scharpenseel, 2001).

The above figure showing stable emissions since 2000 is not consistent with the picture of increased emissions from aviation. However, the total emissions from international aviation increases if you include the increasing number of *foreign* residents who fly to Sweden²¹. But looking at the *Swedish* population's emissions from aviation, they have not increased. The reason for this is that the emissions reduction per passenger km has been offset by the increase in the number of trips. Figure 8 shows the trend in the number of passenger km, emissions from the Swedish population's international air travel and emissions per passenger km, with the base year as 1990.

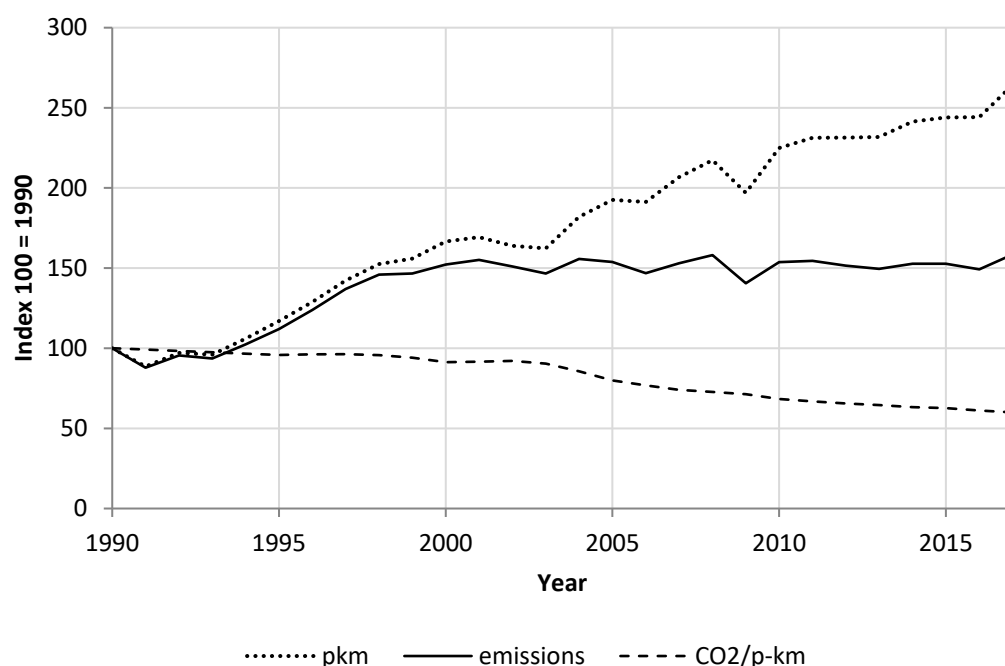


Figure 8 Figure 1 Trend in the number of passenger km, emissions from the Swedish population's international air travel and emissions per passenger km (based on Swedish international traffic). Base year 1990 = 100.

Until the millennium shift, total emissions follow the increase in the number of passenger km relatively well. After this, emissions do not increase because the increase in volume is compensated for by the substantial reductions in emissions per passenger km. About half of this reduction in emissions per passenger km is due to the increase in the cabin factor (Kamb et al., 2016). Because the cabin factor has a theoretical limit of 100 %, and a practical limit which is lower, other powerful measures are needed in order to maintain the same rate of reduction in emissions per passenger km. If this does not occur, and if flying continues to increase at the same rate, emissions from Swedish residents' air travel will increase in the future.

In conclusion, the total emissions from the Swedish population's air travel have increased by 47 % since 1990, but since 2000 they have levelled out and remained at roughly the same level. In order to achieve the climate goals, reductions in emissions from virtually all sectors in all countries are needed. To have a good chance of limiting global warming to 2° C, global CO₂ emissions need to rapidly trend downwards to eventually end entirely (net zero) (IPCC, 2018; UNEP, 2018).

Appendix: Emissions per passenger km

Comparison between the global average, international flights from Sweden and domestic flights

As mentioned in the method description in Section 3.3, a global average is used for emissions per passenger km. This data was retrieved from the International Energy Agency (IEA, 2018)²². The ICAO publishes statistics on global passenger km and tonne km for freight and mail that is carried by regular services, as well as estimates of international non-scheduled traffic²³ (ICAO, 2008, 2015, 2018a). IATA also publishes data on passenger km and tonne km for goods, which was used for 1990 and 1995 (IATA, 2015b).

The global average is adjusted downward to take account of the fact that emissions from Swedish international flights is less than the global average. This is based on the bunker fuels statistics for international aviation departing from Swedish airports, obtained from the Swedish Environmental Protection Agency (2018d). The downward adjustment is 6 % for all years and this figure is based on the average difference for the period 1998–2015 (which are the years when data was available for both Swedish international flights and the global average). In Figure 9, CO₂ emissions per passenger km are compared with the global average (without downward adjustment) and Swedish international flights. For comparison, domestic traffic is also presented.

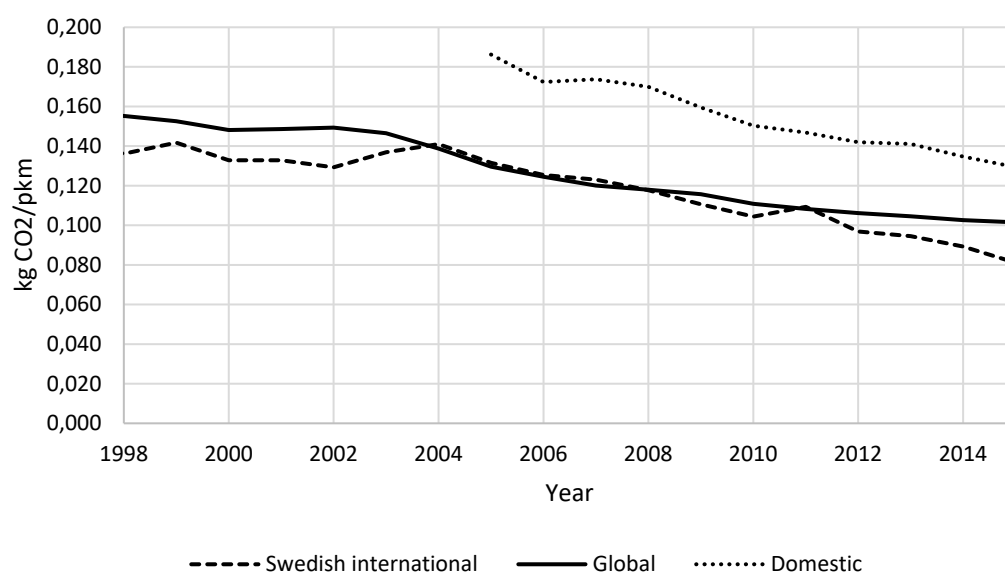


Figure 9 Average emissions per passenger km 1990–2017 measured as kg of CO₂

The series for Swedish international flights fluctuates. This results in this data not being suitable to use directly for calculations of the Swedish population's aviation emissions, since it would result in fluctuations that do not reflect the actual emissions

from Swedish residents' air travel around the world. However, the general downward adjustment of 6 % may be justified by the fact that the Swedish population's international air travel is largely in aircraft that depart from Swedish airports. For more information see the calculation file, sheet 1.1 and 1.2. Sheet 4.2 shows calculations based on the Swedish Transport Agency's emissions data. However, these were not used since they fluctuate more than the bunker fuels statistic, and because they are inexplicably much lower than both the global average and the bunker fuels statistic.

Carbon dioxide emissions per passenger km for domestic air traffic follows roughly the same development curve but are considerably higher, most likely due to the high emissions at take-off having a greater impact on short trips and a lower cabin factor.

The exclusion of fuel used for freight

Emissions from aviation must be distributed between freight and passengers. Since weight is a key factor for emissions generation in aviation, it has been selected as the basis for the allocation of emissions in these calculations. In order to be able to compare passenger volumes with freight volumes, passengers are assumed to have an average weight (including luggage) of 100 kg (IATA, 2015b; ICAO, 2014).

Passengers also requires seats, toilets, etc., that are not needed for the carriage of goods and passengers should thus also be responsible for this weight. We assume an extra 60 kg in accordance with Wit et al. (2002), which also corresponds well to ICAO (2014)²⁴, resulting in a total weight of 160 kg per passenger. Data over time for the number of tonne km within international aviation from Sweden is unfortunately lacking, but an estimate has been made for 2017 based on data from Transportstyrelsen (2018c). Passengers are then assumed to account for the same proportion backwards in time according to the following equation.

$$\gamma = \frac{V_{pkm} \cdot v_{pass}}{V_{pkm} \cdot v_{pass} + V_{tkm}}$$

Where:

$$\begin{aligned} V_{pkm} &= (\text{travel volumes}) [pkm] \\ v_{pass} &= 0.160 (\text{weight per passenger}), \left[\frac{\text{tonnes}}{\text{passanger}} \right] \\ V_{tkm} &= (\text{freight and mail volumes}) [tkm] \end{aligned}$$

Emissions per passenger km are then calculated using the following equation:

$$u_{pkm} = \frac{U_{TtW} \cdot \beta \cdot \eta_{int} \cdot \gamma}{V_{pkm}}, \left[\frac{kg CO_2eq}{pkm} \right]$$

Where:

$$\begin{aligned} U_{TtW} &= (\text{calculated emissions, Tank to Wheel}), [kg CO_2] \\ \beta &= (\text{adjustment to match Swedish statistics}) [\%] \\ \eta_{int} &= 1.9 (\text{high altitude emission weighing factor for international trips}), \left[\frac{kg CO_2eq}{kg CO_2} \right] \\ \gamma &= (\text{passangers' share}) [\%] \end{aligned}$$

The exclusion of fuel for military use

Since the data from the IEA also includes fuel consumption from military aviation, the military share has been deducted with estimates compiled by the IPCC (1999) and Lee et al. (2009). Emissions from fuel consumption are then allocated between passengers and goods in the same way as described above, based on statistics from the ICAO (2008, 2018a) and IATA (2015b). This resulted in the equation below.

$$u_{pkm} = \frac{F(1 - \alpha) \cdot u_{TtW} \cdot \eta_{int} \cdot \gamma}{V_{pkm}} \cdot \left[\frac{kg \ CO_2e}{pkm} \right]$$

Where:

F = (global fuel consumption)[kg]

α = (the military's share of fuel consumption) [%]

$u_{TtW} = 3.16$ (combustion emissions, Tank to Wheel), $\left[\frac{kg \ CO_2}{kg \ fuel} \right]$

$\eta_{int} = 1.9$ (high altitude emission weighing factor for international trips), $\left[\frac{kg \ CO_2eq}{kg \ CO_2} \right]$

γ = (passangers's share) [%]

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Final remarks

¹ This includes what are termed the non-CO₂ effects. In policy debates, it is important to know that carbon dioxide has an effect for a very long time while non-CO₂ effects have an effect for a short period of time. For instruments designed to reduce emissions by dampening volumes, this is not problematic since this will reduce both CO₂ emissions and the high-altitude effects. Instruments designed to reduce non-CO₂ effects, but at the expense of increased CO₂ emissions (such as changed routes), entail striking a more difficult balance that is not fully captured by the Global Warming Potential (GWP) measure.

² The bunker fuels metric also provides some picture of this, but it is not as comprehensive since it does not include Swedes' air travel departing from Denmark for example, and because it includes foreign nationals' air travel from Sweden.

³ Radiative forcing (RF) is defined by the IPCC as the change in the net, downward minus upward, radiative flux (expressed in W/m²) at the tropopause or top of atmosphere due to a change in a driver of climate change, such as a change in the concentration of carbon dioxide (CO₂) or the output of the Sun. The traditional radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. (Myhre et al., 2013).

⁴ Effective radiative forcing (ERF) also takes into account the rapid adjustments in the troposphere and is generally a better measurement of the potential climate impact than radiative forcing (Myhre et al., 2013).

⁵ Global Warming Potential with 100-year horizon.

⁶ However, short-lived environmentally harmful substances are not included in (or not central to) these negotiations.

⁷ <https://research.chalmers.se/publication/506746>

⁸ Based on Swedavia's passenger survey done at Stockholm Arlanda Airport, and Stockholm Bromma, Gothenburg/Landvetter, Luleå, Malmö and Umeå Airports. This survey has been carried out for different years at different airports and consequently a linear adjustment or mean value of the existing data has been used for the years in which this data is missing. For the other airports where no survey has been carried out, the median for the airports in Umeå and in Luleå was assumed, since these are of comparable size.

⁹ Other smaller airports such as Torp in Norway may also be applicable, but these were not taken into account in this investigation.

¹⁰ The data here includes only those passengers starting their trips from these airports not transfer passengers, trips to Sweden are excluded as far as possible since these are captured in the data from Swedish airports.

¹¹ See <https://chrome.google.com/webstore/detail/geocode-by-awesome-table/cnhboknahecjdnkjinlodacdjelppfg?hl=en>

¹² The great-circle distance (GCD) is defined as the shortest distance between two points with coordinates (lat1, lon1) and (lat2, lon2), on the surface of a sphere. It is given by: $GCD = R \cos^{-1}[\sin(\text{lat1})\sin(\text{lat2}) + \cos(\text{lat1})\cos(\text{lat2})\cos(\text{lon1}-\text{lon2})]$, where R the Earth's radius. R = 6371.01 km.

¹³ In some emissions calculators, an extra distance of approximately 50 km is added to take into account deviations from the great-circle distance. Since we used calculations for emissions per person kilometre which is based on the great-circle distance, we did not add this extra distance.

¹⁴ <https://research.chalmers.se/publication/506746>

¹⁵ For international travel, the travel volume has been calculated by multiplying the number of trips by the average distance. For domestic trips, statistics are available for 1995 and for 1997–2017 (Transportstyrelsen, 2018b). For the other years, the travel volume has been estimated by extrapolating the average distance for domestic trips and multiply this by the number of passengers (where there is data for all years). It would have been more intuitive to extrapolate the number of pkm straight off, but since 1990 was a record year for the number of domestic passengers, the number of pkm would thus be significantly underestimated, hence the workaround via the average distance and the number of passengers.

¹⁶ Passengers are estimated to be responsible for 95 % of the emissions between 1990-2017 (the remainder is freight).

¹⁷ These results are relatively consistent with the results from our previous report covering the trends up to 2014. However, emissions are slightly lower due to the slightly shorter average distance and the downward adjustment of the global figures for emissions per passenger km (see Appendix A).

¹⁸ According to the Swedish Environment Protection Agency and Statistics Sweden (2017), emissions from passenger vehicles in Sweden amounted to 10.3 Mt CO₂eq in 2016. Emissions from foreign residents' passenger vehicle trips in Sweden ought to be removed, but we do not have the data for this. Swedish residents' passenger vehicle trips abroad ought to be added and they were the equivalent of 0.3 Mt CO₂eq in 2016. However, all in all, emissions from passenger vehicle trips lie close to emissions from the Swedish population's air travel. It is important to emphasise here that this is only passenger vehicle trips and not all road traffic, and that it does not include complete life-cycle emissions (which air travel emissions do not include either).

¹⁹ Our own calculations based on Tillväxtverket (2018) and Trafikanalys (2017). However, no account has been taken of the fact that business trips sometimes use business class where the space per passenger is greater.

²⁰ Based on calculations using the global statistics described in the appendix.

²¹ Of international passengers at Arlanda Airport, 61 % were Swedish residents in 2000 while this share in 2017 was 52 %.

²² Data for 2016 and 2017 were not available at the time of publication of this report, so for these years the data were extrapolations.

²³ ICAO's data contains only data from regular services within its member states (see <http://www.icao.int/MemberStates/Member%20States.Multilingual.pdf>)

²⁴ The ICAO calculates the total weight of passengers, baggage, seats, toilets, etc. as $100\text{kg} \cdot \text{number of passengers (pass.)} + 50\text{kg} \cdot \text{number of seats (seats)}$. With the cabin factor of $\frac{\text{pass}}{\text{seats}} = 80\%$, the weight per passenger $\frac{100\text{kg} \cdot \text{pass} + 50\text{kg} \cdot \text{seats}}{\text{pass}} = 100\text{kg} + 50\text{kg} \cdot \frac{1}{\text{cabin factor}} = 162\text{ kg}$, in other words the same as Wit et al. (2002).