Grantham Research Institute on Climate Change and the Environment

Centre for Climate Change Economics and Policy

The behavioural, welfare and environmental impacts of air travel reductions during and beyond COVID-19

Roger Fouquet and Tanya O'Garra

July 2020

Centre for Climate Change Economics and Policy Working Paper No. 372
ISSN 2515-5709 (Online)

Grantham Research Institute on Climate Change and the Environment
Working Paper No. 342
ISSN 2515-5717 (Online)

E·S·R·C ECONOMIC & SOCIAL RESEARCH COUNCIL

The Grantham Foundation for the Protection of the Environment

University of Leeds

LSE The London School of Economics and Political Science

The Centre for Climate Change Economics and Policy (CCCEP) was established by the University of Leeds and the London School of Economics and Political Science in 2008 to advance public and private action on climate change through innovative, rigorous research. The Centre is funded by the UK Economic and Social Research Council. Its third phase started in October 2018 with seven projects:

1. Low-carbon, climate-resilient cities
2. Sustainable infrastructure finance
3. Low-carbon industrial strategies in challenging contexts
4. Integrating climate and development policies for 'climate compatible development'
5. Competitiveness in the low-carbon economy
6. Incentives for behaviour change
7. Climate information for adaptation

More information about CCCEP is available at www.cccep.ac.uk

The Grantham Research Institute on Climate Change and the Environment was established by the London School of Economics and Political Science in 2008 to bring together international expertise on economics, finance, geography, the environment, international development and political economy to create a world-leading centre for policy-relevant research and training. The Institute is funded by the Grantham Foundation for the Protection of the Environment and a number of other sources. It has 11 broad research areas:

1. Climate change adaptation and resilience
2. Climate change governance, legislation and litigation
3. Environmental behaviour
4. Environmental economic theory
5. Environmental policy evaluation
6. International climate politics
7. Science and impacts of climate change
8. Sustainable finance
9. Sustainable natural resources
10. Transition to zero emissions growth
11. UK national and local climate policies

More information about the Grantham Research Institute is available at www.lse.ac.uk/GranthamInstitute

Suggested citation:
Fouquet R, O'Garra T (2020) *The behavioural, welfare and environmental impacts of air travel reductions during and beyond COVID-19*. Centre for Climate Change Economics and Policy Working Paper 372/Grantham Research Institute on Climate Change and the Environment Working Paper 342. London: London School of Economics and Political Science

The Behavioural, Welfare and Environmental Impacts of Air Travel Reductions During and Beyond Covid-19

Roger Fouquet[1] and Tanya O'Garra[23]

Abstract

By 2050, aviation threatens to become the single largest source of carbon dioxide emissions due to rapidly increasing demand. Given the disruption in air travel due to Covid-19, we are faced with a unique opportunity to examine whether reductions in air travel can be sustained beyond the crisis so as to mitigate carbon dioxide emissions. Analysis of the short-run impact of Covid-19 indicates that large reductions in emissions (41.5% for the whole of 2020) can be achieved with relatively low losses in welfare. However, relative impacts on the poorest income quintile are three times greater than impacts on the richest income quintile; more generally, such a drastic approach to reducing demand is not politically acceptable. Examination of potential longer-term policies aimed at curbing carbon dioxide emissions beyond the lifetime of the pandemic indicates that substantial mitigation can be achieved with minimal impacts on welfare. Results show that, compared with a carbon tax, a frequent flyer levy is almost twice as effective (i.e., half the welfare loss for the same emissions reduction), with little impact on lower income quintiles. Such a levy has the potential to be an effective and politically acceptable environmental policy to curb rising emissions from air travel.

Key words: air travel; carbon dioxide emissions; Covid-19; welfare impacts; inequality; carbon tax; frequent flyer levy; environmental policy.

JEL Code: Q54, Q58, R41

---

[1]. Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science (LSE). Contact: r.fouquet@lse.ac.uk. Houghton Street, London WC2A 2AE, United Kingdom.

[2]. Department of Economics, Middlesex University, The Burroughs, NW4 4BT, London, United Kingdom.

3. Department of Geography and the Environment, London School of Economics and Political Science (LSE).

[3]. We would like to thank Paul Bloomfield at the ONS and David Young at the Civil Aviation Authority for providing crucial data, and Josh Burke for comments. We gratefully acknowledge support from the Grantham Foundation. We have not received any additional financial support from any interested parties, and do not hold paid or unpaid positions in any relevant entities.

The Behavioural, Welfare and Environmental Impacts of Air Travel Reductions During and Beyond Covid-19

1. Introduction

Not since the 2010 eruption of Eyjafjallajokull in Iceland, or the 9/11 attacks on the World Trade Center in 2001 in New York, have the skies experienced such quiet. The Covid-19 global lockdown has seen entire airplane fleets grounded across the world, resulting in an average 75% reduction in air passenger capacity worldwide (Le Quéré et al. 2020). This has led to unprecedented declines in carbon emissions and other pollutants associated with aviation. Although a global pandemic that has caused the deaths of 500,000 people as of 30 June 2020 (John Hopkins University 2020) and debilitated the world economy should not be heralded as the way to bring about carbon emission reductions, it does however present an opportunity to examine whether some of the reductions in air travel might be sustained beyond the lifetime of the pandemic, and to identify the policy mechanisms that might support this reduction.

Although passenger air travel currently only accounts for about 2-3% of global carbon emissions (Graver et al. 2019), this is largely generated by the fraction of the world population that flies regularly. Indeed, high-income countries were responsible for 62% of CO_2 emitted from passenger aircraft in 2018 (Graver et al. 2019)[4]. However, demand has been rising by about 5.9% globally a year since 2010 (ICAO 2019) with studies estimating that by 2050 aviation will account for about one quarter of all global carbon emissions (Pidcock and Yeo 2016). Technological improvements and alternative fuels, such as biofuel, have some potential (Prussi et al. 2019), yet studies show that these improvements will not be enough to reduce emissions in the context of such pronounced growth in demand (Prussi et al. 2019; Pavlenko 2018; Graver et al. 2019; Kousoulidou and Lonza 2016). It is therefore vital to identify opportunities to moderate this demand, albeit with minimum impacts on welfare. What are needed are policy measures that reduce demand for the least valuable flights while ensuring that those with limited resources maintain access to acceptable levels of air travel.

Given the severe disruption to air travel due to Covid-19 and the huge financial losses suffered by airline companies, the timing is propitious to curb the growth in demand for air travel and stimulate an enduring shift towards sustainability in the air travel sector, and redirect bevhaiour towards more sustainable forms of transport, such as trains. Attempts to stimulate a recovery in this sector through public spending (e.g., loans and bailouts) could be feasibly conditioned on stipulations requiring lowering of carbon emissions. Indeed, there is increasing demand from civil society groups for such conditionalities attached to airline

[4]. See Sager (2019) and Oswald et al (2020) on the inequalities of energy consumption and carbon emissions.

bailouts (Watts 2020)[5]. We are in the midst of a critical juncture; the decisions made by government today about how to rescue the ailing airlines will determine whether demand for air travel 'bounces' back to its inexorable incline, or whether it follows a more sustainable long-term trajectory.

To help inform these decisions, this paper has two aims: first, it estimates the short-run behavioural, welfare and environmental impacts of air travel reductions due to Covid-19; and, second, it explores the potential for different policy measures to curb demand and reduce carbon dioxide emissions beyond the lifetime of the pandemic with minimal impacts on welfare[6].

With this in mind, the study starts by considering the most drastic approach to reducing emissions: the air travel restrictions due to Covid-19 with a focus on estimating outcomes at different income levels. This allows us, firstly, to identify whether the air travel restrictions have had uneven impacts along the income distribution. Crucially, it allows us to establish an analytical framework for the second aim of the paper, which is to examine the potential impacts along the income distribution of different low-carbon policies *beyond* the lifetime of the pandemic. In particular, this paper aims to shed light on the effectiveness of different policy measures to promote sustained, long-term reductions in air passenger travel in 2030 and in 2050, so as to deliver meaningful carbon emission reductions without major losses in wellbeing. By assessing the differential effects of policies along the income distribution, it is possible to identify those environmental policy measures that minimise unfair burdens on the poor – a step closer towards offering a just transition to a low carbon economy and society.

To do this, behavioural and environmental impacts are assessed using daily flight data, industry forecasts of the recovery, and estimates of the relationship between air traffic and carbon dioxide emissions. The large declines in air travel due to Covid-19 mean that it is necessary to identify the shape of the demand curve to assess welfare losses. Therefore, welfare impacts are estimated using demand curves constructed following a method developed in Fouquet (2018). This method (described in Section 2) offers an opportunity to estimate the net benefits of air travel, and the losses from large reductions in consumption.

The analysis in this paper focuses on passenger air travel in the UK. Passenger traffic in the UK is estimated to nearly double by 2050 (DfT 2018), which implies increases of about 68 $mtCO_2e$ emissions with current technologies (see estimates below). Some of this increase may well occur as a result of increasing incomes; for these consumers, the benefits from air travel are likely to be significant. However,

5. Indeed, the European Union has proposed €750 billion fund to help recover from the coronavirus crisis with 'green strings' attached, and with 25% of all funding set aside for climate action (Simon 2020).

6. While distributional impacts of land travel taxation policies have been analysed (Bento et al. 2009, Rausch et al. 2011), to our knowledge, this is the first distributional analysis of environmental policies on air travel demand.

the low costs of air travel promote travel that deliver minimal marginal benefits – weekend getaways, short-haul flights, and business meetings that could be conducted online. A recent survey study conducted in England by the UK Government (Kommenda 2019) found that only 1% of English residents are responsible for nearly one fifth of all international flights; and 48% of residents had not flown in the previous year. Thus, the challenge is to identify mechanisms that can reduce low-value air travel among the frequent fliers, while allowing for growth in demand for air travel that generates substantial benefits to individual passengers.

The analysis of the short-run impact of Covid-19 indicates that large reductions in emissions (41.5% for the whole of 2020) can be achieved with relatively low losses in welfare (a minimum of 9%, – equivalent to a loss of £155 per person, and a median of 31.1%) – see Section 5. However, the drastic measures associated with the lockdown clearly cannot be used as a long run strategy to reduce emissions both for reasons of civil liberty and because the welfare impacts disproportionately harm the poor. Analysis of more pragmatic policy options (namely carbon taxes and frequent flyer levies) shows that demand for low-value flights can be reduced substantially over the next 30 years with minor impacts on welfare, whilst contributing significantly to carbon emission reductions - see Section 6. Frequent flyer levies are found to impact the wealthy (who tend to fly more) more than the poor; they act as highly progressive taxes. By 2050, a frequent flyer levy (starting at a real price of £50 per tonne of carbon for the second ‘flight’ and rising by £50 per tonne of carbon for each subsequent ‘flight’) could potentially reduce carbon emissions by 12.7% compared to a scenario of growth in air travel, with a 16% reduction in welfare among the top income quintile and a 0.7% reduction in welfare among the lowest income quintile. Thus, such a levy is likely to be more politically-acceptable than a carbon tax charged on all flights.

It is important to acknowledge that aviation is responsible for other pollutants, such as nitrogen oxides (NO_x) aerosols, particle emissions and water vapour in the form of contrails. Research suggests that these other non-CO_2 emissions may increase the impact of aviation on the climate by a factor of 2 - 5 (IPCC 1999) via a process known as ‘radiative forcing’ (Lee et al. 2009). The impact of taking account of radiative forcing in taxes or levies is considered in the scenarios analysed in this paper (Section 6).

This study is a timely contribution to the discussion around the recovery from Covid-19, and the types of low-carbon policy measures that government could implement in tandem with bailouts for the airline industry. It also more generally contributes to the debate around how to achieve the ‘zero emissions’ target of the aviation industry for 2050 (Sustainable Aviation 2020). More broadly, by investigating how to maintain UK passenger air travel at reduced levels with minimal losses in welfare, it becomes possible to identify the potential for similar measures to moderate the predicted increase in demand in developing countries, whilst ensuring that first-time fliers are able to travel by plane. Finally, this paper contributes to the wider debate on the inequalities of consumption and pollution generation (Sager 2019, Oswald et al 2020), and the policies that might seek to address socially and environmentally undesirable imbalances.

2. Method to Construct Demand Curves

To estimate the welfare losses from restrictions on air travel due to Covid-19, as well as those losses associated with long run efforts to minimise the environmental impacts of passenger aviation, it is necessary to identify the demand curves for air transport and calculate the area under the demand curve and above the price line. Given the limited contemporary information on willingness to pay values along the demand curve, this study uses a method developed in Fouquet (2018) which locates the demand curve and estimates the consumer surplus[7] using temporal benefit transfers[8] to estimate willingness to pay (WTP) values.

To do this, the analysis starts with the understanding that, in any year, a single WTP value on the demand curve is known. This value is the price paid by the consumer and indicates the WTP for the marginal unit of consumption (m) provided demand and supply are in equilibrium at the marginal unit of consumption (m). Based on this assumption, it can be inferred that the average consumer's WTP for the equilibrium level of consumption (m) is equivalent (or very close) to the price level in the current period (t):

$$WTP_{im} = P_{it} \tag{1}$$

The crucial insight is that this value also provides information about how much the representative consumer will be willing to pay for that same marginal quantity consumed in the next year, assuming that preferences remain unchanged, or change only gradually over time. This knowledge creates the opportunity to transfer WTP values (or benefits) to different time periods. For instance, if all constraints

[7]. For the purpose of the analysis, it is assumed that the demand for air travel is well-behaved, reflecting the objective of the traveller trying to maximize utility by combining air travel and all other goods and services subject to income and price constraints. Fouquet (2018) uses this framework to develop a method to identify the Marshallian demand curve. Marshallian demand relates to the primal problem of utility maximization, representing the relationship between quantity consumed and prices faced by the consumer. However, moving down the Marshallian demand curve, as the price of good declines, utility is not held constant, because of the increase in purchasing power due to the income effect. Thus, bundles of x and y are not comparable, in terms of their utility. Fortunately, Willig (1976) shows that for goods and services where the budget share is small, the Marshallian demand curve approximates the more desirable (utility-constant) Hicksian demand curve closely. Given that the expenditure on air travel is less than 2% for all income categories (see the Supplementary Material), this approximation appears satisfactory for generating meaningful values – though a project is underway to develop a method for converting the Marshallian demand curves into Hicksian demand curves using the Slutsky equation.

[8]. Benefit transfers have been traditionally used in not-marketed goods situations, where data availability on willingness-to-pay values is limited. For these situations, the transfers are across space rather over time, and this 'spatial' benefit transfer methodology forms the foundation of numerous economic analyses and policy assessments (Loomis 1992, Bateman et al. 2011, Johnston et al. 2015).

(including budgetary ones) remain unchanged in the next time period (t+1), then it can be assumed that the WTP for this marginal level of consumption of good i will be the same in both years.

$$WTP_{imt} = WTP_{imt+1} \text{ (provided all remains unchanged)} \quad (2)$$

More generally, WTP will be a function of income and price of other goods j,

$$WTP_{imt+1} = f(WTP_{im}, Y_{t+1}, P_{jt+1}) \quad (3)$$

Here, it will be assumed that this ’value function’ transfer holds across time, as well as across space, as is traditionally done (Johnston and Rosenberger 2010, Bateman et al. 2011).

Using equilibrium quantity-price combinations for a wide range of quantities consumed (m) it is possible to locate a large portion of the demand curve. For instance, in 1950, the equilibrium level of consumption for a normal good is likely to have been smaller than in 2020, so, $m_{1950} < m_{2000}$. Knowing the equilibrium price for the level of consumption in 1950 (m_{1950}) offers the opportunity to locate an additional point on the demand curve in 2020, because

$$WTP_{im_{1950}2020} = f(WTP_{im_{1950}}, Y_{2020}, P_{j2020}) \quad (4)$$

The greater the range of quantities consumed for which data exists (in combination with the price), the greater the amount of the demand curve that can be located. Thus, historical data on equilibrium quantity-price combinations can provide useful information about the shape of the demand curve.

A critical question for generating demand curves - and ultimately, estimating consumer surplus - is how exactly to transfer WTP values through time. The transfer will depend on the details of the benefit transfer function in equation (3). Here, the assumption is that changes in WTP values are the outcome of changes in income multiplied by the income elasticity of demand for air transport.

The income elasticity in question (3) is, however, not the standard income elasticity of demand for a good or service, which is defined as the percentage change in the quantity demanded for a given increase in income at constant prices. Instead, the objective is to determine the change in WTP for a given marginal quantity following an income change - also known as the ‘price flexibility’ of income (Randall and Stoll 1980). Hanemann (1991) shows that this income elasticity of WTP (or price flexibility of income) is analytically equivalent to the ratio of the income elasticity of demand for the good to the elasticity of substitution between the good or service of interest and the composite good.

Here, it is helpful to use the Slutsky equation. Snow and Warren (2015) emphasize the relationship:

$$\eta_{iY} = -\eta_{WTPY} \,/\, \eta_{pi}^{H} \quad (5)$$

where η_{iY} is the income elasticity of demand for i, η_{WTPY} is the income elasticity of the willingness to pay for good i, and η_{pi}^{H} is the Hicksian or compensated own-price elasticity of demand for good i.

This equation can be re-written to isolate the income elasticity of the willingness to pay for good i:

$$\eta_{WTPY} = \eta_{iY} / \eta_{pi}^{H} \tag{6}$$

In other words, the income elasticity of the willingness to pay for good x, $\eta_{WTPY,}$ is equal to the income elasticity divided by the Hicksian (compensated) own price elasticity, which can be calculated from Slutsky's equation. Flores and Carson (1997 p.293) highlight that the two income elasticities can indeed be different, but in conclusion their analysis "suggests that the ... income elasticity for most values … are reasonably close in magnitude to the income elasticity of WTP". However, crucial to determining the difference is the size of the elasticity of substitution – the closer to unity, the less the difference will be. Here, the assumption is that the elasticity of substitution is equal to one, though a project is underway to estimate elasticity of substitution.

The value of the income elasticity of the WTP for good x, $\eta_{WTPY,}$ is fed into the following equation and multiplied by the change in income to determine a part of the change in WTP for a marginal change in the consumption of good i:

$$WTP_{mit}(m) = WTP_{mit}(m) \,.\, [1 + \eta_{WTPY} \cdot \frac{\partial y_t}{\partial y_{t-1}} + \sum_{j=1}^{k} \eta_{pij}^{H} \quad \cdot \frac{\partial p_{jt}}{\partial p_{jt-1}}] \tag{7}$$

Another of the assumptions in Fouquet (2018) was that the there were no cross price effects, implying either prices of other goods were constant, that is, $P_{jt} = P_{jt-1}$, or the cross price elasticities were zero. This was introduced due to the lack of data on other prices. Here, again, this restriction has to be maintained – although a major project is underway to collect this price information, offering an opportunity to compare the impact of including and relaxing this restriction.

Thus, the WTP for air travel for any marginal level of consumption is estimated as the previous year's WTP for air travel for the same marginal level of consumption multiplied by one plus the change in income to determine a part of the change in WTP for a marginal change in the consumption of good i:

$$WTP_{mit}(m) = WTP_{mit}(m) \,.\, [1 + \eta_{WTPY} \cdot \frac{\partial y_t}{\partial y_{t-1}}] \tag{8}$$

For each year, a series of points indicates the WTP at different particular marginal quantities of air travel. In other words, this series "locates" the demand curve for marginal quantities where market information was available. Given that this data is available since the beginning of the commercial air travel (discussed below), the full demand curves can be constructed.

The information about income elasticities in each year is used to calculate η_{WTPY} in equation (8) and to estimate the WTP at each marginal level of consumption in each year, for which data is available. Putting together the WTP at each marginal level of consumption enables the demand curve for each year.

3. Data

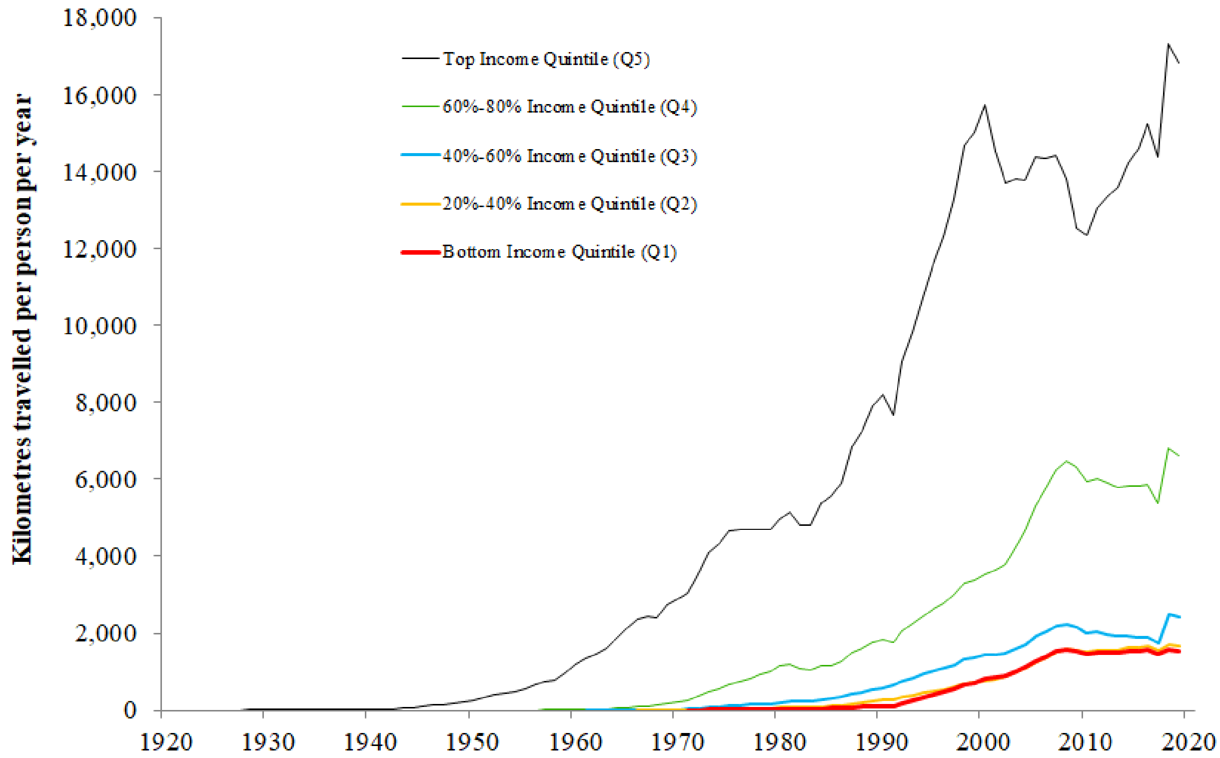
This section presents an overview of the data used to construct the demand curves for analysis. Historical data on consumption and prices for air travel has been compiled from various sources (Birkhead (1960), Stone (1966), Mitchell (1988), DfT (2019), CAA (2020a), ONS (2019)) so as to cover the entire period of commercial air travel, from 1920 to 2019. Given the interest in examining the demand and welfare effects at different income levels, this study estimates travel behaviour by income quintiles. Data on travel behaviour by income level has been collected by the Civil Aviation Authority (CAA 2020b), and combined with more qualitative information for early years. Table A1 in the Appendix summarises the shares by income quintile for each decade, as well as process for generating the data. Figure 1 presents the long run trends in air travel by income quintile since 1920, as well as the total quantity travelled in billions of passenger kilometres (bpk).

As the figure shows, for the first few decades, air travel was for the benefit of the wealthy. The introduction of jet airplanes in the 1960s led to a reduction in price and attempts to expand the market for air travel to the middle and working classes (Lyth 1993, 2009; Barton 2005). This expansion, combined with major increases in income (see Figure 2), meant that a less wealthy segment of the population was introduced to the joys of long-distance holidays. Rapid growth rates in air travel were experienced by all income levels, apart from a slow-down in the 1970s due to the oil shocks and the recessions that followed.

Nevertheless, in the early 1990s, the 20% of highest earners still accounted for 75% of all flights (see Table AAppendix1 in the Appendix for estimates of shares by income quintile). It is estimated that, in 1990, the average person in the top income quintile (Q5) travelled close to 8,200km per year – close to three return-flights to Alicante (in Spain) from London Gatwick. Indeed, the average person in the highest income quintile flew 4 times more than the average person in the next highest (Q4) income quintile and 78 times more than the average person in the lowest (Q1) income quintile[9]. In 2000, air travel in the wealthiest quintile peaked at an average 15,750km (see Figure 1).

[9] The average person in the highest income quintile (Q5) flew 14 times more than the average person in Q3 and 29 times more than the average person in Q2.

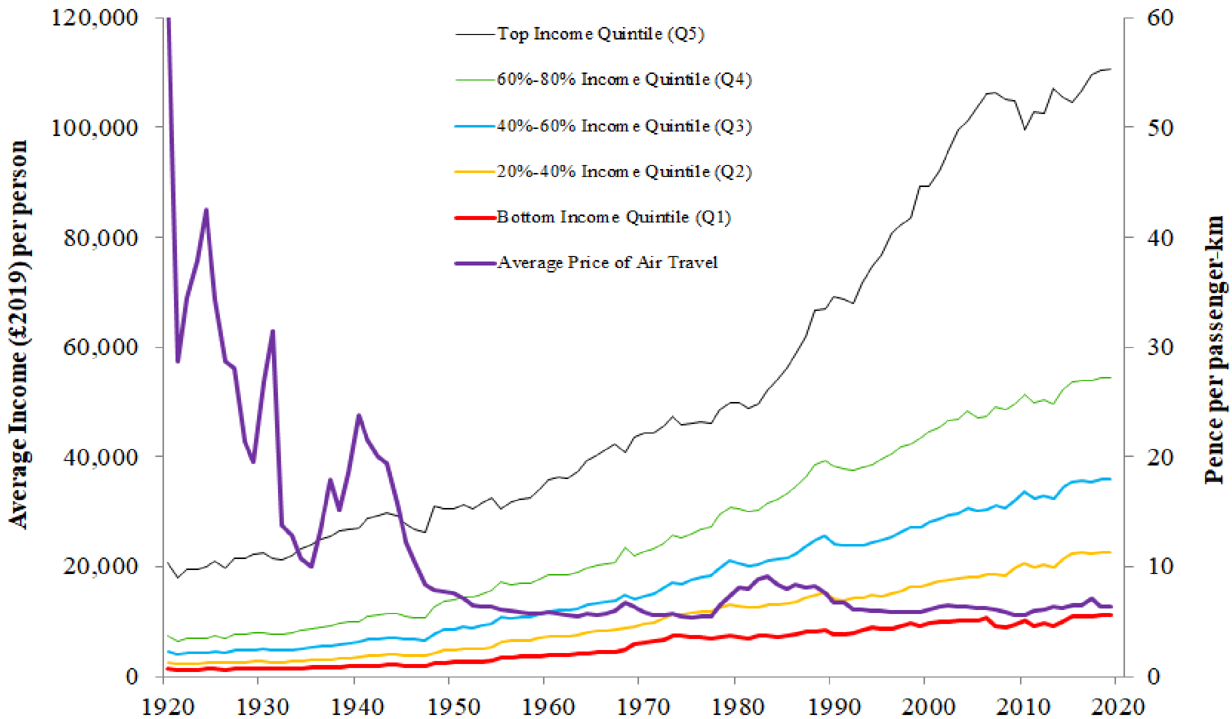
Figure 1. Air Travel by Income Quintile in the United Kingdom, 1920-2019



Source: Birkhead (1960), Stone (1966), Lyth (1993), (2009), Barton (2005), CAA (2019), GBTS (2020)

Interestingly, flying behaviour amongst the top income quintile was 13% lower in 2003. This drop may be due to factors associated with the terrorist attack on the Twin Towers in 2001. Ito and Lee (2005) find that travel within Europe (including the UK) did decline after 9/11, but that European air travel leaving the EU was affected far more. The CAA (2020b) surveys (discussed in the data section) indicate that British travellers in the top income quintile are most likely to undertake the longest journeys (i.e. outside the EU) and, therefore, most likely to have been affected by factors related to the terrorist attacks. In addition, Blalock et al (2007) find a decline in the demand for air travel due to the increase in security screening. It is possible that wealthier travellers place a higher value on time and hence were more impacted by the time spent on security controls than poorer travellers. This is supported by the fact that average travel of other quintiles appears not to have been affected after 2001 and shows continued growth until the financial crash of 2008. Most probably, due to the decline in income levels (see Figure 2), this economic crisis led to a reduction in average air travel for all quintiles, with a rebound only in 2018. This growth may represent the beginning of a new phase of expansion in air travel – and associated carbon dioxide emissions.

Figure 2. Income by Quintile[10] and Average Price of Air Travel in the United Kingdom, 1920-2019



Source: Income: Atkinson (2007), WID (2019), ONS (2019); Price of Air Travel: Stone (1966), ONS (2020)

4. The Demand for Air Travel

This section discusses the analysis of air travel demand undertaken to estimate income and price elasticities. The demand for passenger transport services reflects individuals´ willingness to pay (WTP) for travelling from one place to another (Button and Taylor 2000). Travellers' responsiveness to changes in prices and income has depended on a number of factors, most prominently income and real prices, which constrain their WTP and consumption (Brons et al 2002). So, the demand for air travel (of income quintile AT_{it}) is a function of average income for quintile i (y_{it}) and the price of air travel (p_t):

$$AT_{it} = f(\,Y_{it}\,,\; P_t\,) \qquad (9)$$

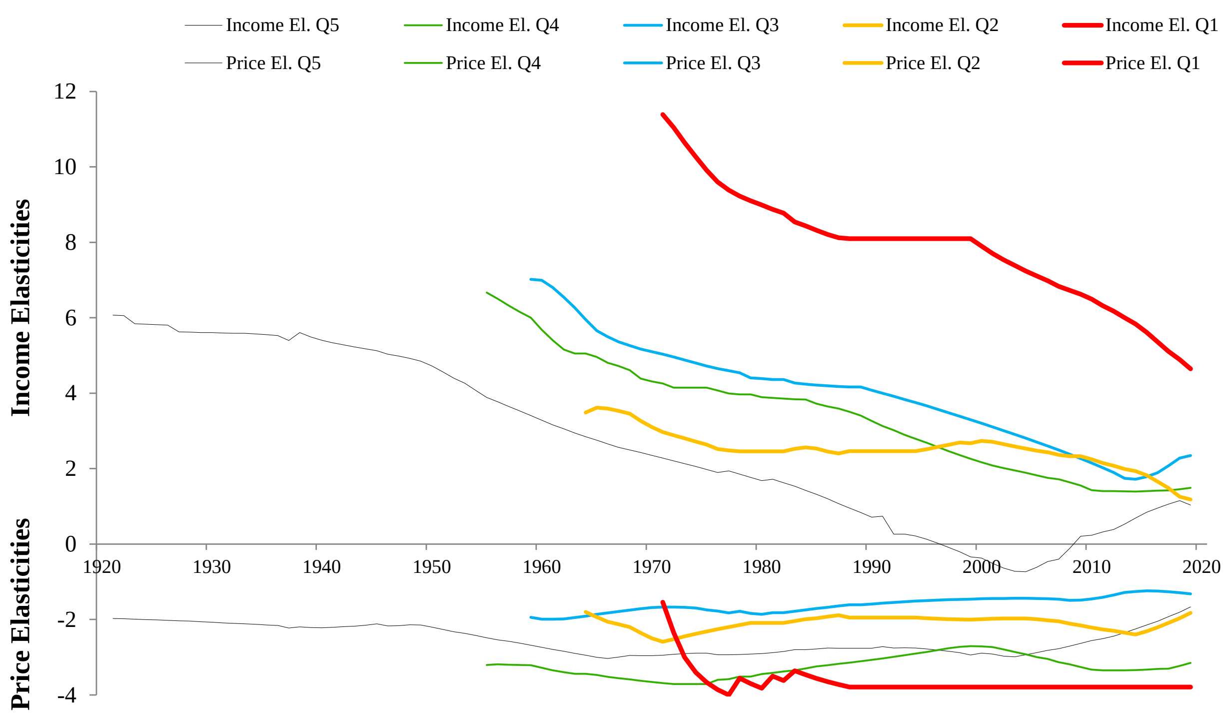
The data on air travel consumption by income quintile and explanatory variables presented in the previous section are used to estimate the income and price elasticity in order to construct full demand curves, as explained in equations (6) and (8). The estimates were generated using annual time series data on energy

[10]. The income data was based on combining from Atkinson (2007), WID (2019) and ONS (2019) - for 2019, in which the data is not yet available, it was assumed that there were no new changes in income distribution and each quintile increased by the same amount as GDP per capita (ONS 2020).

service consumption, prices, and average income per household by quintile from 1920 to 2019 – following the method presented in Fouquet (2014). The method underlying these estimates is discussed at length in the Appendix. Figure 3 presents the income and price elasticities over time.

Figure 3 shows that - as for land transport, and other energy services (Fouquet 2014) - income elasticities decline with rising income levels (also discussed in Deaton (1975) in the context of Pigou's Law, which links income and price elasticities and how this relationship changes with rising income). For most years and quintiles, air travel appears to be 'luxury' good – i.e., income elasticity is above one. The only exception is associated with the early 2000s, when individuals in the top income quintile reduced their air travel, most possibly as a reaction to the terrorist concerns following 9/11, as discussed above[11].

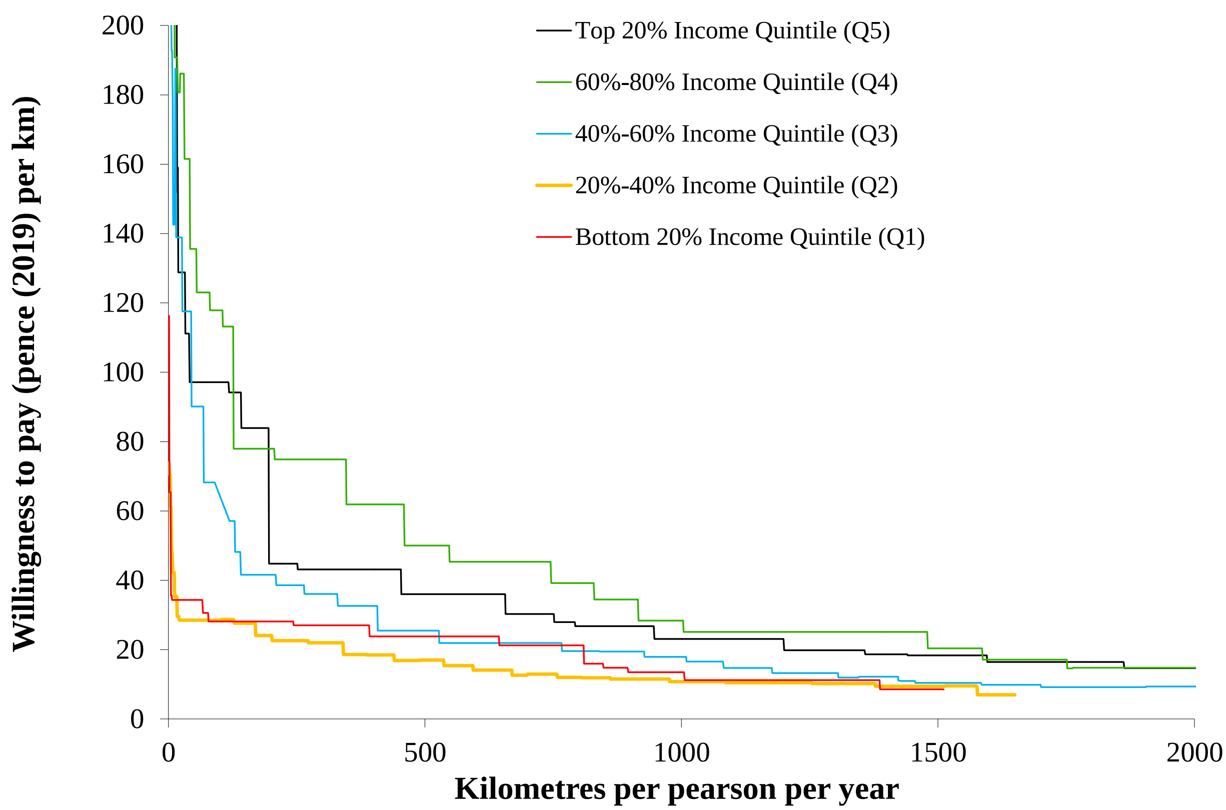
Figure 3. Income and Price Elasticity of Demand for Air Transport by Income Quintile in the United Kingdom, 1920-2019



[11] Here, elasticities are calculated as the average of elasticity estimates in which a particular year is included in a regression. That is, regressions are run for 50-year periods (e.g. 1950-1999, 1951-2000, 1952-2001, 1953-2002, etc..). The implication is that, for instance, the year 2001, in which travel dropped suddenly for the top income quintile, may well have influenced the elasticity for a number of regressions in which 2001 was included and, thus, the average elasticity estimates in previous years (e.g., 2000, 1999, etc..) - for more details on this method, see Fouquet (2014) and the Supplementary Material. As a result, the decline in average elasticities for the top income quintile appears to begin before 2001 (see Figure 3). However, the fact that the trough occurs in the early 2000s and yet returns to earlier levels soon after (Figure 1 also shows the dramatic drop in 2001), suggests, in-line with Ito and Lee (2005) and Blalock et al (2007), that demand was affected by factors associated with 9/11 (as discussed in the previous section).

Using the temporal benefit transfer method outlined in equation (8) and the income elasticities presented in Figure 3, it possible to construct demand curves for air travel by income quintile. Figure 4 shows the counterfactual of 'normal 2020 year' demand curves - i.e., what demand would have been without Covid-19. The most recent annual data is for 2019. However, using temporal benefit transfers, and the assumption of an increase in GDP per capita of 0.8% for 2020 (under the BAU scenario) based on the OECD's forecast (see Supplementary Material for further details), it is possible to construct these demand curves for air travel in 2020. This projection will be vital for estimating the counterfactual of 'a normal 2020 year' (i.e., air travel in 2020 without Covid-19). Similarly, it is possible to produce a 2020 counterfactual scenario of air transport use for each quintile using the assumption of 0.8% rise in income (taking account of the income elasticities) and a constant real price of air travel (which implies the supply curve shifts also; see Figure 2 for support of this assumption). With assumptions (see the Appendix), demand curves and air travel can be projected further into the future. Specifically, analysis of longer-run impacts in Section 6 will focus on the demand curves and air travel in 2030 and 2050.

Figure 4. Counterfactual Demand for Air Transport in the United Kingdom by Income Quintile in 2020



Given the differences in income, it was expected that the demand curve would the highest for the richest income quintile (Q5), descending to the lowest for the poorest income quintile. This is broadly correct. However, as shown in Figure 4, the demand curve of Q4 (i.e., the top 20% to 40%) is actually higher than the demand curve of Q5 (i.e., the top income quintile) for most of the first 1,500 km travelled per person per year. This might reflect differences in lifestyle. For instance, the top income quintiles may own homes in the UK and travel slightly less abroad than the second highest quintiles – certainly, half of the individuals with additional properties are in the top income quintile, whereas one quarter of these individuals are in the second highest income quintile (Gardiner 2017). Similarly, the bottom income quintile's (Q1) demand curve is higher than the demand curve of Q2 (i.e., the bottom 20% to 40%). The lowest income quintile may also include retired and other non-workers with more flexibility about when they can travel. On the whole however, it is clear that willingness to pay values are generally higher for the richer income quintiles than the poorer income quintiles.

Figure 4 also shows that, as expected, estimated WTP is highest for the first few kilometres travelled[12]. However, these values vary widely according to the income quintile. For instance, at the 10th km, the WTP of the top income quintile (Q5) is 375 pence (£2019), whereas it is only 34 pence for the bottom quintile (Q1). Naturally, the WTP for the marginal km is the same – 8.5 pence (£2019), which is the current price. As a result, there are greater differences in the WTP from, say, the 10th km to the 100th km (or the 100th km to the 1,000th km) of the upper quintiles than the lower quintiles. In other words, as income rises, the demand curves become more convex – and the differences in convexity have crucial implications for the welfare impacts of behavioural restrictions and carbon taxes, for instance, across the income distribution, as discussed below.

5. The Short-Run Impacts of Covid-19

This section will focus on the behavioural, welfare and environmental effects of Covid-19 on air travel over the course of the year 2020. Impacts over the whole year have been estimated because the demand curves have been constructed on an annual basis and there is no information about WTP at a finer timescale, thus, hampering the ability to construct monthly, weekly or daily demand curves for air travel. In addition, as will be discussed below, it will take at least until the end of 2020 for air travel to approach normality.

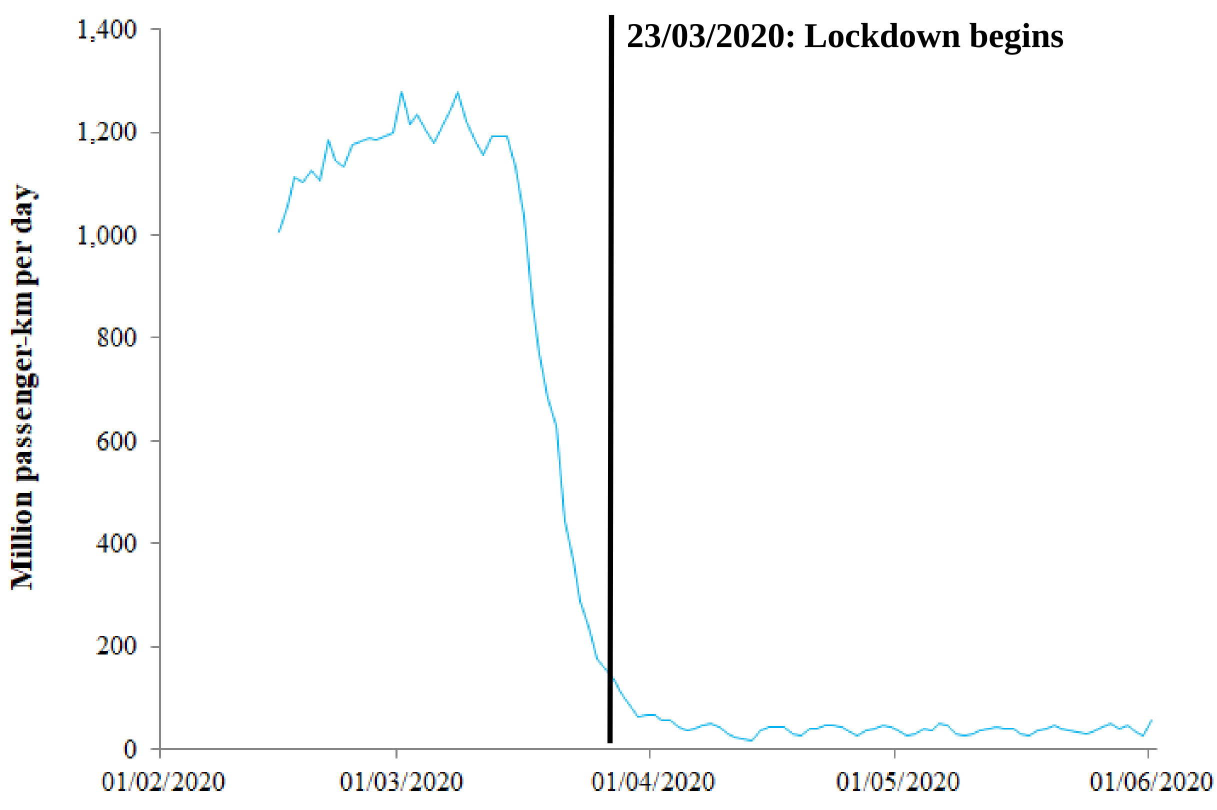
[12] It is important to stress this is an average of millions of consumers. In reality, individual consumers value travel to a certain destination and, therefore, would place equal waiting on each kilometre associated with a first flight equally, and then presumably place equal waiting on each kilometre associated with the second flight equally, and so on. For instance, 2,300km is equivalent to a return flight from London Gatwick Airport to Alicante in Spain. Thus, this analysis is based on the average consumer for each income quintile.

(i) Behavioural impacts

The first issue to address is the impact of Covid-19 on air transport behaviour. The level of air travel is affected both by the formal travel restrictions – which were imposed in the UK on the 23 March - as well as by self-imposed travel restrictions and cancellations by passengers due to concerns about Covid-19 and/or restrictions in place in destination countries.

Despite the difficulty in identifying how much of the decline in air travel was specifically due to Covid-19, daily flight data from Eurocontrol (2020) provides detailed insight into the timing of behavioural change before the formal lockdown. Combining this data on daily flights in the UK, with data from the Civil Aviation Authority on monthly averages of passengers per flight and average distance per flight (CAA 2020a), it is possible to estimate the decline in passenger-kilometres – shown in Figure 5. This data is discussed in more detail in the Appendix.

Figure 5. Estimated Daily Air Travel in the United Kingdom, 15 February-1 June 2020



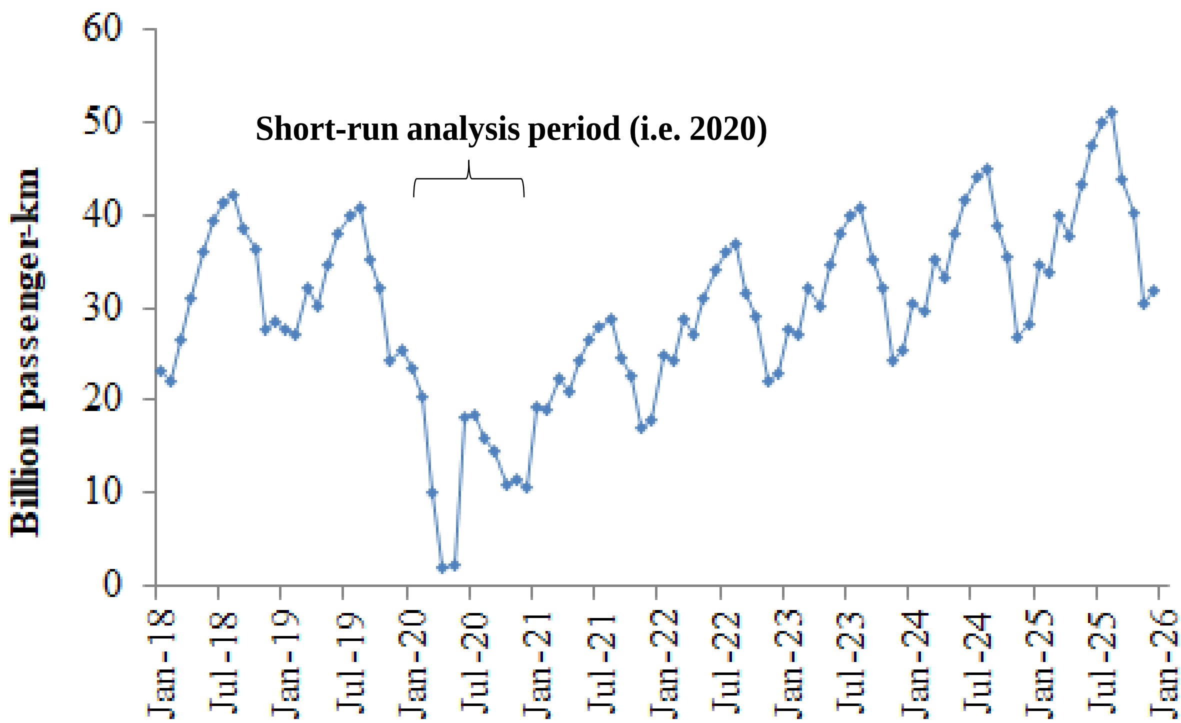
Source: Eurocontrol (2020), CAA (2020); for details, see Supplementary Material.

Figure 5 shows that, in early March 2020, there were around 1.2 billion passenger-km travelled per day in the UK. The decline began on Monday 16 March 2020 (1.03 billion passenger-km), with passenger-km travelled 15% down compared to Monday 9 March. By Sunday 22 March, passenger-km had dropped 67% (368 million passenger-km) relative to the previous Sunday and on Monday 23 March, when the lockdown began, levels of air travel dropped to an estimated 287 million passenger-km, representing a 76% decrease compared to Monday 9 March. As Figure 5 shows, this decline continued rapidly for one week after the lockdown had started, and then gradually for another two weeks. Daily air travel in May had fallen by 90% on average relative to February 2020, and also relative to its equivalent day in May 2019. *Overall, it is estimated that the formal lockdown led to a 96.3% reduction in passenger air travel compared with the equivalent days in 2019 and that this lockdown between 23 March and 31 May 2020 reduced passenger air travel by 17.7% compared with the whole of 2019 (and relative to the counterfactual 2020)*. For details on these estimates, see the Appendix.

Regarding air travel reductions after 1 June (the last day for which daily data has been collected), various sources offer insights. The European Commission (Iacus et al. 2020) has explored possible recovery scenarios at a global level by considering past disruptions to air travel due to pandemics. For instance, after the MERS outbreak in 2015 air travel took five months to return to normal and, during SARS in 2003, air travel behaviour in South East Asia took seven months to return to normal (Iacus et al. 2020 p.5). Based on this information, Iacus et al (2020) propose that the 'return to normality' may take seven to twelve months. Eurocontrol (2020b) on the other hand considers the recovery of the broad European air space, including the UK. It offers two scenarios related to flight recovery – a 'managed' and an 'unmanaged' recovery. These differ by about 20% in the first few months to 5% by December 2020. In the managed recovery scenario, all EU commercial flights are forecast to be 22% of their 2019 level in June, 38% in July, 50% in August, 60% in September, 70% in October, 80% in November and December.

The exact nature of the recovery is thus unclear, and will depend on numerous factors; for the purpose of the current study, we have opted to use the Eurocontrol (2020) 'managed recovery' scenario for 2020 (given that coordinated efforts are being discussed) and assume that the UK will recover at the average European rate of all (i.e. including cargo) flights. Flight number estimates are combined with UK CAA (2020a) monthly passenger-km data for 2019 to generate a monthly forecast of passenger-kms until the end of 2020. Figure 6 presents these forecasts. In addition, Figure 6 also presents air travel forecasts to 2025, as produced by Pearce (2020), chief economist for IATA. This additional information – described in more detail in Section 6 - will form the basis for analysing the return of air travel towards its longer-run trend. We present it here in order to locate short run forecasts of air travel behaviour within the broader picture of air travel recovery over the next 5 years.

Figure 6. Estimated and Projected Monthly Air Travel in the United Kingdom, January 2018-December 2025



Source: Pre-June 2020 : CAA (2020),;June 2020-December 2020: Eurocontrol (2020); From 2021: Pearce (2020)

This forecast of the recovery shows a summer peak, as in other years. However, the gradual return to normality implies that the summer peak will be less pronounced than in normal years. Summing the estimates (up to 1 June) and forecasts (June to December) of monthly air travel*, it is estimated that air travel will be 52.6% lower in 2020 than in 2019 and 53% lower than the counterfactual 2020*. This forecast will be used as the basis for estimating the short-run welfare and environmental impacts (presented in the next two sub-sections).

(ii) Welfare effects of air travel reductions due to Covid-19

To understand the welfare impacts of the reductions in passenger air transport, this study estimates the welfare loss from Covid-19 occurring *and* the restrictions (formal and self-imposed) on air travel. This point is specified because there may have been a temporary shift in preferences and the demand for air travel due to the health risks – people may no longer have wanted to fly because of Covid-19. There may also have been changes in demand due to reductions in income triggered by the economic collapse from the lockdown. Finally, there may have been supply changes. So, the market may be in disequilibrium (e.g., during the lockdown) or there may be a new equilibrium (e.g., outside of the lockdown period). However, this study remains agnostic about the causes of the reductions in air travel. Here, the assumption is that, in the absence of Covid-19 and any associated factors, the counterfactual demand and counterfactual supply would have met in equilibrium. As presented in the previous sub-section, consumption in 2020 is estimated to be 53% lower than the counterfactual equilibrium in 2020.

With this assumption, the welfare analysis estimates the area under the counterfactual demand curves (and above the price line) for each income quintile from the margin to the 47th percentile (i.e. 100%-53%). This area indicates the reduction in welfare from being 53% below the equilibrium (see Figure A4 in the Appendix for further clarification). The difference in net benefits is the estimated welfare loss from Covid-19 and the restrictions being imposed. Thus, this study constructs a demand curve for 2020 assuming that Covid-19 had not occurred (the 'counterfactual'), and estimates the loss in net benefits from being 53% below the 2020 counterfactual equilibrium.

Table 1 presents the estimates of a 53% reduction in air travel for each income quintile. The minimum average welfare loss (compared with the BAU counterfactual of air travel in 2020) is 9%[13]. This can be found in the right-most column of the second bottom row. This indicates that the flights at the margin create limited welfare gains, and that a large proportion of air travel can be reduced without a major burden on average welfare.

However, there is substantial variation across the income distribution. For instance, at the second lowest income quintile, the reductions in air travel due to Covid-19 lead to an estimated a 22.1% decline in welfare; meanwhile, the second highest income quintile only experiences a 4.8% decline in welfare. As discussed in the previous section, the convexities of the demand curves at different income levels imply that, in relative terms, the poorer travellers have missed out on flights for which they have relatively high WTP. By comparison, the higher income quintiles have demand curves with longer 'tails'. The implication is that, when the rich experience reductions of more than half of their annual air travel, they miss out on flights that provide only relatively small levels of welfare – while still taking those flights which they highly value. In sum, results suggest that the short-run reductions in air travel due to Covid-19 have negatively impacted the poor (i.e. the bottom two income quintiles) around two-and-a-half times more than the wealthier segments of the UK population (i.e. top two income quintiles).

[13] Another assumption is that travellers got their money back from any flights they bought but could not take.

Table 1. Welfare impacts of Covid-19-related air travel reductions in 2020[14]

	Q1	Q2	Q3	Q4	Q5	Average
Average household income 2019	£11,115	£22,623	£35,890	£54,475	£110,661	£46,953
Air travel 2019 (% of total)	5.2%	5.7%	8.3%	22.8%	58.0%	
Air travel 2020 Counterfactual (Average km per person)	1,521km	1,653km	2,427km	6,624km	16,836km	5,812km
Minimum welfare loss from Covid-19 in 2020	**25.6%**	**22.1%**	**6.9%**	**4.8%**	**9.1%**	**9.0%**
Median welfare loss from Covid-19 in 2020	**50.8%**	**41.6%**	**25.2%**	**17.5%**	**17.1%**	**31.1%**

Sources: Income (ONS 2020); Actual air travel 2020 based on the actual reductions in air travel up to 1 June 2020 and, from June to December 2020, the Eurocontrol (2020) forecast of a 'managed recovery' – thus, *an overall 53% reduction in air travel and a 41.5% decline in emissions in 2020* compared with the BAU counterfactual of air travel in 2020. Air travel counterfactual 2020 and Welfare losses: authors' calculations – see Appendix.

So, far, this analysis has assumed that reductions to air travel occur at the margin; this is considered a reasonable assumption given that – even during the lock-down period - people were still flying, albeit only for the most essential flights. Analysis using alternative assumptions about the location of affected flights (or passenger-km) along the 2020 demand curve indicates that even if we assume that reductions to air travel occur at the median level of travel, the poor experience greater welfare losses than the affluent (see Table 1 and the Appendix for the method of estimation). On average, a median welfare loss is estimated to be 31.1% - substantially larger than the 9% minimum average loss.

(iii) Short-run environmental impacts

This sub-section presents an estimate of the carbon dioxide emissions reduction in 2020 associated with Covid-19. Using UK data on air travel and emissions (BEIS 2020), an estimate of the coefficient of the influence of air travel on emissions is 0.78 (see Appendix). That is, a 10% reduction in passenger-km leads to 7.8% reduction in emissions. This result indicates that, although much of the reduction in air travel feeds through into lower emissions, it is less than proportional.

The three-month period between the beginning of March 2020 and the end of May 2020 was associated with an 87% reduction in air travel and a 68% decline in emissions (or 14.3 mtCO_2e avoided) relative to the counterfactual. In comparison, Le Quéré et al (2020) estimate that around the world, on average, the

[14] Due to space limitations, additional information can be found in the Supplementary Material. These include the assumptions made to generate the welfare impacts and the separate impacts of the official restrictions (i.e., the lockdown) and the behavioural.

aviation industry experienced a 75% reduction in activity and 60% in carbon dioxide emissions. In other words, the UK appears to have been affected more severely than the global average. They argue that the aviation industry has been the most crippled sector – and has been responsible for 10% of the global reductions in CO_2 due to Covid-19.

Looking at the whole year, assuming the same travel-emission coefficient, *CO_2 emissions from air travel in the UK are estimated to be 41.5% lower as a result of Covid-19 and the associated travel restrictions relative to the counterfactual 2020. This is equivalent to 34.8 tonnes of avoided CO_2 emissions*. Table 1 indicates that the minimum average welfare loss was only 9%. This implies an emissions-reductions-to-welfare loss (E-W) ratio for the whole of 2020 is estimated to be a 5.9. Using the median average welfare loss of 31.1%, the ratio is 1.7.

6. Covid-19 and Aviation's Low Carbon Take-off

This section explores the longer run behavioural, welfare and environmental impacts of Covid-19. Because of the disruptive nature of Covid-19 for the airline industry, it is impossible to offer robust predictions of the long run impacts. This is especially the case given the current uncertainty around the scale and conditionality of government assistance that may be disbursed to assist the airlines, and the future of key environmental aviation policies, such as CORSIA (see below), that are currently under discussion. In light of these uncertainties, this section presents an exploratory analysis of the possible impacts of key environmental policy measures – specifically, carbon taxes and frequent flyer levies - between 2021 and 2050. The impacts of these measures will be compared to a baseline scenario, in which the aviation industry returns to a 'business as usual' scenario.

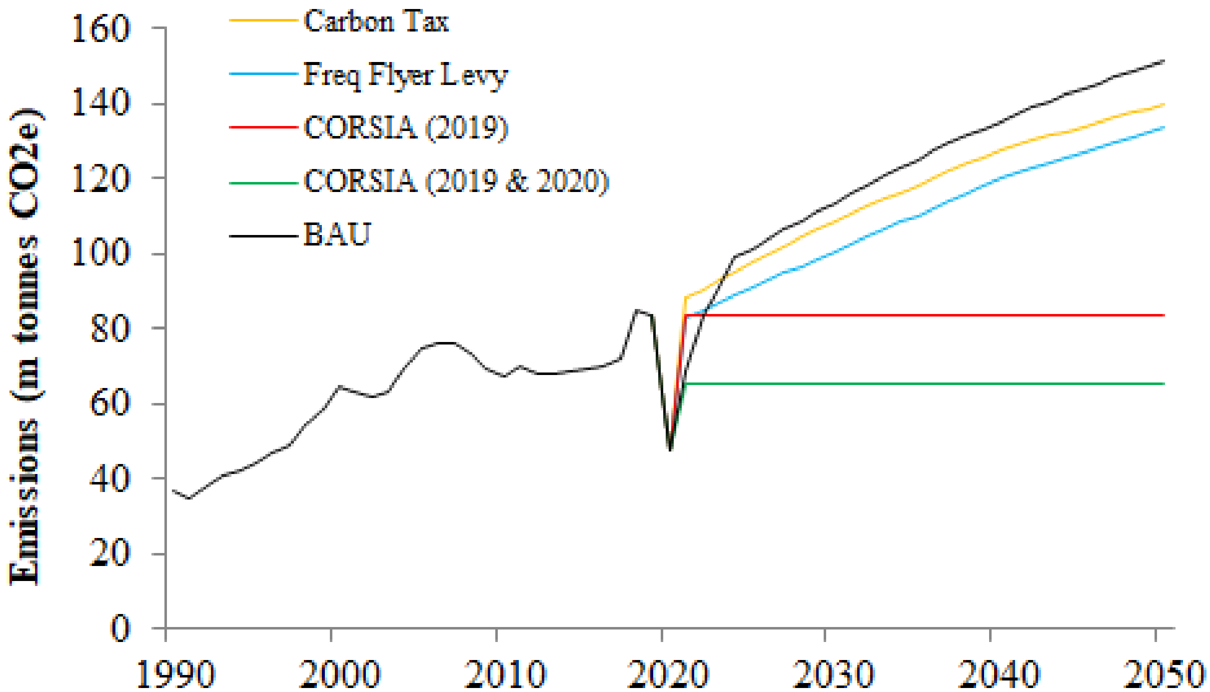
This section also considers the role of CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation), a voluntary but non-enforceable aviation industry agreement, in delivering CO_2 emissions. CORSIA aims to stabilise CO_2 emissions from aviation at 2019/2020 levels via carbon offsets, fuel substitution and technological developments. The disruption to air travel caused by Covid-19 has led to considerable uncertainty about the future of CORSIA, and its ability to deliver emissions reductions from air travel (Graver 2020). Furthermore, studies (Larsson et al. 2019; Winchester, 2019; Pavlenko, 2018) suggest that CORSIA alone will be insufficient in the face of increasing demand for air travel. Hence, finding policy measures that can contribute towards demand reduction and maintenance is essential.

This paper remains agnostic about what level of air passenger travel is desirable or required to ensure zero emission targets. The central aim of this section *is to identify which policies have the greatest potential to maintain reduced consumption – and associated carbon dioxide emissions – with minimal impacts on welfare*. The criticality of addressing this issue at this particular point in time could not be greater. The severe impact of Covid-19 on the airline industry, and its inevitable reliance on government assistance to support its recovery, means that governments are potentially in a position to condition bailouts on environmental and low-carbon clauses. Thus, the year 2020 is a critical juncture for the aviation industry, during which decisions made by government and the aviation industry about the scale and type of recovery will lead to dramatic differences in the long-run behavioural, welfare and environmental outcomes.

With this in mind, this section presents *four main long run scenarios*: (i) business-as-usual, in which travellers return to the pre-Covid-19 long-run trend; (ii) net emissions associated with air travel are stabilised in line with the CORSIA agreement; (iii) introduction of a carbon tax; and (iv) introduction of a frequent flyer levy. Scenarios (iii) – (iv) are assessed in comparison to the baseline scenario and estimate how passenger air travel behaviour, consumer welfare and carbon dioxide emissions might be affected. Scenario (ii) does not consider behavioural and welfare impacts, as the scheme aims to reduce carbon emissions by targeting the industry directly; this does not mean that industry will not pass on the costs of offsetting their carbon footprint to consumers, however, due to the uncertainty and complexity inherent in such an analysis, welfare estimates are not produced here (see footnote 11 for a brief discussion). Together, these four scenarios cover the range of likely outcomes following negotiations within the airline industry and with governments at this critical time.

The **business-as-usual (BAU) scenario** would see a return to the long-run trend with no efforts to address carbon dioxide emissions, albeit taking account of the recovery following Covid-19. Inevitably, there are many uncertainties around GDP growth, travel-related policies, airline industry survival and bailouts, and traveller concerns about health and other risks. Acknowledging but without explicitly addressing these uncertainties, Pearce (2020), as chief economist for IATA, offers a forecast to 2025. He suggests that air travel will take two to three years for demand to return to 'normality' – 2021 would be 70%, 2022 would be 90% and 2023 would be 100% of the 2019 level. These forecasts, shown in Figure 6 as monthly data, create the link between the recovery of air travel with the long run trend in air travel presented in Figure 7.

Figure 7. Scenarios of Net Carbon Dioxide Emissions from UK Air Travel, 1990-2050



Source: Pre-2019: BEIS (2020); 2019: see text and Supplementary Material. Note that the BAU scenario takes account of the gradual recovery to 2025 presented in Eurocontrol (2020) and Pearce (2020). However, the Carbon Tax and Frequent Flyer Levy Scenarios do not take account of the recovery., and are based on demand curves that are unaffected by Covid-19. Thus, for the first few years after Covid-19, emissions in the BAU Scenario are lower than the emissions related to the Carbon Tax and Frequent Flyer Levy Scenarios..

This scenario uses OECD's (2019) long run projection of UK GDP up to 2060 and ONS's (2019) projection of UK population to 2100 to estimate per capita GDP growth (discussed in more detail in the Appendix). By assuming no changes to the income distribution between 2018 and 2050, estimates of average income by quintile are produced. By combining them with income elasticities of demand for air travel, and constant real prices and constant emissions-to-flight coefficients, the BAU scenario anticipates a rise in passenger-kms travelled of 42% by 2030, and 91% by 2050, compared with 2019. Based on these assumptions, emissions from air travel in the UK are estimated at 114 million tonnes of carbon dioxide by 2030 and 152 million tonnes by 2050. Figure 7 shows the pathway of emissions for this (BAU) scenario from 2020 to 2050. As way of comparison, these would be equivalent to 36% and 81% of the total emissions for the UK in 2019 (BEIS 2020). Thus, given the anticipated shrinkage of emissions from the power sector, and possibly car travel with a shift to electric vehicles over the next thirty years, air travel unchecked could become the single most important source of carbon dioxide emissions in the UK by 2050.

Scenario (ii) (**implementation of CORSIA**) is particularly interesting in the context of Covid-19. From 2021, the CORSIA scheme will come into effect. This resolution was agreed in October 2016 by the International Civil Aviation Organization (ICAO), a UN specialized agency, as a means to address CO_2 emissions from international aviation as of 2021. As noted, CORSIA aims to stabilise CO_2 emissions at the average of the 2019 and 2020 levels by requiring airlines to offset the growth of their emissions after 2020. Based on actual levels of air travel to 31 May 2020 and forecasts from June to December 2020 discussed in the previous section, Figure 7 shows the extreme scenario in which air travel net emissions are indeed stabilised at the 2019-2020 average level – 22% below the 2019 level – at 65.5 million tonnes of carbon dioxide equivalent (mtCO_2e). The challenge is actually achieving this net level of emissions.

To meet CORSIA targets, airline companies will essentially rely on carbon offsetting, at least initially, since the introduction of alternative jet fuel is currently non-viable due to prohibitive production costs, regulatory uncertainty and competition with demand from other sectors (Prussi et al. 2019, Pavlenko 2018, Kousoulidou and Lonza 2016). Technological improvements in aircraft efficiency are an even more distant prospect, with no alternative propulsion technologies yet certified for commercial use let alone considered for market penetration (Kousoulidou and Lonza 2016). Thus, what will be required are very large levels of offsetting, especially for a sector that is experiencing such a steep increase in demand, as shown in the BAU scenario.

Crucially, the Covid-19 crisis has caused levels of CO_2 from aviation to plummet. Based on the BAU projections, by 2030, the airline industry associated with UK air travel would need to offset 42% of its emissions and, by 2050, 57% of its emissions to meet the CORSIA emissions target. Assuming a real price of £20 per tonne to offset emissions, and that offsetting is the only method of reducing emissions, the industry would spend annually £0.96 billion by 2030 and £1.7 billion (in real terms) on carbon offsets related to UK passenger air travel. To put this in perspective, between 2005 and 2013, as a whole, the UK airline industries managed to make a pre-tax profit of more than £1 billion in only one year, 2013 (CAA 2020c). Thus, the scale of the offset (or alternative fuel) expenditure would impose a major new burden on the airline industry, from 2024, once air travel had risen above 2019 level (see Figure 7). An alternative option currently under discussion is that CORSIA should use 2019 emission levels instead of the 2019-2020 average as the baseline. A modified CORSIA agreement implies that the UK airline industry would need to maintain its net emissions at roughly 86.6mtCO_2e. Using the BAU projections, by 2030, the airline industry associated with UK air travel would need to offset 26% of its emissions by 2030 and 45% of its emissions by 2050. Again, with a real price of £20 per tonne, the industry would spend £0.6 billion by 2030 and £1.3 billion (in real terms) on carbon offsets related to UK passenger air travel - still a very large burden.

Nonetheless, even if the airline industry could shoulder this burden, the ability of CORSIA to deliver the required emissions reductions is under debate, with studies showing that carbon offsetting may reduce only a fraction of airline emissions (Larsson et al., 2019; Scheelhaase et al., 2018; ICCT, 2017). Hence CORSIA will not be sufficient to counteract the increase in emissions due to increasing demand[15]; for this reason, it is essential to consider other options that actively reduce demand, as we do below.

Scenario (iii) (introduction of carbon tax) assumes that CORSIA is neither maintained nor modified and is replaced with a carbon tax imposed on consumers by the British government[16]. There are many possible values suggested in the literature for an aviation carbon tax[17]. Based on recommendations by Burke et al (2019), which provides a review of the literature on the social costs of carbon and possible carbon taxes for the airline industry, the carbon tax considered in this paper is imposed on the consumers and starts at £50 per tonne of carbon dioxide in 2020 and rises linearly to £160 by 2050. On current technology, this is equivalent to a rise from 0.3 pence to 1 penny per passenger-km travelled – note that the average price of air travel is 6 pence per passenger-km. While there is much debate about the social cost of carbon (Burke et al 2019), this tax can be seen as a reflection of the marginal benefits of abatement. If the consumer is faced with a tax, the demand curve (and particularly the consumer surplus underneath the curve and above the price line) can be seen as the marginal costs of reducing air travel to the consumer, i.e. the net loss from not flying.

Figure 8 shows the demand curves in 2030 and 2050 for two income quintiles. For each income quintile in each year, the point where the price line plus the carbon tax meets the demand curve identifies the optimal level of consumption. Thus, this scenario identifies the optimal consumption pathway for consumers when faced with the proposed carbon tax on aviation.

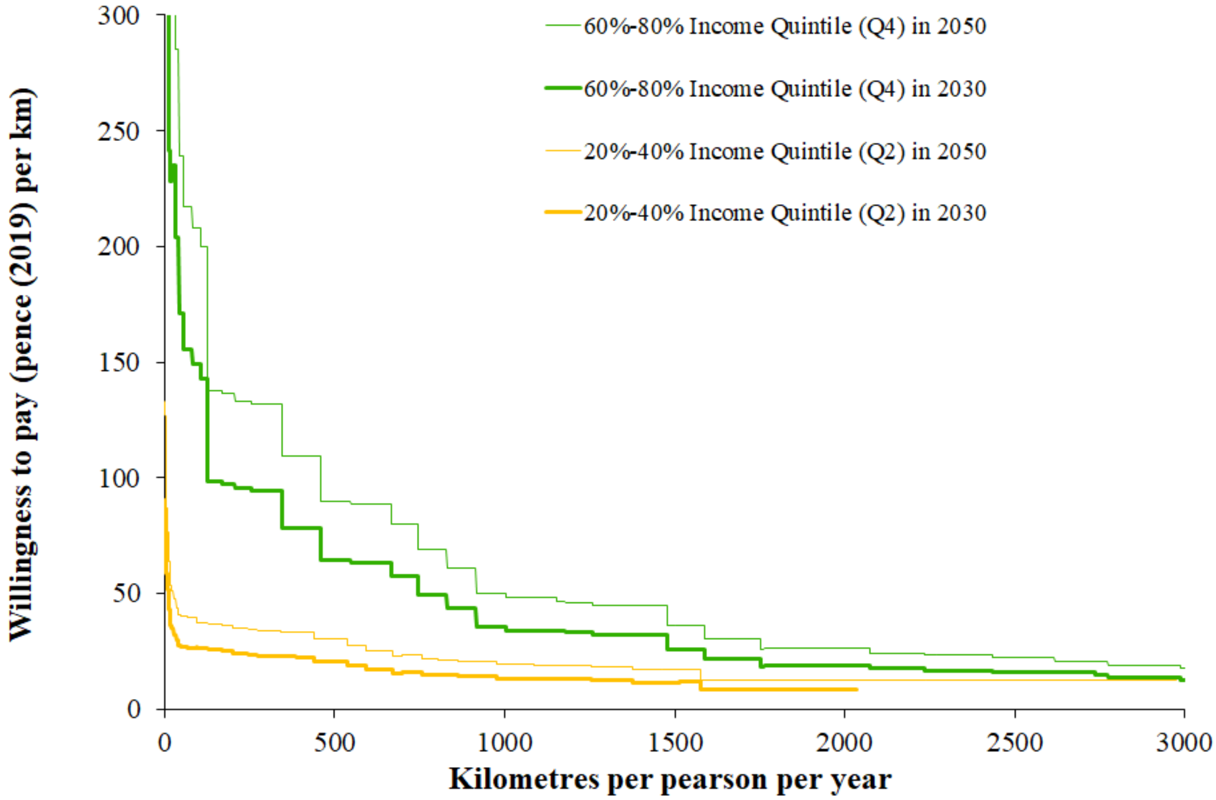
---

[15] Regarding effects on demand and consumer welfare, it is proposed that CORSIA will have minimal direct consumer welfare impacts. Of course, some of the cost of the offsets could be passed on to the consumer. The extent to which airlines can pass on this additional expenditure depends on the price elasticity of demand. The less price-elastic the demand, the more the industry can pass costs onto to the consumer. Attempts to pass on the burden by imposing higher prices would lead to reductions in air travel, lowering the offsets required, but also lowering industry revenue and profits. Given the high price elasticities presented in Figure 2, the airline industry may have to carry much of the burden, passing on perhaps a small proportion to wealthier customers (who are less, but still fairly, price-elastic). Given the uncertainty and complexity of the analysis, estimates of the welfare impacts of CORSIA cannot be presented in this paper.

[16] While demand-reducing measures, such as a carbon tax, could be implemented in conjunction with offsetting policies such as CORSIA, we consider alternative measures in isolation in order to avoid the uncertainty and complexity of analysing two overlapping and interacting systems, and disaggregation of the respective impacts of each policy measure.

[17] For a richer discussion of the introduction of a carbon taxation, its incidence and its revenue, see Goulder (1995), Parry et al (1999), Hassett et al. (2009), Rausch et al. (2011).

Figure 8. Demand for Air Transport in the United Kingdom in 2030 and 2050



Source: see text and Supplementary Material. For presentational purposes, Q2 and Q4 are displayed, as they lie on the extremes – as shown in Figure 4 and discussed in Section 4 on the demand. All income quintiles experience shifts in the demand curves between 2030 and 2050.

Table 2 presents the behavioural, environmental and welfare impacts of introducing this carbon tax. Assuming that average prices remain constant (in real terms) - apart from the carbon tax - air travel by 2030 would be 7.5% lower and 12% lower in 2050 compared to the BAU scenario. Emissions would fall by 5.8% in 2030 and 9.1% in 2050. This leads to an average welfare loss of 4.6% in 2030 and 6.5% in 2050. Here, the poorest income quintiles would lose 2.1% in net benefits from the tax while the richest quintile would lose 6% in net benefits in 2030. In 2050, this loss increases to 2.5% for the lowest income quintile and 14.8% for the top quintile. However, the second income quintile (Q2) would experience, say, in 2030, 5.6% fall in welfare for a modest 2% reduction in emissions. Thus, a carbon tax on aviation would not be a fully progressive tax.

Table 2. Welfare impacts of a Carbon Tax in 2030, 2040 and 2050

	Q1	Q2	Q3	Q4	Q5	Average
2030 % Reductions in:						
Air travel	2.6%	2.6%	6.8%	5.5%	9.9%	7.5%
CO_2 Emissions	2.0%	2.0%	5.3%	4.3%	7.6%	5.8%
Welfare	2.1%	5.6%	4.5%	5.1%	8.9%	5.8%
2040 % Reductions in:						
Air travel	2.3%	3.8%	11.5%	7.9%	11.7%	9.2%
CO_2 Emissions	1.8%	3.0%	9.0%	6.1%	9.1%	7.2%
Welfare	2.3%	6.7%	7.4%	6.5%	14.3%	6.8%
2050 % Reductions in:						
Air travel	2.2%	4.8%	16.1%	10.9%	14.8%	11.7%
CO_2 Emissions	1.7%	3.7%	12.5%	8.5%	11.5%	9.1%
Welfare	2.5%	7.5%	10.8%	7.9%	17.8%	7.5%

Sources: authors' calculations. Carbon tax starts at £50 per tonne of carbon dioxide in 2020 and rises linearly to £160 by 2050.

To offer additional information about the impact of carbon tax, the carbon tax is increased to take account of the increased climate impact from non-CO_2 aviation emissions, otherwise known as 'radiative forcing' (Lee, 2009; 2018). Following UK government guidelines for company greenhouse gas reporting (Hill et al., 2015), we use an emissions multiplier of 1.9 times the effects of CO_2. Although we recognise that multiplication of CO_2 emissions by the 'radiative forcing index' (the multiplier) to account for non-CO_2 impacts is not correct, given the different lifetimes of the various pollutants in the atmosphere (Lee, 2018; 2009), we use this as the next best option to account for non-CO_2 impacts in the absence of a more superior method to account for radiative forcing. It also serves as a sensitivity analysis for the introduction of a carbon tax.

Under this assumption, the carbon tax starts at £95 per tonne of carbon in 2020 and rises linearly to £304 by 2050. On current technology, this is equivalent to a rise from 0.57 pence to 1.8 penny per passenger-km travelled. With the same assumptions as before, air travel would be, by 2030, 14% lower and, by 2050, 24% lower than in the BAU scenario (see Table 3). Emissions would fall by 11.% in 2030 and 18.6% in 2050 relative to the BAU scenario. The average welfare loss would be 7% in 2030 and 9.5% in 2050. Again, this tax would hit the top income quintile much more than the bottom quintile, though the second income quintile would suffer substantially for modest reductions in emissions.

When a carbon tax is introduced, two factors alter the traveller's welfare. First, the cost of air travel rises – that is, every km travelled becomes more expensive. Second, on average, people travel less. It turns out that the former dominates the losses. As an example, in the standard carbon tax scenario presented in Table 2, the higher cost of flying accounts for 99% of the welfare losses of the bottom quintile (Q1) and

83% of the top quintile (Q5) welfare losses. The losses due to the travelling smaller distances are negligible because WTP values for the marginal km (say, the marginal 10%-20% of air travel in any year) are low. The net benefits of these marginal kms are especially low for the higher income quintiles, as discussed in relation to the convexity of the demand curves shown in Figure 4 and 8. Thus, a carbon tax reduces welfare to consumers mostly by charging more, rather than by discouraging travel[18].

Table 3. Welfare impacts of a Carbon Tax (with Radiative Forcing) in 2030, 2040 and 2050

	Q1	Q2	Q3	Q4	Q5	Average
2030 % Reductions in:						
Air travel	4.9%	5.9%	13.1%	10.1%	18.6%	14.2%
CO_2 Emissions	3.8%	3.9%	10.2%	7.9%	14.5%	11.1%
Welfare	3.9%	10.6%	8.3%	9.4%	17.0%	12.0%
2040 % Reductions in:						
Air travel	4.3%	7.4%	21.8%	15.0%	22.3%	17.5%
CO_2 Emissions	3.4%	5.8%	17.0%	11.7%	17.4%	13.7%
Welfare	4.3%	12.4%	13.2%	11.9%	25.6%	12.3%
2050 % Reductions in:						
Air travel	4.2%	9.0%	31.1%	28.2%	27.8%	23.9%
CO_2 Emissions	3.3%	7.0%	24.4%	22.0%	21.7%	18.6%
Welfare	4.6%	13.9%	18.8%	14.4%	31.4%	13.5%

Sources: authors' calculations. Carbon tax starts at £95 per tonne of carbon dioxide in 2020 and rises linearly to £304 by 2050.

Scenario (iv) (frequent flyer levy) considers an alternative policy measure that has been receiving increasing attention in recent years. The measure aims to discourage excessive travel with minimal welfare loss. Recently, the CCC (2019) published a letter urging the UK government to introduce such a policy measure. While the proposal did not provide detail on specific features of the frequent flyer levy, the basic idea is that the levy would target individual consumption of air travel and increase with each additional flight taken by an individual. For the analysis presented here, it is assumed that the first flight would be exempt from the levy, the second flight would be at the rate of the proposed carbon tax (i.e., £50 per tonne of carbon, which is currently equivalent to 0.3 pence per km – in scenario (iii)), the third flight would be double the proposed carbon tax, the fourth flight triple the carbon tax and so on, with linear

[18] The higher cost charged to the traveller is revenue to the government, which could be used to alleviate the welfare losses. So, in overall terms, the sum of the welfare losses to the consumer and the gains to the government cancel each other out, apart from the administration costs of the tax. However, this focus on the overall picture ignores the fact that the traveller suffers a welfare loss in the context of air travel, which affects the political acceptability of the policy – and this remains the focus of this paper.

increments in cost with each additional flight[19]. Here, because the demand curves are constructed based on the kilometres travelled by the average consumer, it is assumed that each (return) flight is equivalent to 2,500km to a return flight (e.g., roughly London to Alicante in Spain, and back)[20]. Thus, *the frequent flyer levy becomes increasingly expensive with each individual's additional flight (or distance travelled) and, therefore, discourages excessive and 'unnecessary'*[21] *travel*.

The emissions related to Scenario (iv) are displayed in Figure 7 (see above). It shows that passenger-kms travelled and associated emissions in the Frequent Flyer Levy Scenarios reduce air travel compared to the baseline and carbon tax scenarios[22]. Table 4 summarises the behavioural, environmental and welfare impacts of a frequent flyer levy. The estimates indicate that in 2030 a 15.6% reduction in air travel and a 12.2% fall in carbon dioxide emissions can be achieved with only a 7% welfare loss on average. By 2050, a 16.2% reduction in air travel and associated emissions can be achieved with only a 4.3% loss in welfare on average, and almost no welfare impact on the bottom two quintiles.

While the frequent flyer levy does not reflect the marginal cost of flying (since each kilometre flown broadly generates the same amount of CO_2 – with variation dependent on aircrafts, wind directions and altitudes), it minimises the consumer welfare losses while discouraging excessive travel. It also has the virtue of being highly progressive, focussing on the higher income quintiles, which tend to be made up of the more frequent flyers. Thus, it is likely to be politically more acceptable than a blanket carbon tax applied to all flights[23].

[19] As with the carbon tax, the assumption is that the levy is imposed on the consumer. However, there is a difference in how the instrument escalates. With the carbon tax, the escalation is over time – rising between 2020 and 2050. With the levy, it escalates as individuals consume more in any year, but it does not change over time.

[20] Given that emissions are related to distance travelled, a levy might be best placed on kms travelled rather than flights.

[21] Here, 'unnecessary' travel is assessed at a personal level and refers to travel which generates relatively little welfare to the individual. Each person faced with a rising cost of each additional flight can assess which flights are necessary and which ones are unnecessary.

[22] It is worth stressing that a particular tax or levy (e.g., £50 per tonne of carbon) will lead to the same reduction, because, in this analysis, the optimal level of consumption is identified as the point where the demand curve (i.e., the marginal benefits of consumption) are equal to the price plus the tax or levy. Thus, the optimal level of consumption will be the same whether it is using a carbon tax or a frequent flyer levy.

[23] While the frequent flyer levy might be seen as logistically more complicated, the passport controls help to monitor behaviour and, therefore, identify the number of flights taken and the total levy due by each person.

Table 4. Welfare impacts of a Frequent Flyer Levy in 2030, 2040 and 2050

	Q1	Q2	Q3	Q4	Q5	Average
2030 % Reductions in:						
Air travel	0.1%	0.0%	4.0%	0.9%	28.2%	15.6%
CO_2 Emissions	0.1%	0.0%	3.1%	0.7%	22.0%	12.2%
Welfare	0.2%	0.0%	0.7%	3.6%	16.7%	7.0%
2040 % Reductions in:						
Air travel	1.4%	0.2%	4.6%	9.5%	26.5%	15.5%
CO_2 Emissions	1.1%	0.1%	3.6%	7.4%	20.6%	12.1%
Welfare	0.5%	0.0%	1.5%	3.8%	15.9%	4.8%
2050 % Reductions in:						
Air travel	1.4%	0.1%	10.2%	12.2%	27.3%	16.2%
CO_2 Emissions	1.1%	0.1%	8.0%	9.5%	21.3%	12.7%
Welfare	0.7%	0.4%	2.5%	4.0%	16.0%	4.3%

Sources: Air travel Reductions (in average km per person), emissions and welfare losses: authors' calculations. Frequent Flyer Levy: 0 for the first flight; £50 per tonne for the second flight, £100 for the third flight, etc. i.e. FFL(f)= (f-1)*£50 where f=flight number taken in any year.

Table 5. Welfare impacts of a Frequent Flyer Levy (with a Radiative Forcing Multiplier) in 2030, 2040 and 2050

	Q1	Q2	Q3	Q4	Q5	Average
2030 % Reductions in:						
Air travel	3.0%	3.0%	0.7%	12.3%	43.2%	26.3%
CO_2 Emissions	2.3%	2.4%	0.6%	9.6%	33.7%	20.5%
Welfare	0.3%	0.1%	1.5%	5.7%	28.1%	11.8%
2040 % Reductions in:						
Air travel	3.7%	0.6%	9.3%	18.0%	38.7%	24.1%
CO_2 Emissions	2.9%	0.4%	7.2%	14.0%	30.2%	18.8%
Welfare	0.9%	0.0%	2.7%	6.5%	24.1%	7.6%
2050 % Reductions in:						
Air travel	3.9%	2.9%	20.5%	19.1%	39.8%	25.1%
CO_2 Emissions	3.1%	2.3%	16.0%	14.9%	31.0%	19.6%
Welfare	1.3%	0.7%	4.2%	6.9%	24.2%	6.9%

Sources: Air travel Reductions (in average km per person), emissions and welfare losses: authors' calculations. Frequent Flyer Levy: 0 for the first flight; £95 per tonne for the second flight, £190 for the third flight, etc.. i.e. FFL(f)= (f-1)*£95 where f=flight number taken in any year.

As with the carbon tax, a multiplier to take account of the radiative forcing was applied to the frequent flyer levy. This leads to greater reductions in travel and emissions and to larger welfare losses. For instance, the average air travel and emissions fall by 20.5% in 2030, causing 11.8% of welfare losses (see Table 5). By 2050, travel and emissions have fallen by 25.1% (relative to the baseline scenario) but only lead to welfare losses of 6.9%. Again, the large air travel reductions, emissions and welfare losses are focussed on the top income quintile.

Summary Findings of Long-Run Scenarios

Table 6 summarises the results from the various carbon taxes and frequent flyer levies. Notably, travel and emissions reductions increase over time, as do the welfare losses, as a consequence of the assumption that the carbon tax rises from £50 in 2020 to £160 by 2050. Instead, the frequent flyer levy ramps-up as an individual travels more in any particular year. However, here, it is assumed that the levy does not change over time. Naturally, if a higher levy is introduced (as with the multiplier sub-scenario (iv) – shown in Table 5 and the fourth column of Table 6), reductions and welfare losses would increase. Based on the assumptions presented, the frequent flyer levy achieves the greatest reductions in emissions. However, both taxes and frequent flyer levies have the potential to achieve almost any level of reductions in emissions.

Table 6. Average air travel, carbon dioxide emissions and welfare impacts of policies in 2030, 2040 and 2050

	Carbon Tax	Carbon Tax (with radiative forcing)	Frequent Flyer Levy	Frequent Flyer Levy (with Multiplier)
2030 % Reductions in:				
Air travel	7.5%	14.2%	15.6%	26.3%
CO_2 Emissions (E)	5.8%	11.1%	12.2%	20.5%
Welfare (W)	5.8%	12.0%	7.0%	11.8%
E-W Ratio	0.9	0.9	1.6	1.6
2040 % Reductions in:				
Air travel	9.2%	17.2%	15.5%	24.1%
CO_2 Emissions (E)	7.2%	13.7%	12.1%	18.8%
Welfare (W)	6.8%	12.3%	4.8%	7.6%
E-W Ratio	0.7	0.8	2.0	2.0
2050 % Reductions in:				
Air travel	11.7%	23.9%	16.2%	25.1%
CO_2 Emissions (E)	9.1%	18.6%	12.7%	19.6%
Welfare (W)	7.5%	13.5%	4.3%	6.9%
E-W Ratio	0.6	0.7	2.2	2.2

Sources: authors' own calculations - see text. As a reminder: (i) the Carbon Tax (column 1) starts at £50 per tonne of carbon dioxide in 2020 and rises linearly to £160 by 2050. (ii) the Carbon Tax with Radiative Forcing (column 2) starts at £95 per tonne of carbon dioxide in 2020 and rises linearly to £304 by 2050; (iii) the Frequent Flyer Levy is £0 for the first flight (i.e., 2,500km); £50 per tonne for the second flight (2,501km-5,000km), £100 for the third flight (5,001km-7,500km), etc.. in any year; (iv) the Frequent Flyer Levy with Radiative Forcing is £0 for the first flight (i.e., 2,500km); £95 per tonne for the second flight (2,501km-5,000km), £190 for the third flight (5,001km-7,500km), etc.. in any year; (v) to ensure a comparable analysis, both taxes and levies are imposed directly on the consumer; (vi) the reductions in travel, emissions and welfare in any particular year (e.g., 2030) are compared with a BAU scenario in the particular year (i.e., 2030).

One way of determining the effectiveness of the policy measures is the welfare loss from a particular level of emissions reduction. The first column of Table 6 indicates that the carbon tax has a ratio of emissions-reduction-to-welfare-loss (E-W Ratio) of 0.9 in 2030 and 0.6 in 2050, suggesting that it becomes less effective over time. Raising the carbon tax increases the reductions in travel and emissions and the welfare losses by similar amounts – thus, a similar ratio (as shown in the second column). In comparison, the ratio associated with the frequent flyer levy is about 1.6 in 2030 (see the third column). Thus, in 2030, the frequent flyer levy is twice as effective at reducing emissions. Increasing the levy simply increases both reductions and losses in the same ratio (fourth column). Furthermore, the ratio is 2.2 in 2050, suggesting that the frequent flyer levy becomes increasingly effective as demand increases.

As mentioned in relation to carbon taxes (above), the largest source of welfare loss is the extra expenditure paid for each km. This monetary penalty for travelling explains the low E-W Ratio (0.9 in 2030) of the carbon tax. The *reductions* in air travel associated with the carbon tax impose relatively little loss because the willingness to pay values are low at the margin. As a result, the frequent flyer levy imposes relatively less harm – with an E-W Ratio of 1.6 in 2030. This also explains why the reductions in air travel and emissions associated with Covid-19 impose relatively minor welfare losses. In fact, the emissions-reductions-to-welfare loss ratio for the whole of 2020 is estimated to be between 1.7 (assuming the median loss) and an impressive 5.9 (based on the minimum average welfare loss), because travellers were not required to pay a penalty for flights they did take. Thus, the Covid-19 experience highlights the potential effectiveness of environmental policies that achieve behavioural reductions without imposing monetary penalties.

7. Conclusion

As we move from the Covid-19 lockdown to recovery, we face a unique opportunity to assess our current economic trajectory, and to identify the mechanisms needed to shift direction onto a more sustainable pathway. Decisions made by policy makers today will inevitably lead to path-dependent processes which will constrain future policy developments to a point where change becomes difficult or even impossible. It is therefore critical to start identifying key opportunities to recover from Covid-19 via an equitable and low-carbon pathway that exacts minimal welfare losses from the UK public.

This paper seeks to do this, by examining opportunities for a low-carbon recovery and longer-term sustainable pathway for the airline industry specifically, with a focus on the UK. We ask to what extent the reductions in air travel due to Covid-19 - and corresponding carbon emission reductions - might be sustained beyond the lifetime of the pandemic, and the policy mechanisms that might support this reduction. The importance of addressing this issue with regards to air travel and the airline industry at the present time cannot be overstated; global demand for air travel is growing at 5.9% a year since 2010 (ICAO 2019), and it is predicted that by 2050 it will be single largest source of carbon emissions worldwide. Given that air travel was particularly hard hit by the pandemic, with airlines suffering huge financial losses (Pearce 2020), attempts to stimulate a recovery in this sector through public spending (bailouts) could be feasibly conditioned on stipulations requiring lowering of carbon emissions. Thus, we are at a critical moment during which the government's decisions about how to proceed with rescuing the airlines - if at all – will determine the future sustainability of air travel.

The evidence indicates that, in the short-run (i.e. over the course of the year 2020), the restrictions on air travel due to Covid-19 - which include mandated restrictions as well as self-imposed restrictions by passengers concerned about Covid-19 – affect the poorest 40 per cent of the income distribution about twice as much as the wealthiest 40 per cent. This uneven impact mirrors the broader picture of inequalities associated with Covid-19 impacts. The reasons for this uneven impact, is that poorer air travellers tend to fly less, and highly value those flights they take; high income air travellers however tend to fly more regularly, so restrictions may not be felt so keenly. Thus, in the short run, drastic reductions in air travel - generate uneven welfare impacts, with the poor suffering more than the wealthy.

In the long-term however, demand reduction and associated CO_2 reductions can be achieved via pricing mechanisms which ensure minimal welfare impacts – particularly among the lower income groups. Carbon taxes are one such mechanism for reducing carbon emissions. Using a carbon tax of £50 per tonne of CO_2e which increases linearly to £160 by 2050, it is estimated that air travel and corresponding CO_2 emissions would decline by 5.8% in 2030 and 9.1% in 2050 compared with a business-as-usual scenario. In absolute terms, the burden of such a carbon tax on passenger air travel would be imposed predominantly on the wealthy, who tend to fly more regularly than the less affluent. Analysis of welfare losses associated with a carbon tax suggests that - in 2030 - the wealthiest 40 per cent of UK travellers would experience relative welfare losses about 1.6 times greater than those of the least wealthy 40 per cent; in 2050, their welfare losses would be two times greater.

An alternative measure considered here is the 'frequent flyer levy', which aims to discourage excessive travel through increasing costs per distance travelled. The evidence indicates that the same reductions, in CO_2 emissions can be achieved using frequent flyer levies (which would focus on the margins) with only half the welfare losses than those resulting from the carbon tax mechanism. The frequent flyer levy becomes more effective at delivering emissions with minimal welfare costs as demand grows. It also has the virtue of being highly progressive, focussing on the higher income quintiles which, as noted, tend to be made up of the frequent flyers.

A key insight from the Covid-19 experience and the analysis of environmental policies beyond the pandemic is the value of achieving behavioural reductions while minimising monetary penalties. At the margin, consumers appear to not suffer greatly from reducing travel, but they suffer from paying more to reflect the environmental costs. Because travellers pay more for each km travelled, a carbon tax leads to an emissions-reduction-to-consumer-welfare-loss (E-W) ratio of less than 1 (see Table 6). A frequent flyer levy manages an E-W ratio of between 1.6 and 2.2, because it does not charge an environmental cost for the first flight a person takes in any particular year. Finally, the Covid-19 experience achieves an E-W ratio of between 1.7 and 5.9 – for the median and minimum average loss, respectively. Although the restrictions and behavioural changes associated with Covid-19 are not desirable or replicable, *they highlight the potential benefits from developing environmental policies that achieve behavioural and emission reductions without imposing large additional expenses on consumers – increasing the political acceptability of environmental policies*.

Inevitably, there are numerous limitations associated with the analysis, which have been discussed at length in Fouquet (2018). These relate to the data, the method for constructing demand curves through temporal benefit transfers, econometric analysis of income and price elasticities, assumptions made about the behaviour, environmental and welfare impacts and projections of future variables. These issues are also discussed in the Appendix. Furthermore, there are still many uncertainties about how Covid-19 experience will unfold. First, it is unclear how Covid-19 restrictions will continue. Second, it is unclear how quickly air travel behaviour will return to normal – indeed, the peak season is the summer and it will be heavily affected by national policies about tourist restrictions and quarantine regulation.

In addition, it was assumed that the carbon tax and frequent flyer levy would be imposed on the consumer. This assumption enabled a direct comparison between policies and a focus on behavioural changes. Instead, policies imposed on the supplier will help to encourage technological substitution and innovation within the aviation industry. However, as mentioned in relation to CORSIA, airlines may struggle to pass on any additional costs to consumers, with negligible impacts on behaviour.

Finally, taxes or levies are unlikely to be imposed in isolation. CORSIA has been discussed. There are a number of additional aviation policies that could also affect travel behaviour. Indeed, given the relatively high prices required to generate meet stringent emission reduction targets, it is likely to be politically out of reach, and the balance between pricing and complimentary policies may tip towards the latter under a net zero target. It is beyond the scope of this paper to identify the combined effect of the tax or levy with the complementary measures. For further discussion on the possible complementarity between climate policies, see Burke et al. (2019), Winchester (2019) and CCC (2020). So, there is considerable uncertainty about the nature of environmental policies that would be introduced, and whether they focus on achieving technological innovation or behavioural changes.

In the longer term, other factors also play a part in modifying air travel from its historical long run trends. Consumers may have reduced their travel because they have found substitutes for air travel such as ICT, especially business-related travel. This substitution has been a long run ongoing process, which has been associated with using communication technologies and their advances (including mail, telephone, mobile phone, texting, emails, WhatsApp, Skype, MS Teams and Zoom). The lockdown experience has encouraged many to adopt these technologies or software. For instance, Zoom use globally has increased 3000% between December 2019 and April 2020 (Iqbal 2020).

In addition, consumers may increasingly reduce air travel for environmental reasons. The lockdown and news on improvements in air and atmospheric pollutants may have raised individuals' awareness of the potential for improvements through behavioural changes.

The final crucial factor is the negotiations between the airline industry and government. Government will inevitably have the upper hand as it negotiates financial assistance to ailing airline companies. It can condition bailouts on compliance with existing environmental standards and/or on the acceptance of binding new environmental agreements. These political economy considerations are hard to anticipate. Yet, they will, more than any other factor, determine the long run environmental trajectory of air travel.

As Figure 7 shows the year 2020 is a critical juncture for the airline industry. Without external pressure, the financial woes of the industry could convince ICAO to abandon or simply ignore the CORSIA environmental standards. This would place air travel on a long run trajectory of potentially becoming the single largest source of carbon dioxide emissions by 2050. Instead, the ICAO could modify CORSIA (to use 2019 as the baseline for net emissions) and encourage the airline industries to genuinely offset a share of its emissions. Alternatively, in light of the weaknesses in CORSIA, the UK government could introduce national-level measures aimed at extending restrictions on air travel behaviour or, at least, making customers pay a reflection of the social costs of their behaviour. Either way, Covid-19 has made 2020 a pivotal year for air travel and our broader ambitions for achieving a low carbon economy.

References

Atkinson, A.B. (2007) 'The Distribution of Top Incomes in the United Kingdom 1908-2000' in Atkinson, A.B. and Piketty, T. (eds.) Top Incomes over the Twentieth Century. A Contrast Between Continental European and English-Speaking Countries. Oxford University Press. Oxford.

Barton, S. (2005) Working-Class Organisations and Popular Tourism, 1840-1970. Manchester University Press. Manchester.

Bateman, I.J., Brouwer, R., Ferrini, S., Schaafsma, M., Barton, D.N. and Dubgaard, A. (2011) 'Making benefit transfers work.' Environmental and Resource Economics 50: 365–387.

BEIS (2020) Provisional UK greenhouse gas emissions national statistics. https://www.gov.uk/government/statistics/provisional-uk-greenhouse-gas-emissions-national-statistics-2019

Bento, A.M., Goulder, L.H., Jacobsen, M.R., and Von Haefen, R.H. (2009) 'Distributional and efficiency impacts of increased US gasoline taxes.' American Economic Review 2009

Birkhead, E. (1960) 'The financial failure of British airline companies.' Journal of Transport History 4(3) 134-150.

Blalock, G., Kadiyali, V., and Simon, D.H. (2007) 'The Impact of Post-9/11 Airport Security Measures on the Demand for Air Travel.' Journal of Law & Economics 50(4) 731-755.

Burke, J., Byrnes, R. and Fankhauser, S. (2019) How to price carbon to reach net-zero emissions in the UK. Policy report. Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy. London School of Economics and Political Science. London.

Button, K., and Taylor, S., (2000) 'International air transportation and economic development.' Journal of Air Transport Management 6(4) 209–222.

Brons, M., Pels, E., Nijkamp, P., and Rietveld, P., (2002) 'Price elasticities of demand for passenger air travel: a meta-analysis.' Journal of Air Transport Management 8(3) 165–175.

CAA (2020a) Airline data. Civil Aviation Authority. https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Airlines/Datasets/

CAA (2020b) Passenger Survey Reports. Civil Aviation Authority. https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Consumer-research/Departing-passenger-survey/Survey-reports/

CAA (2020c) Airline financial tables. Civil Aviation Authority. https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Airlines/Datasets/UK-Airline-financial-tables/Airline-financial-tables-2013-2014/

Cai, Y., and Lontzek, T. S. (2019). 'The social cost of carbon with economic and climate risks.' Journal of Political Economy 127(6), 2684-2734.

CCC (2020) Net-zero and the approach to international aviation and shipping emissions. Letter to the Secretary of State for Transport. Committee on Climate Change .https://www.theccc.org.uk/publication/letter-international-aviation-and-shipping/

Chai, J., Zhang, Z.Y., Wang S.Y., and Liu, K.K. (2014) 'Aviation fuel demand development in China.' Energy Economics 46: 224-35.

Deaton, A.S. (1975) Models and Projections of Demand in Post-War Britain. Chapman and Hall. London.

DfT (2018) Aviation 2050, The future of UK aviation. A Consultation presented to Parliament by the Secretary of State for Transport. HM Government, December 2018.

DfT (2019). GB Transport Statistics (GBTS). HMSO. London.

Eurocontrol (2020) Daily Aircraft Traffic. https://www.eurocontrol.int/Economics/DailyTrafficVariation-States.html

Flores, N.E. and R. Carson (1997) 'The relationship between the income elasticities of demand and willingness to pay.' Journal of Environmental Economics and Management 33: 287–295.

Fouquet, R. (2014) 'Long run demand for energy services: income and price elasticities over 200 years.' Review of Environmental Economics and Policy 8(2) 186-207.

Fouquet, R. (2018) 'Consumer Surplus from Energy Transitions.' The Energy Journal 39(3) 167-88.

Fouquet, R. and Pearson, P.J.G. (2012) 'The long run demand for lighting: elasticities and rebound effects in different phases of economic development.' Economics of Energy and Environmental Policy 1(1) 83-100.

Gardiner, L. (2017) Homes sweet homes – the rise of multiple property ownership in Britain. Resolution Foundation. Available at: https://www.resolutionfoundation.org/comment/homes-sweet-homes-the-rise-of-multiple-property-ownership-in-britain/

Goulder, L.H. (1995) 'Effects of carbon taxes in an economy with prior tax distortions: an intertemporal general equilibrium analysis.' Journal of Environmental economics and Management 29(3) 271-297.

Graver, B. (2019) CO_2 emissions from commercial aviation, 2018. Working Paper 2019-16. The International Council of Clean Transportation.

Graver, B (2020) COVID-19's big impact on ICAO's CORSIA baseline. [Blog] The International Council of Clean Transportation. Posted Tuesday, 26 May 2020. Available at: https://theicct.org/blog/staff/covid-19-impact-icao-corsia-baseline [Accessed: 8th June 2020].

Hanemann, W.M. (1991). 'Willingness to pay and willingness to accept: how much can they differ.' American Economic Review 81: 635–647.

Hassett, K.A., Mathur, A., and Metcalf, G.E. (2009) 'The incidence of a U.S. carbon tax: a lifetime and regional analysis.' The Energy Journal 157–179.

Hicks, J. R. (1943) 'The Four Consumer's Surpluses.' Review of Economic Studies, 11(1) 31-41.

Hicks, J. R. (1945) 'The Generalised Theory of Consumer's Surplus.' Review of Economic Studies 13(2) 68-74.

Hill, N., Watson, R., & James, K. (2016) 2016 Government GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors. Final Report. Sept 2016. Department of Energy and Climate Change (DECC), London.

Iacus, S.M., Natale, F., Satamaria, C., Spyratos, S. and Vespe, M. (2020) Estimating and Projecting Air Passenger Traffic during the COVID-19 Coronavirus Outbreak and its Socio-Economic Impact. Working Paper. European Commission, Joint Research Centre.

ICAO (2020) Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis. International Civil Aviation Organization, Montreal, Canada, 23 March 2020. Available at: https://www.icao.int/sustainability/Documents/COVID-19/ICAO_Coronavirus_Econ_Impact.pdf

ICAO (2019) Annual Report. The World of Air Transport in 2018. https://www.icao.int/annual-report-2018/Pages/the-world-of-air-transport-in-2018.aspx

ICCT (2017) International civil aviation organization's carbon offset and reduction scheme for international aviation (CORSIA). Policy Update, The International Council of Clean Transportation. Available at: http://www.theicct.org.

IPCC, 1999. Aviation and the global atmosphere. In: E Penner, J., Lister, D.H., Griggs, D.J., Dokken, D.J., McFarland, M. (Eds.), Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Ito, H. and Lee, D. (2005) 'Comparing the Impact of the September 11th Terrorist Attacks on International Airline Demand.' International Journal of the Economics of Business 12(2) 225-249.

Kommenda, N. (2019) '1% of English residents take one-fifth of overseas flights, survey shows.' The Guardian. 25 September 2019.

John Hopkins University (2020) Coronavirus Resource Center: Mortality Analyses. Available at: https://coronavirus.jhu.edu/data [Accessed: 10th June 2020)

Johnston, R.J., Rolfe, J., Rosenberger, R.S., and Brouwer, R. (2015) Benefits Transfer of Environmental and Resource Values. London: Springer.

Johnston, R.J., and R.S. Rosenberger (2010). "Methods, trends and controversies in contemporary benefit transfer." Journal of Economic Surveys 24 (3), 479–510

Just, R.E., Hueth, D.L. and Schmitz, A. (2004) The Welfare Economics of Public Policy. Edward Elgar. Cheltenham and Northampton, MA.

Kousoulidou, M., & Lonza, L. (2016). Biofuels in aviation: Fuel demand and CO_2 emissions evolution in Europe toward 2030. Transportation Research Part D: Transport and Environment, 46, 166-181.

Larsson, J., Elofsson, A., Sterner, T., & Åkerman, J. (2019). International and national climate policies for aviation: a review. Climate Policy, 19(6), 787-799.

Lee, D. S. (2018). The current state of scientific understanding of the non-CO_2 effects of aviation on climate. UK Department for Transport, Manchester Metropolitan University.

Lee, David S., David W. Fahey, Piers M. Forster, Peter J. Newton, Ron CN Wit, Ling L. Lim, Bethan Owen, and Robert Sausen. (2009) Aviation and global climate change in the 21st century. Atmospheric Environment, 43(22-23), 3520-3537.

Le Quéré, C., Jackson, R.B., Jones, M.W., Smith, A.J.P., Abernethy, S., Andrew, R.M., De-Gol, A.J., Willis, D.R., Shan, Y., Canadell, J.G., Friedlingstein, P., Creutzig, F. and Peters, G.P. (2020) 'Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement.' Nature Climate Change 10(5) https://www.nature.com/articles/s41558-020-0797-x.pdf

Loomis, J.B. (1992) 'The Evolution of a More Rigorous Approach to Benefit Transfer: Benefit Function Transfer.' Water Resources Research 28(3) 701-705.

Lyth, P.J. (1993) 'The history of commercial air transport: a progress report, 1953-93.' Journal of Transport History 14(2) 166-180.

Lyth, P.J. (2009) 'Flying Visits: The Growth of British Air Package Tours, 1945–1975.' In Segreto, L., Manera, C., and Pohl, M. (eds.) Europe at the Seaside: The Economic History of Mass Tourism in the Mediterranean. Berghahn Books. Oxford.

Marshall, A. (1920). Principles of Economics. Macmillan. London.

Mitchell, B.R. (1988). British Historical Statistics. Cambridge: Cambridge University Press.

ONS (2019) Income by Decile. Office for National Statistics. https://www.ons.gov.uk/peoplepopulationandcommunity/personalandhouseholdfinances/expenditure/adhocs/005250annualexpenditureofhouseholdbyincomequintile

Oswald, Y., Owen A., and Steinberger, J.K.. (2020) 'Large inequality in international and intranational energy footprints between income groups and across consumption categories.' Nature Energy 5(3) 231-239.

Parry, I., R. Williams, and L. Goulder. (1999) When Can Carbon Abatement Policies Increase Welfare? The Fundamental Role of Distorted Factor Markets. Journal of Environmental Economics and Management 37(1): 52-84.

Pavlenko, N. (2018) ICAO's CORSIA scheme provides a weak nudge for in-sector carbon reductions. [Blog] The International Council of Clean Transportation. Posted Monday, 6 August 2018. Available at: https://theicct.org/blog/staff/corsia-carbon-offsets-and-alternative-fuel [Accessed: 8th June 2020]

Pearce, B. (2020) COVID-19. Outlook for air travel in the next 5 years. Speech given for IATA. 13 May 2020. https://www.iata.org/en/iata-repository/publications/economic-reports/covid-19-outlook-for-air-travel-in-the-next-5-years/

Pidock, R. and Yeo, S. (2016) Analysis: Aviation could consume a quarter of 1.5C carbon budget by 2050. International Policy. Carbon Brief. Available at: https://www.carbonbrief.org/aviation-consume-quarter-carbon-budget [Accessed: 10th June 2020]

Randall, A. and J.R. Stoll (1980) 'Consumer's surplus in commodity space.' American Economic Review 71: 449–457.

Rausch, S. and Metcalf, G.E., and Reilly, J.M. (2011) 'Distributional impacts of carbon pricing: A general equilibrium approach with micro-data for households.' Energy Economics 33(1) S20-S33.

Sager, L. (2019) 'Inequality and carbon consumption: evidence from environmental Engel curves." Energy Economics 84(1) 104507.

Scheelhaase, J., Maertens, S., Grimme, W., & Jung, M. (2018). EU ETS versus CORSIA–A critical assessment of two approaches to limit air transport's CO_2 emissions by market-based measures. Journal of Air Transport Management, 67, 55-62.

Simon, F. (2020) ''Do no harm': EU recovery fund has green strings attached.' Euractiv News. https://www.euractiv.com/section/energy-environment/news/do-no-harm-eu-recovery-fund-has-green-strings-attached/

Snow, A. and Warren, R.S., (2015) 'Pigou's Law and the proportionality of income and price elasticities of demand.' Economics Letters 132(C) 136-138.

Stone, R. (1955) The Measurement of Consumer's Expenditure and Behavior in the United Kingdom, 1920-1938. Vol I. Cambridge University Press. Cambridge.

Stone, R. (1966) The Measurement of Consumer's Expenditure and Behavior in the United Kingdom, 1920-1938. Vol II. Cambridge University Press. Cambridge.

Sustainable Aviation (2020) UK aviation commits to net zero carbon emissions by 2050. News article. Posted 4th Feb 2020. Available at: https://www.sustainableaviation.co.uk/news. [Accessed: 10th June 2020]

UNU-WIDER (2019) World Income Inequality Database (WIID). Available at: https://www.wider.unu.edu/database/wiid

Vartia, Y.O. (1983) 'Efficient methods of measuring welfare change and compensated income in terms of ordinary demand functions.' Econometrica 51: 79-98.

Watts, J. (2020) Is the Covid-19 crisis the catalyst for greening the world's airlines? The Guardian. Posted 17 May 2020. Available on: https://www.theguardian.com/world/ [Accessed: 8th June 2020]

WID (2019) The World Inequality Database. https://wid.world/data/#countrytimeseries/aptinc_p0p10_z/GB/1980/2017/cc/c/x/yearly/a

Willig, R.D. (1976) 'Consumer's Surplus Without Apology.' American Economic Review 66(4) 589-597.

Winchester, N. (2019) 'A win-win solution to abate aviation CO_2 emissions.' Journal of Air Transport Management, 80: 101692.

Appendix

A1. Data on air travel by income quintiles

This section explains in more detail the process for quantifying long run trends in air travel at different income levels. As mentioned in the main text, data on air travel behaviour by income level has been collected by the Civil Aviation Authority (CAA 2020b), using surveys conducted in the UK since 1968. Unfortunately, due to travel restrictions, only the digitalised studies are currently available, which go back to 1991 (the CAA agreed to digitalise and send the authors the earlier documents after the lockdown). Thus, to address the gap in the data (due to the lockdown), historical accounts providing qualitative information about behaviour by income are used to estimate the share of travellers from each income quintile (Birkhead 1960, Lyth 1993, 2009, Barton 2005). Table A1 in the Appendix summarises these shares by decade, as well as the total quantity travelled in billions of passenger kilometres (bpk). Figure 1 presents the long run trends in air travel by income quintile since 1920.

Table A1. Estimates of Share of air travellers by income quintile, and total passenger-kms travelled

	Q1	Q2	Q3	Q4	Q5	Total bpk
1920	0%	0%	0%	0%	100%	0.0009
1930	0%	0%	0%	0%	100%	0.03
1940	0%	0%	0%	0%	100%	0.13
1950	0%	0%	0%	0%	100%	2.5
1960	0%	0%	0%	1.0%	99.0%	12.7
1970	0%	0.2%	0.5%	6.6%	92.7%	34.8
1980	0.3%	1.1%	2.9%	18.1%	77.6%	95.2
1990	1.0%	2.6%	5.3%	16.8%	74.5%	125.9
2000	3.6%	3.4%	6.4%	15.8%	70.8%	262.1
2010	6.3%	6.4%	8.6%	25.5%	53.1%	289.3
2019	5.2%	5.7%	8.3%	22.8%	58.0%	387.8

Source: Shares: CAA (1991, 2019); also see text; Quantity: Birkhead (1960), Stone (1966), Mitchell (1988), DfT (2019).

ONS (2020) has data on air travel expenditure by income quintile between 2002 and 2019. When divided by the average income by quintile (see below), this provides an estimate of the share of expenditure on air travel (see Table A2). Before 2002, estimates can be generated by combining travel data and price data, and dividing by average income. This table confirms that air travel expenditure is a small share of the overall budget.

Table A2. Estimates of Share of Air Travel Expenditure in Total Expenditure by income quintile

	Q1	Q2	Q3	Q4	Q5	Average
1920	0%	0%	0%	0%	0%	0%
1930	0%	0%	0%	0%	0%	0%
1940	0%	0%	0%	0%	0%	0%
1950	0%	0%	0%	0%	0.1%	0%
1960	0%	0%	0%	0%	0.2%	0.1%
1970	0%	0%	0%	0.1%	0.4%	0.2%
1980	0.1%	0.1%	0.3%	0.6%	0.8%	0.6%
1990	0.2%	0.4%	0.5%	0.7%	0.8%	0.7%
2000	1.3%	0.8%	1.0%	1.0%	1.1%	1.0%
2010	1.4%	0.7%	0.6%	0.6%	0.4%	1.1%
2019	1.7%	0.7%	0.7%	0.6%	0.4%	0.9%

Source: Shares: 2010-2019: ONS (2020); pre-2010; see text.

A2. Data on average income by quintiles

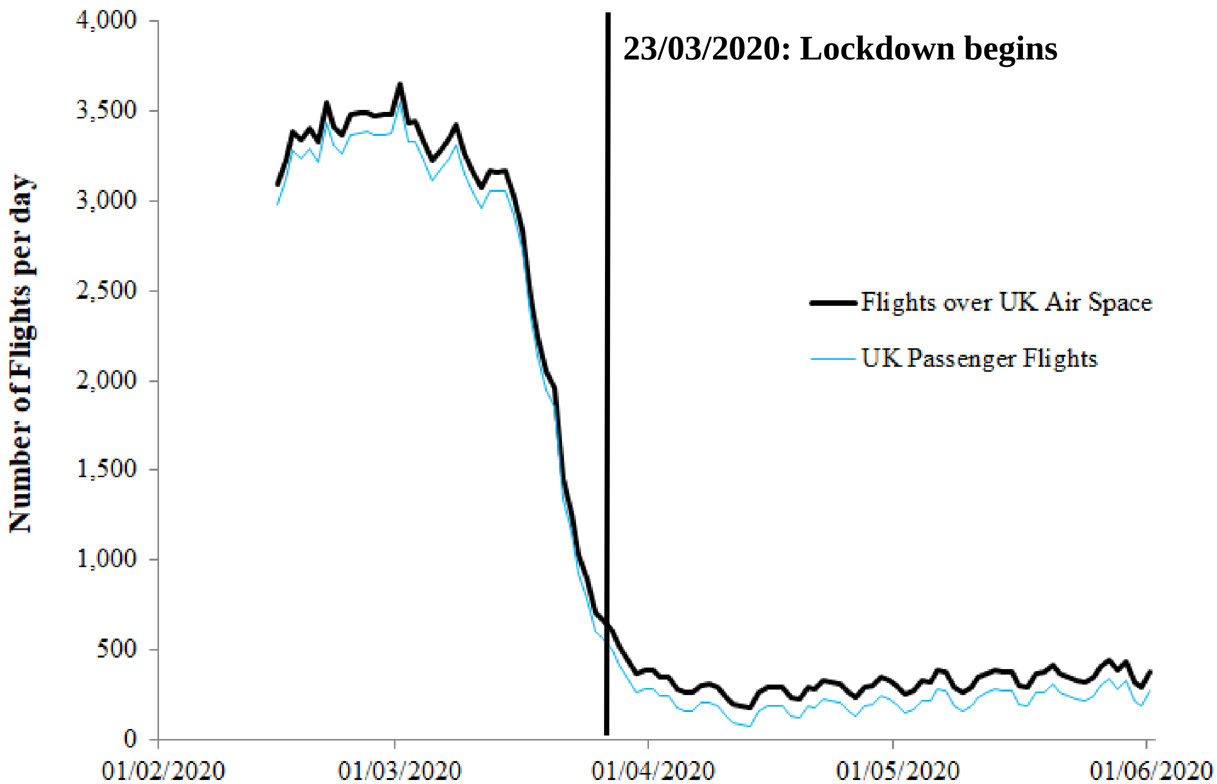
The gross income data used is based on combining data from Atkinson (2007), UNU-WIDER (2019), WID (2019) and ONS (2019). The data starts with the pre-tax average income by decile in 2018 provided by ONS (2019). This is linked to the WID (2019) which provides annual estimates of the UK's gross income by decile from 1980 to 2017. This is linked to the UNU-WIDER (2019) World Income Inequality data, which provides gross income by income decile starting in 1954. Atkinson (2007) offers evidence on the share of the top 10% and bottom 90% average income back to 1918. To generate average income deciles for the bottom 90% during the period 1918 to 1953, it is assumed that the shares amongst the bottom nine income deciles were the same as in 1954 – clearly, there must have been variation, but at least it provides a guide to the values, based on the variation in the top 10%. Finally, the average gross income by decile are combined to provide an indicator of the average income by quintile (by averaging decile 1 and decile 2 to create to quintile 1 (Q1), decile 3 and decile 4 to create to quintile 2 (Q2), etc..) from 1918 to 2018. For 2019, in which the data is not yet available, it was assumed that there were no changes in income distribution between 2018 and 2019, and each quintile increased by the same amount as GDP per capita (ONS 2020).

A3. Daily Data on Flights and Air Travel (15 February 2020-31 May 2020)

This sub-section explains how the daily passenger-km estimates were produced shown in Figure 5. Eurocontrol (2020) provides the number of daily flights over the UK air space up to 31 May 2020. This includes domestic flights, international flights and fly-overs (i.e. flights that neither take-off nor land in the UK). Every two weeks, Eurocontrol (2020) also indicates the share of flights that are domestic flights, international flights and fly-overs. Thus, using a bi-weekly average, it is possible to remove the fly-overs and estimate the number of flights leaving and arriving in the UK.

The Eurocontrol (2020) data includes UK passenger and cargo flights. Fortunately, the CAA's (2020) monthly data indicates whether flights are passenger or cargo flights. In February 2020, cargo accounted for 5.2% of all flights landing and/or arriving in the UK. In March 2020, cargo accounted for 12.3% of flights (CAA 2020). So, failing to take account of the cargo flights would bias the estimates upwards. Cargo flights average just over 100 flights per day. In March 2020, there were on average 101 cargo flights per day. Cargo flights in March 2020 increased by 0.1% on February 2020. Thus, it is assumed that cargo air travel has been broadly unaffected by the lockdown. With this assumption, the daily cargo flights average (using the monthly averages in 2019) is subtracted from the total UK daily flights. This provides an estimate of the daily passenger flights landing and/or leaving the UK, shown in Figure A1.

Figure A1. Number of Flights over UK Air Space and Estimate of UK Passenger Flights, 15 February-31 May 2020



Source: Eurocontrol (2020), CAA (2020).

The number of daily passenger flights provides the foundation for estimating the amount of daily passenger-km travelled, shown in Figure 5 in the main text. To do so, the number of daily passenger flights needs to be multiplied by the number of passengers per flight and the distance per flight. The CAA

(2020) provides monthly data up to March 2020 on the number of passenger km flown, the number of passenger km available (i.e., capacity), the number of flights, the average distance per flight and the average number of passengers per flight. The percentage of capacity used in March 2020 was down to 63.2% (CAA 2020) compared with January 2020 (82.3%) and February 2020 (80.5%). The percentage of capacity in March was likely to be an average of two extremes – of around 80% in early March and below 50% in late March. Given the pressure to ensure social distancing, it is assumed that capacity fell to 30% in April and May 2020. Interestingly, distance travelled per flight was up – to 4,047km in March 2020 from 2,705km in January 2020 and 2,675km in February 2020. It is assumed that this longer distance was maintained throughout April and May 2020. These two forces imply that the daily passenger-km fell slightly more than daily number of flights - for example, Eurocontrol (2020) data indicates that flights into the UK air space fell by 68%, UK passenger flights declined by 71% and passenger-km dropped by 76% on Monday 23 March compared with two weeks before (i.e. Monday 9 March). In the trough, on the 13 April, there were an estimated 80 UK passenger flights on that day providing an estimated 18.5 million passenger-km, which was a 98.5% drop on the 9 March.

One piece of information of interest is the reduction in air travel associated with the government-imposed lockdown. Combining CAA (2020a, 2020b) monthly data and the information presented in Figure A1 enables an estimate to be made. The official beginning was 23 March 2019. The end is a little more ambiguous, and here has been placed at 31 May, as the 'easing of the lockdown' began on 1 June 2020. Using the CAA (2019) data on monthly air travel in 2019, the share of passenger air travel in each month was calculated (column 2 of Table A3). By summing daily air travel presented in Figure A1, monthly passenger-km can be produced for 2020 and compared with the equivalent month in 2019 to estimate the reduction in each month (column 3 in Table A3). This suggests that during the formal lockdown (focussing on April and May, and not March, which was in lockdown only part of the month) air travel was down 96.3% compared with 2019.

Also of interest is the reduction of the annual total due to the lockdown. Multiplying columns 2 with column 3 estimates the reduction for each month in 2020 compared with the annual total air travel in 2019. Adding 9 days in March (i.e., 9/31) to April and May reductions on the 2019 annual level, indicates that the formal lockdown between 23 March and 31 May 2020 led to a reduction of 17.7% of passenger air travel compared with 2019. As will be explained in sections S5 and S6, this will be equivalent to a

Table A3. Share of Annual UK Air Travel in each Month (in 2019) and Reduction in 2020 relative to 2019* and to the 2020 Counterfactual**

Month	Share in 2019	Reduction in 2020 from 2019 Monthly Level	Reduction in 2020 from 2019 Annual Level	Month	Share in 2019	Reduction in 2020 from 2019 Monthly Level	Reduction in 2020 from 2019 Annual Level
Jan.	7.1%	15.6%	1.1%	July	10.3%	62%	6.4%
Feb.	7.0%	24.5%	1.7%	Aug.	10.6%	50%	5.3%
Mar.	8.3%	68.9%	5.7%	Sep.	9.1%	40%	3.6%
Apr.	7.8%	96.0%	7.5%	Oct.	8.3%	30%	2.5%
May	8.9%	96.6%	8.6%	Nov.	6.3%	20%	1.3%
June	9.8%	78%	7.6%	Dec.	6.6%	20%	1.3%
Reduction (Lockdown)						**96.3%**	**17.7%**
Reduction* (Total for 2020)							**52.6%**
Reduction (rel. to 2020 Counterfactual)**							**53.0%**

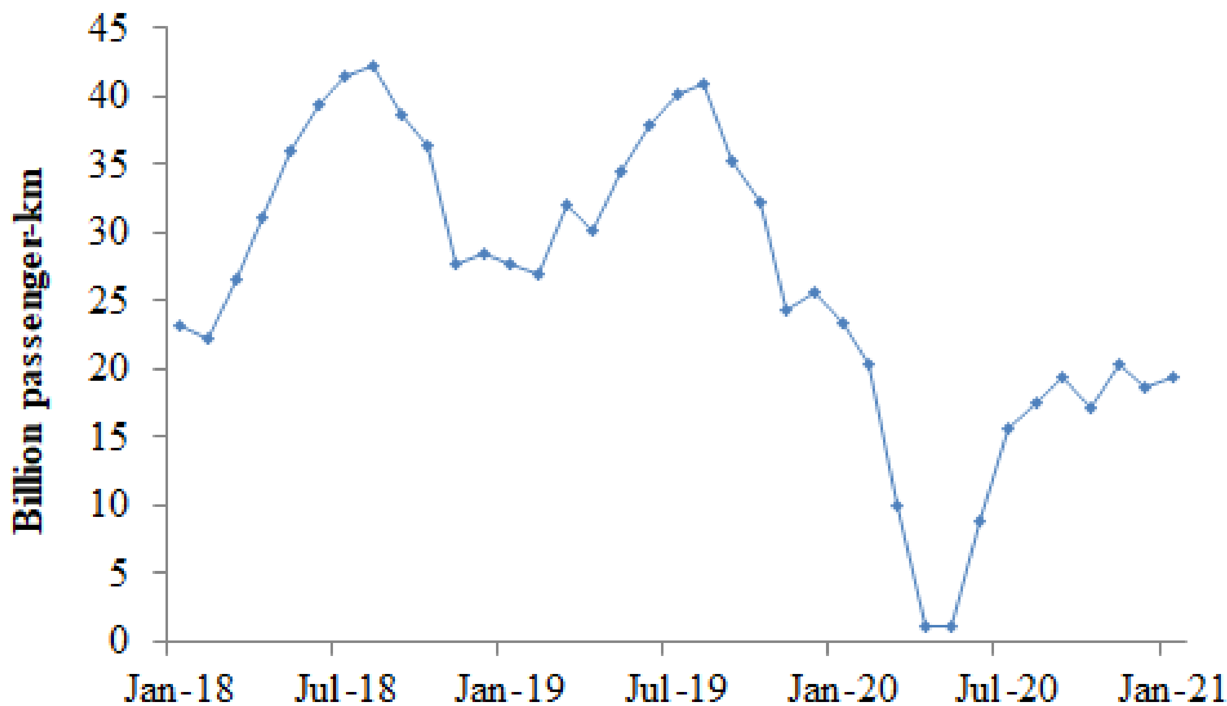
* see Section A4; ** see Section A5 and A6.

A4. Estimation of Air Travel (June 2020-December 2020)

The rest of Table A3 relates to future passenger air travel, and this section explains how this is calculated. As explained above, monthly air travel data is only available until March 2020 (CAA 2020) and daily flight data (converted into daily air travel data) is only available until 31 May 2020 (Eurocontrol 2020). To estimate the impact of losses in welfare from air travel reductions using annual demand curves (for each quintile, as shown in Figure 4), it is necessary to make projections of air travel from June until December 2020.

For this period, the Eurocontrol (2020) forecast of a 'managed' recovery provides the foundation for the projection, as discussed in the main text. Eurocontrol (2020b) considers the recovery of the broad European air space, including the UK. In this scenario, all EU commercial flights are forecast to be 22% of their 2019 level in June, 38% in July, 50% in August, 60% in September, 70% in October, 80% in November and 80% in December. There can be debate about the exact nature of the recovery); for the purpose of the current study, we have opted to use the Eurocontrol (2020) "managed recovery" scenario for 2020 (given that coordinated efforts are being discussed) and assume that the UK will recover at the average European rate of all (i.e. including cargo) flights. The comparison with the 2019 level is used to estimate the number of passenger flights by combining the data with UK CAA (2019) monthly flights data for 2019. Then, the number of monthly passenger flights is multiplied by the monthly average number of passengers per flight and the monthly average distance per flight in each 2019 month to produce a monthly air travel projection (see Figure A2). Note that the data is identical to Figure 6, except that it ends in December 2020. Based on this information, Table A3 (last column, bottom row) presents an estimate of the reduction in passenger air travel in 2020 to be 52.6% of the 2019 level.

Figure A2. Estimated Monthly Air Travel in the UK, January 2018-December 2020



Source: Pre-June 2020 : CAA (2020),;June 2020-December 2020: Eurocontrol (2020); From 2021: Pearce (2020)

A5. Estimation of the Income and Price Elasticity of Demand

This sub-section discusses the analysis of air travel demand undertaken to estimate income and price elasticities. The relationship between the demand for air travel and income and prices are mediated by the income and price elasticity of demand, respectively. As a reminder, the income elasticity of demand for air travel indicates the percentage change in the consumption of the energy service for a one percent change in income. For example, an income elasticity of 2.5 (or 1.5) implies that, if income rises by 10%, consumption will increase by 25% (or 15%, respectively). Similarly, the price elasticity indicates the percentage change in air transport for a one percent change in the price of travelling. That is, a price elasticity of -2.0 (or -1.5) implies that, if prices rise by 10%, consumption will fall by 20% (or 15%, respectively).

Income elasticities tend to reflect whether consumers perceived travel as a "luxury" or as a necessity. For so-called "luxury" travel, as air transport has been considered for much of the twentieth century, consumption increased more than proportionally as income rose (i.e., high income elasticity). As incomes rose, consumption increased more than proportionally. As income increased further, saturation effects may start to reduce consumption, such that expenditure of many previously "luxury" travel grew less than income (Moneta and Chai 2010).

Individual regressions are estimated using time series analysis, following the same approach as Fouquet and Pearson (2012). A vector error correcting model was used to provide an econometric analysis of the data and the trends, and estimate the cointegrated relationship between travel, income and transport prices. The emphasis should not be on the methods used, which are open to some criticism and could be improved upon through the use of more time-consuming panel data analysis. Thus, the elasticity estimates should act as a prosy for the actual values of the income and price elasticity.

Given the trended nature of the data (see Figures 1 and 2) and the tendency for long run transport, GDP and travel costs to be cointegrated (Bentzen 1994, Fouquet 2012), the possibility of using vector error-correcting models (VECM) was test. From a statistical perspective, such models were appropriate.

First, for the long run trends in transport consumption, GDP per capita and the price of transport, non-stationarity could not be rejected. In addition to the standard tests for unit roots, an augmented Dickey-Fuller test where the time series is transformed via a generalized least squares (GLS) regression was used to improve the power of the test (Elliott, Rothenberg and Stock 1996). Here, for up to 15 lags, and incorporating the assumption of a time trend, the tau-statistics could not reject at the 10% confidence level. Thus, unit roots (i.e. non-stationarity) were likely. Second, tests rejected the null hypothesis of no cointegrating equations for the relationship between transport consumption, GDP per capita and the price of transport – for the whole period between 1920 and 2019. Having selected the appropriate number of lags from a series of different tests (Nielson 2001), tests for the existence of cointegrating equations were performed and, when the null hypothesis of no relationship was rejected, almost always one cointegrated relationship could not be rejected (based on methods developed in Johansen 1988, 1995).

Finally, statistical tests of the causality indicate that the causal relationship runs from income and prices to consumption, and not from consumption to income and prices – implying that any changes in income by income quintile and prices were exogenous. Indeed, the likelihood of air travel by income quintile (which is less than two percent of total consumer expenditure, see Table A2) altering GDP, GDP per capita, and consumers' budgets is low. Thus, the statistical analysis confirms the expectation that endogeneity is not a problem for modelling the demand for air travel.

In this study, elasticities (presented in Figure 3 and Table A4) are calculated as the average of elasticity estimates in which a particular year is included in a regression. That is, regressions are run for 50-year periods (e.g. 1920-1969, 1921-1970, …, 1970-2019). To ensure additional estimates of values at the beginning (i.e., 1920) and at the end of the series (i.e. 2019), the period is dropped by one year until the regressions are run for 30-year periods. This follows the method presented in Fouquet (2014).

Table A4 provides the moving average estimates of the income and price elasticities of demand for air travel in the United Kingdom over the last one hundred years by income quintile. The estimated elasticities resulting from the analysis are strongly consistent with the expectations based on basic theory (i.e., positive income elasticities and negative price elasticities). It is worth noting that income elasticities are particularly large, especially in the early phases of expansion of air travel in a particular income quintile. Elasticities decline over time and as demand grows. Although less pronounced, there is also some evidence of a decline in the price elasticities. Although quite high compared to most goods and services, these elasticities fit within the range of estimates on air travel found in the literature (Brons et al. 2002).

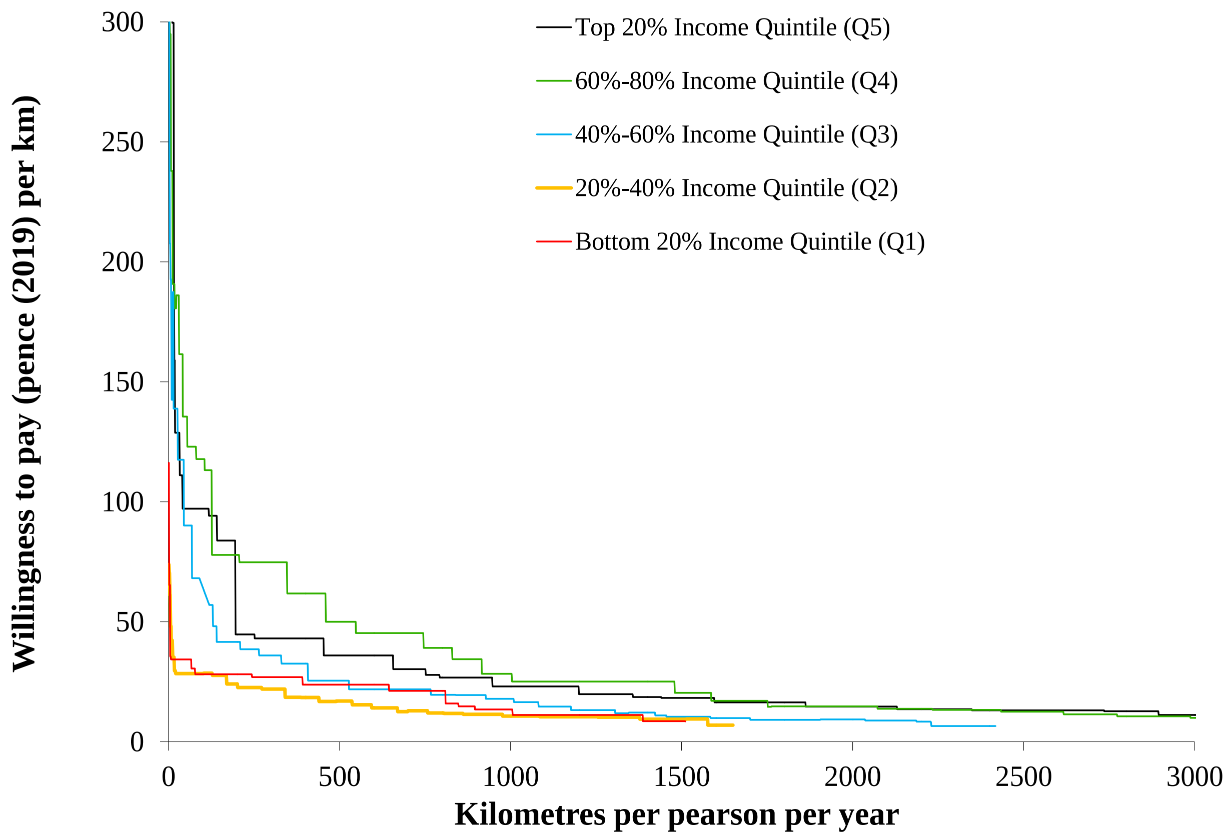
Section 2 of the main text goes into detail about the method in which the income and price elasticities are used to construct the demand curves. The estimate of WTP values for 2020 are based on the WTP values in 2019 augmented by the changes in income multiplied by the income elasticity. It is based on a forecast of UK GDP by the OECD (2019), which was of 0.8% annual growth, and of UK population by the ONS (2019). Sections S8 and S9 explains in more detail the source of the income projections. The demand curves for 2020 are displayed in Figure A3, which is identical to Figure 4 except that it extends the values on the x-axis to 3,000 passenger-kms and on the y-axis to 300 pence per passenger-km. This further accentuates the convex nature of the demand.

Table A4. Estimates of Income and Price Elasticities of Demand for UK Air Travel by Income Quintile, 1920-2019

	Q1		Q2		Q3		Q4		Q5	
	Income Elast.	Price Elast.	Income Elast.	Price Elast.	Income Elast.	Price Elast.	Income Elast.	Price Elast.	Income Elast.	Price Elast.
1920	-	-	-	-	-	-	-	-	6.0	-2.0
1930	-	-	-	-	-	-	-	-	5.6	-2.1
1940	-	-	-	-	-	-	-	-	5.4	-2.2
1950	-	-	-	-	-	-	-	-	4.7	-2.2
1960	-	-	-	-	7.0	-2.0	5.7	-3.2	3.3	-2.7
1970	-	-	3.1	-2.5	5.1	-1.7	4.3	-3.7	2.3	-3.0
1980	9.0	-3.8	2.5	-2.1	4.4	-1.9	3.9	-3.5	1.7	-2.9
1990	8.1	-3.8	2.5	-1.9	4.1	-1.6	3.3	-3.1	0.7	-2.8
2000	7.9	-3.8	2.7	-2.0	3.2	-1.4	2.2	-2.7	-0.4	-2.9
2010	6.5	-3.8	2.2	-2.2	2.1	-1.4	1.4	-3.3	0.2	-2.6
2019	4.6	-3.8	1.2	-1.8	2.3	-1.3	1.5	-3.1	1.0	-1.7

Source: see text.

Figure A3. Counterfactual Demand for Air Transport in the UK by Income Quintile in 2020



A6. Estimation of the Short-Run Welfare Impacts

This section looks at the details of the method (including the assumptions made) to estimate the welfare losses in 2020 from Covid-19. These welfare losses combine losses associated with two parts. The losses during the lockdown, between 23 March and up to 31 May 2020, which are based on data about air travel (see Section A3), and the losses before 23 March 2020 and from June to December 2020, which are based on predictions of the recovery from the Covid-19 lockdown (see Section A4). In the main text, the results of these two phases are combined and summarised due to space limitations. Here, these two phases are presented separately for additional detail.

To begin to understand the welfare effects of the reductions in passenger air transport, an estimate of the formal restrictions' impact is made. As mentioned in the main text, this is an estimate of the welfare loss from Covid-19 occurring and the restrictions being imposed. This point is specified because there were factors (either on the demand-side or the supply-side) that forced temporary reductions in air travel, creating a disequilibrium. This study uses the counterfactual demand curves for 2020 assuming that Covid-19 had not occurred, and measures the reductions in net benefits from the disequilibrium.

Using the counterfactual demand curves for air travel in 2020, it is possible to estimate the loss in consumer surplus associated with the formal restrictions (i.e, the lockdown), as well as for the whole year. However, to do so, assumptions will need to be made. First, *Table A3 indicates that the formal lockdown between 23 March and 31 May 2020 led to a reduction of 17.7% of passenger air travel compared with the total for the year 2019. Table A3 also presents an estimate of the reduction in passenger air travel for the whole year - 53% compared with the counterfactual 2020 level*.

Second, it is assumed that the distribution of travel across the income quintiles in each month is the same as the annual average in 2019 – thus, the distance flown in, say, April (or May) for the middle income quintile (Q3), say - or the top quintile (Q5), for instance - is the same share as its annual share of total travel (e.g., 32.3/387.8 of 8.3% for Q3 or 224.8/387.8 = 58% for Q5 – see the second row of Table 2).

The third assumption relates to the marginal benefits of the flights not taken. Some flights are highly valued by consumers, and others generate only minimal benefit. It is challenging to know whether the flights missed because of the lockdown were the most highly-valued or the least highly-valued. However, since some flights are still being taken (i.e. 10% of flights), it is appropriate to assume that the most highly-valued ones are still being taken. Thus, for this analysis, the minimum and the median welfare losses will be shown (and not the maximum values).

Armed with these assumptions and the demand curves for each quintile in 2020 represented in Figure 4 (and Figure A3), welfare impacts can be estimated. For each quintile, this study estimates the expected consumer surplus had Covid-19 not occurred and compares it with the consumer surplus for the same demand curve if consumption is (i) reduced (due to the lockdown) by 17.7% or (ii) reduced (due to the combination of the lockdown and behavioural changes) by 53% (as shown in Table A4). As a reminder, the consumer surplus is the area under the demand curve and above the price line (see Figure A4 for the minimum welfare loss and Figure A5 for the median welfare loss). Thus, the consumer surplus associated with the lockdown is equivalent to consuming only 82.3% (i.e., 100% - 17.7%) and the consumer surplus associated with Covid-19-related reductions for the whole year is equivalent to consuming only 47% (i.e., 100% - 53%) of the total counterfactual consumption in 2020 had Covid-19 not occurred (for details of these estimates, see Section A8).

Figure A4. Minimum Welfare Loss due to Covid-19 and the Lockdown using the Counterfactual Demand for Air Transport in 2020

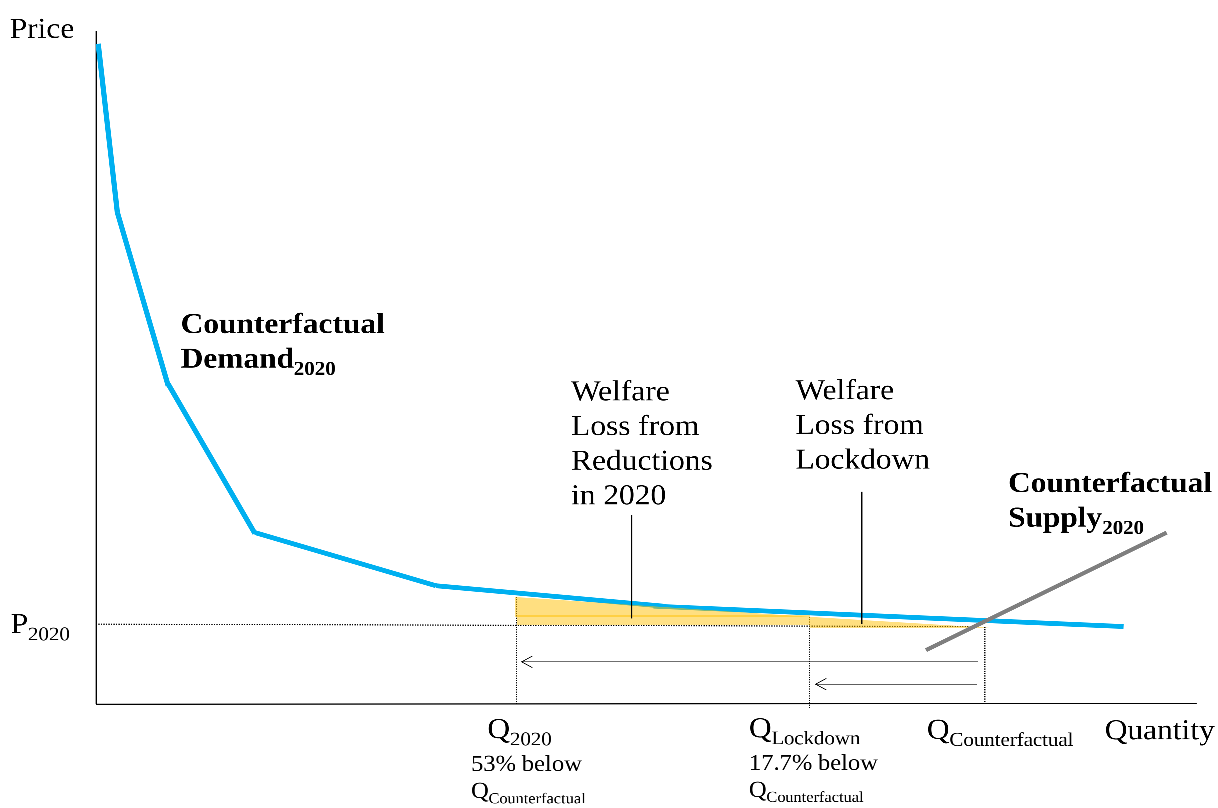


Figure A5. Median Welfare Loss due to Covid-19 using the Counterfactual Demand for Air Transport in 2020

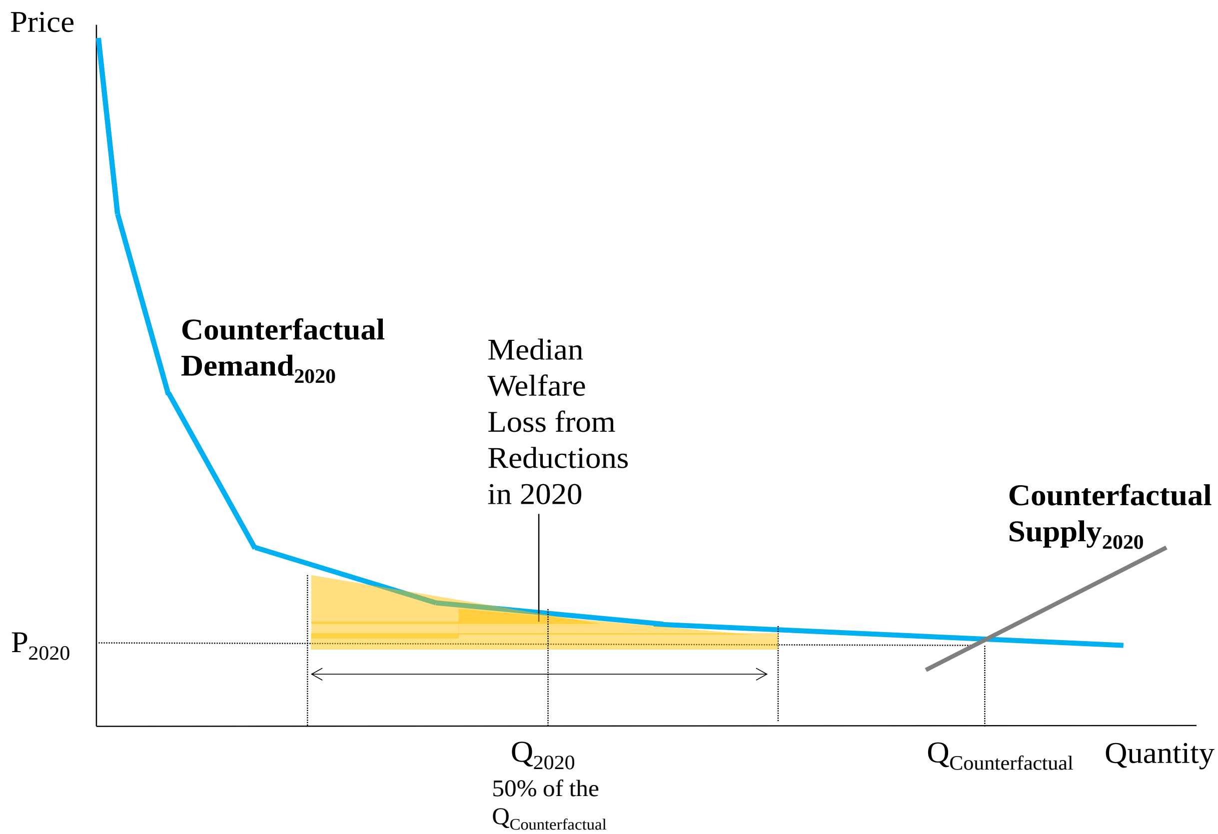


Table A5 shows the minimum and median welfare losses for the formal restriction period (up to 31 May 2020) – as a reminder, the short-term results (Table 2) in the main text only show the minimum values for the two periods combined. To calculate the minimum value, it is assumed that the loss in consumer surplus occurs at the margin. The margin is the final passenger-km (e.g., the 16,836th km for the top income quintile (Q5) in 2019 – see Table A5). The median value removes the consumer surplus associated with the middle section of the demand curve equivalent to the estimated reduction in air travel (e.g., 17.7% for the lockdown and 53% for the whole year).

As Table A5 shows, the median values are substantially larger, as would be expected since they are associated with WTP values in the middle of the demand curve (whereas the minimum estimate is associated with marginal and, therefore, lower WTP values). However, the variation across the income quintiles is similar for the minimum and the median welfare loses. Table A5 indicates that the losses are substantially larger (in percentage terms) for the lower income quintiles than the upper quintiles. For instance, the median welfare loss for the top income quintile (Q5) is 5.1%; and 1% for the minimum value. For the bottom income quintile (Q1), the median welfare loss is estimated to be 18.1%, and the minimum value is 4.6% due to the lockdown.

Table A5. Welfare Impacts of Air Travel Government-Imposed Lockdown (23 March-31 May 2020)

	Q1	Q2	Q3	Q4	Q5	Average/ Total
Air travel 2019 (bpkm)	20.2bpkm	22.1bpkm	32.3bpkm	88.4bpkm	224.8bpkm	387.8bpkm
Air travel 2020 Counterfactual (Average km per person)	1,521km	1,653km	2,427km	6,624km	16,836km	5,812km
Minimum welfare loss from air travel 2020 (17.7% decline)	**4.6%**	**3.3%**	**0.4%**	**0.7%**	**1.0%**	**2.0%**
Max-Minimum welfare loss from air travel 2020 (see Table A6)	**14.4%**	**10.7%**	**4.9%**	**3.0%**	**5.1%**	**7.6%**
Median welfare loss from air travel 2020 (17.7% decline)	**18.1%**	**12.0%**	**20.1%**	**4.0%**	**5.7%**	**12.0%**

Sources: Income (ONS 2020); Air travel 2019: CAA (2020); Air travel 2020: Eurocontrol (2020); Welfare losses: authors' own calculations – based on the actual reductions in air travel up to 31 May 2020 leading to a reduction of 17.7% of the entire air travel in the year 2020 compared with the BAU counterfactual of air travel in 2020.

Table A5 also presents a max-minimum value. The max-minimum values can be explained in reference to Table A6, and might be seen as a middle value. This value is almost three times larger for the bottom income quintile (Q1) than for the top income quintile (Q5).

In the bottom row of Table A6 is an estimate of the minimum welfare losses associated with reductions for the full year – equivalent to a 53% reduction in air travel. This combines the restrictions in air travel associated with the lockdown (i.e., 17.7% decline in air travel) and the behavioural changes in 2020 outside of the lockdown period (i.e., 35.3% reduction in air travel). For the behavioural changes, people will trade-off travel and health risks (or other behavioural factors) decisions at the margin. This implies that the reductions in air travel associated with the lockdown will come next – from 35.3 percentile to the 53 percentile kilometres. Inevitably, the WTP values for these kms are greater than for the marginal kms. The implication is that the 17.7% reduction associated with the lockdown might be greater than the 35.3% reduction associated with behavioural changes. It is important to stress that it is impossible to know where on the demand curve were these 17.7% reduced (and kms missed) due to the lockdown and, therefore, to know the WTP value of those kms. As represented in Table A5, the max-minimum values are between the minimum welfare loss and the median welfare loss. As discussed above, the behavioural changes lead to substantially larger welfare losses to the poor than the rich. The same is the case for the combined value indicating the total reductions in air travel for the whole of 2020.

Table A6. Welfare Effects of Air Travel Government-Imposed Restrictions (23 March-31 May 2020) and the Behavioural Changes (Pre-23 March 2020 and Post-31 May 2020)

	Q1	Q2	Q3	Q4	Q5	Average/ Total
Lockdown Max-Minimum welfare loss from (17.7% decline)	14.4%	10.7%	4.9%	3.0%	5.1%	7.6%
Behavioural changes minimum welfare loss (35.3% decline)	11.3%	11.4%	2.0%	1.8%	3.9%	6.1%
Minimum welfare loss from TOTAL reductions in 2020 (53% decline)	**25.6%**	**22.1%**	**6.9%**	**4.8%**	**9.1%**	**13.7%**
Median welfare loss from TOTAL reductions in 2020 (53% decline)	**50.8%**	**41.6%**	**25.2%**	**17.5%**	**17.1%**	**31.1%**

Sources: authors' own calculations – based on the actual reductions in air travel up to 31 May 2020 leading to a reduction of 17.7% of the entire air travel in the year 2020 compared with the BAU counterfactual of air travel in 2020.

A7. Estimation of the Short-Run Environmental Impacts

The estimation of the environmental impacts in 2020 from Covid-19 follows directly from the estimates of air travel. BEIS (2019) provides estimates of carbon dioxide emissions associated with the aviation industry. To understand the relationship between air travel and emissions, carbon dioxide emission were regressed on air travel between 1990 and 2017. The coefficient was estimated to be 0.78. Thus, this indicates that, for a 10% reduction in passenger-km, emissions would decline by 7.8%. While each additional passenger and each additional kilometre travelled requires additional fuel, this result suggests that the increase in emissions is less proportional. This makes sense because, first, in an normal year 3%-5% of flights are associated with cargo (CAA 2019, see above) and, second, there are 'fixed emission costs' associated with the aviation industry – for instance, some of the decline in passenger-km associated with Covid-19 resulted in reductions in the number of passengers on each plane and with airports remaining open and using electricity and other forms of energy.

The first step is to estimate annual emissions in the UK in 2018 and 2019 associated with the aviation industry. Based on changes in air travel and the estimated coefficient (of 0.78), emissions in the UK would have risen from 72.2 mtCO_2e in 2017 to 85.2 mtCO_2e in 2018 and 83.6 mtCO_2e in 2019. These are then split into monthly emissions levels based on passenger-km in each month (while this will not be exactly correct, the coefficient indicates this is broadly correct). So, using this method, for instance, this suggests that in March 2019 the UK aviation industry generated 6.9 mtCO_2e. Given that air travel was 69% lower in March 2020 than in March 2019, emissions were estimated to be 54% lower. In a similar way, the three-month period between 1 March 2020 to 31 May 2020 was associated with an 87% reduction in air travel and a 68% decline in emissions (or 14.3 mtCO_2e avoided). For the whole year, air travel was estimated to be down 53%, leading to a 43% fall in emissions (or 36.2 mtCO_2e avoided).

A8. Projection of Business-as-Usual (BAU) Air Travel (2020-2050)

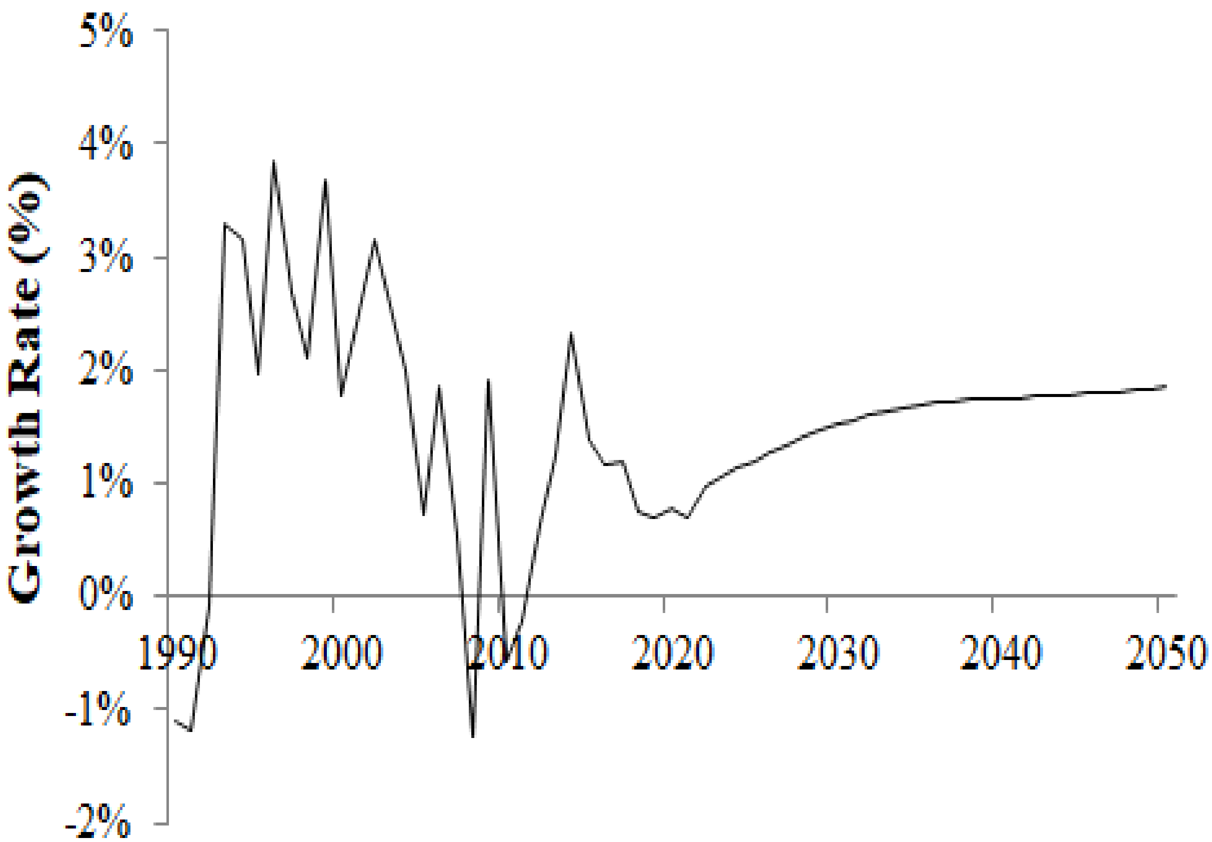
The business-as-usual scenario discussed in the main text is based on a model of the demand for air travel for each income quintile. The air travel (of income quintile i) is determined by air travel in the year before plus the change in the average income for quintile i (y_{it}) multiplied by the income elasticity for quintile i in year t (η_{Yit}) and the change in the average price for air travel (p_t) multiplied by the price elasticity for quintile i in year t (η_{pit}):

$$AT_{it} = AT_{it-1} \,.\, [1 + \eta_{Yit} \cdot \frac{\partial y_{it}}{\partial y_{it-1}} + \eta_{Pit} \cdot \frac{\partial p_t}{\partial p_{t-1}}] \qquad \text{(S1)}$$

To generate an estimate of air travel, it is necessary to have annual estimates of average income in each quintile, average prices, income elasticity for each quintile and price elasticity for each quintile between 2020 and 2050. For each year, it is assumed that there were no new changes in income distribution and each quintile increased by the same amount as GDP per capita. The forecast of UK GDP per capita is based on dividing the OECD (2019) long-term forecast of UK GDP by the ONS (2019) population projections (see Figure A6).

In the absence of clear information about a trend, average prices of air travel are assumed to be constant in real terms between 2020 and 2050 – real prices have been fairly stable between the early 1990s and 2019 (see Figure 2 in the main text). For the income and price elasticities, the trend in elasticities between 1989 and 2019 are used to estimate to determine the trend in elasticities between 2020 and 2050. Figure 3 shows that there is (in absolute terms) a downward trend in the income and price elasticities of demand for each quintile (apart from the top quintile Q5, as discussed in the main text). So, for instance, the income elasticity of Q4 fell by 56% between 1989 and 2019 and, therefore, it is assumed that it would fall by 56% between 2020 and 2050 – thus, declining from 1.49 to 0.65. For Q5, because of the anomaly surrounding air travel after 2001 (and 9/11), the trend between 1979 and 2019 is used instead, which is associated with a 42% decline, and this value is used to project forward the income elasticity for Q5 between 2020 and 2050. In addition, the 30-year trend between 1989 and 2019 is used to project the price elasticties from 2020 to 2050. The values of average income, of average prices, and of income and price elasticities for each quintile are fed into equation (S1) to create the BAU forecast from 2020 to 2050.

Figure A6. Forecast of UK GDP per capita growth rate, 2020-2050



Source: GDP: (OECD 2019), Population: ONS (2019)

However, this BAU forecast needs to be linked in with the recovery following Covid-19. Clearly, there are many uncertainties around GDP growth, travel-related policies, airline industry survival and bailouts, and traveller concerns about health risks. Pearce (2020), as chief economist for IATA, offers a forecast to 2025. He suggests that air travel will take two to three years to return to 'normality' – 2021 would be 70%, 2022 would be 90% and 2023 would be 100% of the 2019 level. These forecasts, also shown in Figure 6 as monthly data, create the link between the recovery of air travel and the BAU scenario.

A9. Projection of Demand for Air Travel (2020-2050)

Section 2 of the main text explains the process for constructing the demand curves in the past. The same method can be used to generate demand curves in the future. Equation (8) describes how to estimate the WTP values for each marginal level of consumption. The estimate of WTP values for 2020 are based on the WTP values in 2019 plus the changes in income multiplied by the income elasticity.

Similarly, 2021 WTP values are based on 2020 values plus the changes occurring in 2021. This process of building on the previous year is extended to 2050. So, the only difference between the past and the future demand curves is that the future WTP values are based on forecasts of the key variables. The most important variables that feed into the process are the average income in each quintile and the income elasticity of WTP (which is proxied by the income elasticity of demand, as explained in section 2). The forecasts of these variables are explained in the previous section of this Appendix (on the Projection of BAU Air Travel). That is, the forecast of UK GDP per capita is based on dividing the OECD (2019) long-term forecast of UK GDP by the ONS (2019) population projections, as shown in Figure A6. Figure 7 shows the demand curves in 2030 and 2050 for two income quintiles, and further details can be sought from the authors.

An important point to note (which is mentioned in the text) is that the demand curves that are unaffected by Covid-19 and, therefore, do not take account of the recovery. This is in contrast to the BAU Scenario which does take account of the gradual recovery to 2025. The implication is that, for the first few years after Covid-19, emissions in the BAU Scenario are lower than the emissions related to the Carbon Tax and Frequent Flyer Levy Scenarios in Figure 7.

A10. Estimation of the Long-Run Welfare Impacts of the Carbon Tax and Frequent Flyer Levy Scenarios

This section explains the welfare impacts of the carbon tax and frequent flyer levy scenarios. The estimation strategy uses the consumer surplus curve and compares it with the tax or the levy. The level of consumption where the consumer surplus curve crosses the tax (or the levy) will be optimal, if the tax (or levy) is imposed. Thus, it is possible to identify the optimal levels of consumption for the average consumer in each income quintile and in each year. The consumer surplus associated with this new optimal level of consumption and including the expenditure on the tax (or the levy) is calculated and compared with the consumer surplus without the tax (or levy). The difference is the estimated welfare loss from the tax (or levy) and is presented in Tables 3, 4, 5, and 6, and summarised in Table 7.