ATA

CLARITY
economic consulting

The Carbon Leakage and Competitiveness Impacts of Carbon Abatement Policy in Aviation

Report to the Department for Transport

Air Transportation Analytics Ltd

and Clarity Ltd

November 2018

List of revisions

Issue number	Date	Reason for revision
1	November 2018	Initial Issue

Authors: Lynnette Dray, David Hart, Andreas Schäfer and Roger Gardner.

Air Transportation Analytics

Air Transportation Analytics (ATA) Ltd was incorporated in May 2018 to support the aviation sector with a new level of economic and analytical capability as it addresses growth challenges. Over the past ten years, experts within the ATA team with roots at University College London (UCL) and previously at the University of Cambridge, have been developing and refining a system modelling capability centered around the Aviation Integrated Modelling (AIM) project. The resulting capability can assist with sector needs on forecasting future levels of air transport demand by airline or market, identifying optimum business models for airline profit maximisation, modelling the economic and environmental implications of system and airport capacity expansion and identifying the most promising technology investment strategies of aircraft / engine manufacturers. For more details please contact Roger Gardner at roger.m.gardner@gmail.com or via LinkedIn.

Clarity Ltd

Clarity Economic Consulting Ltd. is an economic consultancy. We specialise in economic regulation, governance, and policy development and analysis. We use a range of technical expertise and experience gained at senior levels in the public and private sectors, to deliver objective, clear pragmatic advice. Specialising mainly in aviation, our clients include major international airlines, regulators and governments. For more details please contact David Hart at david@claritylimited.co.uk.

For further information on this study please contact Lynnette Dray (l.dray@ucl.ac.uk).

Although this report was commissioned by the Department for Transport (DfT), the findings and recommendations are those of the authors and do not necessarily represent the views of the DfT. The information or guidance in this document (including third party information, products and services) is provided by DfT on an 'as is' basis, without any representation or endorsement made and without warranty of any kind whether express or implied.

The Department for Transport has actively considered the needs of blind and partially sighted people in accessing this document. The text will be made available in full on the Department's website. The text may be freely downloaded and translated by individuals or organisations for conversion into other accessible formats. If you have other needs in this regard please contact the Department.

Department for Transport
Great Minster House
33 Horseferry Road
London SW1P 4DR
Telephone 0300 330 3000
General enquiries https://forms.dft.gov.uk
Website www.gov.uk/dft

Executive Summary

If a carbon dioxide (CO_2) emissions mitigation policy is applied only in one region of the world, emissions outside that region might increase. This is because companies and individuals affected by the policy may try and reduce its impacts on them by, for example, moving their operations to unaffected locations. This phenomenon is known as carbon leakage. If leakage is high, it may reduce or negate the intended emissions-reduction aim of the policy. Leakage of 100% implies that a policy produces no net reduction in global CO_2 at all, just a change in the location of emissions. Although leakage is more widely studied in the case of policies affecting energy-intensive manufacturing, it can apply to any industry where the location of emissions can be moved. This includes the aviation industry. In this report, we examine how the application of UK-specific aviation policy might lead to leakage, using a detailed network-based model of the global aviation system.

Similarly, a policy applied in just one region may disproportionately affect companies in that region, who will be faced with a larger increase in costs than those outside the region. This can lead to competitive disadvantage. This is also likely to be a factor in UK-specific aviation policy. The majority of the operations of UK-based airlines are flights to and from the UK, allowing them relatively few options to reduce potential policy costs. More options may be available for airlines which are not based in the UK. Non-UK airlines typically use only a small proportion of their total fleet on UK flights. Therefore we also investigate whether UK-specific aviation policies have different impacts on UK and non-UK airlines operating to and from the UK, and whether policies would have different impacts on UK and non-UK airports.

There is relatively little existing literature about carbon leakage and competitive disadvantage from aviation policy. In general, existing research focusses on individual flight case studies rather than taking a whole-network approach. However, approaching the problem at a global network level may be necessary to assess the different sources of leakage and their relative magnitude. Aviation is unusual in that it is inherently global in scope. Most passenger journeys lead to emissions that can be attributed to multiple countries. Aviation is also unusual in that, as well as having a leakage component associated with the behaviour of airlines, there is also a leakage component associated with passenger behaviour. We model passenger and airline behaviour on a full itinerary basis for all itineraries to, from and via UK airports, as well as those which could route through the UK but do not currently do so. To do this, we use components from the global aviation systems model AIM. This allows the calculation of how CO_2 emissions will change for flights to and from UK airports and more widely for other global flight segments, when a UK-specific aviation policy is applied.

This study finds that carbon leakage associated with airline behaviour is usually positive. In this case, a decrease in emissions from UK aviation is associated with an increase in emissions from non-UK aviation. Actions airlines can take in response to policy which could cause leakage include swapping fleet between UK and non-UK routes; selling older aircraft and buying or leasing newer ones; and tankering fuel (taking on excess fuel at non-UK airports where possible so that a subsequent flight from a UK airport can be flown without refuelling). Leakage associated with changes in fleet allocation can be close to 100%, depending on fleet availability. This is because airlines can move lower-emission aircraft into use on UK routes and move higher-emission aircraft into use on non-UK routes. This leads to a decrease in the emissions from UK aviation that is roughly matched by an increase in emissions from non-UK aviation. Leakage associated with fuel tankering is variable depending on which flights are most-affected by policy and on how emissions are calculated. If emissions are calculated based on fuel taken up at UK airports, tankering leakage is positive and may be up to 40% in the cases explored here. If emissions are calculated based on fuel used on UK departing flights, regardless of where that fuel was taken on, then tankering leakage is much smaller, typically below 4%.

In contrast, this study finds that leakage associated with passenger behaviour is usually negative. In this case, a decrease in emissions from UK aviation is matched by a decrease in emissions from non-UK aviation. This is because the main effect of a policy which increases UK-specific ticket prices is to decrease passenger demand to and from the UK. Although long-distance connecting passengers who use UK hub airports may switch to competing non-UK airports, the overall impact of this is small compared to the demand impact on passengers who start or end their journey in the UK. In 2015, there were more than twenty times as many passengers on itineraries which started or ended in the UK than passengers who used a UK hub on journeys which started and ended elsewhere.

If the CO_2 emissions from UK aviation are measured on a UK departing flights basis, a decrease in emissions from UK departing flights is within scope, but a decrease in emissions from UK arriving flight is outside scope. However, passenger journeys are generally round-trips with both an arriving and a departing leg. If demand decreases on these journeys, half of the emission reduction will be on departing flights, and half on arriving flights. Therefore if policy response is mainly passenger response, leakage will be close to -100%. This means that the net global reduction in CO_2 will be roughly twice the reduction in CO_2 from UK departing flights only. Additionally, some passengers who start or end their journey in the UK use a further non-UK hub airport (for example, travelling from London to Sydney via Dubai). A demand reduction in this passenger group will lead to negative leakage of more than 100%. This is because demand on all four legs of the round-trip journey will be reduced, but only the UK departing leg is within the UK departing flight scope and therefore treated as UK aviation.

The net carbon leakage for any given policy depends on the balance between passenger and airline response to that policy, as well as on the specific values of uncertain variables which affect the magnitude of passenger and airline response. In this study, we examine three hypothetical policy cases. These are the case of an additional carbon price applied to departing flights at UK airports; a requirement to take on a given percentage of biofuel when refuelling at UK airports; and changes in UK airport landing charges designed to encourage flights by younger, more fuel-efficient aircraft. In each case, we assess the policy across a range of values for uncertain variables. These include the passenger price elasticity of demand, the level of costs passed on at capacity-constrained airports, and the extent to which airlines can swap UK for non-UK fleet.

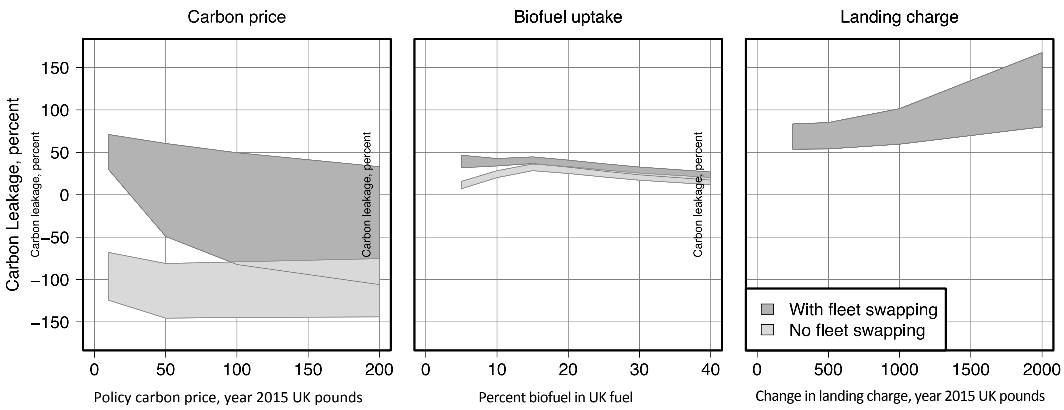

Figure 1. The range of carbon leakage across all uncertain variables examined in this study, by policy type.

A summary of leakage outcomes is shown in Figure 1. In each case, the grey regions show the full range of outcomes across different assumptions for passenger price sensitivity and the amount of cost pass-through at congested airports. The case where airlines are assumed to freely swap fleet between routes and the case where fleet swapping is assumed not to occur are shown separately. Because the landing charge policy targets fleet composition, little change in CO_2 occurs when fleet swapping is assumed not to occur, so leakage is not a useful metric in this case and the results are not shown.

The dominant impact of increasing the carbon price is on demand. Leakage associated with this policy is therefore usually negative even when airline response is accounted for. If the uncertain variables examined in this study are set at central values, leakage from increasing the carbon price is around -50%. This outcome is relatively sensitive to the values of uncertain parameters, particularly the passenger price elasticity of demand, and the amount of cost pass-through at congested airports.

For a hypothetical policy in which some percentage of biofuel is required to refuel at UK airports, it becomes cost-effective for airlines to tanker fuel on short-haul routes. This can lead to positive leakage of 20-40% if emissions from UK aviation are measured on a fuel uptake basis (i.e. based on the amount of fuel taken on at UK airports). If emissions are instead measured based on the amount of fuel used on UK departing flights, leakage will be smaller (around -4 – 30% if uncertain parameters are set at central values). However, the overall UK emissions reduction associated with this policy is much greater than for the carbon price policy, as there is an additional emissions reduction associated with the use of biofuel as well as one associated with increased fuel costs. This also limits the sensitivity of the outcomes to the uncertain parameters examined.

Finally, we also examine a hypothetical policy in which landing charges are increased for older aircraft and decreased for younger aircraft. This policy is primarily aimed at producing an airline response. Overall, it is cost-neutral for airlines with current fleet, but airlines are able to use the policy to reduce their overall costs by moving younger fleet onto UK routes and older fleet onto other routes. As such, leakage is positive and between 50 and 100%. In some cases, the overall impact on global emissions of this policy is a net increase. This is because there is the potential for demand to increase as airlines use the decrease in landing fees for younger aircraft to reduce their costs, and then pass this decrease in costs on to ticket prices.

The extent of competitive disadvantage for UK airlines and airports also depends on the balance of passenger and airline response to a given policy. We measure competitive disadvantage by comparing the change in UK and non-UK airline passenger numbers; the change in direct operating cost per revenue passenger-km (RPK) travelled for UK airlines and non-UK airlines; and the change in number of passengers travelling through major UK and non-UK airports. For most of the combinations of policy and uncertain input variables examined, impacts on UK and non-UK airlines on UK routes are roughly similar. A summary of outcomes is given in Table 1, for hypothetical policies applied in 2015. The exact impact depends on factors such as the extent to which costs are passed on to ticket prices at congested airports, the price-sensitivity of passengers to price increases, and the extent to which fleet can be swapped between UK and non-UK routes. For example, if cost pass-through is lower at congested airports, UK airline profit margins will be reduced by more than those of non-UK airlines on UK routes, because UK airlines tend to use congested airports more. However, in this case the demand reduction will be greater for non-UK airlines, because ticket prices will increase more for those airlines.

In general, the carbon price policy has the largest impacts on demand and operating costs at the levels examined in this study. For comparison to the values in Table 1, airline ticket revenue per RPK is typically around £0.1; and there were around 250 million passengers per annum (mppa) at UK airports in 2015; and demand at each of the UK's five busiest airports has tended to increase by 1-2 mppa per year over the 2010-2015 period. The largest impacts on cost are seen in the case that airlines are assumed not to pass on carbon costs at congested airports; however, as operating cost increases in this case can be larger than typical airline profit margins, it is likely that in reality at least some costs would be passed through at higher carbon prices. Similarly the largest changes in demand apply in the case that airlines are assumed to pass all costs through onto ticket prices. The biofuel policy typically leads to smaller increases in cost and decreases in demand, and the landing charge policy to small decreases in cost and increases in demand, as discussed above.

Table 1. Impact on airline cost per RPK and passenger numbers, by policy type: summary.

Metric	**Scope**	**Carbon price (£10-200/tCO_2)**	**Biofuel uptake (5-40%)**	**Landing charge (£250-2000/landing)**
Change in non-passed on cost/RPK, UK pounds	UK airlines on UK routes	0 – 0.017	-0.0002 – 0.0018	-0.0009 – 0
	Non-UK airlines on UK routes	0 – 0.014	-0.0002 – 0.0015	-0.0007 – 0
Change in passenger numbers, mppa	UK airlines on UK routes	-16.4 - -0.1	-2.0 – 0	0 – 4.2
	Non-UK airlines on UK routes	-15.7 - -0.1	-1.9 – 0.1	0 – 4.9

Contents

Executive Summary....................................4
Contents....................................8
List of Figures....................................10
List of Tables....................................13
1. Introduction....................................14
1.1 Carbon Leakage....................................14
1.2 Competitiveness....................................15
1.3 Application to the aviation sector....................................15
1.4 The case of UK-specific aviation emissions policy....................................18
2. Mechanisms and approximate level of impact....................................20
2.1 Change in passenger or freight routing (to same destination)....................................21
2.2 Change in passenger destination....................................22
2.4 Mode shift (single segment or whole journey)....................................23
2.5 Demand reduction outside the policy area....................................24
2.6 Changes in existing fleet assignment (within-airline)....................................25
2.7 Airlines abandon non-profitable routes and/or don't invest in new routes....................................25
2.8 Airlines add new UK-avoiding routes....................................26
2.9 New airlines locate outside UK and/or existing airlines relocate....................................26
2.10 Fleet leasing/sales between airlines....................................27
2.11 Adoption of carbon-reducing technologies and operations....................................28
2.12 Increases in tankering....................................29
2.13 Reduction in fuel use impacts on fuel price....................................30
3. Metrics and key uncertain variables....................................31
3.1 Metrics....................................31
3.1.1 Carbon Leakage....................................31
3.1.2 Competitive distortion....................................32
3.2 Key uncertain variables....................................33
3.2.1 Cost pass-through....................................33
3.2.2 Price elasticity of demand....................................35
3.2.3 Baseline demand growth to 2050....................................36
3.2.4 Baseline carbon price....................................36
3.2.5 Fuel price....................................37
3.2.6 Technology characteristics of new aircraft models....................................38
3.2.7 The ability of airlines to swap fleet between UK and non-UK routes....................................39
3.2.8 Itinerary choice parameters....................................39
4. Modelling carbon leakage and competitive disadvantage....................................41
4.1 Model scope....................................42
4.2 Model Structure....................................44
4.3 Reproducing the baseline system....................................45
4.3.1 City-pair passenger flows....................................46
4.3.2 Segment-level passenger flows....................................47
4.3.3 Aircraft flows and fleet requirement....................................49
4.3.4 Fleet size and age structure....................................50
4.3.5 Fuel use and emissions....................................51
4.3.6 Baseline costs....................................54

4.3.7 Freight 56
4.3.8 Non-scheduled flights 57
4.3.9 Baseline outcomes 57
4.4 Modelling response to policy 62
4.4.1 Airline response: substituting non-UK for UK fleet 62
4.4.2 Airline response: purchase or leasing of new aircraft 66
4.4.3 Airline response: policy-induced change in technology choice 67
4.4.4 Airline response: tankering fuel 68
4.4.5 Passenger response 70
5. Model outcomes 73
5.1 Hypothetical policies and uncertain parameters 73
5.2 Policies applied in 2015 74
5.2.1 Increased carbon price 74
5.2.2 Increased use of biofuel 80
5.2.3 Environmental landing changes 86
5.3 Policies applied in 2030 90
5.3.1 Increased carbon price 92
5.3.2 Increased use of biofuel 94
5.3.3 Environmental landing charges 97
6. Conclusions 99
References 100
Appendix 1: Quality Assurance 105
Appendix 2: Parameters for the itinerary choice model 106
Appendix 3: Additional results from the 2030 model runs 107

List of Figures

Figure 1. The range of carbon leakage across all uncertain variables examined in this study, by policy type. 6
Figure 2. Relationship between key airline groups, alliances and codeshare partners. 19
Figure 3. Origin-destination city-city passenger flows of more than 100,000 passengers per year (in 2015) for which at least some passengers route via a UK airport. Data: Sabre, 2017. 22
Figure 4. Age distributions of aircraft with operators registered in each region at the end of 2015, from FlightGlobal (2017). 27
Figure 5. The relationship between the uncertain variables examined and policy CO_2 response 31
Figure 6. City-pair routes with at least 100,000 passengers per year on which at least 1% of passengers travel to, from or via the UK. Data is from Sabre (2017). 42
Figure 7.Passengers travelling through Heathrow Airport by yearly itinerary demand threshold. Data: Sabre (2017). 43
Figure 8. Passengers travelling through London Gatwick airport by yearly itinerary demand threshold. Data: Sabre (2017). 43
Figure 9. Number of itineraries by yearly itinerary demand threshold, London Heathrow Airport. Data: Sabre (2017). 44
Figure 10. Model structure. 45
Figure 11. Aircraft retirement curves, from Morrell & Dray (2009). 51
Figure 12. Modelled fuel use by distance and payload. 52
Figure 13.Effective fuel price taking into account carbon and biofuel costs, for the year-2015 and year-2030 central case fuel and biofuel prices 55
Figure 14. Fuel and oil price variation in real terms, 1978-2015, as a ratio with 2015 values. 55
Figure 15. Available responses to fleet policy by UK and non-UK airlines, for a threshold year of manufacture before which aircraft cannot use UK airports, and treating all airlines as individual entities without fleet commonality 63
Figure 16. Available responses to fleet policy by UK and non-UK airlines, for a threshold year of manufacture before which aircraft cannot use UK airports, including the potential impact of airline group fleet commonality. 65
Figure 17. Hypothetical tankering scenario, assuming 2015 fuel prices and operations, biofuel around twice the price of Jet A, and ten percent biofuel requirement for refuelling at UK airports 69
Figure 18. Hypothetical tankering scenario, assuming 2015 fuel prices and operations, biofuel around twice the price of Jet A, and fifty percent biofuel requirement for refuelling at UK airports 70
Figure 19. Carbon leakage for a hypothetical carbon price policy applied in 2015, with fleet response 75
Figure 20. Carbon leakage for a hypothetical carbon price policy applied in 2015, without fleet response. 75
Figure 21. Underlying changes in CO_2 emitted by scope, for a hypothetical carbon price policy applied in 2015 with airline fleet swapping. 76
Figure 22. Underlying changes in CO_2 emitted by scope, for a hypothetical carbon price policy applied in 2015 without airline fleet swapping 77

Figure 23. Change in demand by airline and route type for a hypothetical policy increasing carbon price in 2015, for different assumptions about price elasticity and cost pass-through at congested airports. Airline fleet swapping is included................................77
Figure 24. Change in demand by airline and route type for a hypothetical policy increasing carbon price in 2015, for different assumptions about price elasticity and cost pass-through at congested airports. Airline fleet swapping is not included..........................78
Figure 25. Change in costs not passed on per RPK, for the case of an increased carbon price in 2015 with airline fleet swapping..79
Figure 26. Change in costs not passed on per RPK, for the case of an increase carbon price in 2015 without airline fleet swapping...79
Figure 27. Carbon leakage in the case of a hypothetical UK departing flight biofuel uptake policy, under year-2015 conditions with fleet response...81
Figure 28. Carbon leakage in the case of a hypothetical UK departing flight biofuel uptake policy, under year-2015 conditions without fleet swapping...81
Figure 29. The amount of CO_2 tankered (i.e., removed from a UK departing flight scope and added to a UK arriving flights scope) for the aviation biofuel policy under year-2015 conditions..82
Figure 30. Change in CO_2 by scope for the hypothetical biofuel uptake policy under year-2015 conditions, assuming airline fleet swapping...83
Figure 31. Change in CO_2 by scope for the hypothetical biofuel uptake policy under year-2015 conditions, assuming no airline fleet swapping..83
Figure 32. The change in demand by airline and route type for the hypothetical biofuel policy under year-2015 conditions, with fleet swapping. 84
Figure 33. The change in demand by airline and route type for the hypothetical biofuel policy under year-2015 conditions, without fleet swapping..85
Figure 34. Non passed-on cost per RPK in the case of a hypothetical biofuel uptake policy applied under year-2015 conditions, with fleet swapping assumed..............................86
Figure 35. Non passed-on cost per RPK in the case of a hypothetical biofuel uptake policy applied under year-2015 conditions, without fleet swapping assumed........................86
Figure 36. Carbon leakage in the case of environmental landing charges applied at UK airports under year-2015 conditions, with fleet swapping. 88
Figure 37. Changes in CO_2 by scope for a hypothetical policy in which landing charges are increased for older aircraft and decreased for younger aircraft, under year 2015 conditions with fleet swapping...89
Figure 38.Change in passenger demand by airline type and scope for the landing charge policy, under year 2015 conditions with fleet swapping...89
Figure 39. The change in non passed-through operating cost per RPK for the landing charge policy, for year-2015 conditions in the case that fleet swapping is assumed................90
Figure 40. Carbon leakage for a hypothetical carbon price policy applied in 2030, with fleet response...93
Figure 41. Carbon leakage for a hypothetical carbon price policy applied in 2030, without fleet response. 93
Figure 42. The change in demand with scope and airline type for a hypothetical carbon price policy applied in 2030, with fleet response...94
Figure 43. The change in demand with scope and airline type for a hypothetical carbon price policy applied in 2030, with no fleet swapping assumed...94

Figure 44. Carbon leakage from the biofuel uptake policy applied in 2030, with fleet swapping. 95
Figure 45. Carbon leakage from the biofuel uptake policy applied in 2030, without fleet swapping. 95
Figure 46. Amount of CO_2 tankered, for the biofuel uptake policy under year-2030 conditions....96
Figure 47. Change in number of passengers by scope and airline type, for the biofuel uptake policy under year-2030 conditions with fleet swapping. 96
Figure 48. Change in number of passengers by scope and airline type, for the biofuel uptake policy under year-2030 conditions without fleet swapping. 97
Figure 49. Carbon leakage in the case of the landing charge policy applied in 2030, with fleet swapping. 97
Figure 50. Change in passenger demand by scope and airline type, for the landing charge policy applied under year-2030 conditions, with fleet swapping. 98
Figure 51. Absolute change in emissions by scope for the increased carbon price policy, in the case that no airline fleet swapping is assumed. 107
Figure 52. Absolute change in emissions by scope for the increased carbon price policy in 2030, in the case that airline fleet swapping is assumed. 107
Figure 53. Change in non passed-on cost per RPK by airline type and scope for the increased carbon price policy, in the case that airline fleet swapping is assumed. 107
Figure 54. Absolute change in emissions by scope for the increased carbon price policy in 2030, in the case that no airline fleet swapping is assumed. 108
Figure 55. Absolute change in emissions by scope for the biofuel uptake policy, in the case that airline fleet swapping is assumed. 108
Figure 56. Absolute change in emissions by scope for the biofuel uptake policy, in the case that no airline fleet swapping is assumed. 108
Figure 57. Change in non passed-on cost per RPK by airline type and scope for the biofuel uptake policy, in the case that airline fleet swapping is assumed. 109
Figure 58. Change in non passed-on cost per RPK by airline type and scope for the biofuel uptake policy, in the case that no airline fleet swapping is assumed. 109
Figure 59. Absolute change in emissions by scope for the landing charge policy, in the case that airline fleet swapping is assumed. 109
Figure 60. Change in non passed-on cost per RPK by airline type and scope for the landing charge policy, in the case that airline fleet swapping is assumed....110

List of Tables

Table 1. Impact on airline cost per RPK and passenger numbers, by policy type: summary....7
Table 2. Slot mobility at different airports. Source: EC (2011). 34
Table 3. Assumed growth rate in passenger numbers per year by world region-pair. 46
Table 4. Model itineraries for the example case of New York to Istanbul in 2015. 47
Table 5. Aircraft size categories used in modelling. 49
Table 6. Assumptions about historical and future aircraft technology and cost characteristics, by size class....53
Table 7. Assumptions about future fuel, biofuel and carbon prices. 54
Table 8. Baseline model aircraft movements by scope, thousand flights per year....57
Table 9. Baseline model passengers per year by scope, mppa. 58
Table 10. Baseline passengers per major airport in 2015, in comparison to CAA totals. Note that non-UK airport totals represent only the demand considered for this project, not the absolute totals of passengers travelling through the airport....59
Table 11. Model baseline CO_2 totals by scope in comparison to UK bunker fuel uptake, $MtCO_2$/year....60
Table 12. UK and non-UK airline passenger demand for operations on UK and modelled non-UK routes in 2015, mppa 60
Table 13. Scheduled passenger demand in mppa and CO_2 by in tCO_2/year by itinerary type, 2015, within and outside UK departing flight scope. 61
Table 14. The change in passengers (mppa) and CO_2 (tCO_2) by itinerary type and emissions scope in the case that a $200/$tCO_2$ carbon price with 100% pass-through is applied to the 2015 baseline system, and itinerary choice is the only modelled response....71
Table 15. The change in passengers (mppa) and CO_2 (tCO_2) by itinerary type and emissions scope in the case that a $200/$tCO_2$ carbon price with 100% pass-through is applied to the 2015 baseline system, with itinerary choice and a small price elasticity of demand. 72
Table 16. Scheduled passenger demand and CO_2 by itinerary type for central year-2030 baseline conditions. 91
Table 17. Parameters for major route groups for the itinerary choice model....106

1. Introduction

The purpose of this study is to evaluate whether UK-specific aviation policy carries the risk of increasing CO_2 emissions outside the policy scope (carbon leakage) or of UK airlines or airports losing profits or market share to their non-UK competitors (competitive distortion). To do this, we develop a model to assess passenger and airline response to policy on a network basis. Using this model, we assess different hypothetical policies in terms of the changes in airline fleets, passenger demand and CO_2 that they are likely to produce, and the location of those changes.

The structure of this report is as follows. First, we examine the literature on carbon leakage and competitive disadvantage, with a particular focus on aviation-related studies. We identify potential leakage mechanisms and assess which ones are likely to be important enough to proceed with further modelling on. We also examine key uncertain variables which may affect the outcome of modelling, and compare estimates for these variables from the literature. Second, we describe the modelling system developed for this project, comparing baseline outcomes in 2015 with observable metrics, and discuss how airline and passenger response are modelled. Third, we run the model for a range of UK-specific hypothetical aviation policies and assess its sensitivity to different uncertain variables. We discuss model outcomes in terms of leakage and competitive disadvantage, and how these vary by policy type. Finally, we present overall conclusions.

1.1 Carbon Leakage

The IPCC definition of carbon leakage is '*the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in emissions of these countries*' (IPCC, 2007). This effect depends strongly on the characteristics of the sector in which the policy is applied. Across all sectors, it is typically driven by the cost differential between operating within and outside the policy area when carbon costs are factored in (the *terms-of-trade, non-energy* or *competitiveness* effect; Burniaux & Oliviera Martins, 2000), or by the effect of reduced fossil fuel use within the policy region on global fossil fuel prices (the *energy market* effect). The non-energy effect may be further subdivided into a short-term competitiveness channel (where companies affected by the policy lose market share to those who are not) and an investment channel (where companies relocate or focus investment on non-policy regions; Reinaud, 2008).

The overall impact can be substantial. Most literature analyses target either the Kyoto protocol, the EU Emissions Trading Scheme (ETS) or hypothetical regional policies of similar magnitude. Literature estimates of carbon leakage in this context across all sectors typically range from 2-25%, depending on the policy applied, assumptions about international market integration and structure, substitution and supply elasticities, and the extent to which industry responses in terms of technological change or relocation are considered (Kuik & Hofkes, 2010; Di Maria & van der Werf, 2008; Burniaux & Oliviera Martins, 2000). For individual sectors, such as steel or cement production, leakage rates may be significantly higher. As an extreme example, Babiker (2005) projects carbon leakage rates of up to 130%

in cases where there can be substantial relocation of energy-intensive industries outside the policy region. A leakage rate of 100% indicates that reductions in CO_2 emitted in the policy region are exactly matched by increases in CO_2 emitted elsewhere; therefore, a rate of over 100% implies that total global emissions have actually been increased in this case.

In contrast, some carbon leakage-type mechanisms may induce a reduction in emissions outside the policy area (‘*negative leakages*’). For example, the policy might induce the development of carbon-reduction technology that is then used worldwide (e.g. Porter & van der Linde, 1995). Similarly, reductions in oil price could stimulate a shift away from coal as an energy source, reducing overall CO_2 emissions (e.g. Burniaux & Oliviera-Martins, 2000).

Historical analyses of carbon leakage are typically theoretical rather than empirical. Some empirical estimates of leakage have been made (e.g. Reinaud, 2008; Martin et al., 2016); these indicate that the overall magnitude of leakage resulting from historical policies is likely small, but that the most carbon-intensive industries are typically most at risk of leakage.

The phenomenon of carbon leakage is well-established and is taken into account in the design of many regional carbon policies. For example, the EU Emissions Trading Scheme (ETS) identifies sectors at risk of carbon leakage, including cement and steel manufacture (EC, 2018; Vivid Economics & Ecofys, 2014); these sectors may then be subject to a higher share of free allowances or other mechanisms designed to reduce the risk of leakage. Another option is border adjustment measures, i.e. the obligation for importers to account for the carbon emissions associated with imported goods, and purchase allowances accordingly (e.g. Kuik & Hofkes, 2010).

1.2 Competitiveness

Competitiveness can be defined as the ability of companies in a region to maintain profits and market share (e.g. Reinaud, 2008). In the case of a unilateral carbon policy applied in one region only, companies operating in that region are faced with an increase in costs, whilst those from outside the region are not. As with carbon leakage, this may result both in companies within the region losing market share to those outside, and longer-term investment and relocation decisions favouring other regions (Cosbey & Tarasofsky, 2008). As discussed in CE Delft (2005), competitive distortion in this context arises from the regional nature of cost impacts. Impacts on costs that would still happen if the policy were applied globally are not considered to be distortion.

For example, Reinaud (2008) compare different studies on the impact of a €20/tCO_2 carbon price on the competitiveness of European firms. They find production cost increases of between 1 and 24%, with strong variation between sectors. Aldy & Pizer (2015) estimate competitiveness impacts, as measured by net imports, of up to 0.8% for the most energy-intensive industries in the case of a $15/t$CO_2$ carbon price, a figure which is less than one sixth of the total decrease in production.

1.3 Application to the aviation sector

Aviation differs from other sectors examined in terms of carbon leakage in several ways. First, CO_2 emissions mitigation is typically more expensive in aviation compared to other sectors, and reductions in CO_2 emissions achievable with current and near-future projected technologies are small compared to those achievable in other sectors. Typically, aviation emissions are projected to grow into the future, even with a wide range of alternative technologies available (e.g. Dray et al. 2018). This is a function both of slow reductions in carbon intensity (at most 2-3% reduction per year in tCO_2/RPK even with ambitious technology development; Dray et al. 2018) and rapid projected global demand growth (4-5%/year increase in RPK; e.g. Airbus, 2018; Boeing, 2018). Additionally, fuel is a major component of airline total operating costs (30% in 2015; Al Zayat et al. 2017) and airlines already utilise a wide range of fuel-saving measures which are cost-effective at current fuel prices (e.g. Schäfer et al. 2016). Safety considerations also mean that changes in technology have to go through lengthy testing and certification processes with consequently long lead times. These factors in combination mean that extra within-sector opportunities to reduce carbon intensity in response to policy are limited. Second, aviation is already a highly connected global system. Most passenger round-trip journeys already produce emissions attributable to multiple countries, and intercontinental passengers already have the option to straightforwardly choose between itineraries that route via different airports. Passenger choice is therefore a significant factor in aviation policy leakage in a way that it is not in other sectors.

There are relatively few general analyses of carbon leakage and competitiveness impacts applicable to the aviation sector. However, several studies look at the impact of adding aviation into the EU ETS (e.g. Faber and Brinke (2011); Ernst & Young and York Aviation (2008); Anger & Köhler (2010); SEC (2006); Scheelhaase & Grimme (2007)). These concentrate on the original scope of the EU ETS Aviation directive (EC, 2008), i.e. including all flights to and from countries in the ETS, a scope which was intended to minimize competitive distortion and carbon leakage. Ernst & Young and York Aviation (2008) argue that carbon leakage impacts may be substantial, but illustrate this with a series of route-based case studies rather than a system-wide estimate. Anger and Köhler (2010) assess the overall impact of including aviation in the EU ETS to be small, including only minimal competitive distortion effects. They argue that the projected airline cost increases in the EU ETS are too small to overcome inertial barriers in the existing system, for example the issue of landing slot allocation often being the result of long-standing co-operative agreements, and the structure of existing hub and spoke networks. Similarly, the EC's official analysis (SEC, 2006) concludes that competition between airlines would not be significantly affected. CE Delft (2005) argue that the international nature of aviation, in which most passengers already have fixed geographical origins and destinations, limits the competitive impact compared to that expected in other sectors. Scheelhaase & Grimme (2007) compare the impact of different ways of incorporating aviation into the EU ETS on competition for four airlines with different business models. They find overall impacts are small, but competition effects may be substantial on individual routes.

Faber & Brinke (2007) discuss possible competitive distortion impacts of applying the EU ETS to aviation in three areas:

- Airlines with a greater proportion of routes affected by the policy (e.g. EU-based airlines in the context of the report) will have a reduced ability to cross-subsidise affected routes from profits on unaffected routes (the *cross-subsidisation effect*).
- Airlines with more affected routes will have a larger overall policy-related cost burden (the *volume effect*).
- Airlines with hubs in policy-affected regions will face greater costs than those with hubs outside, and if costs are passed on to fares then ticket prices via these hubs will increase compared to ticket prices via other hubs, likely leading to a shift in market share towards other airlines (the *hub effect*).

CE Delft and MVA (2007) and CE Delft (2005) argue the cross-subsidisation effect will be minimal on a city-pair basis if airlines are assumed to be profit-maximising. This is because, if fares on other routes are already set at a profit-maximizing level, then changing them will reduce overall profit and also put the cross-subsidising routes at a competitive disadvantage against other competitors. However, Scheelhaase & Grimme (2007) find scope for competitive distortion if cross-subsidisation is assumed.

In the case of the volume effect, airlines based in the policy region will certainly be more affected on a whole-network basis than those based outside. However, this is arguably not a competition distortion as airlines compete on a city-pair basis, and at the city-pair level they are affected equally on most routes (Faber & Brinke, 2007). However, the hub effect is potentially substantial. CE Delft and MVA (2007) found a complex overall response to a modelled EU ETS, with non-EU airlines potentially suffering larger reductions in demand on some scopes than EU ones. For a fully passed on allowance price of €30 with no free allowances, they projected an overall increase in demand to North America of 5.0% for EU carriers, compared to a decrease in demand of 4.4% for non-EU carriers. However, in the case of flights to the Asia/Pacific region, EU carrier demand was projected to fall by 5.9% but non-EU carrier demand by 5.2%.

CE Delft (2005) also consider the situation in which there is a difference in environmental efficiency between airlines, leading to those that have higher emissions for the same segments being at a cost disadvantage in the case that a carbon price or other emissions-linked increase in cost is applied.

Vivid Economics (2008) examined how airline profits would be affected by the EU ETS, and did not specifically look at the case of competitive distortion between EU and non-EU carriers. They found that airlines with more price-sensitive passengers were likely to face greater decreases in profits, and that larger airlines may face more adverse impacts on profit than smaller airlines. With substantial allocations of free allowances (over 20-40% of pre-ETS emissions levels) they projected an increase in airline profits due to windfall profits. Without free allowances, the reduction in profits on markets with four competitors was found to be between 20 and 40% of the cost of allowances on those routes, and was relatively insensitive to demand parameters.

In terms of carbon leakage, Faber & Brinke (2007) conclude that leakage related to the EU ETS would primarily occur via the short-term competitiveness channel identified above, i.e. via airlines operating in the policy region losing market share on a city-pair basis to airlines or ground transportation not affected by the policy. This could occur in a number of ways. For example, passengers or freight may choose to hub via a non-EU airport; passengers or freight who would normally have made a direct journey from the EU may add an intermediate stop in a non-EU airport to reduce the affected portion of their journey; passengers or freight may choose a ground transportation mode instead; or passengers who would have visited the EU may choose an alternate destination instead. In the case of a passenger switching to high-speed rail, the impact may be a reduction in overall emissions. Secondarily, there might be a limited impact on fuel prices via the energy market effect, which could increase demand outside the policy region.

1.4 The case of UK-specific aviation emissions policy

The impact of the EU ETS may differ substantially from the impact of an individual country imposing unilateral aviation emissions mitigation policies. In 2015, flights under the original scope of the EU ETS accounted for around 21% of global departures and 29% of global aviation fuel use (15% and 7% respectively if excluding flights to and from the ETS region). In contrast, around 5% of global scheduled flights started or finished in the UK in 2015 (Sabre, 2015), accounting for around 8% of global fuel use (Lissys, 2017; the relatively high fuel use reflects that this total includes many long-haul, intercontinental flights).

In the case of aviation policy applying just to the UK, the scope for changes in hub choice is significantly greater. This is because the UK is a much smaller region, containing only one major global hub airport (London Heathrow), and is close to several other global hub airports (Amsterdam Schiphol; Paris Charles de Gaulle; Frankfurt). Even in the context of the EU ETS, CE Delft and MVA (2007) note that London Heathrow is relatively vulnerable to policy impacts in comparison to other hubs, due to its wide catchment area and geographical location.

Measuring competitive distortion impacts on UK airlines requires defining what a UK airline is. This can be complex. Relatively few airlines operate in isolation. Many individual airlines are members of airline groups which operate internationally, with members from multiple countries. Airlines within a group may act as a combined entity. For example, some airline groups manage fleet at a group rather than an airline level. Airlines may also be members of airline alliances and/or codeshare with other airlines. This has less impact on fleet but does affect which airlines can be considered to be competing with each other on a route level. Figure 2 shows some of the key current and future relationships between UK airlines.

For the purposes of this report, we consider a UK airline to be any airline which holds a Type A Operating license in the UK (CAA, 2017), excluding helicopter-only operators. These carriers currently are, with IATA/ICAO codes where assigned: 2Excel Aviation Ltd; Air Kilroe Ltd, trading as Eastern Airways (T3/EZE); Air Tanker Services Ltd (9L/TOW); BA CityFlyer Ltd (CJ/CFE); Bae Systems (Corporate Air Travel) Ltd (BAE); British Airways plc (BA/BAW); British Midland Regional Ltd (BM/BMR); *CargoLogicAir Ltd (P3/CLU)*; Cello Aviation Ltd (CLJ); *DHL Air Ltd (D0/DHK)*; EasyJet UK Ltd (U2/EZY); Flybe Ltd (BE/BEE); Jet2.com Ltd (LS/EXS); Jota Aviation Ltd (ENZ); LoganAir Ltd (LM/LOG); Norwegian Air UK Ltd (DI/NRS); RVL Aviation Ltd (REV); TAG Aviation UK Ltd; Thomas Cook Airlines Ltd (MT/TCX); TUI Airlines Ltd (BY/TOM); Titan Airways Ltd (ZT/AWC); Virgin Atlantic Airways Ltd (VS/VIR); Virgin Atlantic

International Ltd (VS/VGI); *West Atlantic UK Ltd (NPT)*; Wizz Air UK Ltd (WUK). Cargo-only operators are shown in italics. Note that IATA codes for airlines are frequently reused; the codes shown are from 2018. For the 2015 data, we also include Monarch Airlines (ZB/MON), which ceased operations in 2017.

This definition includes UK subsidiaries of carriers based outside the UK, for example Norwegian Air UK. It also excludes non-UK subsidiaries of UK airlines, for example EasyJet Switzerland.

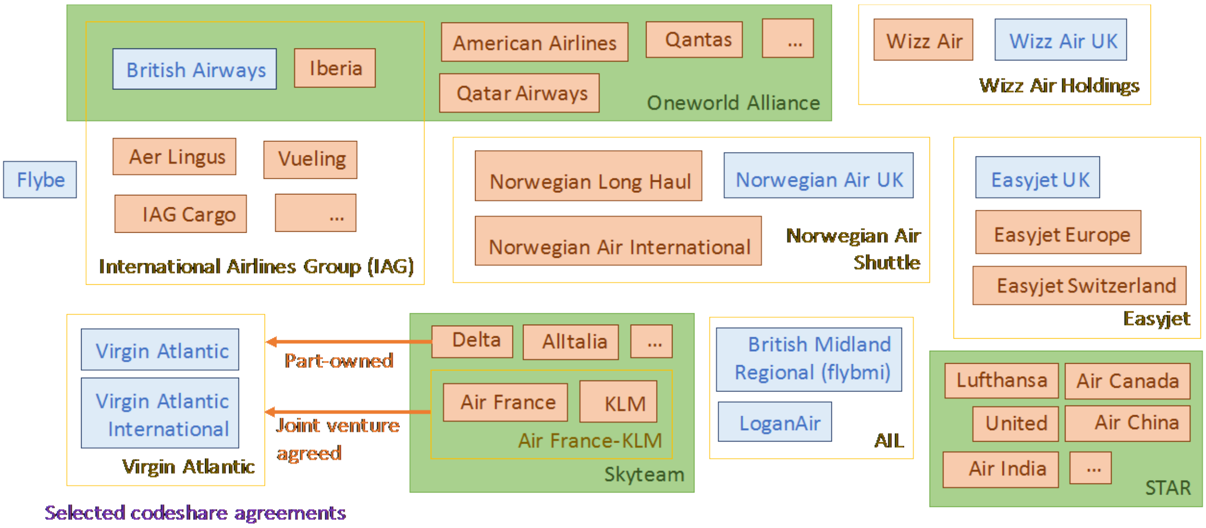

Figure 2. Relationship between key airline groups, alliances and codeshare partners.

We neglect airlines with Type B operating licenses to fly passengers on aircraft with fewer than 20 seats and /or weighing less than 10 tonnes; these are typically small-scale domestic operations where the scope for competitive distortion and carbon leakage is minimal.

2. Mechanisms and approximate level of impact

In this section, we discuss individual mechanisms by which carbon leakage and/or competitive distortion may occur, in the context of unilateral policy affecting airline costs, operations or fleet at UK airports. For each mechanism, we examine the literature and assess the order of magnitude of potential impact.

In 2015, UK international aviation-related emissions were estimated to be around 33.3 $MtCO_2$ from aviation fuel uptake at UK airports, with domestic aviation emissions adding an extra 1.6 $MtCO_2$ (BEIS, 2017). The most recent set of DfT demand projections (DfT, 2017) project emissions on this scope to be between around 35 and 44.3 $MtCO_2$ in 2050. The relatively low growth rate (compared to those projected for global emissions) is the result primarily of capacity constraints and assumptions about the maturity of different aviation markets.

Freight carried at UK airports was around 2.4 million tonnes in 2016, with 69% carried in the holds of passenger aircraft and only around 5% growth during the period 2011-2016 (DfT, 2017). Hold freight is implicitly accounted for in the emissions totals derived below, assuming hold freight weight per aircraft remains roughly constant. Freighter aircraft movements declined between 2001 and 2006, from around 70,000 movements per year to just over 50,000 and are concentrated at Nottingham East Midlands International Airport and Stansted airport. In 2015, they accounted for around 1 $MtCO_2$ (DfT, 2017).

Because any aircraft which flies into the UK must also fly out of the UK, and because air passenger journeys are usually made on a round-trip basis, the analysis below considers flights to as well as from the UK. On this scope, total emissions in 2015 were around 68.2 $MtCO_2$ if it is assumed that emissions from flights to the UK are roughly equal to those from the UK (BEIS, 2017).

In 2015, around 270 million passengers travelled on scheduled city-pair routes where at least one percent of passengers used a route involving the UK (Sabre, 2017). Of these, around 180 million were on routes with the UK as an initial or final destination. 11 million used a hub airport in the UK, of whom 8.7 million neither started nor ended their journeys in the UK. Additionally, approximately an extra 14% passengers travelled on non-scheduled flights, primarily charter flights to holiday destinations.

These numbers may be affected in several ways by a policy that changes airline costs. If airlines pass on costs to passengers via ticket prices, passengers may choose not to fly, to travel via a different route, or to use ground transportation instead (where appropriate). Passenger demand may also change outside the policy area, potentially leading to negative leakage. Similarly freight shippers may choose not to send freight, to reroute freight to avoid extra policy costs, or to send it by truck. Passengers may choose to travel to a different destination which is less-affected by policy costs. Airlines may choose to reassign fleet to reduce their policy costs, or may abandon affected routes altogether. When making decisions about future investment, they may choose to focus that investment outside the policy area. Similarly, new airlines may choose to locate outside the policy area. Airlines might sell older aircraft and buy new ones, or otherwise invest in emissions-reduction technology. If they can avoid costs by doing so, they may also tanker fuel on routes into the policy area. Finally, reductions in fuel use due to the policy may lead to a reduction in the global price of fuel and therefore increases in fuel use outside the policy area. We consider each mechanism, and its approximate level of impact, individually below.

2.1 Change in passenger or freight routing (to same destination**)**

There are several mechanisms which may count as a change in routing. In the most frequently cited case in the literature, passengers who route via the UK on journeys not starting or ending in the UK may respond to increased costs by choosing another route. This is the 8.7 million passengers mentioned above. The highest-demand routes involved are shown in Figure 3. These passengers are typically on long-haul intercontinental routes and account for around 9.5 $MtCO_2$ if typical carbon intensities per route from the AIM aircraft performance model are used (e.g. Dray et al., 2018). About half of these emissions are from flights departing from the UK (' a UK departing flight scope'). In the most extreme case where all these passengers change their routing to comparable itineraries not via the UK, these emissions will shift from within a UK-related scope to outside it. Thus the potential effect here could be substantial compared to possible reductions in emissions. Around 70% of these passengers travelled on UK-based airlines and total revenue from these passengers was $3.6 billion year 2015 US dollars in 2015 ($5.3 billion if including all taxes and charges; Sabre, 2017).

Another mechanism for routing change is for UK international origin and destination passengers who hub in the UK (around 1.6 million passengers in 2015, accounting for around 1.1 $MtCO_2$ across their whole journeys) to switch to non-UK hubs.

A third potential mechanism is for UK origin and destination passengers on long-haul direct flights to switch to short-haul transfers to non-UK hubs, followed by a long-haul flight to their final destination. As well as moving passengers out of UK scope, this mechanism could also involve an increase in overall emissions for these passengers due to increased distance flown. In 2015, 42 million UK origin and destination passengers who did not hub in the UK travelled on itineraries of over 3000 km, accounting for around 30 $MtCO_2$ across their whole journeys and revenue of $9.56 billion (excluding taxes and charges) for UK-based airlines. However, as discussed in the section on itinerary choice, below, passengers tend to strongly prefer direct routes over transfer routes when given the choice between the two, even when all other parameters (time, fare, etc.) remain constant, so the overall impact on these passengers is likely small.

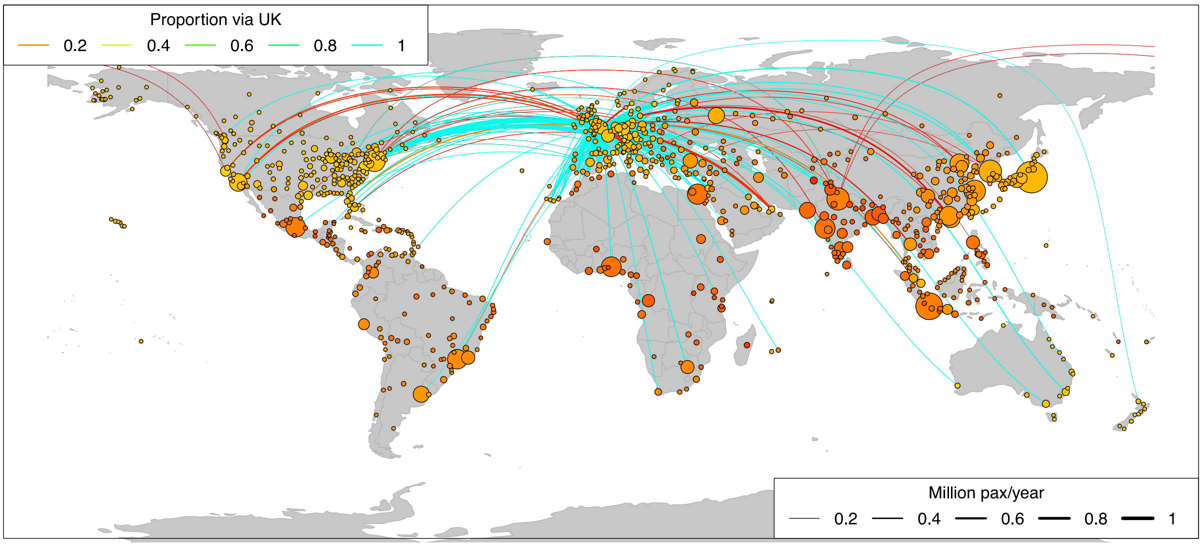

Figure 3. Origin-destination city-city passenger flows of more than 100,000 passengers per year (in 2015) for which at least some passengers route via a UK airport. Data: Sabre, 2017.

The corresponding impact on freight operators may also be substantial. Because freight flights are less labour-intensive than passenger flights, fuel and landing costs are a higher proportion of total operating costs for freight operators, so they may be more impacted by policy. Freighter aircraft are also typically older and less fuel-efficient (e.g. Dray, 2013). However, UK departing freight carried in freighter aircraft (as opposed to in the holds of passenger aircraft) accounted for only around 1 $MtCO_2$ in 2015 (DfT, 2017). There is limited data to assess how much of this freight is being shipped through the UK as opposed to being transported to or from UK destinations, but the likely impact of changes in freight route choice is small in absolute terms compared to the passenger impact.

2.2 Change in passenger destination

As leisure passengers are more price-sensitive than business passengers (e.g. Brons et al. 2002) the largest impact on destination switching is likely to be on leisure trips, either from UK passengers staying at home or from international visitors travelling elsewhere. In the first case no leakage is likely. In the second case, 13.9 million visits to the UK by overseas residents were made for tourism purposes in 2015 (ONS, 2015). The overall impact of destination switching is difficult to estimate without knowing which destinations passengers will switch to. It is also unclear whether this would be a positive or negative effect, as this depends on whether destination-switching passengers travel further to their new destination than they would have to the UK. The impact will also vary by policy, depending on whether cost increases are larger for further-away destinations (as for an increase in fuel or carbon price) or apply per flight (as would be the case for an increase in landing costs). In the latter case, the largest relative impact would be on short-haul flights, discouraging visitors primarily from European destinations. Tourism destination choice is in any case variable year on year and depends on many difficult to measure factors such as destination image and destination loyalty (e.g. Chi & Qu, 2008).

Mayor and Tol (2007) estimate the impact of a comparable policy (Air Passenger Duty) on UK tourism, using the Hamburg Tourism Model with airfare elasticity of destination choice of -0.45 for the UK. They find only a small fall in tourism to the UK of around 1.2%, considerably below typical year-on-year growth rates of 4%; they also note that carbon leakage is possible due to the change in the relative price differential between short-haul and long-haul destinations in this specific case.

Given the uncertainty in estimating which destinations passengers might switch to, we do not directly model destination switching in this study. However, some of this impact will be captured by the demand reduction effect discussed in Section 2.5, below, in the case that UK origin or destination passengers decide to holiday in the UK instead of flying to a more distant destination.

2.4 Mode shift (single segment or whole journey)

Mode shift could affect carbon leakage and/or competitive distortion in two ways. First, passengers or freight could switch to an alternative mode for their entire journey. Depending on the emissions intensity of the alternative mode and the method of accounting used, this may lead to a decrease or increase in overall UK-attributed emissions. For passengers, the most likely mode shift option is high-speed rail via the channel tunnel. High-speed rail is typically a (partial) substitute for air journeys where the rail travel time is under about 200 minutes (e.g. Behrens & Pels, 2012), which limits the number of routes for which mode shift to rail for the whole journey is plausible. Many of these routes already have substantial rail market share, with airlines targeting less price-sensitive business passengers for any remaining flights. For example, high-speed rail had around an 80% mode share of the London-Paris route in 2009 (Behrens & Pels, 2012); in 2015, scheduled air passengers travelling between London and Paris accounted for around 0.25 $MtCO_2$. The impact of more of these passengers switching to rail is therefore relatively small. The channel tunnel also acts as a capacity bottleneck, providing a practical limit to the number of passengers who can switch modes in this way. In 2015, around 21 million passengers used the channel tunnel (DfT, 2016).

For freight, long-distance freight which is less time-sensitive could switch to ship transport, which is associated with a substantially lower carbon intensity than aviation. Domestic air freight could switch to truck transport. However, UK domestic air freighter fuel use is around 0.1% of total UK-associated fuel use, so changes to this total are unlikely to make a large difference to leakage or distortion.

In the second case, UK origin and destination passengers could use a ground transportation mode to access a nearby non-UK hub, e.g. Paris Charles de Gaulle, Brussels or Amsterdam Schiphol. This is similar to the case discussed above of passengers taking a short-haul flight to a nearby non-UK hub and a subsequent long-haul flight from there. In this case, however, passengers will face longer journey times on the ground transportation leg, additional airport access logistics, and a smaller selection of feasible non-UK hubs to choose from.

For freight, adding a truck segment to a continental airport is effectively trading off increased journey time against a reduction in costs. Ohashi et al. (2005), in the context of Northeast Asia, find a 1 hour reduction in transport plus processing time to be more attractive to freight operators that a $1000 reduction in costs when considering transshipment location. This is consistent with air freight being primarily used for high value and/or time-sensitive goods (e.g. Mitra & Leon, 2014). Road transportation time for London-area airports to Paris Charles de Gaulle and Brussels airports is approximately 5 hours (e.g. Google, 2018) in comparison to flight times of around an hour (e.g. Sabre, 2017). This suggests that policy-imposed costs would need to be at least $4000 per flight before freight operators would consider switching in this way. Gardiner et al. (2005a, 2005b) survey freight operators and find that airport location and operational restrictions (for example, night curfew) are the primary criteria used to determine transshipment airport, with airport costs entering the decision process at a later stage. Cargo operators may change airport relatively frequently, with 43% surveyed in Gardiner et al. (2005b) having moved a cargo service in the past two years and 47% of those who had moved doing so partly due to cost reductions available elsewhere. However, such moves are between different airports within the same region. Similarly, Yuen et al. (2017) discuss freight operator airport choice primarily in terms of primary and secondary airports within a given catchment area. These factors in combination suggest that most freighter flights, particularly those which are transporting freight to or from rather than through the UK (which are likely to be the vast majority) are not likely to switch to non-UK airports in response to policy.

Given the constraints on mode choice for passengers and freight discussed above, we do not model mode-switching in response to policy in this study.

2.5 Demand reduction outside the policy area

The global aviation system is highly interconnected. Passengers typically do not just travel one-way on a single flight segment. Most journeys are round-trips, and many journeys involve multiple flight segments in either direction. If a policy increases the cost of travelling on a single segment, this will be experienced by passengers as an increase in the ticket price of their whole itinerary. Additionally, if an aircraft flies into an airport it also has to fly out again (airlines do sometimes carry out empty ‘positioning flights’, but flying without passengers means no passenger revenue for that flight, so these are relatively rare). These factors mean that demand reduction on a given route is likely to be symmetric across outbound and inbound flights, even when the increased costs apply in only one direction. Similarly, demand may decrease on flight segments that are not to or from the policy area, but which serve passengers on multi-segment itineraries to or from the policy area. One example is flights from Asian or Middle Eastern hub airports to Australia which serve UK-Australia demand.

A demand decrease outside the policy area will lead (all other things being equal) to a decrease in CO_2 emitted outside the policy area. This will lead to negative leakage. In the case that leakage is measured on a departing flights basis, a corresponding reduction in arriving flights will lead to leakage of around -100%, i.e. the same reduction within and outside policy scope.

The vast majority of UK-related passenger round-trip journeys contain flight segments inside and outside policy scope. Therefore demand reduction effects are potentially a major contributor to overall leakage, and need to be considered.

2.6 Changes in existing fleet assignment (within-airline)

Airlines which operate primarily outside the UK will have the option of moving more fuel-efficient aircraft onto their UK routes and using less fuel-efficient aircraft on their non-UK routes in response to UK-based mitigation policies. Airlines which operate primarily to and from the UK will not have this option. In the most extreme case, where non-UK airlines are able to satisfy all policy requirements by rearranging their fleet in this way, all of the carbon reductions achieved by applying the policy to non-UK airlines will be effectively leaked (plus or minus a small extra amount due to the more or less efficient use of each aircraft on its new routes). Non-UK airlines operating to and from the UK accounted for around 28 $MtCO_2$ in 2015; reductions in emissions from switching to the most efficient aircraft types available depend on aircraft type, but could in theory be up to around 15-20% if switching between older single-aisle aircraft types and the most recent generation of single-aisle aircraft. However, this does not account for other requirements on aircraft type that apply at UK airports, which may already effectively restrict the use of older aircraft and make substitution of aircraft from other routes less likely. For example, noise regulations already effectively restrict the aircraft models that can operate to and from Heathrow airport. There is also some evidence that airlines in practice do not reconfigure their fleets in this way in response to policy (e.g. Roy, 2007; Nero & Black, 2000), making the overall impact of this option uncertain.

This mechanism also has substantial potential for competitive distortion. This is because non-UK airlines use a much greater percentage of their fleets on non-UK routes. They can therefore reduce their policy costs to a greater extent by reassigning aircraft between routes.

Due to the large potential leakage and distortion impacts, we include this mechanism in the modelling for this study; however, due to the uncertainty about the extent to which airlines can swap fleet in practice, we model outcomes with and without this option.

2.7 Airlines abandon non-profitable routes and/or don't invest in new routes

This can be considered as another sub-case of the itinerary choice-based carbon leakage route discussed above. In the case that a direct route to the UK is discontinued, passengers on that route will choose either not to travel, to take an indirect route for their journey, or to switch modes, potentially resulting in a change in emissions per passenger. Ernst & Young and York Aviation (2008) use UK domestic flights as a case study; in the case that flights from Southampton to Leeds are discontinued and all passengers travel by car instead, they project an increase in emissions on that one route by 18%. However, this outcome depends strongly on the model and occupancy of car assumed. In any case, UK domestic flights are a small proportion of total emissions.

Airlines will consider abandoning a route if it falls below some threshold rate of return. Generally routes need not only to be profitable on a long-term basis but to generate profit that the carrier deems sufficient. Airlines will generally need to earn their cost of capital plus a premium, and so the route network generally needs to achieve this level. For example, IAG has committed to a 15% Return on Capital Employed (ROCE). Exceptions to this rule may apply in the case that a route has been in operation for less than three years, or in the case of network carriers where the route in itself is not sufficiently profitable but plays an important role in overall network profitability. Airlines may also be reluctant to cut routes to and from 'premium' global airports, such as Heathrow, or to cede routes to a competitor airline in the case that not many airlines compete on the route. However, ultimately the decision is a cost-based one.

We do not directly model airlines abandoning routes in this study. However, we do assess the increase in direct operating cost (DOC) per revenue passenger-km (RPK) by route and airline type. This can be compared to typical values of ticket revenue per RPK of around £0.1/RPK (e.g. Dray et al. 2017). In the case that increases in DOC/RPK become a significant fraction of ticket revenue, we might expect to see routes cancelled to and from UK airports.

2.8 Airlines add new UK-avoiding routes

This affects the passenger choice of itinerary discussed above, with the additional factor that the choice set for passengers may change, reducing the market share of UK airlines further. However, for most of the major routes considered, the choice set is already relatively large and includes UK and non-UK routes as appropriate to scope. The issue of whether the EU ETS would instigate network reconfiguration for passenger and cargo airlines was investigated by Albers et al. (2009) and Derigs & Illing (2013). In the case of passenger networks, a €20/tCO_2 carbon price is found to be insufficient to justify network change. For cargo, which is more impacted by changes in fuel-related cost, a range of €20/tCO_2 - €70/tCO_2 is explored. Some network reconfiguration is seen at high allowance prices and/or high auctioning percentages; however, the costs associated with hub relocation still exceed the savings in emissions cost achievable in nearly all cases.

As with the case of airlines cancelling routes, above, we do not model this directly. However, we do model the increase in DOC/RPK by airline and route type. In the case that this becomes significant in comparison to ticket revenue per RPK, we would expect to see some level of network reconfiguration where possible for airlines. However, in this case airlines will also have weaker balance sheets in general, which can reduce their ability to invest in new routes.

2.9 New airlines locate outside UK and/or existing airlines relocate

This mechanism is dismissed as unlikely by Ernst and Young and York Aviation (2008) in the context of the EU ETS, due to bilateral agreements and ownership regulations. However, this may be less applicable on a UK-only policy basis. Our initial examination of airline operations indicated multiple cases where airlines have recently set up subsidiaries in other countries (for example: EasyJet Europe; Wizz Air UK). However, many of these subsidiaries are directly in response to the uncertainties arising from the UK's exit from the European

Union. Whether a change in costs (as opposed to the risk that they may not be able to operate at all) would be enough to prompt airlines to set-up non-UK subsidiaries is uncertain. Although we do not model this mechanism in this study, it does represent a potential risk to the competitiveness of UK airlines by potentially removing airlines from UK scope.

2.10 Fleet leasing/sales between airlines

The age distribution of the UK fleet in comparison to fleet age distributions by world region is shown in Figure 4, by aircraft size class (RJ = Regional jet; SA = Single-aisle; TA = Twin-aisle; VLA = Very large aircraft). Age distributions depend largely on the history of demand growth per region, as well as individual airline practice on aircraft retirements and sales. For example, recent high growth in the Asia-Pacific and Middle East regions has resulted in relatively young fleets as airlines purchase new aircraft to meet demand. Historically, policies targeted at changing fleet composition (e.g. in terms of noise or local emissions) have targeted aircraft design specifications, with restrictions on older aircraft operations resulting in relatively few retirements (Dray, 2013).

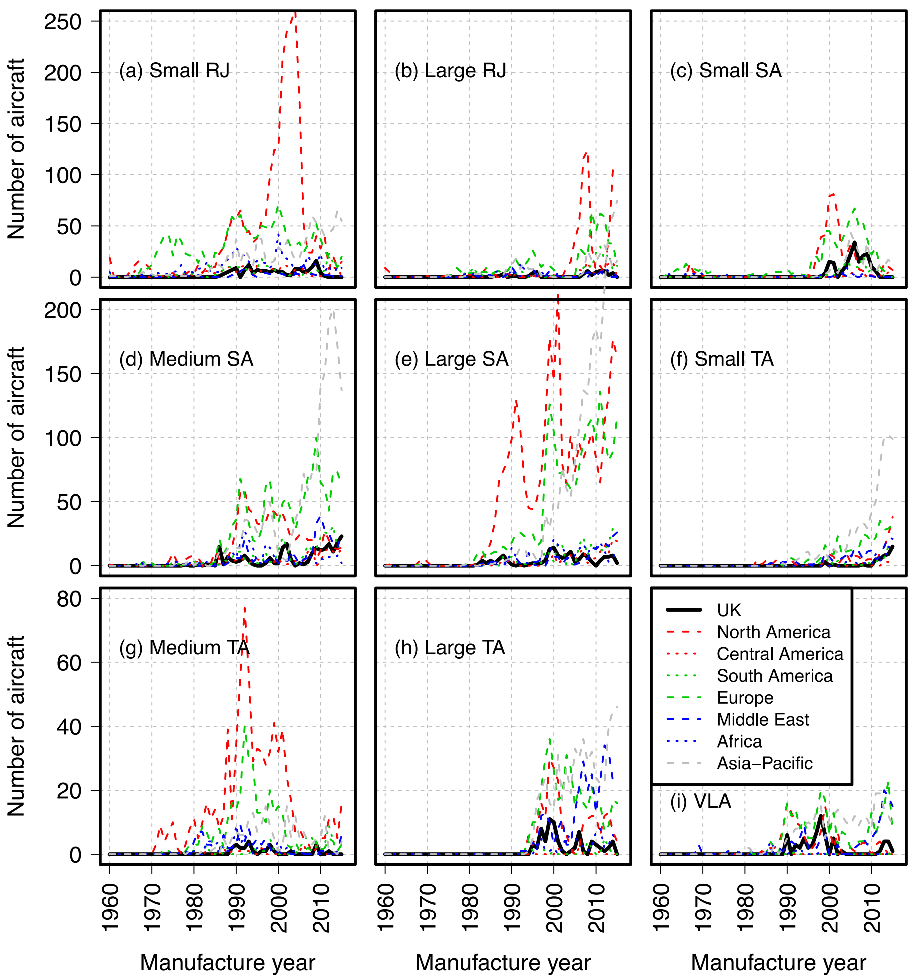

Figure 4. Age distributions of aircraft with operators registered in each region at the end of 2015, from FlightGlobal (2017).

Leakage in this context is likely to occur if, instead of scrapping older aircraft retired from the UK fleet as a result of policy, airlines sell or lease them on to airlines unaffected by the policy. The overall impact on emissions then depends on the extent to which these aircraft are being used as a replacement for even older and/or higher-emission aircraft, or not. In the case that they do replace higher-emitting aircraft then there is the potential for negative leakage. Across most size classes, however, the UK's aircraft age distribution is broadly typical of other world regions, i.e. aircraft retired from the UK fleet may not provide a significant benefit in replacing older aircraft from other world regions.

Additionally, airlines in other world regions that need extra aircraft will have the choice between second-hand older aircraft and new aircraft models with significantly lower fuel burn. Older aircraft are typically less fuel-efficient and noisier. Dray et al. (2018) find a reduction in fuel burn per RPK in new aircraft models of an average 0.7% per year across the different aircraft size classes shown here between 1990 and 2016; major improvements in aircraft technology occur at roughly 15-20 year intervals per size class. This means that relatively large emissions and airline cost reductions may be achievable from fleet replacement, subject to production line capacity. Recent new models of aircraft include the Airbus A320neo, Boeing 737MAX and Bombardier C-Series families, which provide 15-20% reduction in fuel use per RPK over the previous generation. The 777X and A330neo are projected to be available before 2025, with similar reductions in fuel use.

The impact of new UK-based policy on the fleet will also vary by policy specification, and by the other constraints (noise, local emissions) that apply at UK airports. Morrell & Dray (2009) modelled the airline financial decision of whether or not to replace an older aircraft with a new model. They found that fuel and carbon costs need to be significant before this becomes a cost-effective option. For example, replacing a 150-seat single-aisle aircraft was found not to be cost-effective even at oil prices of \$140/bbl and carbon prices of \$100/tCO_2.

Based on the potentially large emissions benefits, we include the option of aircraft sales due to policy cost in the model. As discussed in Morrell & Dray (2009), aircraft which are younger than typical retirement ages of around 30 years are usually sold on rather than scrapped. We therefore assume that sold aircraft join the non-UK fleet and are used for typical non-UK operations. As this affects mainly the oldest UK aircraft, and these aircraft are also old in comparison to global fleets, this produces a small amount of positive leakage.

2.11 Adoption of carbon-reducing technologies and operations

The adoption of carbon-reducing technologies offers the opportunity for negative carbon leakage, in that technologies adopted to reduce emissions-related costs in the UK may then also be used elsewhere. Normally an aircraft is used across multiple routes in the course of a year. In general most UK airline aircraft are used on UK routes, but a non-UK airline aircraft purchased specifically to meet UK requirements could be used on non-UK routes as well. However, as discussed above, policy costs may need to be substantial before they justify the purchase of new aircraft. In this case, non-UK airlines will have a strong incentive to use any aircraft purchased to meet UK requirements primarily on UK routes, as this reduces the number of aircraft required.

If an airline which is purchasing a new aircraft has a choice of future new aircraft models with radically different capabilities, policy costs might prompt them to change their purchasing decision. For example, potentially an airline might have a choice between a hybrid electric aircraft and a more conventional design. However historically technology decisions of this sort have been taken at the manufacturer level. Where competing manufacturers have released new models at similar times, those aircraft models have tended to be comparable in terms of fuel use and technology used. As such, we do not model the airlines' choice between different technology options. However, manufacturer choice of which technologies to invest research and development in may be influenced by their perception of likely future airline costs. We therefore include the user option to include different future trends in new technology emissions, derived from ATA & Ellondee (2018), where more optimistic technology assumptions may be appropriate in the case that fuel and carbon prices are projected to be particularly high, provided the technical challenges in developing each technology can still be met.

The case in which compliance with UK regulation results in new aircraft designs which have lower CO_2 emissions than they would otherwise is a potential further, long-term negative leakage mechanism. However, policy costs would need to be significant to outweigh the impact of future projected trends in fuel and carbon costs. The high importance of fuel costs to airlines also means that manufacturers are already strongly incentivised to design for greater fuel efficiency.

2.12 Increases in tankering

Because fuel prices differ between airports, airlines sometimes take a sufficiently large amount of fuel on board at an airport with lower fuel prices to cover both legs of a return trip, as long as the maximum landing weight is not exceeded. Tankering is profitable if the cost associated with carrying the extra fuel is lower than the difference in fuel costs between the two airports. Thus if UK-based regulation results in significantly higher fuel costs at UK airports, this may lead to increases in tankering on short-haul flights. Analysis for this study (Section 4.4.4) suggests that tankering on an individual flight increases emissions by around 3-10%. The net impact of increasing tankering would be to take emissions outside a UK fuel uptake scope plus a small increase (less than 0.2 $MtCO_2$) in overall emissions. Depending on how many flights are able to tanker fuel, the movement of emissions outside UK fuel uptake scope may result in a significant amount of leakage (effectively in excess of 100% in the case that tankering is the only outcome of the policy). Therefore we include it in this study's modelling of airline response.

If emissions are measured on a departing flights basis rather than a fuel uptake basis, the main impacts of tankering on emissions will be the 3-10% increase in arriving flight emissions on tankering routes discussed above. The departing flight using tankered fuel would be counted as UK emissions and not as leakage. In this case, leakage from tankering will be less than a tenth of what it would be on a fuel uptake basis. The leakage impacts of any policy avoidance from tankering will still apply, though. For example, if tankering is being carried out to avoid taking on biofuel, there will still be a reduction in biofuel use on UK departing flights which will affect within-system emissions reductions and hence the overall value of leakage metrics.

2.13 Reduction in fuel use impacts on fuel price

In the case that a policy causes aviation fuel use to decrease in one area of the world, this may result in a global decrease in fuel prices. In turn, this reduction in fuel price outside the policy area may cause an increase in demand.

Past research on this mechanism has concentrated on the EU ETS and/or Kyoto protocol, both of which (under the original EU ETS scope) account for a significantly higher percentage of global aviation fuel use than flights to and from the UK. The current total fuel use on flights to, from and within the UK is around 22 Mt. Policy-related emissions reductions are likely to be small in comparison to this total, and will be achieved by a combination of within-sector emissions reductions and demand reduction due to increased costs. Global Jet A/Jet A1 consumption was around 252 Mt in 2015 (IEA, 2017) and global demand is projected to grow faster than UK based demand (Airbus, 2018; Boeing, 2018; DfT, 2017), so UK-related fuel use as a proportion of total global fuel use is likely to fall.

The magnitude of this impact depends on the supply elasticity of fossil fuels (e.g. Gerlagh & Kuik, 2007; Boeters & Bollen, 2012). In the case that supply is perfectly inelastic (elasticity = 0), adjustment is via price only and all decreases in use in policy-affected regions are matched by increases in use elsewhere, i.e. 100% leakage. In contrast, a perfectly elastic supply (elasticity = ∞) would imply 0% leakage via this channel. Based on a survey of the literature, Gerlagh & Kuik (2007) find elasticity values of between 0.5 and 8, with the majority of values between 1 and 3. Based on an analysis of the output of a selection of associated CGE models, they conclude that this channel may be the predominant source of leakage observed.

We do not model this channel in this study, due to its high level of uncertainty. However, it should be noted that it potentially represents a significant extra leakage risk. This risk will be greater for policies which reduce fossil fuel use by larger amounts. Therefore, of the policies considered in this study, changes in landing charges are likely to have the lowest risk of this mechanism occurring, followed by changes in carbon price, followed by increases in biofuel use.

3. Metrics and key uncertain variables

To assess the extent of leakage and competitive distortion, we need to define appropriate metrics. The values of these metrics, and hence also the amount of projected impact, depend on key variables that are uncertain. Therefore in this section we explore both which metrics are suitable to use, and which uncertain variables their values may be sensitive to.

3.1 Metrics

3.1.1 Carbon Leakage

For carbon leakage, we use the IPCC definition, in which carbon leakage is the ratio between the increase in emissions from a sector in the non carbon constrained country (or region) as a result of domestic mitigation action, and the decrease in emissions of the carbon constrained sector as a result of the carbon policy:

$$Leakage = \frac{-\Delta CO_{2,outside\,policy\,area}}{\Delta CO_{2,within\,policy\,area}} \quad .$$

If the policy is applied to UK departing flights, then all UK domestic flights and UK departing international flights count as within the policy area. UK arriving flights and non-UK flights are outside the policy area.

This ratio is affected by the change in emissions per flight both within and outside the policy area, and the change in the number of flights within and outside the policy area. In turn, the emissions per flight are affected by the aircraft used; older aircraft typically have higher emissions. The number of flights is affected by changes in ticket price.

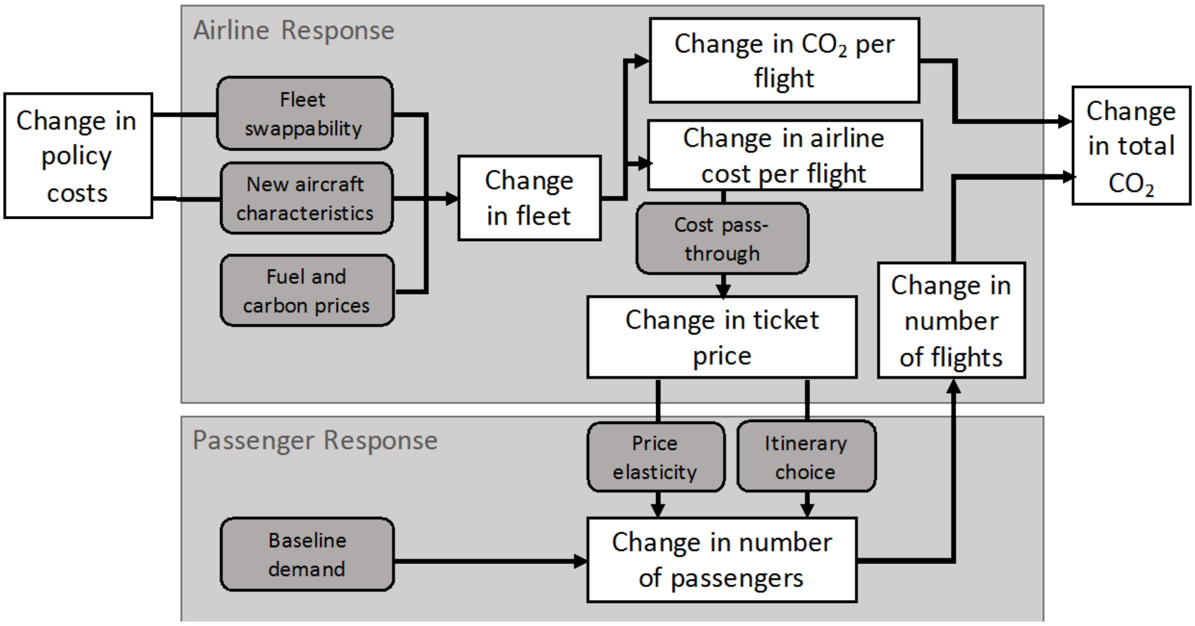

Figure 5. The relationship between the uncertain variables examined and policy CO_2 response.

Figure 5 shows the uncertain variables we consider in this section, and their relationship to the amount of CO_2 reduction. The key variables that affect the magnitude of impact will vary depending on the policy mechanism. In the case of a carbon price, airline costs will be increased by an amount determined by the carbon price (which itself may depend on the carbon intensity of other sectors and mitigation measures available to them), and airlines will have to choose how much of that cost to pass onto tickets. Fuel and carbon prices, cost pass-through and trends in the fuel use of new aircraft models are therefore all relevant uncertain variables.

In turn, passengers will respond to changes in ticket price by choosing not to fly or by changing to a less-affected itinerary. Therefore the passenger (and freight) price elasticities of demand, and itinerary choice parameters, are important variables as well. Similarly, baseline demand growth to the year that the policy is assessed in affects outcomes and is also uncertain.

Airlines may also choose to respond by swapping UK and non-UK fleet or by purchasing new aircraft. The extent to which UK and non-UK fleet are straightforwardly exchangeable, and airline fleet purchasing criteria, are therefore also important uncertain variables. As discussed in Burniaux & Oliviera Martins (2000), this is complicated by interactions between individual parameters, which are typically drawn from separate probability distributions rather than considered as part of a joint probability distribution.

In some cases, leakage is not a useful metric to use. For example, it does not straightforwardly capture the absolute level of emissions reduction. A policy can have relatively high positive leakage and still have a high net reduction in emissions; conversely, a policy can result in negative leakage but still only have a tiny impact on global emissions if the totals involved are small. Because different mechanisms lead to different amounts of positive and/or negative leakage, the value of the leakage metric can also appear to be volatile in the case that small totals of emissions reductions are involved, even when underlying changes in emissions are well-behaved. In the extreme case that a policy causes unintended increases in emissions both inside and outside the system, for example if reduced costs for low-emission aircraft cause a demand rebound, leakage will also technically be negative. Because of this, we also report absolute changes in emissions by scope as well as leakage values.

3.1.2 Competitive distortion

As discussed in Section 1, competitive distortion arises via similar mechanisms to carbon leakage and hence is affected by the same uncertain variables. There is no single universally-accepted metric for measuring competitive distortion. Indeed, as several forms of competitive distortion are possible, several different metrics may be appropriate to fully capture their impacts. Metrics used in the literature include passengers by airline type, changes in demand by airline type, and changes in airline operating margin (e.g. Ernst & Young and York Aviation (2008)). Broadly, these are affected by the same uncertain parameters as leakage, although in the case of airline operating margin, assumptions about current operating margins are required. Ernst & Young and York Aviation (2008) assume a typical operating margin of 4% for network airlines, 2-14% for low-cost carriers and 4% for cargo airlines, but acknowledge that this is optimistic. DEFRA (2008) show that under Cournot competition, airlines with larger market shares in a given market will have higher operating profit margins. However, airline profits can vary substantially year on year (e.g. CE Delft, 2005) and are influenced by the accounting practices that the airline uses to report profits, which may be geared towards presenting a particular situation for the company to shareholders or regulatory bodies. Therefore if the operating margin is used as a metric, the baseline value used counts as an uncertain parameter.

Based on an analysis of model output data, we choose the following as metrics for competitive distortion:

- The number of passengers by airline (UK/non-UK) and route type (UK/non-UK). This captures the extent to which airline revenues will be disproportionately affected between airlines.
- The change in airline direct operating cost per RPK (DOC/RPK) by airline and route type; this captures similar impacts to using airline operating margin without having to estimate current airline operating margins, on which limited data is available.
- The number of passengers per airport, for major UK airports and major non-UK hubs. This captures whether there will be a significant impact on UK airport competitiveness.

3.2 Key uncertain variables

3.2.1 Cost pass-through

Cost pass-through is the extent to which airlines pass on increases in costs to ticket price as opposed to reducing their operating margin. Ultimately, this decision will be made on a profit- (or market share-) maximisation basis and will interact with passenger price sensitivity; applying one or several rates of cost pass-through is an approximation to this. If airlines pass on all costs to passengers, as would be the case in a perfectly competitive market, the pass-through is 100%. Ernst & Young and York Aviation (2008) argue that airlines will be unable to pass on costs at congested airports where demand exceeds capacity as optimal prices are set by the (constrained) airport supply rather than marginal costs. In this case, pass-through would be 0%. For other routes they recommend 50%, 75% and 90% pass-through for the case where the route is operated by one, three or nine competitors respectively. They model cargo cost pass-through of 40-46%. In contrast, Derigs & Illing (2013) assume cargo emissions-related costs are not passed onto customers at all. CE Delft (2005) argue that empirical evidence suggests pass-through at congested airports is close to 100%. Anger & Köhler (2010) review literature rates of pass-through and find assumptions between 0% (for freely allocated allowances only) to 100% (purchased allowances only), with several studies using intermediate values in the range of 30-50%. SEC (2006) argue that where all airlines on each route are treated equally, they will pass on all or most of their increase in costs. Scheelhaase & Grimme (2007) find opportunities for cost pass-through vary by airline business model, assuming airline willingness to cross-subsidise between routes.

Wang et al. (2018) model pass-through as an elasticity-type term, using historical fare data across different routes and airline cost estimates to specify an econometric model for fare. They find different response to cost increases for different cost categories and different world regions; however, the effective pass-through rates for fuel and non-fuel type costs for a $100 cost increase are typically in the range of 40-70%.

DEFRA (2007) examine cost pass-through due to aviation's inclusion in the EU ETS, where cost pass-through is defined as the proportion of the full cost of emissions at current allowance prices that is passed through to ticket prices, i.e. it is affected by the proportion of free allowances. In most circumstances they find close to 100% pass-through, consistent with a perfectly competitive market. For individual routes they find a range of 80-150% pass-through due to diversity primarily in airline business models and amount of competition. Pass-through is typically projected to be higher for mixed business and leisure (110-150%) than leisure-only (80-100%) due mainly to the higher price sensitivity of leisure passengers; i.e., there is interaction between pass-through rates and price elasticities. Ranges of 80-150% for time sensitive freight, and 95-100% for non time-sensitive freight, are found. For higher-volume routes they project rates closer to 100%.

Faber & Brinke (2007) argue that, because slots at Heathrow are auctioned, pass-through is effectively 0%; i.e. increases in environmental cost for operating at Heathrow will be offset by a reduction in slot costs. However, a recent EC study on slot mobility (EC, 2011) found that slots change hands only infrequently at Heathrow. As shown in Table 2, over 99% of slots at Heathrow remained with the same airlines over the 2006-2010 period.

Because slot trading is rare, this limits the likelihood of slot auctions delivering an economically-efficient outcome. Because Heathrow is perceived as a 'premium' airport there is also the possibility of non-rational or non-profit maximising behaviour. These factors in combination make the level of pass-through uncertain.

Table 2. Slot mobility at different airports. Source: EC (2011).

Slot mobility				**Slot stasis**	
Change in total allocations by carrier	**Period**	**Average annual change**		**Historics as % of total allocation**	**Period covered by data**
13.1%	S07-S10	4.4%	**AMS**	no data	
8.6%	S09-S10	8.6%	**CDG**	89.7%	W08-S10
9.5%	S07-S10	3.2%	**FRA**	91.6%	W09-S10
10.6%	S08-S10	5.3%	**ORY**	no data	
6.6%	S07-S10	2.2%	**LHR**	99.1%	S06-W10

Based on our analysis of the literature, we assume 100% passenger cost pass-through at all non-congested airports. However, we treat pass-through at congested airports (in particular, Heathrow and Gatwick) as an uncertain variable. We use values of 0%, 50% and 100% to represent the level of uncertainty in the literature. For freight, we assume a pass-through rate of 80%, roughly in the middle of the range of literature values.

3.2.2 Price elasticity of demand

The price elasticity of demand is a measure of consumers' sensitivity to price changes for a given service, in this case air transportation. It is defined as:

$$Price\ Elasticity = \frac{\%\ change\ in\ quantity\ demanded}{\%\ change\ in\ price}.$$

As with virtually all goods and services, aviation ticket price elasticities are negative, i.e. an increase in price results in a reduction in demand. Different estimates may be obtained depending on the time horizon considered for the reduction in demand, the geographic scope, the characteristics of the journeys considered and the availability of substitute routes. IATA (2007) review literature fare elasticities and supplement them with their own economic modelling. They find typical fare elasticities at the individual market level (i.e. where fares vary on an individual route, leading to some level of route substitution) of between -1.2 and -1.5. At a national level (i.e. where all fares in a country increase by some amount, so there is less scope for route substitution) they recommend a base fare elasticity of -0.8, modified by the characteristics of the route group considered (-1.12 for intra-European flights, -0.96 for transatlantic flights, and -0.72 for Europe-Asia). They additionally propose a short-haul elasticity multiplier of 1.1 for flights of under an hour. Brons et al. (2002) carry out a meta-analysis of aviation price elasticities, using literature price elasticities varying between 0.2 and -3.2 in different contexts, with distributions peaked at -0.8 for business passengers and -1.5 for leisure passengers. These are similar to the assumptions used by Ernst & Young and York Aviation (2008); a similar range of elasticities was found by Oum et al. (1992). DfT (2017) use -0.2 for business passengers, -0.7 for leisure and -0.5 for international to international transfers and domestic passengers; similarly, DEFRA (2007) use -0.7 - -1.3 for leisure passengers and -0.3 - -0.7 for business passengers, and CE Delft (2005) use -0.2 - -0.3 for business passengers and -0.7 - -1.0 for leisure passengers. Scheelhaase & Grimme (2007) use -0.5 to -0.9 for business travellers and -1.1 to -1.5 for leisure travellers.

As discussed in DEFRA (2007), there also is some evidence that passengers are becoming less price-sensitive over time. For example, Brons et al. (2001) project price elasticity reductions by 0.01 per year.

Relatively few studies look at the response of air freight demand to changes in freight rates, in part because less data is available than for passengers. Wai Wang Lo et al. (2015) estimate elasticities of -0.74 to -0.29 in the context of Hong Kong International airport. Chi & Baek (2012) find a range of -1.5 to -3.0 in previous literature on US air freight demand, but themselves estimate a long-run value of -5.6. Ernst & Young and York Aviation use -0.8 for express cargo airlines and -1.6 for standard cargo, citing World Bank research giving this as a typical range. DEFRA (2007) use -0.5—1.5 and CE Delft (2005) use -0.7 throughout. Cargo is less labour-intensive than passenger transport so a higher proportion of cargo airline costs are fuel-related, making cargo airlines more vulnerable to changes in fuel costs.

Several considerations affect which elasticities are most appropriate to use in this study. Because the results and modelling are intended to be compatible with DfT (2017), including the use of demand growth rates over time from DfT (2017), elasticities that are compatible with DfT modelling should be used. Given that we have limited data on the number of business and leisure passengers per route, we use combined elasticities for all passengers and for all freight. The specific circumstances modelled (increase in costs at a country level, with itinerary choice modelled separately) also suggest that values on the low end of literature estimates are appropriate to avoid double-counting impacts from route substitution. We therefore use a range of values between -0.2 and -0.8, taking -0.5 as a central value. For cargo, we use -0.5 throughout.

3.2.3 Baseline demand growth to 2050

UK demand growth will depend on many uncertain factors, including income growth, the application of other policies, and assumptions about market maturity. The most recent set of DfT demand projections (DfT, 2017) project demand in 2050 of between 410 and 435 million passengers per year (mppa). Additionally, DfT (2017) model a range of sensitivity cases including different market maturity, carbon price, GDP and oil price assumptions. The range of demand in 2050 over all of these cases is 354-455 mppa. The relatively low growth rate (compared to those projected for global emissions) is the result of capacity constraints and assumptions about the market maturity of different aviation markets. We use these DfT projections to generate baseline, high and low growth scenarios in passenger demand which can be selected by the model user. More information about the projections used is given in Section 4.3.1.

Freight carried in the holds of passenger aircraft is implicitly included via aircraft payload assumptions. For freight carried in freighter aircraft, few estimates are available for future demand growth. We include in the model a user-set freighter flight demand growth rate. However, as in DfT (2017) this is set by default to zero, consistently with recent trends in UK freight.

Demand growth can affect leakage and distortion in several ways. First, it affects the absolute level of reductions in CO_2 that are possible. Second, it affects the age distribution of aircraft fleets, as more new aircraft are needed if demand growth is higher. Third, some mechanisms to avoid increased policy costs may become more or less effective if patterns in demand change. For example, if there is a switch to longer-haul flights, tankering will become less important as a way of avoiding policy costs. However, both leakage and distortion largely depend on relative rather than absolute changes in cost and emissions, so demand growth is likely to be less important than pass-through and price elasticity in determining outcomes. We group demand growth together with other background variables affecting system development in investigating model sensitivity, and run one set of model runs for year-2015 conditions (lower demand, lower fuel price, lower baseline carbon price) and one for year-2030 conditions (higher demand, higher fuel price, higher baseline carbon price)

3.2.4 Baseline carbon price

Historically, the EU ETS price has never risen above the equivalent of £30 per tonne of CO_2 (year 2015 UK pounds) and, despite recent rises, it is still currently much lower than this (European Climate Exchange, 2018). However, future scenarios aimed at achieving IPCC climate goals often include a higher carbon price applied on a global level. DfT (2017) assumes a carbon price in 2016 of £4 / tCO_2, rising to £77 in 2030 and £221 in 2050 (year 2016 UK pounds). This value is implicit in the central forecast used for baseline demand, above and any increases in carbon price due to policy are effectively additional to it. Carbon prices in the other DfT (2017) demand scenarios used in this study range from 39-116 £/tCO_2 in 2030, and 111-332 £/tCO_2 in 2050.

A higher baseline carbon price increases the cost savings that airlines can make from making reductions in fossil fuel use and from using biofuels (depending on how and whether the carbon price is applied to biofuels). Therefore airline responses to policy-related cost increases may be more likely in the case that the baseline carbon price is high. Since the future baseline carbon price is assumed to apply globally, it also acts to decrease the difference in fuel costs between UK and non-UK routes, i.e. any change in cost due to new policies is a smaller fraction of total costs.

We group baseline carbon price together with other background variables affecting system development in investigating model sensitivity, and run one set of model runs for year-2015 conditions (lower demand, lower fuel price, lower baseline carbon price) and one for year-2030 conditions (higher demand, higher fuel price, higher baseline carbon price).

3.2.5 Fuel price

Future jet fuel prices are highly uncertain. Fluctuations in fuel price will have a similar impact to fluctuations in carbon price, and may be of greater magnitude, particularly over the short term. For consistency with the DfT (2017) demand forecasts discussed above, we use to use the range of oil prices given by BEIS (2016). These project oil prices in 2030-2040 of between 55 and 120 year 2016 US dollars per barrel, with a central case of $80/bbl and a stress test case of $30/bbl. As with DfT (2017), these are assumed to remain constant in real terms between 2040 and 2050. In terms of the price of Jet A, this translates into £0.406 per kg in 2015, rising to £0.601 (0.413-0.902) per kg in 2030 and staying constant at this value in real terms thereafter.

Additionally, in the case that biofuel uptake is simulated, we need the price of biofuel. This is uncertain and depends on the feedstock assumed. Although algae-based fuels are potentially promising, they are associated with high uncertainty and potentially high cost (Quinn & Davis, 2015). Cellulosic biomass is a relatively abundant feedstock which has low impact on food production and favourable cost and scalability characteristics. For example, using data from DoE (2011), Schäfer et al. (2016) estimate that US biomass production potential is comparable to Jet A demand, and that costs of $3.0 – 3.6 per gallon are feasible for commercial-scale production beginning in 2020, with a reduction of 80 – 85% in lifecycle CO_2 compared to fossil-derived Jet A.

Ricardo (2017) assume a biofuel price of £0.789 per kg in 2015. This is around twice the price of fossil Jet A. It is assumed to rise to £1.370 (1.18-1.67) per kg in 2030, and remain at that value thereafter. This means that in all scenarios the biofuel price is significantly greater than that of fossil Jet A, typically greater than twice as large. For consistency with the Ricardo (2017) projections, we use these values, and assume a 70% reduction in CO2 compared to Jet A. We also assume that no carbon price is charged on biofuel.

We group baseline fossil fuel and biofuel prices together with other background variables affecting system development in investigating model sensitivity, and run one set of model runs for year-2015 conditions (lower demand, lower fuel price, lower baseline carbon price) and one for year-2030 conditions (higher demand, higher fuel price, higher baseline carbon price).

3.2.6 Technology characteristics of new aircraft models

The typical lifetime of an aircraft is around 30 years (Morrell & Dray, 2009). This means that, over the time period to 2050, and to a lesser extent 2030, substantial numbers of aircraft currently in global fleets will retire and be replaced by new aircraft. Other new aircraft will be purchased to serve growing demand, particularly in world regions where rapid growth is projected. Although the characteristics of the current and near-future generation of new aircraft are well-known (for example, the Airbus A320neo and Boeing 737MAX families, the Bombardier C-Series, the Airbus A350 and Boeing 777-X), the characteristics of the subsequent generation of aircraft are more uncertain.

There are several characteristics of new aircraft models which will have an impact on leakage and competitive distortion. First, the fuel use of new aircraft models will affect absolute CO_2 emissions and therefore the amount of change in aviation CO_2 that is achievable; in turn, this affects the cost impact on airlines of fuel prices, the baseline carbon price and any additional policy carbon price. If the fuel efficiency available from new technologies increases rapidly, then airlines in regions of the world with recent fast demand growth will be at an advantage, as they will end up with younger and more efficient fleets than airlines in regions of the world with slower growth. If the purchase price of new aircraft models (which may be a discount of 50% or more from manufacturer list price) changes over time, this in turn changes the attractiveness to airlines of selling older aircraft and buying new ones. Similarly, if aircraft maintenance costs continue their historical downward trend (e.g. ATA & Ellondee, 2018) then this helps to make purchasing a new aircraft more cost-effective. Finally, some proposed new low-CO_2 aircraft technologies may require changes in airline operations; for example, aircraft designs optimised for slower cruise speeds, or in the very long term electric aircraft with reduced range capabilities. Using these aircraft would require a complicated trade-off between reduced emissions-related cost, reduced demand, and increased costs in other areas.

We assume current fleets when modelling policy impact in the 2015 base year. For 2015, we use data from ATA & Ellondee (2018) on the average yearly trends in new aircraft model fuel use, purchase price and maintenance costs. These vary between different aircraft size classes, but typically maintenance costs are projected to decline by around 1% per year on average; fuel use on a comparable mission is projected to decline by 0.7-1.4% per year; and new aircraft prices are projected to remain broadly constant in real terms. Since using more pessimistic or optimistic assumptions for fuel use does not make a substantial difference to leakage in 2030, we use central case assumptions in the model runs in this study; however, the model contains the option to use the other sets of projections if necessary.

3.2.7 The ability of airlines to swap fleet between UK and non-UK routes

As discussed in Section 2.6, one plausible response of airlines to increased carbon-related policy costs is to move younger aircraft onto UK routes and older aircraft onto non-UK routes. In theory, this is a straightforward action which has minimal costs for the airline. Airlines typically have multiple aircraft of the same size; the exact aircraft used to fly a given route is often only assigned 24 hours in advance and substitution at short notice is possible in the case that there is a problem with the original aircraft. Although slightly less straightforward, there is also the option for airlines in airline groups which hold fleet in common (for example, IAG) to swap aircraft between different airlines in the group.

Empirically, however, there is little evidence that this occurs. Roy (2007) examined airline response to environmental landing charges at Zurich and Stockholm airports and found that, although fleet developed over the time period after the landing charges were applied, fleet also developed similarly at comparable airports without environmental landing charges. Similarly, Nero & Black (2000) find that airlines have tended to simply pay environmental charges rather than adapt fleet in response to them. Some of these restrictions may be due to practical constraints in aircraft use, as discussed further in Section 4.4.1. One potential constraint is that fleet swapping in this way effectively acts as a cross-subsidisation from non-UK to UK routes, because older aircraft with higher fuel costs are moved to the non-UK routes. However, airlines may instead choose to direct investment away from UK routes if UK routes become less profitable.

In this study, we consider two cases: the case in which airlines are able to swap fleet between routes to the fullest extent possible, and the case in which airlines cannot (or are unwilling to) swap fleet at all. The modelling of fleet swapping behaviour and how the maximum potential amount of fleet swapping is calculated, are discussed further in Section 4.4.1.

3.2.8 Itinerary choice parameters

Passenger choices of itinerary between those available are generally modelled using discrete choice models of various types (e.g. Coldren et al. 2003; Warburg et al. 2006; Adler et al. 2005; Lurkin et al., 2017). These models are used by airlines to help manage their networks and test future development scenarios. Most usually, a multinomial or nested logit formulation is used. In the case of a multinomial logit model, each itinerary in the choice set is assigned a utility V_i which is a function of various characteristics of the itinerary, and then the share of passengers using this itinerary is modelled as:

$$Share_i = \frac{e^{V_i}}{\sum_j e^{V_j}} \ ,$$

where j is the full set of itineraries available for a given airport-pair or city-pair route. This choice may be affected by a wide range of factors, including journey time, ticket price, flight frequency, the number of flight legs, the level of service offered, carrier loyalty, flight time of day, aircraft type, airport access, frequent flyer programmes, and the demographic characteristics of the passengers themselves. Although fare is an important factor, estimated models using real-world data suggest that it is far from the only factor in passengers' decisions. Data on these different factors may be derived from real-world ticket purchase data (revealed preference) or obtained using surveys with a range of hypothetical itinerary options (stated preference). In the case of revealed preference data, relatively little information may be available on many of these characteristics.

For this study, we use the itinerary choice model estimated as part of the global aviation systems model AIM (e.g. Dray et al. 2017). This model is estimated using Sabre (2017) data on global passenger flows on an itinerary basis, including fares, exact routing and the number of passengers using the itinerary. The utility of each airport-airport itinerary for passengers travelling between a given city-pair is modelled as a function of fare, journey time, itinerary-level flight frequency, number of flight legs and lagged passenger numbers for origin and destination airports, by global region-pair. This model is further described in Section 4.3.2, and parameter estimates for key region-pairs are given in Appendix 2. For this study, the most important parameter is the fare parameter in the utility function, as this affects how much a change in fare per itinerary will affect a passenger's choice compared to the impact of other factors. For intra-European flights, the fare parameter is -0.0051, compared to a journey time parameter of -0.0028 and a parameter for the number of legs of -3.43. This implies that a ten minute increase in journey time roughly trades off against an 5 dollar increase in fare, and that segments with more flight legs are only rarely fully competitive against those with fewer. Parameters for other world region-pairs are broadly similar.

As discussed in Section 4.3.9, using these parameters with baseline year-2015 estimated passenger flows reproduces well the number of UK air passengers and movements. Changing the parameters from their central values produces a less accurate representation of the current system. In this study, we therefore use the estimated values for the AIM itinerary choice model for all model runs.

4. Modelling carbon leakage and competitive disadvantage

In this section, we discuss how we model changes in UK and other air passenger numbers, flights and CO_2 due to the application of policy. The modelling strategy is broadly based on that used in the Aviation Integrated Model (AIM; e.g. Dray et al., 2017), a global open-source aviation systems model. AIM has been used to assess numerous aviation policies and emissions mitigation strategies, including carbon trading, the use of biofuels, adoption of future aircraft technologies and early aircraft retirement (e.g. Dray et al. 2017; Krammer et al. 2013; Dray et al. 2013). It is composed of an interacting system of models for different aspects of the aviation system, including passenger demand; itinerary choice; fares; scheduling; aircraft size choice; routing inefficiencies; local and global emissions; airline costs; technology choice; climate impact; the distribution of airport-level emissions; and airport-level noise. These model components have been validated by peer review in the academic literature and have been shown to closely reproduce global aviation system behaviour between 2005-2015 in a backcasting validation exercise (Dray et al. 2017), as well as matching closely to alternative projections of future global aviation system growth (e.g. Airbus, 2018; Boeing, 2018). Because of the constraints of the current study requirements, including the need to produce a model in Excel as a project deliverable, to concentrate on the UK and regions affected by a change in UK demand only and to maintain consistency with DfT (2017) projections, we use model components from AIM and adapt them to an Excel format rather than directly using the model itself.

Global aviation is a complex, interacting system with multiple stakeholders who may react to policies in different and interacting ways. A policy applied in one region may have wide-reaching impacts outside that region. Therefore any modelling of aviation policy must consider the parts of the wider system that may be affected. This is particularly true in the case of the UK because London Heathrow is one of the world's busiest airports, with an unusually high proportion of long-distance transfer passengers (e.g. ACI, 2018; CAA, 2018).

As discussed in Section 1, a UK-specific change in airline or passenger costs may affect the global aviation system in several ways. In the modelling for this project, we consider the following mechanisms:

- Airlines may pass costs on to passengers or freight shippers, who may in response choose not to fly; this includes passengers on multi-segment itineraries of which only one segment is affected. For example, a reduction in demand from London to Sydney via Dubai will include a reduction in demand for the London-Dubai segment but also for the Dubai-Sydney segment, and a similar reduction for both segments on the return journey.
- Airlines may pass costs onto passengers on a given itinerary, leading to passengers choosing an alternative itinerary which is less-affected. For example, a passenger travelling from New York to Istanbul via Heathrow may choose to travel via Paris Charles de Gaulle instead.
- Airlines may move their existing fleet between UK and non-UK routes in an attempt to minimise their overall policy-related costs.

- Airlines may sell older aircraft and purchase new ones in an attempt to minimise their overall policy-related costs.
- Airlines may tanker fuel to the extent that it is possible to do so to avoid UK fuel uptake-related increases in costs.
- Airlines may choose not to pass costs onto passengers and instead accept a reduced profit margin.

Modelling these impacts requires modelling passenger demand and itinerary choice on an individual itinerary basis; the resulting airport-airport segment demand by airline type, and which aircraft are used to fulfil it; overall fleet structure by airline type; the costs and emissions associated with different aircraft types; and the cost and emissions associated with airline strategies to reduce policy costs. As discussed above, the modelling strategies used in this project are based on models already developed for the global open-source aviation systems model AIM (e.g. Dray et al, 2018) which are adapted for this project requirements, including the need to produce a spreadsheet form of the model. The model scope and components are discussed individually below.

4.1 Model scope

To capture the full impact of the leakage mechanisms discussed above, all passenger itineraries and flight segments that could be impacted by UK aviation policy need to be considered. This includes flight segments which do not go to or from the UK at all but which could see a change in demand or in aircraft type used. It also includes passengers who could choose to travel via the UK but currently do not. Based on an analysis of passenger data from Sabre (2017), we choose to model passengers on all city-city routes where at least one percent of traffic travels via a UK airport. In 2015, this covers approximately 270 million passenger journeys. Figure 6 shows all city-pair routes of over 100,000 passengers per year which meet this definition. As well as routes to and from UK cities, many long-haul flows between a wide range of global cities are also captured.

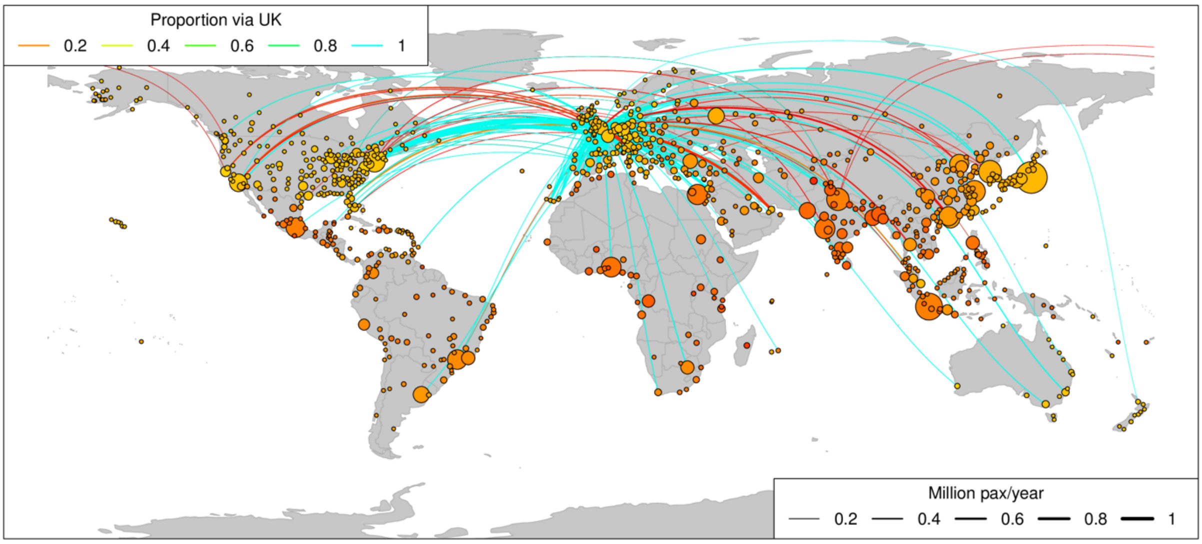

Figure 6. City-pair routes with at least 100,000 passengers per year on which at least 1% of passengers travel to, from or via the UK. Data is from Sabre (2017).

Because of the potentially large impact on leakage of passengers on international-international transfer routes switching hubs, it is important to be able to fully model transfer passengers. Typically, transfer passengers using major global hubs are making long-distance journeys for which there are few or no direct flight options. Transfer demand through London Heathrow Airport in particular is the aggregate of many small passenger flows between a diverse range of global origins and destinations. Figure 7 shows the distribution of passengers by itinerary demand for Heathrow. If itineraries with fewer than 10,000 yearly passengers – roughly the equivalent of one single-aisle aircraft flight a week – are neglected, the majority of demand travelling to and from Heathrow is captured. However, almost none of the transfer passenger demand is captured. To fully cover transfer passenger demand, itineraries with as few as 50 passengers per year may need to be included.

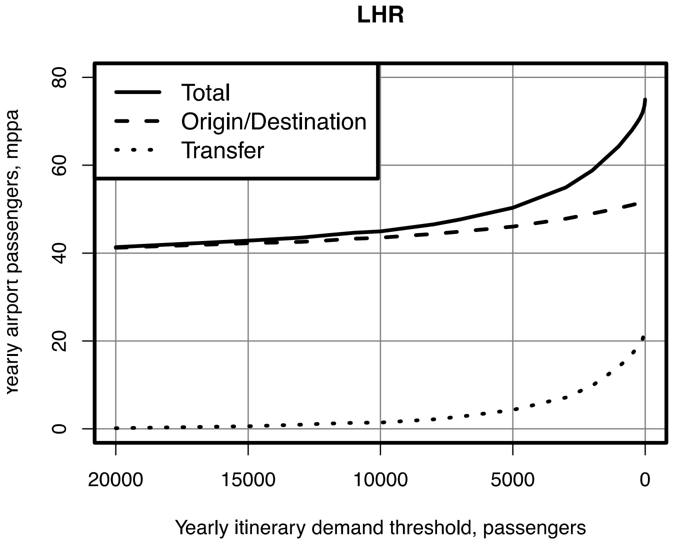

Figure 7.Passengers travelling through Heathrow Airport by yearly itinerary demand threshold. Data: Sabre (2017).

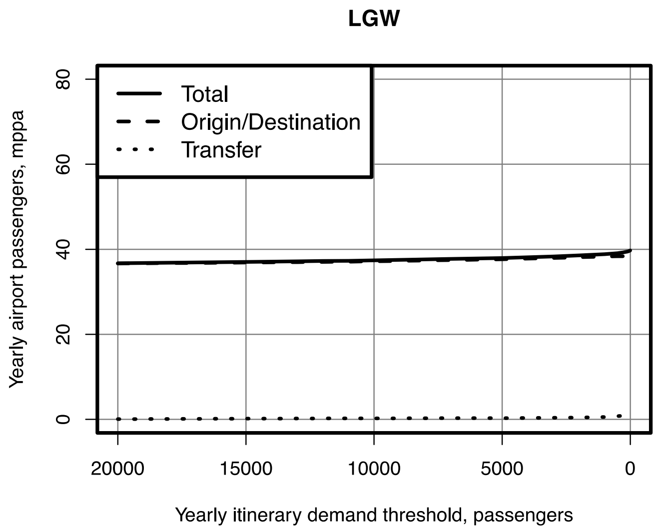

Figure 8. Passengers travelling through London Gatwick airport by yearly itinerary demand threshold. Data: Sabre (2017).

This is not the case with London Gatwick airport, as shown in Figure 8. Heathrow is a global airport with unusually high connectivity to long-haul destinations. As a result, finding a connecting route through Heathrow for passengers travelling between low-demand city-pairs may be more straightforward than constructing a connecting route through another airport.

In modelling terms, this suggests that any model set up to examine leakage needs to consider all city-city OD flows which may travel through an airport, even very minor ones. However, in practice this can add an unacceptably large computational burden. As shown in Figure 9, the number of itineraries that need to be considered rises rapidly as the demand threshold decreases. Therefore a hybrid approach is taken in this project. Itineraries with more than 1,000 passengers per year are modelled directly. Passengers on itineraries with fewer than 1,000 passengers per year are modelled by adding their demand totals to geographically similar itineraries above this demand threshold (for example, demand travelling from minor Alaskan destinations to London is added to aggregate demand travelling through Anchorage to London). Using this approximation, around 80,000 itineraries need to be modelled to capture demand to, from and through UK airports, including non-UK itineraries which can act as a substitute for UK itineraries. This allows total transfer passenger demand to be examined without greatly increasing model run time. These 80,000 itineraries cover demand between around 20,000 individual city-pairs, and make use of around 20,000 different flight segments.

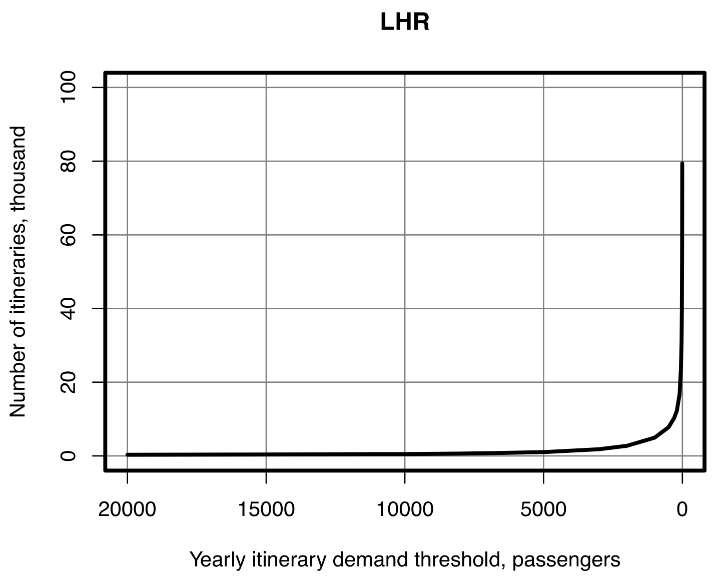

Figure 9. Number of itineraries by yearly itinerary demand threshold, London Heathrow Airport. Data: Sabre (2017).

4.2 Model Structure

The broad structure of the model developed for this project is shown in Figure 10. Initially, values for policy characteristics and key uncertain variables are specified. Policy characteristics include carbon prices, the percentage of biofuel in UK fuel and changes in landing charges by UK airport and aircraft size. The uncertain variables considered are discussed in Section 3. They include cost pass-through on a system-wide basis and for congested airports, price elasticities of demand, itinerary choice parameters, and variables related to airline response (discussed below in Section 4.4).

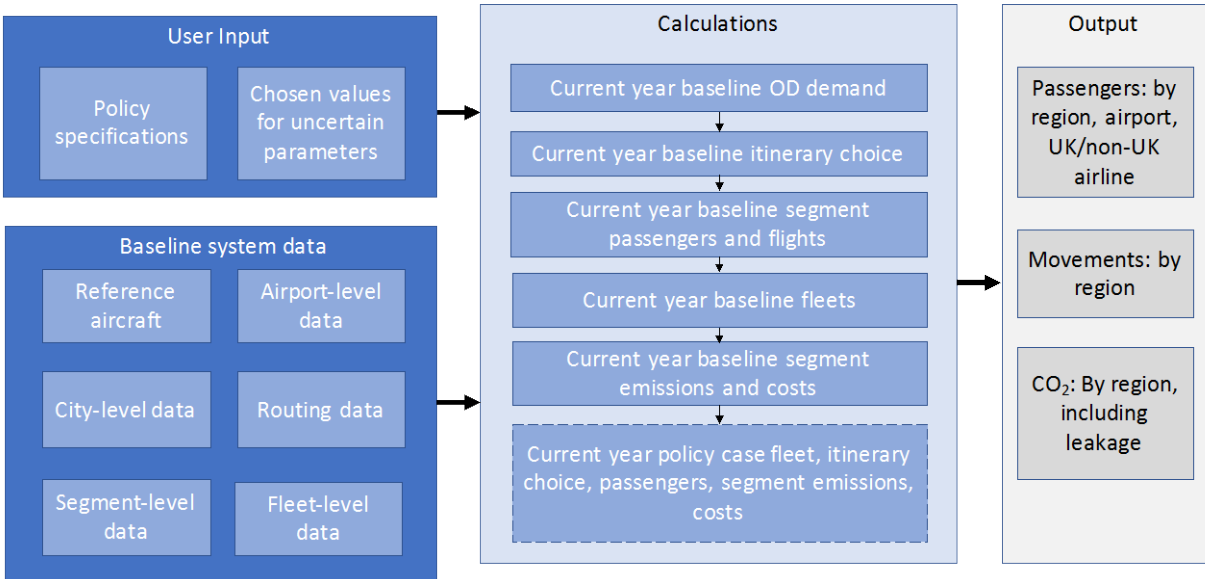

Figure 10. Model structure.

Subsequently, data describing the baseline aviation system in 2015 are specified. These data are discussed below in Section 4.3 on reproducing the baseline system, and include the characteristics of existing aircraft, airports, cities, fleets by airline type, flight segments and itineraries offered. Using these data, the baseline city-pair demand, itinerary choice, fleet structure and emissions with no policies applied are estimated. The segment-level costs that airlines will experience from applying the user-specified policy option are then calculated. It is assumed that airlines will respond first. Initially, they have the option of switching fleet between routes; subsequently they can also choose to purchase new fleet and sell older aircraft, and to tanker fuel. Any remaining policy costs are assumed to be passed on to ticket prices to the extent specified by the user. Passengers then respond to the resulting changes in itinerary-level ticket prices. Finally, the segment-level emissions and changes in costs following airline and passenger response is calculated, and compared to the baseline to generate metrics for carbon leakage and competitive disadvantage for UK airlines and airports. This represents a first-order calculation of policy impacts; in reality, some of the calculated impacts will in turn generate second-order impacts on other variables, requiring an iterative or optimisation-type solution as is carried out in the full AIM model. For example, reductions in passenger demand will lead to reductions in fleet needed, which in turn will lead to a slightly different fleet age structure. However, tests with the full AIM model suggest that these second-order impacts are typically small.

4.3 Reproducing the baseline system

The first modelling step is to reproduce the baseline (i.e. before imposing any of the policies modelled here) aviation system in the year modelled. This includes passenger flows by itinerary and by flight segment, aircraft used, fleets, costs and emissions. The individual stages of this process are discussed in the sections below.

4.3.1 City-pair passenger flows

As the model examines trends in demand including airport and itinerary choice, the initial specification of demand is on a regional rather than an individual airport basis. We use the city-based specification utilised in the aviation systems model AIM (e.g. Dray et al. 2018). A city-pair flow is specified as the number of yearly passengers which travel between two cities across all possible air routes. Year-2015 demand between cities is based on the output of a global city-pair level demand model within AIM estimated from Sabre (2017) data on passenger flows. For consistency with DfT modelling, the baseline trends in city-pair demand by region-pair are externally specified to agree with DfT scenarios (e.g. DfT, 2017). Therefore the baseline city-pair flow between a pair of cities in a given year is given by the year-2015 value multiplied by a demand growth factor appropriate for the origin and destination city world regions. Because the DfT model does not project demand for city-pair routes which are not to and from the UK, but these routes may still be important in estimating leakage, we also add growth rates for non-UK region-pairs as well. Central values are sourced from Airbus (2018), with upper and lower values of 1%/year higher and lower demand growth. These projections are also broadly consistent with past AIM projections using the IPCC SSP range of socioeconomic scenarios (Dray et al. 2017). Table 3 shows projected growth rates in passenger numbers by key region-pairs and scenario. We use the DfT (2017) region specification: Western Europe (WE), OECD, Newly Industrialised Countries (NIC) and Least Developed Countries (LDC). A more detailed specification of which country is assigned to which region is given in DfT (2017). The values in brackets show the range between the high and low scenario in each case; note that for the DfT values the high and low demand labels are applied on an aggregate basis, so trends may differ on an individual region-pair basis.

Table 3. Assumed growth rate in passenger numbers per year by world region-pair.

Origin Region	**Destination Region**	**Growth rate 2015-2020, %/year**	**Growth rate 2020-2030, %/year**	**Growth rate 2030-2040, %/year**	**Growth rate 2040-2050, %/year**
UK	LDC	1.3 (0.1 – 2.7)	2.8 (2.9 – 2.9)	1.1 (1.2 – 1.5)	1.2 (1.2 – 2.0)
UK	NIC	2.4 (1.2 – 3.9)	2.9 (3.1 – 3.1)	1.2 (1.3 – 1.8)	1.4 (1.0 – 1.8)
UK	OECD	2.4 (1.5 – 3.2)	2.6 (2.3 – 2.6)	0.6 (0.4 – 0.7)	0.1 (0.0 – 0.7)
UK	WE	1.1 (0.2 – 1.8)	1.6 (2.1 – 1.9)	1.3 (1.5 – 1.4)	1.7 (1.5 – 1.2)
UK	UK	1.0 (-0.2- 1.8)	2.0 (1.2 – 1.8)	1.4 (1.0 – 1.4)	1.2 (1.6 – 1.7)
WE	LDC	1.4 (0.4 – 2.4)	1.4 (0.4 – 2.4)	3.5 (2.5 – 4.5)	3.5 (2.5 – 4.5)
WE	NIC	3.0 (2.0 – 4.0)	3.0 (2.0 – 4.0)	4.1 (3.1 – 5.1)	4.1 (3.1 – 5.1)
WE	OECD	2.8 (1.8 – 3.8)	2.8 (1.8 – 3.8)	2.8 (1.8 – 3.8)	2.8 (1.8 – 3.8)
WE	WE	2.9 (1.9 – 3.9)	2.9 (1.9 – 3.9)	2.3 (1.3 – 3.3)	2.3 (1.3 – 3.3)
OECD	LDC	2.4 (1.4 – 3.4)	2.4 (1.4 – 3.4)	3.5 (2.5 – 4.5)	3.5 (2.5 – 4.5)
OECD	NIC	3.3 (2.3 – 4.3)	3.3 (2.3 – 4.3)	6.3 (5.3 – 7.3)	6.3 (5.3 – 7.3)
OECD	OECD	1.9 (0.9 – 2.9)	1.9 (0.9 – 2.9)	2.2 (1.2 – 3.2)	2.2 (1.2 – 3.2)
NIC	LDC	6.4 (5.4 – 7.4)	6.4 (5.4 – 7.4)	4.6 (3.6 – 5.6)	4.6 (3.6 – 5.6)
NIC	NIC	7.4 (6.4 – 8.4)	7.4 (6.4 – 8.4)	5.6 (4.6 – 6.6)	5.6 (4.6 – 6.6)
LDC	LDC	6.5 (5.5 – 7.5)	6.5 (5.5 – 7.5)	5.9 (4.9 – 6.9)	5.9 (4.9 – 6.9)

4.3.2 Segment-level passenger flows

To project segment-level passenger flows, a model for itinerary and airport choice is needed. We use the itinerary choice model from AIM (e.g. Dray et al., 2017), which is estimated using data on passenger demand and routing from Sabre (2017). A passenger's choice of itinerary between those available will depend on multiple characteristics of each itinerary. The number of passengers between cities *o* and *d* on itinerary *k* in year *y* is modelled as

$$N_{odky} = \frac{N_{ody} e^{V_{odky}}}{\sum_j e^{V_{odjy}}} \ ,$$

where the deterministic part of the utility, V_{odky}, for an itinerary *k* between cities *o* and *d*, travelling between airport *m* in *o* and and airport *n* in *d*, is:

$$V_{odky} = \gamma_0 + \gamma_1 f_{odky} + \gamma_2 t_{odky} + \gamma_3 \ln freq_{odky} + \gamma_4 Nlegs_{odky} + \gamma_5 P_{m,y-1} + \gamma_6 P_{n,y-q} \ ,$$

and f_{odky} is the itinerary fare, t_{odky} is the total itinerary travel time, $freq_{odky}$ is the itinerary frequency, $Nlegs_{odky}$ is the number of flight legs in the itinerary, $P_{m,y-1}$ is the total number of non-transfer scheduled passengers using airport *m* in the previous year, and the parameters γ are estimated. Of these, the fare, time and number of legs parameters are the most important, as they govern how passengers may choose routes with fewer, shorter or no UK segments in the case of an increase in UK-based fares. The model parameters for major route groups used are given in Appendix 2.

Table 4. Model itineraries for the example case of New York to Istanbul in 2015.

Origin Airport	**Destination Airport**	**Hub Airport**	**Journey time, min**	**One-way fare, year 2015 USD**	**Minimum leg frequency, flights/year**	**Modelled passengers, 2015**
JFK	IST	-	590	740	930	59000
JFK	IST	CDG	710	520	2480	8500
JFK	*IST*	*LHR*	*710*	*780*	*2800*	*8600*
JFK	IST	FCO	720	420	1100	6500
JFK	IST	SVO	840	360	810	4600
JFK	IST	FRA	700	760	1400	7100
JFK	IST	AMS	710	540	1100	6600
JFK	IST	ZRH	700	520	960	6400
JFK	IST	KBP	770	340	110	2800

To apply this model to the demand totals used here, some additional data is needed. The itineraries available for travel between each city-pair are derived from Sabre (2017) data, including up to the top nine itineraries for each city-pair but excluding itineraries which served less than 1% of city-pair demand in 2015. The choice set for a give city pair is specified in terms of airport-airport itineraries. For example, one itinerary between New York and London is the direct flight from JFK airport to Heathrow. The baseline fare for each of these itineraries is derived from a fare model estimated from Sabre (2017) data by Wang et al. (2018). A set of itineraries for an example route (New York to Istanbul) is shown in Table 4. Routes with UK carrier presence are shown in italics. IATA three letter airport codes are used to identify airports (for example: New York John F. Kennedy International (JFK); Istanbul Atatürk (IST); London Heathrow (LHR); Paris Charles de Gaulle (CDG)). A full list of these codes can be found in IATA (2018).

How fares will develop over time is uncertain. Although for policy costs we use a simple pass-through model, this is less appropriate for long-term fare developments where a wide range of factors that are not directly modelled here (for example: airline business models; ancillary revenue; changes in labour costs) may impact on future ticket prices. Although baseline demand growth is taken directly from DfT projections and so is not dependent on future fares assumed, the absolute value of baseline fares will affect the relative size of any policy-induced change in fare, and hence the relative size of the demand and itinerary choice responses. AIM model runs using the Wang et al. (2018) fare model over long-term changes in airline costs with a range of different carbon price options suggest that fares per RPK are likely to remain broadly at the same level over time; although some cost categories, such as fuel and carbon costs, are projected to increase in real terms, other categories, such as maintenance, are projected to decrease, and others are projected to remain at a similar level. We include the overall trend in absolute baseline fare levels over time as a variable which can be set by the user. Although the default value is for fares to remain constant, a small increasing value may be appropriate for scenarios in which the background carbon price is particularly high. Journey time is derived from airline schedule data on individual segment travel time (Sabre, 2017). A change time of one hour is assumed for multi-segment journeys, based on an analysis of feasible minimum connection times in Sabre (2017) schedule data. Journey time is assumed to remain constant over time. Similarly, frequency is derived from schedule data on yearly flight frequencies per segment. For multi-segment itineraries, the overall frequency is assumed equal to the smallest yearly frequency of the segments that make up the itinerary. Itinerary frequency is assumed to scale over time by the same factor as city-pair level demand for itineraries serving each city pair. Similarly, future lagged airport-level scheduled demand is scaled using the model city-level OD demand growth projections for the appropriate city.

Using this model, the share of each itinerary for each city-pair is modelled. Summing over each flight segment for all itinerary-level demand using that segment gives segment-level passenger demand. Because the model scope only includes city-pair demand where a UK itinerary is a feasible route, segment-level demand totals do not necessarily include all demand from all sources on a segment. In this case, only the flights and emissions on that segment that relate to UK-substituting itineraries are modelled.

Additionally, using data aggregated from Sabre (2017) passenger flows by airline, we estimate what proportion of each itinerary is marketed by UK and non-UK airlines. The distinction between marketing and operating airlines can be complex and depends on the details of airline alliances, subsidiaries and code-share agreements. In this study, we count demand as UK airline demand if the tickets are marketed by a UK airline. We also assume that fleet requirements calculated on a marketing airline basis will in aggregate be similar to those required on an operating airline basis.

4.3.3 Aircraft flows and fleet requirement

Aircraft are classified by size according to the nine categories used by Sustainable Aviation (e.g. Sustainable Aviation, 2015). This classification is used because the models from AIM that are used here are estimated using it. Broadly, the SA size category 1 (small regional jet) corresponds to size class 1 in DfT (2017), SA categories 2-4 (large regional jet – medium single aisle) correspond to size class 2, SA categories 5-6 (large single aisle – small twin aisle) correspond to size class 3, SA category 7 (medium twin aisle) corresponds to size class 4, SA category 8 (large twin aisle) corresponds to size class 5, and SA category 9 (very large aircraft) corresponds to size class 6. Table 5 shows the size classes and the reference aircraft that aircraft characteristics for each are derived from. These reference aircraft are chosen based on an analysis of the current and likely near future most-used aircraft in 2015 on an aircraft-kilometre basis, using flight schedule data from Sabre (2017).

Table 5. Aircraft size categories used in modelling.

Size Category	Approx. seat range	Reference aircraft	Reference engine
Small regional jet (Small RJ)	30-69	CRJ 700	GE CF34 8C5B1
Large regional jet (Large RJ)	70-109	Embraer 190	GE CF34 10E6
Small narrowbody (Small SA)	110-129	Airbus A319	V.2522
Medium narrowbody (Medium SA)	130-159	Airbus A320	CFM56-5B4
Large narrowbody (Large SA)	160-199	Boeing 737-800	CFM56-7B27
Small twin aisle (Small TA)	200-249	Boeing 787-800	Genx-1B67
Medium twin aisle (Medium TA)	259-299	Airbus A330-300	Trent 772B
Large twin aisle (Large TA)	300-399	Boeing 777-300ER	PW4090
Very large aircraft (VLA)	400+	Airbus A380-800	EA GP7270

Year-2015 scheduled flight frequencies per segment by size class are derived from Sabre (2017) schedule data, and passenger typical load factors per segment in 2015 are derived from Sabre (2017) passenger flow data in combination with scheduled seat capacities. We assume for simplicity that the ratio between the number of flights in different size categories for each segment will remain constant over time. The choice of aircraft size for a particular segment is driven by several factors, most notably the segment demand, the number of airlines competing on the segment, distance, runway length and available fleet. For example, shorter segments are usually flown with smaller aircraft. As discussed by Givoni & Rietvald (2009), size choice is largely unrelated to the characteristics of the airports used (provided that aircraft of that size are able to land and take off there). Keeping the ratio of aircraft sizes used constant per segment effectively assumes that any changes in these variables over time are small or have net small impact.

Given the ratio between aircraft different size class frequencies on a route, a typical load factor, and estimated passenger demand, the number of flights by each size class in a year can be estimated. Additionally, data on typical aircraft utilisation from FlightGlobal (2017) is used to estimate how many aircraft would be needed to fly that schedule in a year. Similarly, UK airline-marketed demand is summed across segments to estimate how many of these flights can be allocated to UK airlines.

Typically, smaller aircraft carry out more flights per day than larger ones, but are in the air for a smaller proportion of the day. This difference affects how they are relatively affected by different policies. For example, a small regional jet which makes eight landings per day on a short-haul route will be affected much more by a blanket change in landing cost than a large twin aisle aircraft which makes one or two landings a day on a long-haul route, but the twin aisle aircraft will be much more affected by policies where the increase in costs is proportional to fuel used. As noted previously, the demand modelled on a segment is only demand on routes which are in or can substitute for UK-related itineraries. Therefore the frequency totals and fleet requirement estimated for each route only cover this demand.

4.3.4 Fleet size and age structure

The fleet required for different airline types (UK/non-UK) is summed across all segments to estimate how many aircraft of each size class are needed to fulfil scheduled passenger demand on the modelled routes in the current year. To calculate the fleet age structure, we use data on the initial (year-2015) fleet age structure for UK and non-UK airlines, as shown in Figure 4. We assume that aircraft of all ages are evenly distributed over modelled and non-modelled demand in the case of non-UK airlines; we assume UK airline demand is fully modelled. For 2015, we use schedule and fleet data to estimate the number of aircraft that are required to fulfil demand on modelled routes, and how many aircraft are required to fulfil demand on routes that are not directly modelled in this study.

In years after the base year, some proportion of these aircraft will have been retired. Typically, aircraft retire from the global fleet at around 30 years old, showing a remarkably consistent s-curve behaviour over time (Figure 11). As discussed in Morrell & Dray (2009), early scrappage is unusual and was seen in only one circumstance in the data examined: during a recession, with weak demand growth, high fuel prices and with significantly more fuel-efficient new aircraft available from manufacturers. The specific 30-year timeframe is likely related to the necessity of carrying out costly aircraft major maintenance checks (D-checks) at around this time.

For model years after 2015, we retire aircraft with age according to the retirement curves estimated in Morrell & Dray (2009). In this framework, the number of active aircraft $N_{Active,\,t}$ remaining at age t, compared to the number of aircraft that have retired from the global fleet $N_{Retired,\,t}$, is given by:

$$\frac{N_{Active,t}}{N_{Active,t} + N_{Retired,t}} = \frac{1}{1 + e^{-\varphi_1 - \varphi_2 t}},$$

where the parameters φ_1 and φ_2 are estimated by aircraft size from historical fleet data (e.g. FlightGlobal, 2017).

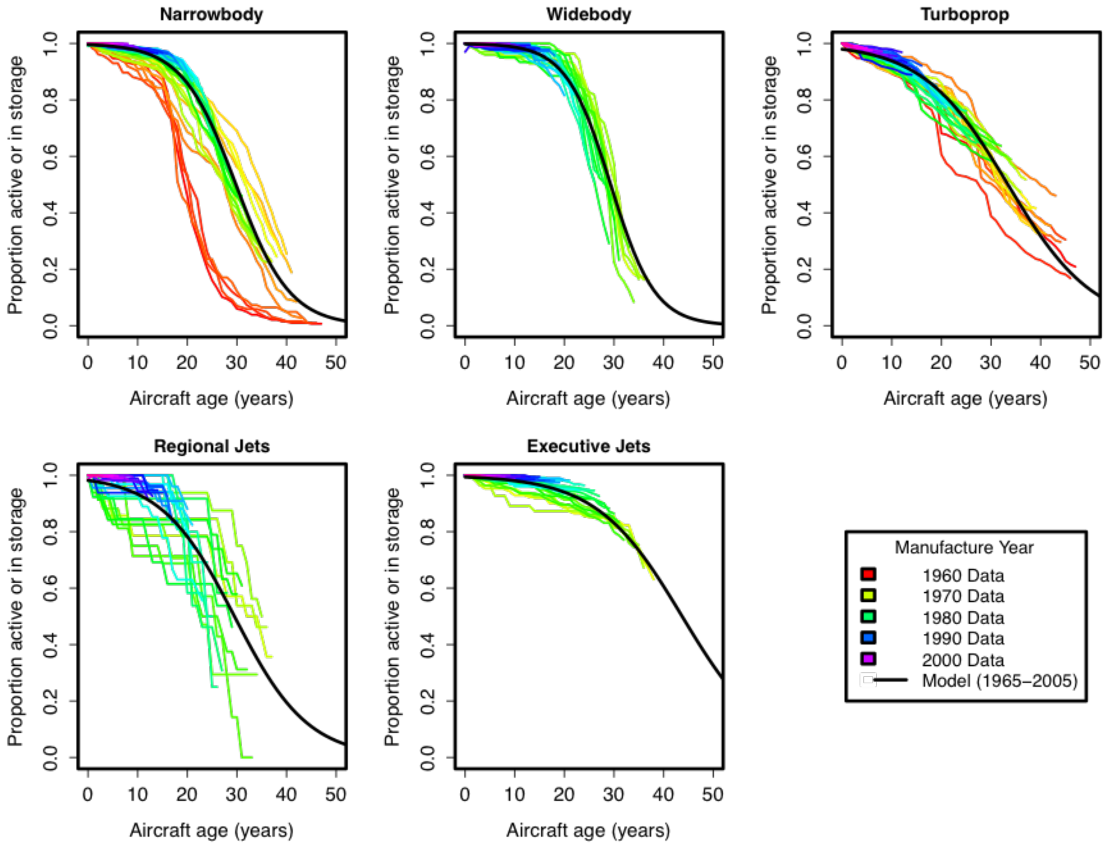

Figure 11. Aircraft retirement curves, from Morrell & Dray (2009).

After these retirement curves have been applied, the remaining aircraft after retirement are then compared to the demand for aircraft from the demand calculations. There are several components to the demand for aircraft: demand from UK airlines, demand from non-UK airlines for aircraft operating on modelled routes, and demand from non-UK airlines for aircraft operating on non-modelled routes. In the latter case, we assume a rate in increase of overall fleet size that is consistent with the Airbus (2017) Global Market Forecast, for consistency with the demand growth rates used in Section 4.3.1 to fill in route groups not modelled by DfT (2017). Additionally we distinguish between demand for aircraft to operate on UK and non-UK routes, and also between non-UK airlines which are in groups with UK airlines versus those which are not, as discussed in Section 4.4.1.

For each fleet component, we assume any shortfall between fleet remaining from 2015 and fleet needed to serve demand is met by the purchase of new aircraft. In reality, the age distribution of these new aircraft will reflect historical demand trends between 2015 and the modelled year. However, as the model assesses a single future year only, we assume an even distribution of aircraft purchases across the years between 2015 and the model year, consistent with relatively smooth growth in demand and constant production line capacity.

4.3.5 Fuel use and emissions

To model fuel use and emissions per flight, we use a model fit to the output of the aircraft performance model PIANO-X (Lissys, 2017) with distance and payload. This is also the approach used in AIM. Fuel use per flight phase for climb, cruise and descent for each aircraft size class is modelled as:

$$F_{phase} = \sigma_1 + \sigma_2 D + \sigma_3 P + \sigma_4 D^2 + \sigma_5 PD + \sigma_6 D^2 P,$$

where D is the flight distance, P is the payload carried and the parameters σ are estimated for each aircraft size class and flight phase using grids of PIANO-X model runs. We assume 95 kg for a passenger with luggage and an average of 4,500 kg hold freight (ICAO, 2009; ICAO, 2014); the distribution of hold freight is further discussed in the section on freight modelling, below. For landing and takeoff, emissions totals by aircraft type are used. For taxi and holding, fuel use rates per second, again derived from PIANO-X, are used.

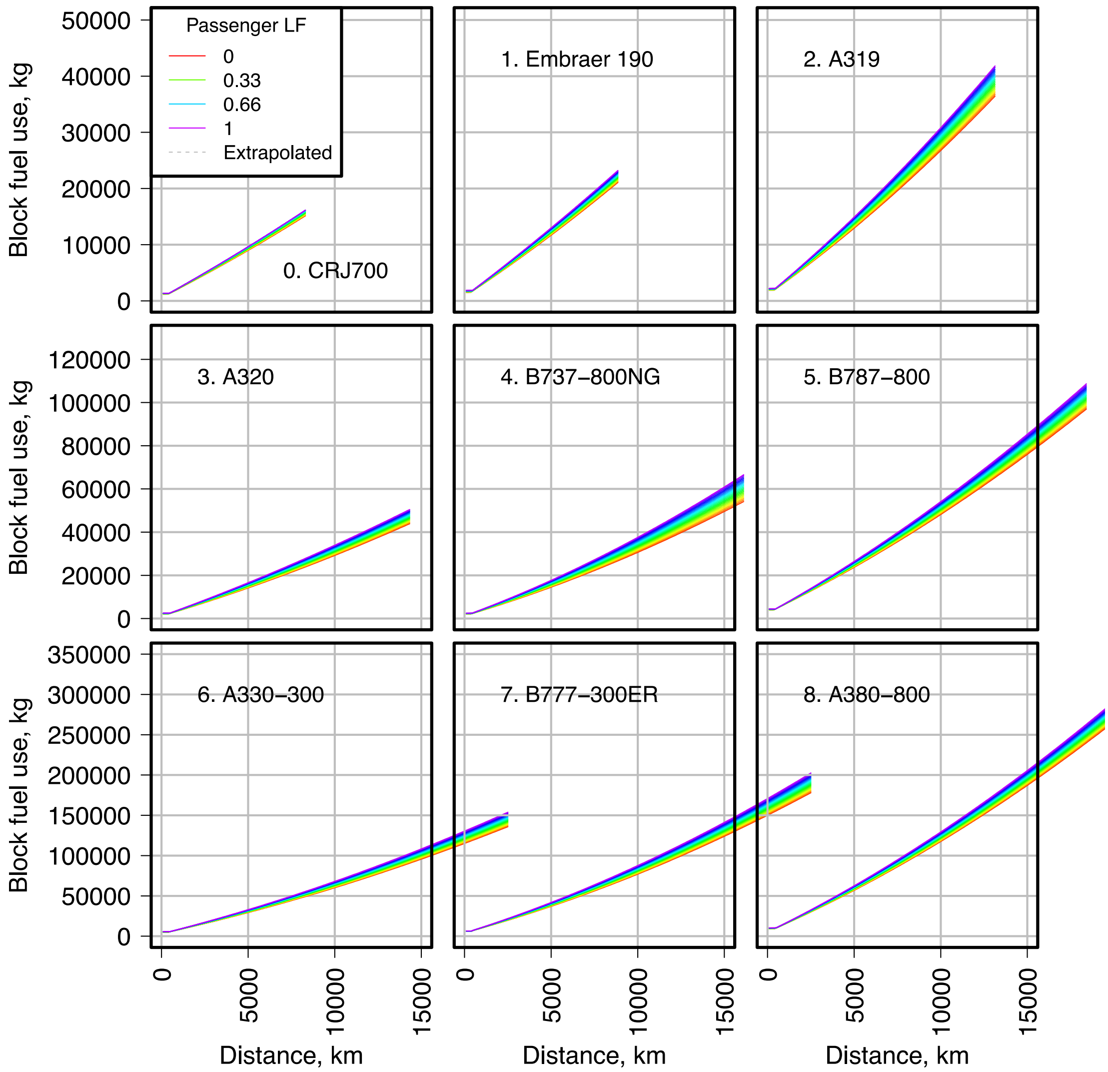

Figure 12. Modelled fuel use by distance and payload.

The flown distance between a given pair of airports is usually greater than the great circle distance due to practical inefficiencies in routing (for example, avoiding military airspace; maintaining separation between aircraft; routing around weather). We use track extension distances from Reynolds (2009). For some routes these result in lower amounts of track extension than assumed in DfT (2017) and in this case we use the DfT (2017) assumptions for consistency in fuel use. The total block fuel burn is calculated as the sum of fuel burn across all flight phases. An average of 15 minutes taxi (in + out) and 10 minutes holding is assumed (e.g. Eurocontrol, 2018). This formulation has been tested against an interpolation model directly using PIANO-X output and has been found to have less than 1% difference in block fuel burn across the range of feasible input values. Typical fuel use values by payload and ground track distance are given in Figure 12 (LF = passenger load factor).

This model gives fuel use as appropriate for the nine reference aircraft under ideal conditions. However, typical fleet fuel use will differ from this value. First, older aircraft tend to have higher fuel use and emissions. Based on the analyses of historical fuel burn trends in DfT (2017) and Dray et al. (2018) we model long-term historical decreases per year in the fuel use of new aircraft models on comparable routes as in Table 6 ('Historical new aircraft model fuel use'). These trends define the extent to which older aircraft currently in the fleet may have higher fuel use because technologies to reduce fuel use were less advanced when they were built. Technologies to reduce fuel use are expected to improve in future. For future aircraft models, however, this trend will differ depending on what new technologies are assumed to become available. Using data from ATA & Ellondee (2018), we model these changes by aircraft size as shown in Table 6 ('Future new aircraft model fuel use'). Values in brackets represent upper and lower ranges for each size class. Although these trends are expressed in percent per year, in reality the fuel burn of new aircraft models will behave like a step function as new generations of aircraft become available for purchase. However, over the long term the overall impact will be broadly similar.

Table 6. Assumptions about historical and future aircraft technology and cost characteristics, by size class.

Aircraft size class	**Future new aircraft model fuel use, %/year decrease**	**New aircraft model maintenance costs, %/year decrease**	**Historical new aircraft model fuel use, %/year decrease**
Small RJ	1.2 (0.8 – 1.4)	0.7 (0.0 – 1.1)	1.1
Large RJ	1.2 (0.8 – 1.4)	0.7 (0.0 – 1.1)	1.1
Small SA	1.2 (0.8 – 1.4)	0.7 (0.0 – 1.1)	1.2
Medium SA	1.2 (0.8 – 1.4)	0.7 (0.0 – 1.1)	1.2
Large SA	1.0 (0.7 – 1.2)	0.8 (0.0 – 1.2)	1.2
Small TA	1.0 (0.7 – 1.2)	0.8 (0.0 – 1.2)	1.2
Medium TA	1.2 (0.7 – 1.4)	0.9 (0.0 – 1.4)	1.2
Large TA	1.1 (0.7 – 1.3)	1.0 (0.0 – 1.5)	1.2
VLA	1.1 (0.7 – 1.3)	1.0 (0.0 – 1.5)	1.2

Second, aircraft fuel burn deteriorates with age. Some of this deterioration is correctable with maintenance and some is not; therefore, the exact amount of deterioration will go up and down over an aircraft's lifetime. We assume an average deterioration with age of 0.2% per year (Morrell & Dray, 2009). This adds up to around a 6% increase in fuel burn on a comparable mission for a 30 year old aircraft compared to the same aircraft when it was new.

CO_2 emissions are derived from fuel burn by assuming a factor of 3.15 kg CO_2 emitted per kg fossil-derived Jet A burnt. For biofuel, this factor is multiplied by 0.3 to reflect a reduction in fuel lifecycle emissions, for consistency with DfT (2017).

4.3.6 Baseline costs

Airline costs are modelled using the cost model developed in Al Zayat et al. (2017), which is also in use in AIM. Airline direct operating costs are divided into fuel, carbon, maintenance, crew, finance (interest, depreciation and insurance), landing and enroute costs. Because baseline demand and fare developments are modelled with user-set trends in this study, we do not need to model the development of costs which will do not change in response to policy. We assume crew costs will remain the same between the baseline and policy cases. Similarly, although small changes in baseline landing and enroute costs may occur in response to policy if newer aircraft which have lower maximum takeoff weight (MTOW) are substituted in, we assume that these costs will also broadly remain constant. Fuel and carbon costs are modelled using fuel use totals and external projections for fossil Jet A, biofuel and baseline carbon prices (DfT, 2017). These are given Table 7. Values in brackets indicate the range between the high and low scenarios in each case. In Figure 13 we show how the year-2015 and year-2030 central case fuel and biofuel prices combine under different biofuel percentage and carbon price scenarios to give the effective price of a kilogram of fuel, assuming that no carbon price is charged on biofuel use and that changes in the amount of biofuel used do not have an impact on biofuel price. For example, under year-2015 conditions a £200/tCO_2 carbon price would more than double the price of fuel.

Table 7. Assumptions about future fuel, biofuel and carbon prices.

Year	**Fossil Jet A price, UK pounds per kg**	**Aviation biofuel price, UK pounds per kg**	**Baseline carbon price, UK pounds per tonne CO_2**
2015	0.41	0.79 (0.73 – 0.89)	5.2
2020	0.40 (0.23-0.56)	0.90 (0.73 – 1.10)	4.6 (0.0 – 9.1)
2030	0.60 (0.41-0.90)	1.4 (1.2 – 1.7)	78 (39 – 120)
2040	0.60 (0.41-0.90)	1.4 (1.2 – 1.7)	150 (75-220)
2050	0.60 (0.41-0.90)	1.4 (1.2 – 1.7)	220 (110 – 330)

It should be noted, however, that this is similar to the range of recent variation in jet fuel prices due to fluctuation in oil prices. Figure 14 shows the variation of oil and jet A prices in real terms since 1978, in comparison with year-2015 values, using data from EIA (2018). Jet fuel prices have varied between about half and about two times the year-2015 value over that time period. Only in the case that a future increase in fuel price is combined with a high carbon price would projected effective fuel price be significantly greater than that experienced in the recent past. However, in the policy cases looked at here, effective fuel prices are different for the UK and for non-UK regions. This will produce different behaviour than the case of a globally high fuel price, because there are more options available to reduce fuel costs.

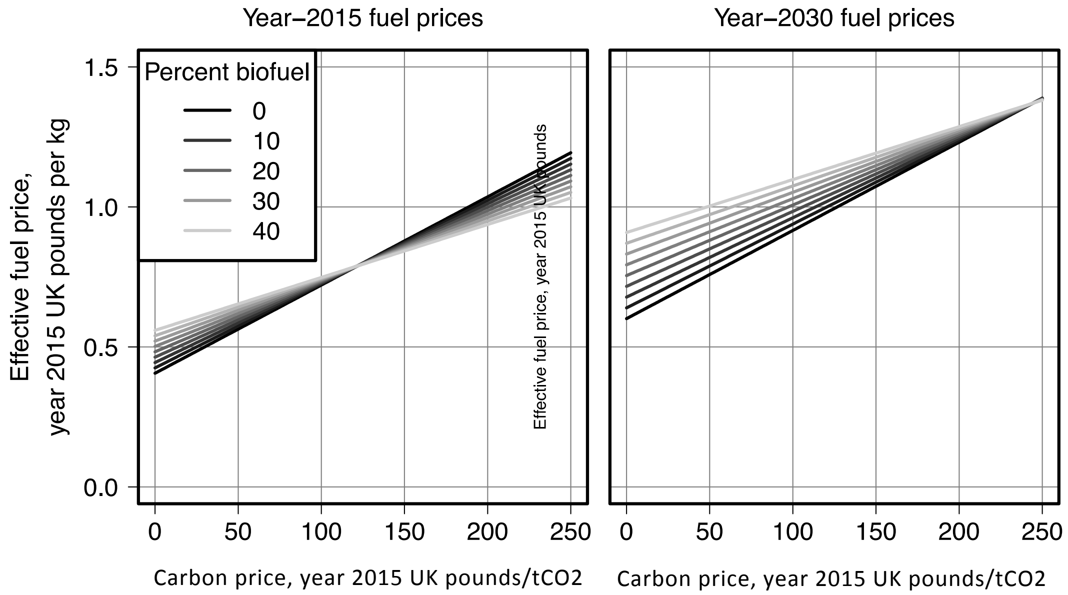

Figure 13.Effective fuel price taking into account carbon and biofuel costs, for the year-2015 and year-2030 central case fuel and biofuel prices.

One other notable feature of Figure 13 is that, under year-2015 conditions, there is a break-even carbon price within the range examined at which biofuel becomes the cheaper option to use. If a large supply of aviation biofuel were available, this might prompt airlines to use it, providing another route for biofuel into the system. In this case, the carbon pricing policy examined below would behave similarly to the biofuel uptake policy examined below after the break-even carbon price. In reality, however, there are likely to be complex interactions between biofuel pricing, supply, carbon and fuel prices, biomass demand from other sectors and the level of policy support.

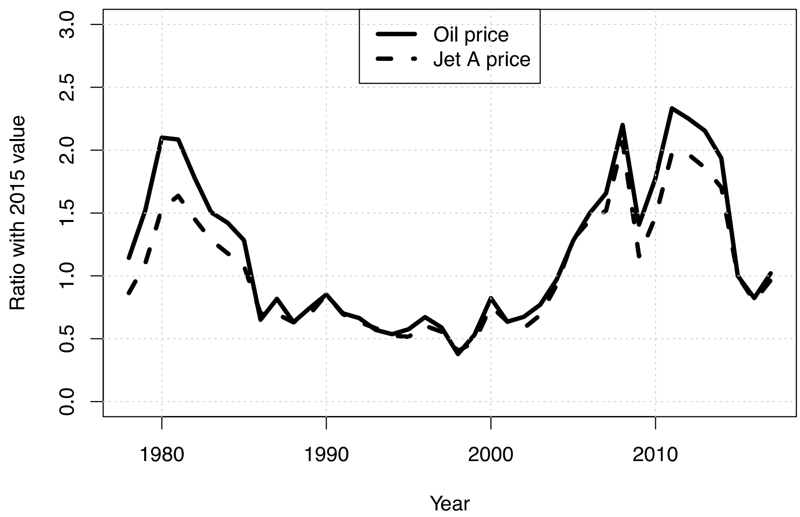

Figure 14. Fuel and oil price variation in real terms, 1978-2015, as a ratio with 2015 values.

Aircraft engine and airframe maintenance is modelled as the sum of per-cycle and per-flight hour components. As with fuel costs, maintenance costs are likely to change over time as new aircraft models become available and as aircraft already in the fleet age. This will affect overall costs if the fleet age structure changes as a result of policy. Typically, newer aircraft models have lower maintenance costs. We use data from ATA & Ellondee (2018) to model historical and future likely trends in maintenance costs. For historical trends in maintenance costs we assume 1% per year decrease, based on analysis of US Form 41 data (BTS, 2018). For future maintenance costs we use the trends shown in Table 6. Additionally, maintenance costs tend to increase with increasing aircraft age. We model this as in Morrell & Dray (2009), using a 2.5% per year increase.

Finance-type costs depend primarily on the aircraft purchase price and assumptions about depreciation. We assume that purchase price (after typical discount from manufacturer list price, which can be in excess of 50%) remains constant in real terms over time, based on the analysis of ATA & Ellondee (2018). We use assumptions from Morrell & Dray (2009) for key financial parameters, including insurance costs of 1.2% of market value, a depreciation period of 20 years, and residual value of 5% of purchase price.

4.3.7 Freight

The lack of readily-available data about air freight makes it difficult to model. Around 70% of UK air freight is carried in the holds of passenger aircraft (DfT, 2017). This freight is implicitly included in the passenger emission totals via the addition of an extra payload factor for freight carried. ICAO (2014) estimate that an average of 4500 kg freight is carried per flight across the global fleet. To estimate how this factor varies by aircraft size class, we calculate the remaining payload capacity for each reference aircraft once the weight of passengers at a typical load factor is accounted for. Assuming the 4500 kg total is appropriate for a large single-aisle aircraft, we scale the freight load for the other aircraft types so that freight makes up the same fraction of available non-passenger payload capacity in all cases.

For air freight carried in freighter aircraft, little information is available about routing. DfT (2017) calculate that there were around 70,000 UK freighter flights in 2015, the vast majority of which were international rather than domestic flights. These flights primarily operated from London Stansted and East Midlands airports (CAA, 2017). They accounted for around 1 $MtCO_2$ in 2015. Demand for all-freight flights to and from the UK is projected to remain broadly constant in future (DfT, 2017). To account for these flights and emissions we use a simple aggregate model. As with passenger demand, baseline freight demand is assumed to grow by a user-set growth factor to the policy year. It is assumed that the current network, load factors and aircraft size distribution are maintained, such that this growth rate can be applied to both number of flights and tonne-km. Baseline trends in fuel efficiency are assumed to be the same as for passenger aircraft. This represents a significant simplification, as freighter aircraft are usually older than passenger aircraft and are often converted from old passenger aircraft (e.g. Morrell & Dray, 2009). US DoT (2017) report air freight revenue of $2.22 (year 2015 US dollars) per tonne-km. We take this value as a baseline. Cost changes due to policy are calculated on a tonne-km basis assuming a typical flight distance of 1,450 km (consistent with current CO_2 and number of flights) and landing charges appropriate to London Stansted airport. Demand changes due to policy are then calculated assuming user-specified levels of cost pass-through and price elasticity.

This model is a highly simplified representation of UK air freight, consistent with the limited data available about UK freight networks and the small percentage of UK aviation emissions attributable to freight. Further discussion of how freight networks could change in response to policy is given in Section 2.8, above; however, given the relatively small emissions totals and low growth rates projected for freight flights, combined with freight journey time requirements, any impact due to freight network change is likely to be small.

4.3.8 Non-scheduled flights

The baseline passenger, aircraft movement, fleet and emissions totals generated thus far are appropriate for scheduled flights. However, many non-scheduled flights also use UK airports. In particular, many charter flights, primarily to holiday destinations, contribute to total UK fuel use and emissions. As with freight, relatively little data is available about these flights. CAA (2018) provide statistics on the proportion of UK movements which are scheduled and non-scheduled; approximately 9% of UK domestic movements are non-scheduled, and approximately 14% of international movements are non-scheduled. To reproduce absolute passenger, movement and emission totals, we assume a constant factor over the scheduled totals for non-scheduled flights of these amounts. This assumes that patterns of non-scheduled passenger demand are broadly similar to scheduled demand.

Table 8. Baseline model aircraft movements by scope, thousand flights per year.

	2015 modelled aircraft movements	**CAA (2015) airport data aircraft movementa**
Domestic	635.035	600
UK departing international flights	736.935	755.5
UK arriving international flights	733.938	755.5
UK-related total	2105.907	2111
London departing flights	560.876	
Other South East departing flights	29.501	
Midlands departing flights	59.134	
South West and Wales departing flights	70.687	
North departing flights	157.764	
Scotland departing flights	128.748	
Northern Ireland departing flights	47.742	
Non-UK, total	1601.212	-

4.3.9 Baseline outcomes

The modelled baseline system for 2015 in terms of passengers, movements and CO_2 is given in Table 8-Table 13. Several features are apparent. First, as shown in Table 8, the overall number of aircraft movements is relatively well-captured. The model over-predicts domestic demand by around 6% and under-predicts international demand by around 2.5%, with overall totals similar to those from CAA (2017) once double-counting of domestic flight movements is accounted for. The geographical distribution of flights is centred on London, with much smaller totals in other regions of the UK. The number of non-UK movements included in the model is of a similar order of magnitude to the number of UK movements.

Non-UK flights in the model include alternatives to itineraries hubbing through the UK and non-UK segments of itineraries starting and ending in the UK; for example, the Hong Kong-Australia leg of passengers travelling from the UK to Australia via Hong Kong.

Table 9. Baseline model passengers per year by scope, mppa.

	2015 modelled passengers, mppa	CAA 2015 airport data, mppa
Domestic	43.670	41.2
UK departing international flights	99.590	105.15
UK arriving international flights	100.303	105.15
UK-related total	243.564	251.5
London departing flights	75.616	
Other South East departing flights	1.459	
Midlands departing flights	6.433	
South West and Wales departing flights	5.172	
North departing flights	16.471	
Scotland departing flights	11.909	
Northern Ireland departing flights	3.736	
Non-UK, total	138.842	

Similarly, as shown in Table 9, total passenger numbers are close to those reported by CAA (2015), with a slight over-prediction for domestic flights and a slight under-prediction for international flights. Passenger totals are even more strongly concentrated in the London area than movement totals, reflecting the larger size of aircraft in use for flights from the major London airports. These totals can also be divided by airport, as in Table 10. On an airport level they are broadly consistent with CAA totals, although Heathrow demand is slightly over-predicted and demand at Stansted and Manchester airports is under-predicted. These differences may have to do with the number of charter flights in operation at different airports; since a single factor is applied at all airports, differences between different airports in terms of the amount of charter demand are not captured.

Finally, CO_2 totals are around 10% lower than those calculated from fuel uptake. There are several reasons why this may be the case. First, the model slightly under-predicts the number of international passengers. If this under-prediction applies most strongly for longer-haul passengers, this may lead to a larger under-prediction in CO_2. Many of the longest, highest-emission journeys are part of the 'long tail' of low-demand itineraries connecting through London Heathrow, as discussed in Section 4.1. By aggregating these itineraries, it is possible that the full CO_2 impact is slightly lower than it would otherwise be. Second, the model fuel use calculations are derived from a performance model (PIANO-X; Lissys, 2017) which assumes ideal operating conditions for new aircraft rather than practical use conditions.

Table 10. Baseline passengers per major airport in 2015, in comparison to CAA totals. Note that non-UK airport totals represent only the demand considered for this project, not the absolute totals of passengers travelling through the airport.

Airport	**2015 modelled passengers, mppa**	**CAA 2015 airport data passengers, mppa**
LHR (London Heathrow)	79.281	75
LGW (London Gatwick)	39.169	40
STN (London Stansted)	17.803	23
MAN (Manchester)	19.968	23
EDI (Edinburgh)	11.310	11
GLA (Glasgow International)	7.867	9
EMA (East Midlands)	3.981	4
DXB (Dubai)	16.222	-
CDG (Paris Charles de Gaulle)	20.992	-
FRA (Frankfurt International)	18.040	-
AMS (Amsterdam Schiphol)	23.252	-
BRU (Brussels International)	4.239	-
IST (Istanbul Atatürk)	8.658	-
DUB (Dublin)	15.332	-

Although we model the deterioration of aircraft fuel efficiency with increasing age and the impact of track extension, we do not model any other sources of non-ideal conditions which may cause increases in emissions; additionally, as discussed in ATA & Ellondee (2018), different performance models can produce fuel use outcomes that are several percent different at long flight distances, which are also the flights that are disproportionately important for matching CO_2 totals. Analysis of radar track data, as used in Reynolds et al. (2009), also suggests that individual fuel use totals can vary by up to 10% between the same flight with the same equipment on different days. Finally, the adjustment used above to account for charter flights assumes that charter flights are similar in distance and emissions per flight to scheduled flights, which may not be the case. Since the analysis of leakage and to some extent competitive disadvantage depend on relative changes in emissions rather than emissions totals, this under-prediction of CO_2 is unlikely to make a large difference to model outcome. We therefore leave the totals as they are without attempting to correct for these differences.

Table 12 shows the number of passengers by UK and non-UK airlines on UK and non-UK routes, counting routes both to and from the UK as UK routes. As noted above, we count demand as UK airline demand if the ticket is marketed by a UK airline. On this basis, about half of demand to and from UK airports is served by UK airlines. Conversely, only a small amount of demand that is not to or from UK airports is served by UK airlines. This means that the majority of UK airline fleet is involved in UK operations.

Table 11. Model baseline CO_2 totals by scope in comparison to UK bunker fuel uptake, $MtCO_2$/year.

	2015 model CO_2, tonnes	**NAEI 2015 bunker fuel uptake totals, tonnes CO_2**
Domestic	1.832	1.52
UK departing international passenger flights	28.641	
UK arriving international passenger flights	29.154	
UK domestic freighter flights	0.064	
UK departing international freighter flights	0.961	
UK arriving international freighter flights	0.961	
UK departing international total	29.601	32.95
UK-related total	61.612	
London departing passenger flights	24.108	
Other South East departing passenger flights	0.208	
Midlands departing passenger flights	0.930	
South West and Wales departing passenger flights	0.550	
North departing passenger flights	2.862	
Scotland departing passenger flights	1.467	
Northern Ireland departing passenger flights	0.348	
Modelled non-UK passenger flights, total	75.580	

Finally, Table 13 shows the number of scheduled passengers and associated CO_2 by itinerary type and scope. Because only scheduled passengers are shown and the totals are not adjusted for freight, absolute values are smaller than those above which include charter and freighter flights. If emissions are measured on a UK departing flight basis, the different parts of UK-associated demand and emissions that fall within and outside this scope will affect how leakage is measured.

Table 12. UK and non-UK airline passenger demand for operations on UK and modelled non-UK routes in 2015, mppa

	UK route passengers, mppa	**Non-UK route passengers, mppa**	**Total passengers, mppa**
UK airline	112.906	1.890	114.796
Non-UK airlines	108.823	136.952	245.774
Total	221.729	138.842	360.571

The largest part of UK-associated demand and emissions is in passengers who start or finish their journey in the UK, and take a direct flight only. Because the vast majority of these passengers are making round-trip journeys, the CO_2 associated with them is evenly divided between UK arriving and departing flights. This means that half of the emissions associated with UK origin-destination (OD) direct itinerary passengers are within UK departing flight scope, and half are outside. If a policy affects the demand of these passengers and has no other impact, we would expect roughly equal reductions in emissions inside and outside UK departing flight scope. Since carbon leakage is defined as the increase in emissions outside the policy scope divided by the decrease in emissions within scope, this would result in leakage of -100%.

Table 13. Scheduled passenger demand in mppa and CO_2 by in tCO_2/year by itinerary type, 2015, within and outside UK departing flight scope.

	Itinerary passengers, mppa	**CO_2 in UK departing flight scope, tonnes**	**CO_2 outside UK departing flight scope, tonnes**
UK domestic direct itineraries	18.802	1.600	0.000
UK international departing direct itineraries	68.922	15.208	0.000
UK international arriving direct itineraries	68.484	0.000	15.150
UK departing via UK hub	0.775	0.530	0.027
UK arriving via UK hub	0.795	0.057	0.520
UK departing via non-UK hub	9.832	5.019	4.457
UK arriving via non-UK hub	10.637	0.005	10.135
International-international transfer via UK	8.700	4.724	4.882
International-International transfer via non-UK	37.390	0.000	38.744
International-International direct	25.219	0.000	18.923

The next largest component of UK departing flight emissions is passengers who start their journey in the UK but travel via a non-UK hub. On average, these passengers emit about half of the CO_2 on the UK departing leg of their journey in reaching the non-UK hub (within UK departing flight scope) and about half in travelling from the non-UK hub to their final destination (outside UK departing flight scope). None of the CO_2 on the UK arriving leg of their journey is within UK departing flight scope. For a typical round-trip journey of this type, therefore, only a quarter of emissions are within UK departing flight scope. If demand falls on these routes, a quarter of the corresponding emissions reductions will be in UK departing flight scope and the rest will count as leakage. Leakage for policies which affect demand in this group of passengers would therefore be greater than 100%.

The third largest component of UK departing flight CO_2 is international-international transfer passengers travelling via a UK hub. This is the component of passengers most-discussed in the literature on aviation carbon leakage. About half of the CO_2 associated with these passengers is in UK departing flight scope, in either direction. Although routes with a UK origin or destination cannot eliminate policy impacts by changing routing, UK transfer passengers can. Therefore policies which affect this group of passengers are likely to result in positive leakage, i.e. emissions moving outside UK scope. However, for policies which primarily affect demand, this effect may be swamped by emissions reductions and negative leakage from the much larger set UK OD demand itineraries. Other components of UK departing flight CO_2, including domestic flights and UK OD connecting itineraries via a UK hub, are much smaller components of overall CO_2.

4.4 Modelling response to policy

The application of policies can affect this baseline system in several ways. We assume the main impact of policy on airlines and passengers will be via airline costs. In the case of an additional carbon price, this would act as an increase in an airline's fuel-related costs. The case of a requirement to take on biofuel would similarly act to change an airline's fuel costs, depending on the price of biofuel and any applicable carbon price at the time. Both of these changes effectively act on a per-RPK basis, penalising longer-haul flights and larger aircraft to a greater extent. A change in landing charges, in comparison, acts on a per-flight basis, penalising aircraft that make more landings in the UK (typically smaller aircraft) to a greater extent. A requirement to adopt specific mitigation options or technologies will typically provide per-RPK type cost savings (or per-landing cost savings in the case of technologies such as electric taxi which target ground-related emissions only) set against a per-aircraft cost.

In all of these cases, the airline is faced with a change in its operating costs which it can either act to reduce by changing fleet or operations, pass on to passengers, or accept as a decrease in its operating margin. We assume that any policy will be announced sufficiently far in advance that airlines will have ample chance to respond. In the case of purchasing new aircraft, typical order-delivery times mean that this may need to be at least eight years in advance (e.g. FlightGlobal, 2017). We assume that airline responses are made purely on a cost basis, and that decisions relating to fleet and operations are made before the decision on whether or not to pass any remaining costs onto passengers. Once costs are passed on to ticket prices, passengers in turn respond to this.

Based on the analysis in Section 2, we concentrate on airline response in terms of switching fleet between UK and non-UK routes, buying new aircraft, and tankering fuel; and passenger response in terms of switching routes and/or choosing not to fly. These areas are discussed individually below.

4.4.1 Airline response: substituting non-UK for UK fleet

Airlines which operate primarily outside the UK will have the option of moving more fuel-efficient aircraft onto their UK routes and using less fuel-efficient aircraft on their non-UK routes in response to UK-based carbon reduction policies. Airlines which operate primarily to and from the UK will not have this option. In the most extreme case, where non-UK airlines are able to satisfy all policy requirements by rearranging their fleet in this way, all of the carbon reductions achieved by applying the policy to non-UK airlines will be effectively leaked (plus or minus a small extra amount due to the more or less efficient use of each aircraft on its new routes). Non-UK airlines operating to and from the UK accounted for around 28 $MtCO_2$ in 2015; reductions in emissions from switching to the most efficient aircraft types available depend on aircraft type, but could in theory be up to around 15-20% if switching between older single-aisle aircraft types and the most recent generation of single-aisle aircraft. However, this does not account for other requirements on aircraft type that apply at UK airports, which may already effectively restrict the use of older aircraft and make substitution of aircraft from other routes less likely.

This situation is complicated by airline groups which purchase fleet in common. These groups may contain UK and non-UK airlines and potentially have the option to switch fleet between the two, allowing the UK airline greater flexibility in responding to policy at the cost of increased fuel costs and emissions for the non-UK airline. A summary of major airline groups and their relationship to individual UK airlines was given in Figure 2. Current airline groups which may choose to use their fleet in this way are IAG (BA, Iberia, Vueling, Aer Lingus) and Easyjet (Easyjet UK, Easyjet Switzerland, Easyjet Europe). After Virgin joins the Air France-KLM group its fleet may also be similarly affected. There may be some additional costs associated with switching in this manner, for example rebranding.

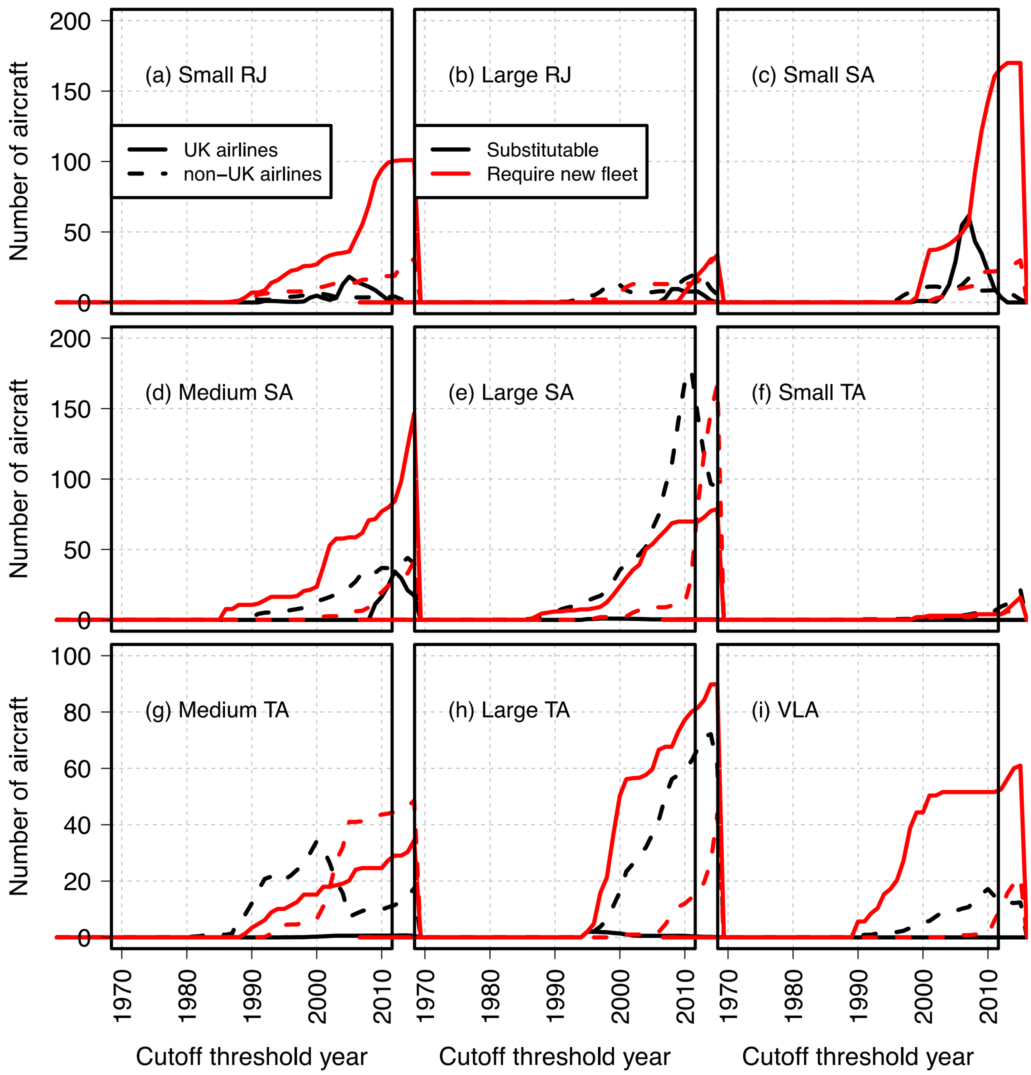

Figure 15. Available responses to fleet policy by UK and non-UK airlines, for a threshold year of manufacture before which aircraft cannot use UK airports, and treating all airlines as individual entities without fleet commonality.

Fleet-related policies could be applied either as regulatory restrictions on movements (for example, aircraft which do not meet some fuel efficiency threshold cannot land at UK airports) or cost-based policies (for example, aircraft which do not meet some fuel efficiency threshold have significantly increased landing fees at UK airports). In practice, the first situation is a special case of the second in which fees for some aircraft types are high enough to completely discourage their use. Figure 15 shows the options which were available to UK and non-UK airlines by aircraft size class in 2015 for a hypothetical policy restricting use of less fuel-efficient aircraft. Aircraft manufacture year is used as a proxy for fuel efficiency, with aircraft manufactured before a cutoff year assumed no longer usable at UK airports. The fleet size needed to carry out UK and non-UK operations by airline is derived from schedule data (Sabre, 2017) plus data on typical aircraft utilization (FlightGlobal, 2017). Aircraft age distributions by airline and size class were derived from FlightGlobal (2017). In Figure 15 it is assumed that all airlines are individual entities which cannot exchange fleet, and that the initial (non-policy) situation is that there is no difference in the age distributions of the fleet used in the UK per airline and those used elsewhere. It is also assumed that airlines will not switch between different size classes on any routes in response to the policy but will seek a like-for-like replacement. Switching between size classes implies either a change in frequency or operating at lower load factor, both of which may come with significant additional costs.

Several features are apparent. First, there is a large disparity in how UK and non-UK airlines can respond. Nearly all of the UK airline fleet is engaged in UK-related operations. Using 2015 data, the main exception is Easyjet; however, many of Easyjet's fleet used for European operations are due to be transferred to Easyjet Europe. In contrast, non-UK airlines tend to require only a small number of aircraft for their UK operations compared to their total fleets. Most airlines have aircraft with a range of different manufacture years. Therefore, if a policy is applied which strongly discourages the use of older aircraft, non-UK airlines will typically be able to substitute those aircraft with younger aircraft already in their fleet, assuming no other restrictions apply to their non-UK flights. UK airlines will not be able to do this unless they have fleet commonality via an airline group with non-UK airlines. This implies both a risk of carbon leakage and one of competitive distortion.

Secondly, these risks primarily affect larger aircraft and hence longer-haul journeys. The majority of non-UK airline aircraft operating to and from the UK are in the medium single-aisle and above size classes. These aircraft are also associated with higher emissions than smaller aircraft.

Figure 16 shows the corresponding situation in which fleet commonality within airline groups is assumed. This has little impact on the three smallest size classes, where flights are often performed by smaller regional airlines. However, it increases the number of aircraft that UK airlines can substitute for the other size classes. This increases the potential for leakage, but decreases the competitive distortion impacts expected.

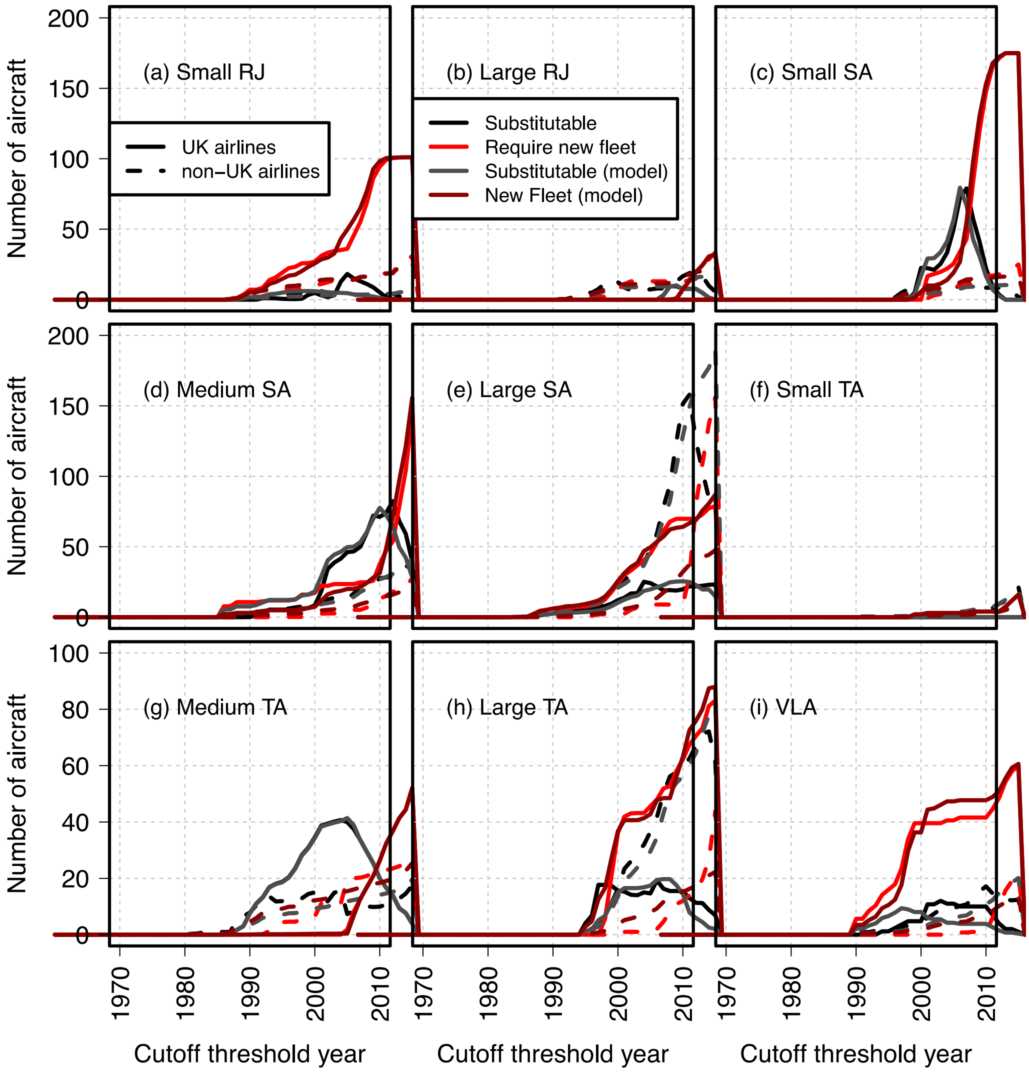

Figure 16. Available responses to fleet policy by UK and non-UK airlines, for a threshold year of manufacture before which aircraft cannot use UK airports, including the potential impact of airline group fleet commonality.

To include this mechanism in the model, we first calculate the size and age distribution of the 2015 fleet per size class for three airline types: UK airlines, those which may have fleet commonality with UK airlines, and other airlines. Grouping them in this way avoids having to model the fleet of individual airlines, which would add significant complexity to the model and is also unlikely to be accurate to 2050. Airlines in the UK group will not be able to fully substitute fleet on UK operations from fleet on non-UK operations because this group in reality includes a number of competing airlines; similarly, other restrictions may apply on substitutability, for example noise or emissions regulations at non-UK airports. We therefore also apply a substitutability parameter to each size class in each group indicating what proportion of the non-UK operations fleet can be substituted in for UK operations. This is one of the model uncertain parameters, with initial values per size class estimated from the year-2015 data shown in Figure 16. These initial values are typically between 0.3 and 0.7 for UK airlines and are a function of current airline networks and competition in each size class. If there are additional barriers to substitution, these numbers will decrease. The comparable modelled curves are also shown in Figure 16 and are implemented in the spreadsheet model.

Fleet substitution can in theory be done at minimal extra cost to an airline. Although the airline type is assigned will in advance of flights on any given route, the exact aircraft used to fly the route is typically only assigned 24 hours in advance and can be substituted at short notice if unplanned maintenance is required. However, there is some evidence in practice that airlines have not changed the fleet that they use at individual airports in response to environmental policy. Roy (2007) examined airline response to environmental landing charges at Zurich and Stockholm airports, finding that, although fleet developed over the time period after the landing charges were applied, it did so only in line with wider fleet developments that would have been expected without the landing charges and which also applied at other airports without similar environmental policies. Similarly, Nero & Black (2000) find that airlines have tended to simply pay environmental charges rather than adapt fleet in response to them. Some of these restrictions may be due to practical constraints in aircraft use. For example, airlines may have configured different aircraft of the same class differently to suit their requirements on different routes; they may be using an aircraft allocation model which is relatively unsophisticated and is not easy to adapt to the requirements of environmental policy; or there may be technical constraints which limit how different aircraft can be used, such as the requirement for an aircraft flying over open water to have two VHF radios. Another potential constraint is that fleet swapping in this way effectively acts as a cross-subsidisation from non-UK to UK routes, because older aircraft with higher fuel costs are moved to the non-UK routes. This is in direct opposition to the possibility that airlines will instead direct investment away from UK routes if policies significantly increase costs there, because those routes will become less profitable. It may also be a difficult situation to justify if fleet is swapped from other airlines within the same airline group.

Because in theory there is no barrier to reallocating aircraft from non-UK to UK routes, the model recommends this as a cost-effective option for policies which increase airline costs even by only a small amount, provided only that costs increase for some aircraft more than others. As discussed above, this is probably unlikely. The real situation likely lies somewhere between ‘no aircraft are reallocated’ and ‘aircraft are reallocated to the extent possible’, with the balance between the two depending on the stringency of the policy applied. We therefore run both cases as another dimension of uncertainty in our policy runs.

4.4.2 Airline response: purchase or leasing of new aircraft

As discussed in the previous section, one potential policy response of airlines is to stop using older aircraft (by selling them, terminating the lease, leasing them out to other airlines or retiring them early) and buy or lease new aircraft. This might either be in response to an outright prohibition on using older aircraft, or it might be a decision based on the increased costs of operating those aircraft. In either case, the airline will experience increased costs associated with this decision which may or may not be balanced out by fuel, maintenance or carbon savings from operating the new aircraft. The size of those increased costs depends on several factors, including whether enough aircraft of this type are up for sale due to the policy to reduce the likely sale price.

We assume that airline economic decisions are taken on a Net Present Value (NPV) basis, as in Morrell & Dray (2009). In this framework, purchasing decisions are approved if the NPV associated with them is positive, where:

$$NPV_x = \sum_{t=0}^{T_N} R_{t,x}/(1 + i^t),$$

and T_N is the time horizon over which the technology is evaluated, i is the discount rate, and $R_{t,x}$ is the cash flow associated with technology x in year t. The discount rate and time horizon are user input values. By default they are set at ten percent and seven years. These are the values used in Dray et al. (2018). To simplify the modelling process we make several assumptions. First, we concentrate on the case where an aircraft that is owned by an airline is sold onwards and a new aircraft is purchased, rather than situations which involve leasing either the old aircraft, the new aircraft, or both. Based on the fleet analysis in Dray (2014) we assume that early scrappage is less likely than sale onwards in an environment of increasing global demand. We assume that costs across all categories will remain broadly constant over the assessment time horizon for both the new and old aircraft. We also assume that crew costs, baseline landing charges and enroute charges will remain the same between the two aircraft, and neglect the impact of any reduction in aircraft utilization with increasing age. Other costs are assumed to change over time as discussed in Section 4.3.6. The aircraft purchasing model from Morrell & Dray (2009) was directly adapted (with some simplifications) to use as part of this study.

As discussed in Morrell & Dray (2009) and Roy (2007), increases in policy-related costs have to be significant before they can be used to justify the purchase of a new aircraft, and may need to apply in conjunction with a high fuel price. The main barrier is the high capital costs associated with new aircraft purchase. Morrell & Dray (2009) found that early replacement of a 15 year old 150-seat single-aisle aircraft is not cost-effective even at oil prices of \$140/bbl and carbon prices of \$100/tCO_2. Similarly, we find that most combinations of modelled fuel, carbon and extra policy costs are insufficient to justify the purchase of significant numbers of new aircraft, with the number of new purchases due to policy projected to be below ten aircraft in most cases modelled here. In the case that a new aircraft is purchased, we model the overall change in finance-related and maintenance costs to be spread across the whole modelled aircraft fleet for a given airline type, rather than assigned to specific flight segments.

4.4.3 Airline response: policy-induced change in technology choice

As well as inducing sales of older aircraft, emissions reduction policies may also change airlines' choice of aircraft for new purchases (e.g. to meet new demand, or to replace aircraft that were going to be retired anyway). If aircraft models with different capabilities are available for purchase, then increased fuel-related costs may influence which model is chosen. However, historically this decision has been made more at manufacturer level than airline level; when major manufacturers have offered new aircraft models at similar times, those models have tended to have similar capabilities. We therefore include the fuel- and carbon-price dependent technology trends from ATA & Ellondee (2018) as discussed in Section 4.3.6. It is assumed that new aircraft purchases will be consistent with these trends.

4.4.4 Airline response: tankering fuel

Aircraft on short-haul flights sometimes have enough spare payload and fuel capacity to be able to carry fuel for the return as well as the outbound leg of a return journey. If the fuel price at the destination airport is greater than that at the origin airport, it may be cost-effective to do so even though the increased fuel load slightly increases fuel use and emissions on the outbound leg. This practice is known as tankering, and airlines already often use it in cases where it is cost-effective (e.g. Schäfer et al. 2016). If a policy is applied to UK flights which effectively increases the fuel price at UK airports, then airlines may attempt to tanker fuel where possible to avoid it. This applies particularly to the hypothetical case where some fraction of biofuel is required for refueling at UK airports. Projected biofuel prices vary, but in general they are projected to be higher than those for fossil Jet A (e.g. Schäfer et al. 2016). The assumptions for fuel and carbon costs over time used in this study are discussed in Section 4.3.6 above and given in Table 7.

We assume tankering is feasible on a flight if:

- The fuel prices at the origin and destination airports differ
- The aircraft's initial take-off weight including extra fuel weight is less than its Maximum Takeoff Weight (MTOW)
- The landing weight at the end of the first flight segment is less than the aircraft's Maximum Landing Weight (MLW)
- The initial fuel load needed is less than the aircraft's maximum fuel capacity.

Data on MTOW, MLW and maximum fuel load is sourced from manufacturer specifications for the reference aircraft models in each size class with typical configurations.

To calculate the extra fuel use arising from tankering, the performance model described in Section 4.3.5 is used, treating the extra fuel weight on the outbound leg as extra payload. Typically, the extra fuel weight adds between 3 and 10 percent extra fuel use for this outbound leg. Tankering is assumed adopted if the increased cost due to the extra fuel needed (both in terms of fuel cost and in terms of any change in carbon costs from the baseline carbon price) is less than the cost saving of not taking on the more expensive fuel. Using these assumptions, tankering is sometimes cost-effective for flights facing increased costs from mandatory UK biofuel uptake, with the exact amount of tankering depending on the relative prices associated with Jet A, biofuel and carbon.

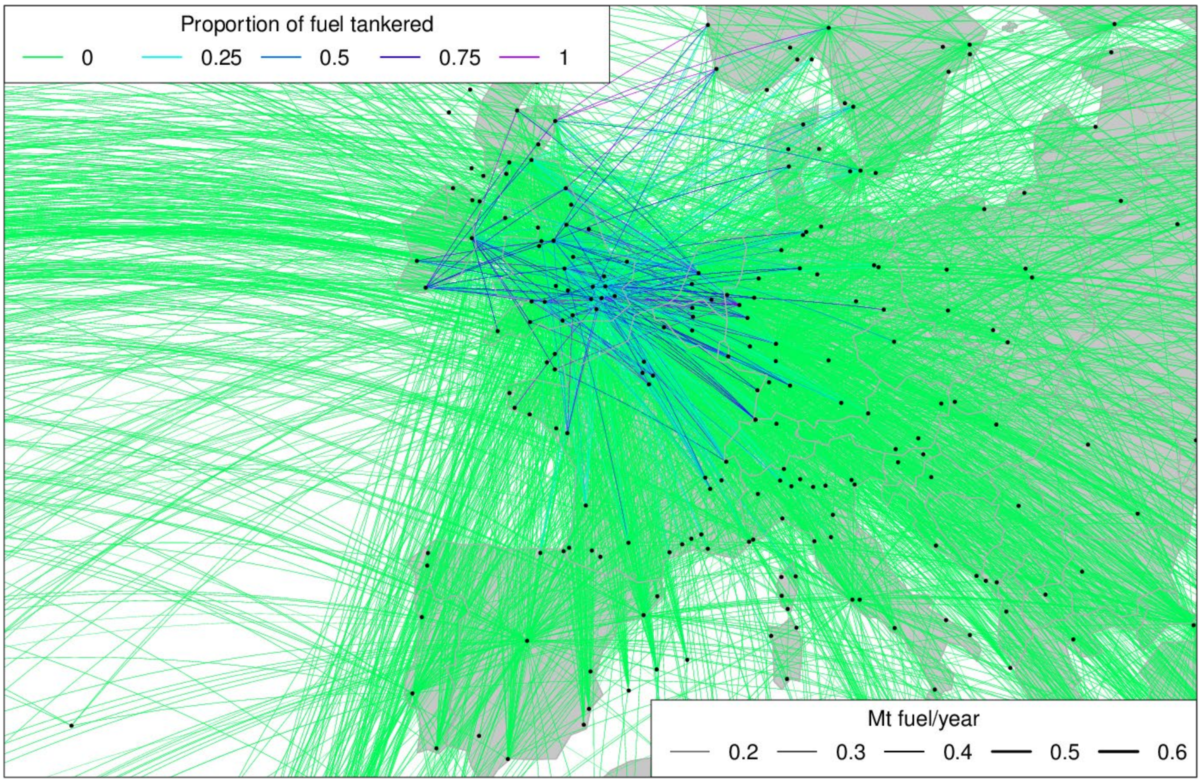

Figure 17. Hypothetical tankering scenario, assuming 2015 fuel prices and operations, biofuel around twice the price of Jet A, and ten percent biofuel requirement for refuelling at UK airports.

Figure 17 shows a hypothetical tankering scenario, based on applying a ten percent biofuel requirement to the 2015 baseline system. In this case, around 0.9 $MtCO_2$ is tankered. If CO_2 emissions from UK aviation are measured on a fuel uptake basis, these emissions are moved from being treated as UK aviation to being treated as non-UK aviation, leading to positive leakage. If instead CO_2 emissions are considered on a departing flights basis, positive leakage still occurs because the extra weight from carrying the tankering fuel increases emissions slightly on UK arriving flights. However, this leakage is much less, because the changes in fuel amounts involved on a departing flights scope are under 10% of those on a fuel uptake scope. Figure 18 shows a more extreme case in which a 50% biofuel requirement is applied. In this case, it is cost-effective to tanker fuel on all flights which are physically capable of doing so. Around 2.2 $MtCO_2$ is tankered in this case. Typically, under the year-2015 assumptions used here, tankering capability begins to saturate at around 20-30% biofuel requirement.

We assume that tankering is available only as a response to policies which directly change UK fuel price. Carbon pricing is assumed to be based on the airline's own carbon accounting (as for the EU ETS; EC, 2018a) rather than fuel uptake within a specific jurisdiction. This means that airlines cannot avoid paying carbon prices on UK departing flight fuel by tankering.

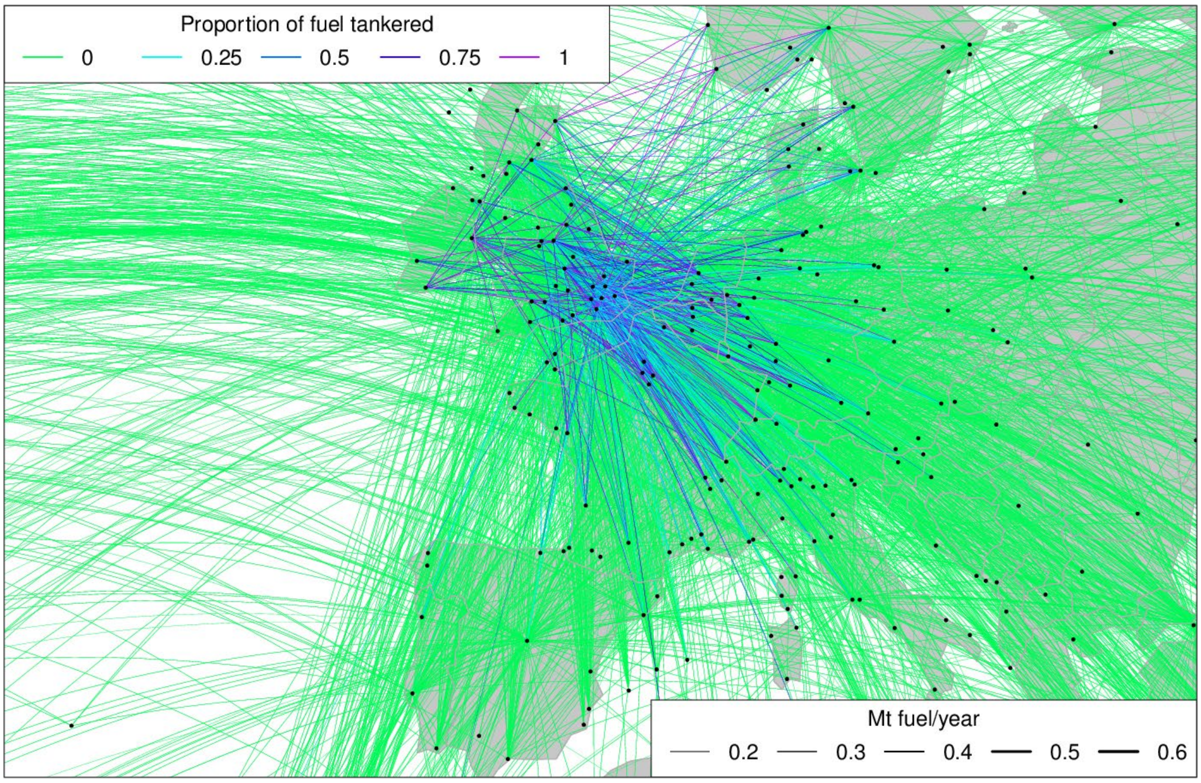

Figure 18. Hypothetical tankering scenario, assuming 2015 fuel prices and operations, biofuel around twice the price of Jet A, and fifty percent biofuel requirement for refuelling at UK airports

4.4.5 Passenger response

Once airlines have made the decision whether or not to reallocate fleet, purchase new aircraft or tanker fuel, they have the choice of whether or not to pass on the resulting changes in costs to passengers. As discussed in Section 3.2.1, the amount of cost pass-though is likely variable depending on the specific circumstances of a given flight: for example, the amount of competition and whether the origin or destination airports are capacity-constrained. Based on the literature review in Section 3, we assume different rates of pass-through at congested airports and all other airports. Literature estimates of pass-through at non-congested airports tend to be close to 100% (e.g. DEFRA, 2007). However, estimates of pass-through at congested airports vary more widely. This will affect demand travelling through Heathrow and to some extent Gatwick airports. Therefore we model a range of values of pass-through for these airports between 0 and 100%.

After some proportion of increased airline costs on a segment is passed through to passengers, this value is added to ticket prices on a round-trip itinerary basis. For example, typically a passenger travelling from London to Sydney and back will not book each leg of their journey separately, but will purchase tickets for all legs of their journey at the same time from the same airline.

Faced with an increase in ticket prices, passengers may choose not to travel and/or to take a different itinerary. To model itinerary choice, we rerun the itinerary choice model discussed in Section 4.3.2 with the new ticket prices appropriate for each itinerary. Parameters for this model are given in Appendix 2. We assume that the choice set of itineraries per city-pair remains the same as in the non-policy case, i.e. airline network change in response to the policy is limited, as discussed in Section 2.8. Increasing the fare prompts passengers who have a choice of routes to move towards routes that are less affected by policy; for example, changing from a UK to a non-UK hub, flying from the UK to a nearer hub airport than they would otherwise have used, or adding a hub to what was previously a direct journey. However, fare is only one of the parameters affecting this decision. Routes with fewer flight legs tend to be strongly preferred over those with more, and journey time and route flight frequency are also important. Therefore an increase in fare may need to be significant to prompt a large-scale change in itinerary choice.

Table 14 shows the change in passengers by itinerary type in the case where a large carbon price ($200/t$CO_2$) with 100% cost pass-through is applied to the baseline system in 2015, and the only policy response modelled is itinerary choice (i.e., the price elasticity of demand is set to zero, and no airline response is modelled). For a long-haul round-trip flight from the UK this adds around 20% to the overall ticket price. In this case, passenger responses are similar to those frequently discussed in the literature with regard to carbon leakage.

Table 14. The change in passengers (mppa) and CO_2 (tCO_2) by itinerary type and emissions scope in the case that a $200/t$CO_2$ carbon price with 100% pass-through is applied to the 2015 baseline system, and itinerary choice is the only modelled response.

	Itinerary passengers, mppa	**CO_2 in UK departing flight scope, tonnes**	**CO_2 outside UK departing flight scope, tonnes**
UK domestic direct itineraries	0.000	-0.008	0.000
UK international departing direct itineraries	-0.072	-0.095	0.000
UK international arriving direct itineraries	-0.084	0.000	-0.091
UK departing via UK hub	-0.054	-0.034	-0.001
UK arriving via UK hub	-0.054	-0.004	-0.031
UK departing via non-UK hub	0.132	-0.015	0.108
UK arriving via non-UK hub	0.141	0.000	0.101
International-international transfer via UK	-0.576	-0.265	-0.279
International-International transfer via non-UK	0.407	0.000	0.347
International-International direct	0.169	0.000	0.120
Total	0.000	-0.421	0.274

The largest change in passenger numbers and emissions is associated with international-international transfer passengers travelling via UK hubs. These passengers switch primarily to non-UK hub routes, with a smaller number taking alternative direct more expensive direct routes. However, the demand decrease is well under 10% of the baseline absolute international-international UK transfer passenger total (Table 13). The net impact once charter flights are included is a decrease of just under 0.5 $MtCO_2$ in UK departing flight scope, a similar decrease of just under 0.5 $MtCO_2$ in UK arriving flights (as UK transfer passengers have both a UK arriving and departing leg), and an increase of around 0.75 $MtCO_2$ in flights on non-UK routes. The net leakage on a UK departing flight basis is thus around 50%.

However, in reality passengers faced with increased costs will also have to make the choice of whether to fly or not. As discussed in Section 3.2.2, this is handled using the price elasticity of demand for passengers at a city-pair level, based on the average passenger-weighted increase in fare across all routes on that city-pair. The range of demand elasticities estimated in the literature is discussed in Section 3.2.2. Estimates vary depending on the geographic scope, time horizon, the substitutes available, the type of passenger and the type of route. In the case of the current study, substitution to and from other air routes is already modelled separately, so a value of price elasticity on the low end of literature estimates is appropriate. If the test case in Table 14 is rerun with a small price elasticity (-0.2), the resulting outcomes by itinerary type are shown in Table 15. Although there is still a switch from UK to non-UK emissions due to itinerary choice of similar magnitude to the previous case, there is now a much larger impact on UK departing and arriving direct itineraries. The decrease in demand for these itineraries is only around 2% of total demand. But, because many more passengers travel on UK departing and arriving direct itineraries than transfer via the UK, the resulting change in CO_2 in UK departing flight scope is greater than the change in CO_2 due to itinerary choice.

Table 15. The change in passengers (mppa) and CO_2 (tCO_2) by itinerary type and emissions scope in the case that a \$200/tCO_2 carbon price with 100% pass-through is applied to the 2015 baseline system, with itinerary choice and a small price elasticity of demand.

	Itinerary passengers, mppa	**CO_2 in UK departing flight scope, tonnes**	**CO_2 outside UK departing flight scope, tonnes**
UK domestic direct itineraries	-0.603	-0.061	0.000
UK international departing direct itineraries	-1.438	-0.438	0.000
UK international arriving direct itineraries	-1.486	0.000	-0.450
UK departing via UK hub	-0.068	-0.044	-0.002
UK arriving via UK hub	-0.068	-0.005	-0.041
UK departing via non-UK hub	-0.097	-0.146	0.010
UK arriving via non-UK hub	-0.107	0.000	-0.145
International-international transfer via UK	-0.636	-0.300	-0.316
International-International transfer via non-UK	0.306	0.000	0.280
International-International direct	0.116	0.000	0.082
Total	-4.081	-0.994	-0.582

As discussed in Section 2.5, the main impact of a decrease in demand on UK OD flights is negative leakage. This is because any decrease in demand and CO_2 emissions on UK departing flights is matched by a similar decrease in UK arriving flights; additionally, there may be extra negative leakage from the decrease in demand on non-UK flight legs of passengers originating in the UK but travelling via a non-UK hub. As the demand impact on UK-origin passengers exceeds the impact of itinerary choice, overall leakage in this case is around -60%. If the same test case is repeated with a price elasticity of demand of -0.8, the effect of demand decreases on UK OD passengers increases, but the amount of change in itineracy choice remains the same. Overall leakage in this case is around -115%. This leakage is made up of multiple components, of which the most important are:

- Changes in itinerary choice (around 50% leakage on their own, but affecting a smaller fraction of total CO_2 compared with other leakage sources).
- Changes in the demand of UK OD direct passengers, which lead to around -100% leakage as there are equal decreases in arriving and departing round-trip passengers.
- Changes in the demand of UK OD passengers who travel via an additional non-UK hub. Around three quarters of the CO_2 these passengers emit is outside UK departing flight scope, so the leakage associated with them is in excess of -100%.

In general, therefore, carbon leakage due to passenger response is likely to be negative. Carbon leakage due to airline response tends to be positive. The overall leakage impact of a policy thus depends on the balance between its demand-side and supply-side impacts.

In terms of competitive disadvantage between airlines, policies which have only a demand impact have an approximately symmetric impact on UK and non-UK airlines operating on UK routes, with some small differences arising from the different fleet and networks of different airline types. However, the ability of airlines to respond to policy differs by airline type. Therefore we would also expect policies which have a greater supply-side impact to also have a higher risk of competitive disadvantage. Policies which mainly affect demand are likely to affect the competitiveness of UK airports, however, as demand shifts between them and non-UK hubs.

5. Model outcomes

5.1 Hypothetical policies and uncertain parameters

Using the demand baseline calculated above, we explore the model response to three categories of hypothetical policy:

- An increased carbon price applying to all UK departing flights. This is assumed additional to the baseline global carbon price used in DfT (2017).
- A requirement for aircraft refuelling in the UK to use a given percentage of biofuel.
- An increase in landing charges across all UK airports, formulated such that older aircraft have higher landing charges and younger aircraft lower landing charges, with the overall outcome being roughly revenue-neutral.

These different policy categories are likely to have different outcomes on leakage and competitive disadvantage, based on their relative demand impacts and the available strategies that airlines can use to try and reduce their policy-related costs.

Additionally, we explore the model response to these policies with different assumptions about uncertain parameters. As discussed in Section 3, there are many uncertain parameters which may affect outcomes. We select a range of parameters that we believe are likely to have the largest impact on outcomes, and which are affected by the largest amount of uncertainty, to explore:

- Cost pass-through at congested airports. We assume cost pass-through at non-congested airports is always 100%, but explore cost pass-through values of 0%, 50% and 100% for congested airports.
- Passenger price elasticity of demand. We explore values of -0.2, -0.5 and -0.8. These values are relatively small compared to the range given in the literature but are chosen for consistency with the values used in DfT (2017) and because the impact of itinerary choice on demand is already separately modelled.
- The extent to which airlines can swap aircraft from UK to non-UK routes. We examine two cases: that in which they can swap to the full extent possible, as examined in Section 4.4.1, and that in which they cannot or choose not to swap aircraft at all.
- The baseline system conditions, in terms of fleet, fuel price, baseline carbon price, etc. We assume two cases: policies applied in 2015, which has relatively low fuel and baseline carbon prices, and policies applied in the 2030 central case, which has higher fuel and baseline carbon prices.

Outcomes in each case are discussed individually below.

5.2 Policies applied in 2015

5.2.1 Increased carbon price

Figure 19 shows carbon leakage in the case that an increased carbon price is applied to the 2015 baseline system, with values up to £200/tCO_2 for UK departing flights only. For comparison, the baseline carbon price assumed in 2015 is around £5/tCO_2, so the upper end of the range modelled would represent a substantial change from present-day values. As shown in Figure 13, this level of carbon tax would more than double year-2015 fuel prices. The model runs in Figure 19 assume airlines can respond to any new policy by exchanging their fleet between different routes. Figure 20 shows the corresponding case where fleet swapping does not occur. Both sets of model runs consider a range of values for price elasticity and congested airport cost pass-through (‘CA pass-through’).

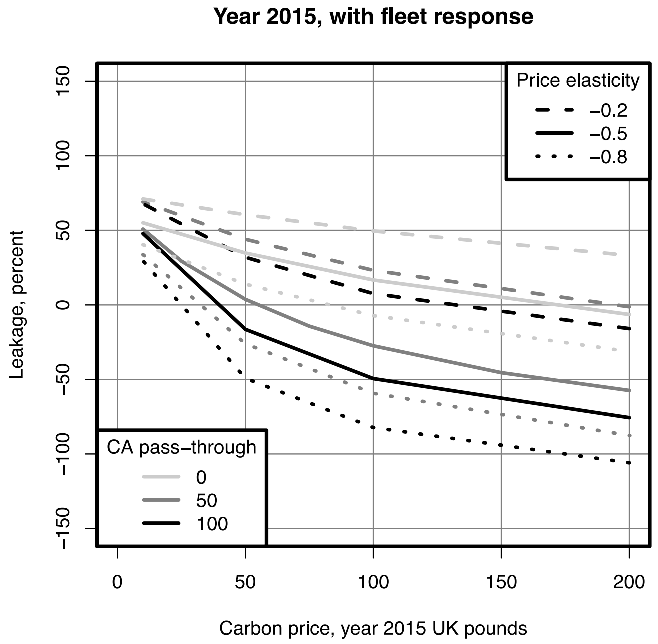

Figure 19. Carbon leakage for a hypothetical carbon price policy applied in 2015, with fleet response.

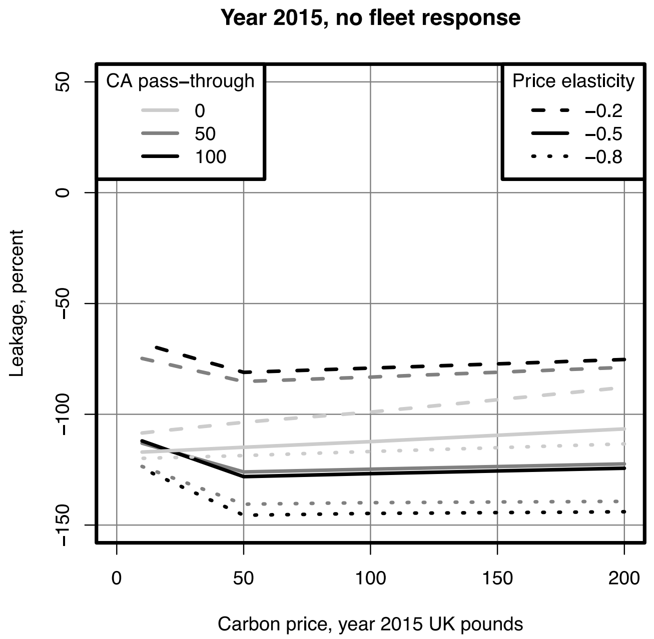

Figure 20. Carbon leakage for a hypothetical carbon price policy applied in 2015, without fleet response.

Several features are apparent. First, leakage is negative in the majority of cases when airlines can respond to policy by swapping fleet between routes, and negative in all cases in the case that they cannot. The origin of this negative leakage is discussed in Section 2.5. In the case that airlines cannot swap fleet, the main outcome of the increased carbon price policy is an increase in ticket price, i.e. it primarily has an impact on demand. Because passengers usually make round trips, a demand reduction on the outbound leg of a journey is matched by a demand reduction on the inbound leg. But leakage here is measured on a UK departing flights basis. Therefore in the simplest case, there is a reduction in demand and hence emissions for UK departing flights, and a similar reduction in demand and emissions for UK arriving flights, leading to leakage of around -100%.

However, the actual amount of leakage varies between around 50% and -150%, depending on the level of carbon price assumed and the values used for uncertain parameters. This is due to the interaction of several different effects. First, fleet swapping is assumed to be a minimal-cost option for airlines. Therefore it is cost-effective for airlines to move lower-emission fleet onto UK routes even where the additional carbon price is small (as discussed in Section 4.4.1, there are several reasons to believe that this level of response in unlikely). Fleet swapping results in positive leakage because higher-emission aircraft are moved onto non-UK routes, increasing the CO_2 attributed to them. The underlying changes in emissions by scope are shown in Figure 21 (with fleet swapping) and Figure 22 (without fleet swapping). As shown in Figure 21, fleet swapping leads to increases in emissions on routes that are not to or from the UK in all cases. At low carbon prices, this fleet swapping impact is greater than the negative leakage from demand reduction, so the overall leakage is positive.

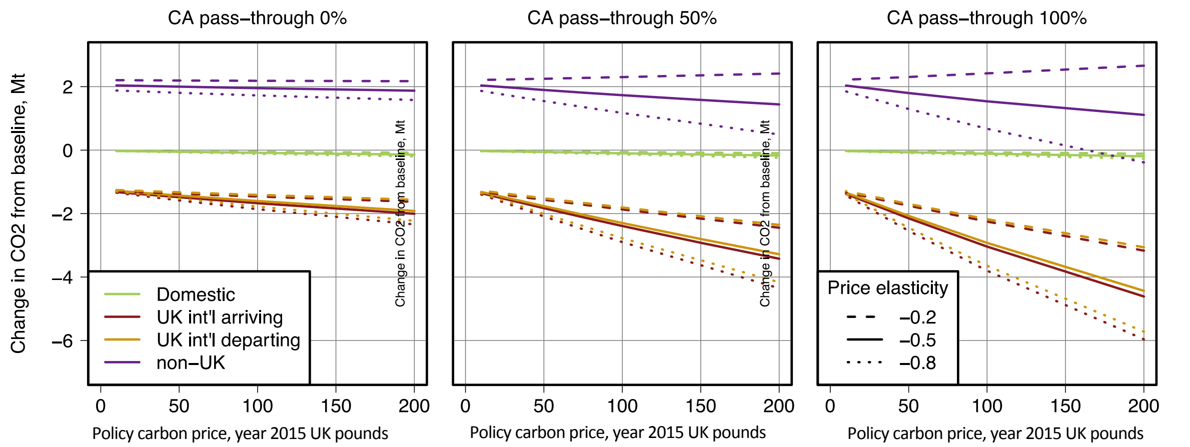

Figure 21. Underlying changes in CO_2 emitted by scope, for a hypothetical carbon price policy applied in 2015 with airline fleet swapping.

Another source of positive leakage is passengers changing itineraries from UK-hubbing routes to non UK-hubbing routes. As discussed in Section 4.4.5, this effect is comparable to that from demand reduction if the price elasticity of demand is small. Therefore model runs with lower price elasticity of demand have net positive leakage (in the case that fleet response is assumed) or less negative leakage than other runs (in the case that there is no fleet response).

The model runs also investigate the impact of cost pass-through at congested airports ('CA pass-through'). At 0% pass-through, there is no change in ticket price for passengers travelling through Heathrow and Gatwick airports. As Heathrow takes the vast majority of UK international-international transfer passengers, this means that the itinerary choice effect in the case of zero pass-through is extremely limited. The amount of pass-through also affects the balance between demand-based negative leakage and supply-based positive leakage. Airlines are assumed to try and reduce their costs by swapping fleet, buying new aircraft or tankering before they decide how much of the remaining cost increase to pass on to passengers. Therefore model runs with lower pass-through at congested airports have higher positive or less negative leakage. The greater the proportion of cost that is passed on to passengers, the larger the demand-based negative leakage effect.

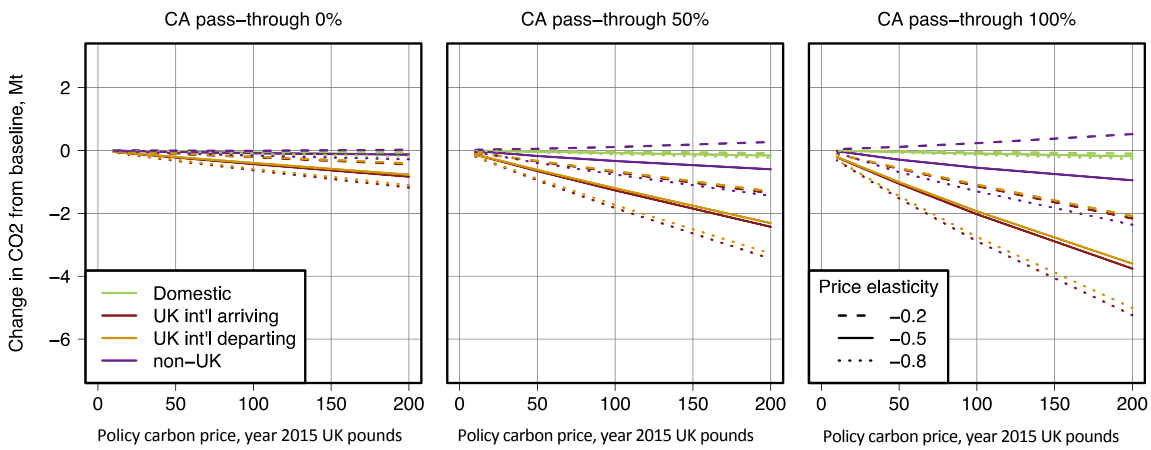

Figure 22. Underlying changes in CO_2 emitted by scope, for a hypothetical carbon price policy applied in 2015 without airline fleet swapping.

To assess competitive disadvantage impacts, we look at the change in demand by carrier and route type and the amount of cost not passed on by carrier and route type. The change in passenger demand due to an increased carbon price is shown in Figure 22 (with fleet swapping) and Figure 24 (without fleet swapping). The cases with and without fleet swapping are generally similar, although demand reductions on UK routes are slightly greater without fleet swapping, as airlines have fewer ways of reducing their policy-related increased costs.

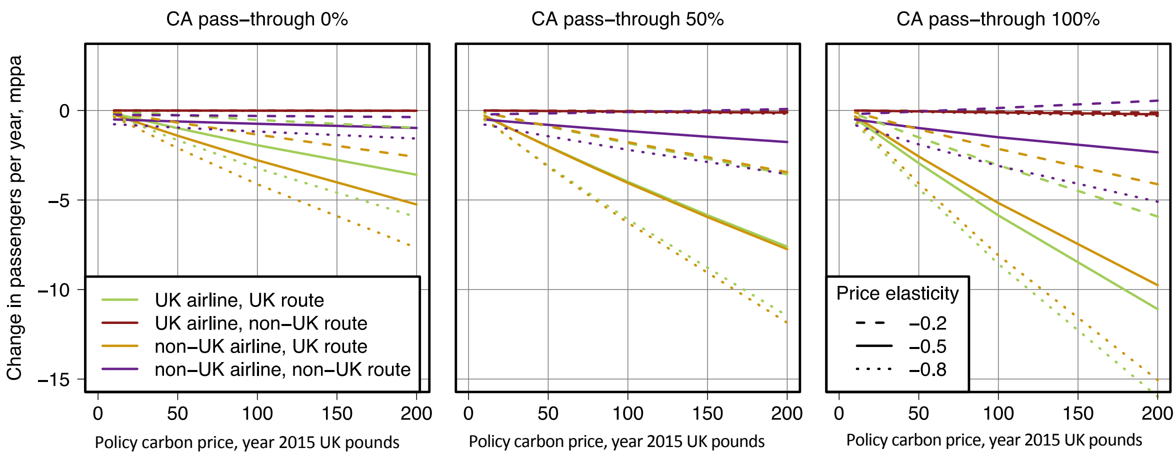

Figure 23. Change in demand by airline and route type for a hypothetical policy increasing carbon price in 2015, for different assumptions about price elasticity and cost pass-through at congested airports. Airline fleet swapping is included.

In general, changes in demand on non-UK routes are small compared to those on UK routes. In most cases demand reduction for UK OD passengers, rather than changes in itinerary choice for international-international transfer passengers, is the dominant demand impact. In the case that fleet swapping occurs, non-UK routes may also have increased costs from using older aircraft, leading to a small damping effect on demand. As non-UK airlines are more able to swap fleet, this effect is greater for non-UK airlines.

On UK routes (which includes both routes to the UK and those from the UK), changes in demand depend primarily on the amount of cost pass-through at congested airports and the assumed price elasticity of demand. Larger amounts of pass-through, and passengers who are more price-sensitive, lead to greater reductions. These reductions are usually at similar levels for UK and non-UK airlines. Generally, non-UK airlines are more impacted than UK airlines at low levels of congested airport pass-through, and UK airlines are more impacted than non-UK airlines at higher levels of congested airport pass-through. This reflects the different distribution of UK and non-UK carriers between congested and non-congested airports. Major UK carriers, for example BA and Virgin Atlantic, have many flights from Heathrow and Gatwick airports. If pass-through is assumed to be low at these airports, then the demand impact on these carriers will be small. However, the reduction in their profit margins may be substantial.

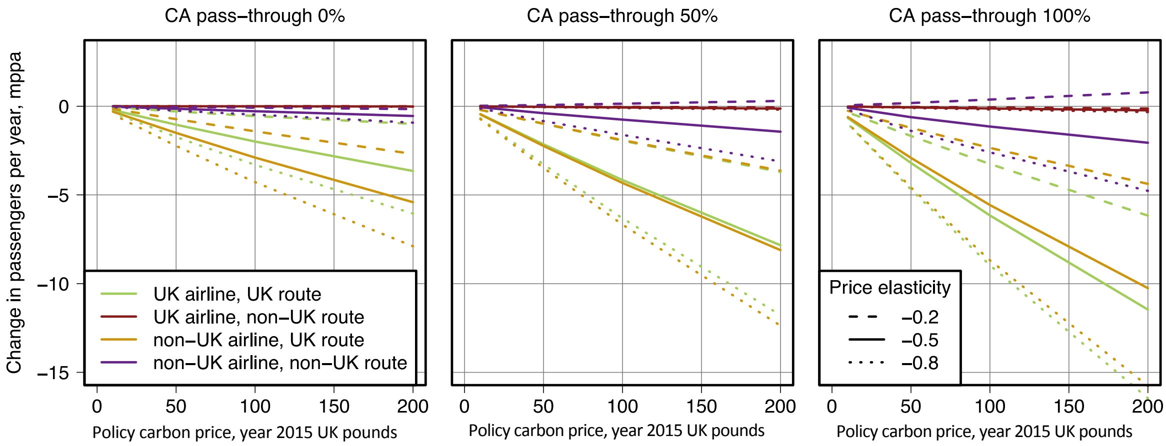

Figure 24. Change in demand by airline and route type for a hypothetical policy increasing carbon price in 2015, for different assumptions about price elasticity and cost pass-through at congested airports. Airline fleet swapping is not included.

The change in non passed-through cost per RPK (i.e. the overall increase in airline costs that is not passed onto ticket price divided by revenue passenger-kilometre travelled) is shown in Figure 25 (with fleet swapping) and Figure 26 (without fleet swapping). For reference, average global airline ticket revenue per RPK is around £0.1 (e.g. ICAO, 2016). Therefore an increase in costs of £0.015 is substantial. Although airlines have other sources of revenue (for example, for low-cost airlines ancillary revenue from activities such as website advertising, car hire and hotel booking tie-ins and selling food on board is an important component of total revenue without which the airline may appear to be loss-making), ticket revenues are usually their dominant revenue source. Assuming typical operating margins pre-policy of 4% (Ernst & Young and York Aviation, 2008), this suggests that airlines which did not pass on costs at congested airports would be making a loss at the higher end of the carbon price range explored here. In reality, this suggests that after some threshold carbon price they would pass on at least some of their increased costs.

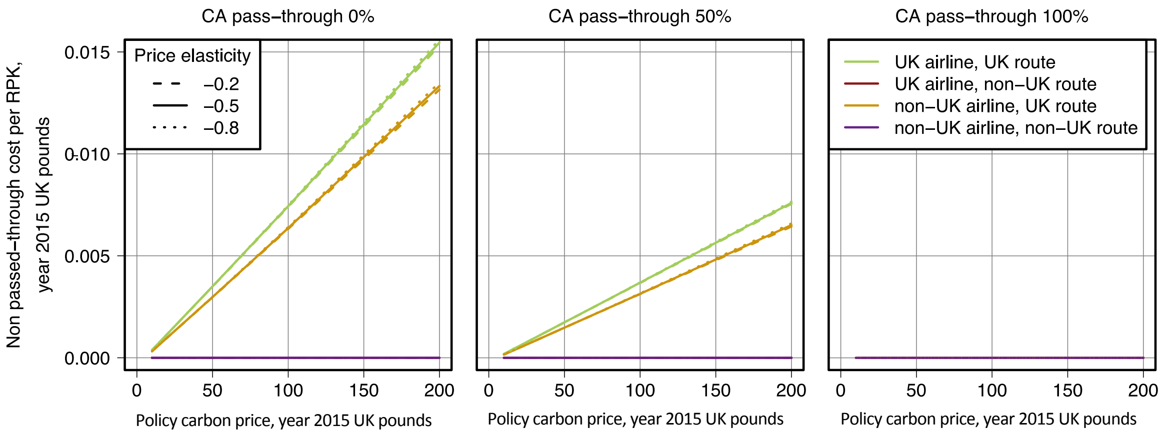

Figure 25. Change in costs not passed on per RPK, for the case of an increased carbon price in 2015 with airline fleet swapping.

As discussed above, the differences between UK and non-UK airlines in terms of who is most affected are mainly related to the airports that they operate from. In the case that some costs are not passed on at congested airports, UK airlines are more affected because of the heavy presence of major UK carriers at Heathrow and Gatwick airports. Additionally, there are differences between UK and non-UK carriers in terms of the type of operations carried out. For example, most UK domestic flights are carried out by UK carriers. This has relatively little impact in the case of an increased carbon price because domestic flights are typically short, carried out by smaller aircraft, and associated with relatively low total CO_2.

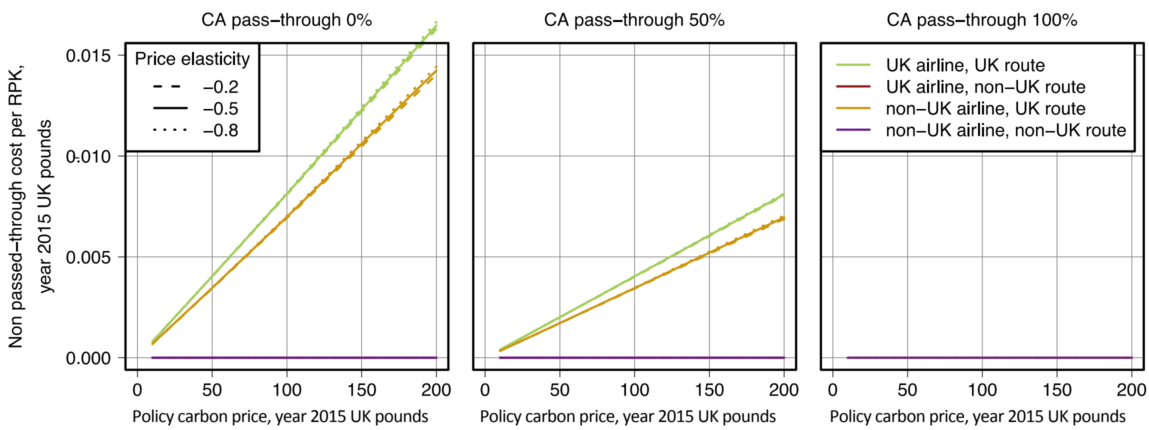

Figure 26. Change in costs not passed on per RPK, for the case of an increase carbon price in 2015 without airline fleet swapping.

Finally, we examine the change in demand per major airport. Here results again reflect that demand reduction on routes to and from the UK is the major impact of the increased carbon price policy. UK airports see reductions in demand in all cases. For example, in the case that 50% of cost is passed through at congested airports and price elasticity is -0.5, demand at Heathrow reduces by up to 4.8 mppa (around 6% of the modelled Heathrow total). For comparison, demand at Heathrow over the 2010-2016 period has tended to increase by 1-2 mppa per year (CAA, 2016). However, non-UK airports see reductions in demand in most cases as well. The extent of the demand reduction depends on the airport's connections to the UK and how much it is used as a hub for UK-originating traffic. For example, Dubai airport passenger demand reduces in almost all model runs because it is used as a hub for passengers flying to Asian destinations from the UK, rather than as an alternative hub to Heathrow for long-distance passengers travelling between non-UK destinations. For nearer hub airports, such as Paris Charles de Gaulle, outcomes are mixed. In the case that there is 100% or 50% cost pass-through at congested airports and a price elasticity of -0.2, itinerary choice effects dominate and demand increases at Charles de Gaulle by up to 0.2 mppa. However, for more negative price elasticities, the reduction in demand for UK origin and destination passengers is greater than the increase in demand from passengers changing routing.

The overall most likely outcome of this policy on airports is therefore that nearly all airports, UK and non-UK, will see a reduction in revenues caused by decreasing passenger throughput. However, UK airports will have larger decreases in throughput than non-UK airports.

5.2.2 Increased use of biofuel

This hypothetical policy case assumes that airlines are required to use a particular percentage of biofuel when refuelling at UK airports. For 2015, this is wholly theoretical; the supply and delivery infrastructure for aviation biofuels is not yet in place. However, small amounts of aviation biofuel are in everyday use for scheduled flights at Los Angeles International Airport (LAWA, 2016), including delivery infrastructure from a commercial biofuel plant (AltAir), and other aviation biofuel production facilities are under construction. Therefore, depending on the priority that aviation biofuel development is given in comparison to other uses of biomass, it may be a feasible option in the near future. It is assumed that biofuel is around twice the price of Jet A; therefore, a 40% biofuel blend would increase fuel prices by around 40%. This can be compared to the impact of a \$200/tCO_2 carbon price, which would more than double year-2015 fuel prices. Therefore the largest biofuel blends investigated here have a significantly smaller cost impact on airlines than the largest carbon prices investigated above.

In this section, we assume that emissions changes are evaluated on a UK fuel uptake basis. In practice this is identical to a UK departing flights basis unless tankering occurs. In the case that tankering occurs, fuel for some UK departing flights will be taken on board at non-UK airports and the amount of fuel taken on board at UK airports will decrease. As discussed in Section 2.12, leakage on a departing flights basis from tankering will be around a tenth of leakage on a fuel uptake basis from tankering, and will be roughly similar to the case without tankering. To quantify this difference, we also carry out biofuel model runs without tankering and compare the outcomes to those with tankering.

Figure 27 shows leakage on a UK fuel uptake scope due to the biofuel policy in the case that airline fleet swapping between UK and non-UK routes is assumed. Figure 28 shows the case in which airlines are assumed not to swap fleet. Leakage in both cases is relatively similar and is typically between 10 and 40% positive, i.e. an emissions reduction on a UK departing flight scope with a smaller emissions increase on non-UK flights. In both cases leakage has a peaked structure with increasing biofuel percentage, with maximum leakage at around 15% biofuel.

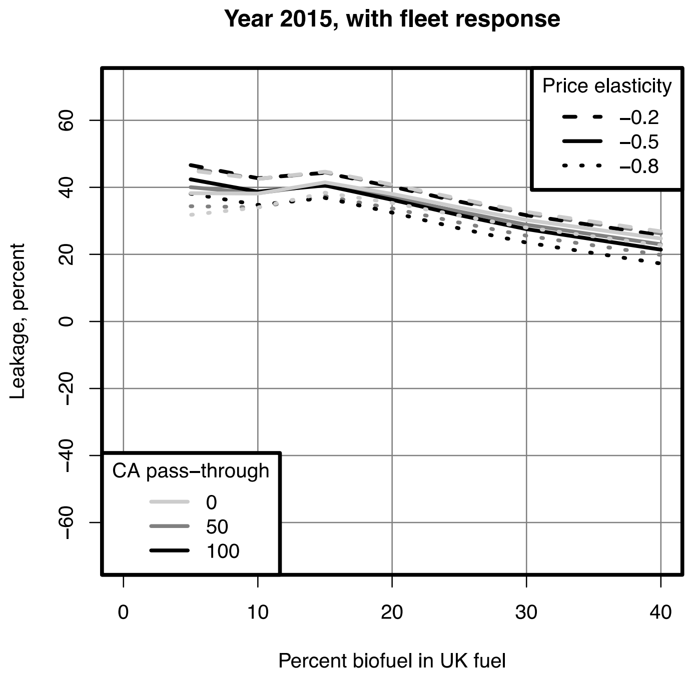

Figure 27. Carbon leakage in the case of a hypothetical UK departing flight biofuel uptake policy, under year-2015 conditions with fleet response.

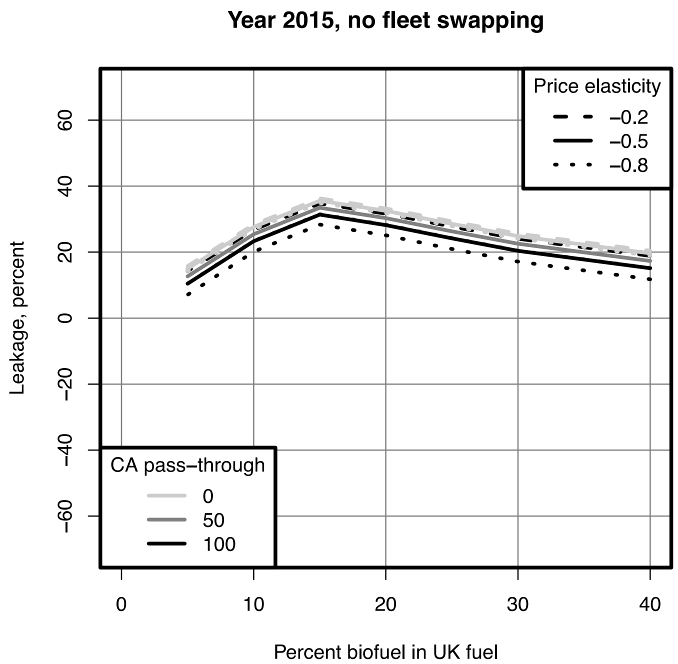

Figure 28. Carbon leakage in the case of a hypothetical UK departing flight biofuel uptake policy, under year-2015 conditions without fleet swapping.

Several interacting factors are behind these trends. In particular, there are two factors that apply to the biofuel policy which do not apply to the carbon price policy. One is that the policy is assumed applied on a UK fuel uptake basis. Therefore airlines on short-haul routes can avoid it by tankering fuel. The second is that using biofuel results in a decrease in emissions for UK departing flights regardless of any demand reduction, because biofuel is assumed to have lower emissions than fossil-derived aviation fuel. Tankering is the practice of taking enough fuel on board at an airport with lower fuel prices to cover both legs of a return journey, rather than paying higher fuel prices to refuel at the intermediate airport. The net impact of tankering is to take emissions outside a UK departing flights scope, plus a small additional increase in fuel use from increased aircraft weight on the outbound journey. If emissions are derived from fuel uptake, tankered fuel will be counted as emissions attributed to the non-UK airports where tankering flights took on their increased fuel load.

Tankering therefore causes positive leakage. The amount of leakage depends on how many flights it is cost-effective to tanker on, and how many flights it is possible to tanker on. As discussed in Section 4.4.4, there are practical limits on which flights can tanker. For example, the aircraft must have the available fuel tank capacity to take on the extra fuel and cannot be over its maximum takeoff weight on initial departure, or maximum landing weight on first landing. These constraints limit tankering use to short-haul flights only. Figure 29 shows the amount of CO_2 taken outside a UK departing flights scope by tankering for different UK fuel uptake biofuel percentages. The case with fleet swapping is shown, but all scenarios have similar outcomes. As the increased costs associated with taking on more biofuel at UK airports increase, more fuel is tankered. However, for year-2015 conditions tankering potential begins to level off at around 15% biofuel. By 20% biofuel, all flights that can tanker are doing so, taking around 2 $MtCO_2$ outside of a UK departing flights scope.

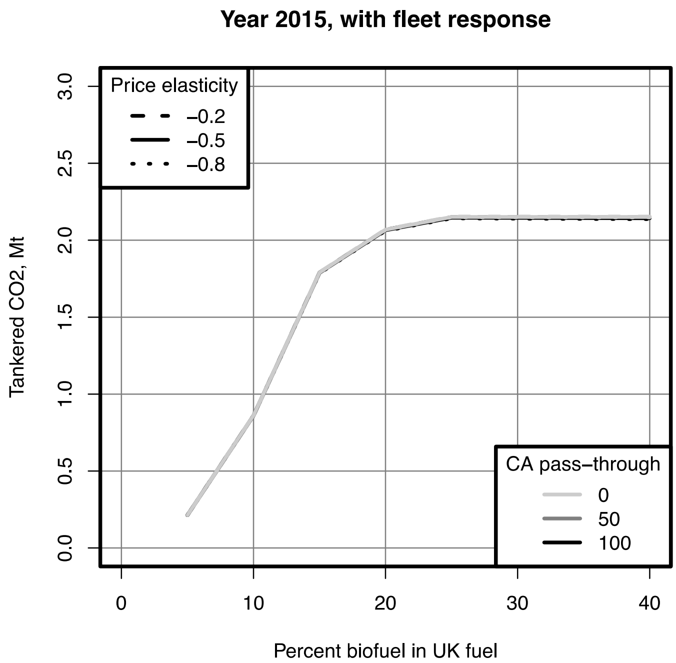

Figure 29. The amount of CO_2 tankered (i.e., removed from a UK departing flight scope and added to a UK arriving flights scope) for the aviation biofuel policy under year-2015 conditions.

The impact of emissions reductions caused by biofuel use, in contrast, is linear with increasing biofuel uptake. This reduction applies only to UK departing flights. Figure 30 shows the absolute change in emissions by scope caused by the policy in the case with airline fleet swapping. Figure 31 shows the corresponding case without airline fleet swapping. Outcomes with and without fleet swapping are more similar than they were in the increased carbon price case. This is because the potential emissions reduction from using biofuel is much greater than the change in emissions from fleet swapping. However, fleet swapping is still widely employed in this scenario where allowed. Because we have assumed fleet swapping is a minimal-cost option to airlines, airlines will use it wherever they can reduce their costs by using a newer aircraft on a route. Because a newer aircraft of a given size class typically uses less fuel, this reduces the overall increase in fuel costs to airlines from using biofuels. Therefore, where fleet swapping is allowed, the model projects airlines using it even at relatively low biofuel uptake percentages. Widespread fleet swapping potentially moves around 2 $MtCO_2$ from flights to and from the UK to flights unrelated to the UK. This is distinct from the impact of tankering; for tankering, emissions on flights to the UK are slightly increased, whereas fleet swapping reduces the emissions of these flights.

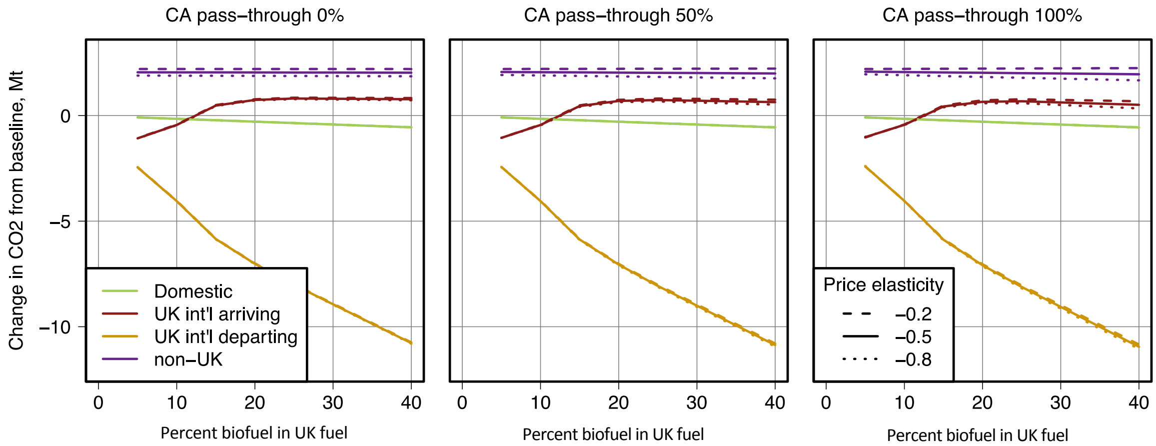

Figure 30. Change in CO_2 by scope for the hypothetical biofuel uptake policy under year-2015 conditions, assuming airline fleet swapping.

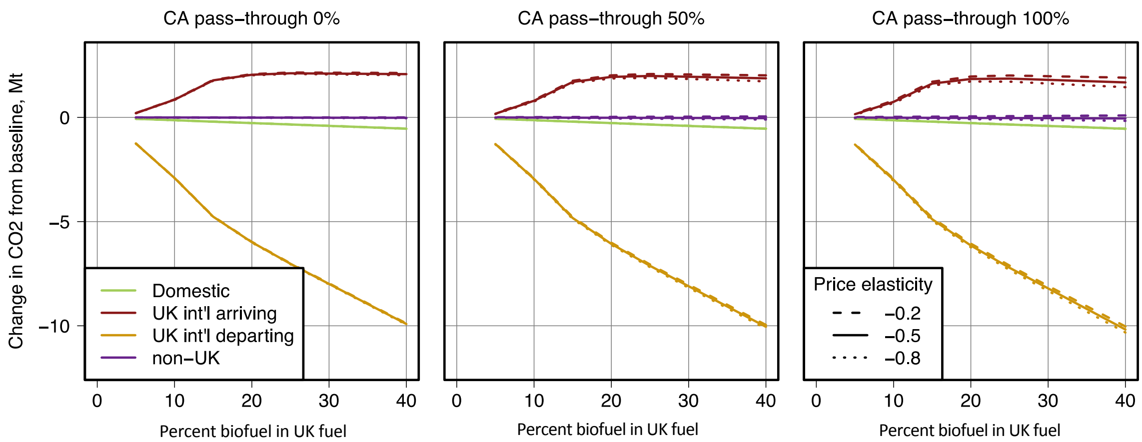

Figure 31. Change in CO_2 by scope for the hypothetical biofuel uptake policy under year-2015 conditions, assuming no airline fleet swapping.

The largest impact on overall CO_2, however, comes from the use of biofuel itself. Biofuel is assumed to have 30% of the CO_2 emissions of fossil-derived Jet A (Section 4.3.5). This is a simplified way of accounting for its lower emissions on a fuel lifecycle basis; when in use, drop-in biofuels will result in the around the same amount of CO_2 being emitted directly from aircraft engines as fossil-derived Jet A. However, growing feedstock for biofuels absorbs CO_2 from the atmosphere. Biofuel is assumed in use only on UK departing flights. The net impact of the biofuel policy on leakage is thus made up of the following components:

- A large reduction in UK departing flight emissions from the use of biofuel (up to 10 $MtCO_2$ in the extreme case of 40% biofuel use).
- A smaller shift of emissions from a UK to a non-UK fuel uptake scope due to tankering (up to $2MtCO_2$ at 20% biofuel, at which point the maximum tankering potential is reached).
- If fleet swapping is considered, a shift of around $2MtCO_2$ from UK departing and arriving flights to non-UK flights, which is roughly the same across all policy levels.
- Similar (but smaller-magnitude due to an overall lower cost to airlines) demand and itinerary choice impacts as for the increased carbon price policy.

Of these, the most important factors are the tankering-led movement of emissions outside a UK fuel uptake scope, which results in net-positive leakage; and the large reduction in UK departing flight emissions from biofuel use, which makes the leakage percentage smaller. The end result is positive leakage of around 10-40% which is relatively insensitive to demand and congested airport cost pass-through parameters.

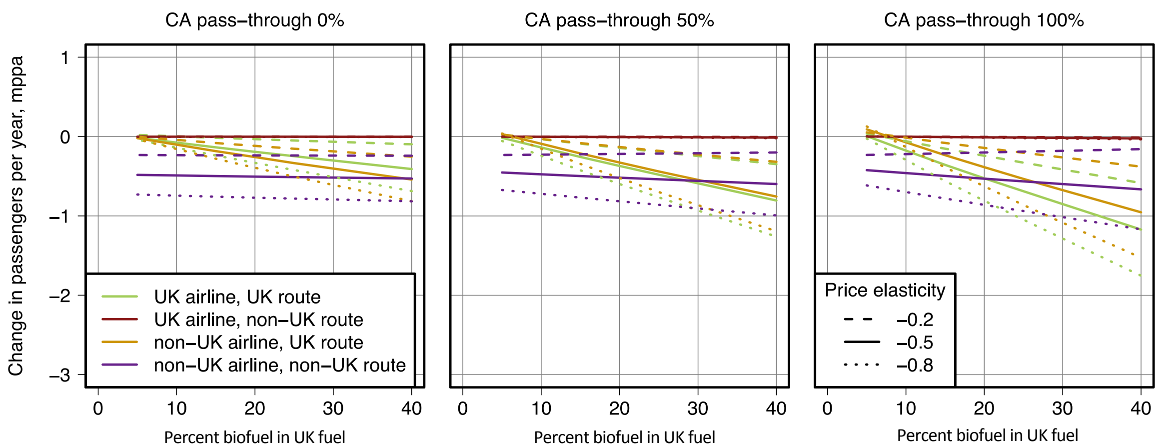

Figure 32. The change in demand by airline and route type for the hypothetical biofuel policy under year-2015 conditions, with fleet swapping.

If tankering does not allow policy avoidance (for example, if the policy is specified as a requirement on all flights departing UK airports, rather than all fuel taken on at UK airports) then the overall leakage total is smaller. For passenger price elasticity of demand of -0.5 and 50% cost pass-through at congested airports, leakage without tankering but with fleet swapping is around 5-35%, compared to 23-40% with tankering. If neither tankering or fleet swapping is assumed, leakage in this case is close to zero, i.e. the demand and itinerary choice impacts for non-UK flights are small compared to the biofuel reduction in UK departing flight CO_2. In the case that tankering occurs but emissions are measured on a UK departing flight basis, outcomes will be closer to the no-tankering case than the tankering case with emissions on a fuel uptake scope. This is because tankering in this case only increases non-UK emissions by a small amount (the 3-10% increase per arriving tankering flight discussed above).

The corresponding change in passenger demand by airline and route type is shown in Figure 32 (with fleet swapping) and Figure 33 (without fleet swapping). As noted above, the effective fuel cost increase associated with the higher levels of biofuel uptake modelled here is much less than that associated with the higher levels of carbon price modelled in the carbon price case. Therefore the demand impact is correspondingly smaller. However, the overall broad patterns of response are similar. Because most air journeys are round-trips, demand reduction is similar on UK departing and UK arriving flights, even though the emissions associated with these flights are different. In the case of fleet swapping, there is a demand reduction on non-UK flights associated with higher fuel use on those routes from older aircraft swapped out from UK routes. Without fleet swapping, demand response is broadly linear with policy level.

As with the carbon price policy, UK and non-UK airlines on UK routes are affected at a similar level by demand reductions. The exact balance between them depends on the amount of cost pass-through at congested airports. This is because UK carriers have more flights from the congested airports modelled.

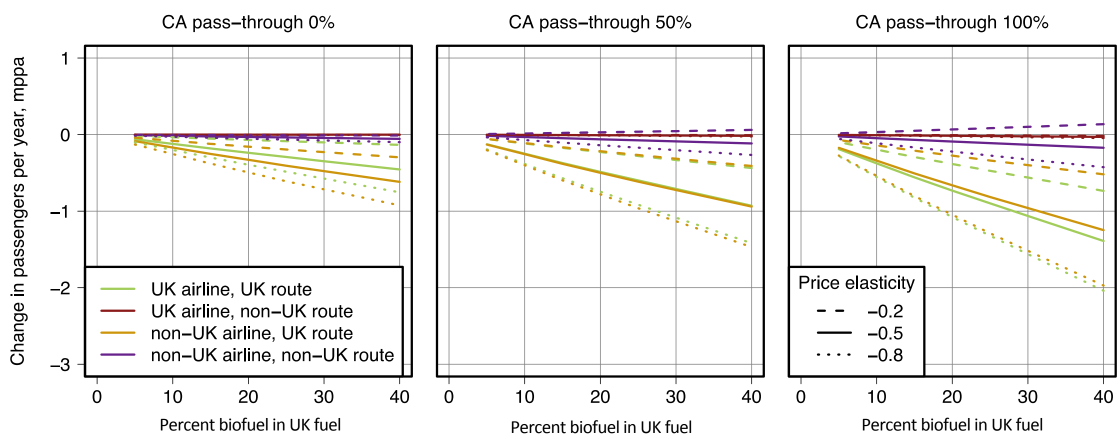

Figure 33. The change in demand by airline and route type for the hypothetical biofuel policy under year-2015 conditions, without fleet swapping.

The corresponding changes in non passed-through operating cost per RPK are shown in Figure 34 (with fleet swapping) and Figure 35(without fleet swapping). For comparison, airline ticket revenue per RPK is around £0.1 (e.g. ICAO, 2016). The projected increases in non passed-through cost are small relative to this value and probably lie within existing airline operating margins, making it more feasible that airlines will absorb some or all of the cost increases for operations to and from congested airports.

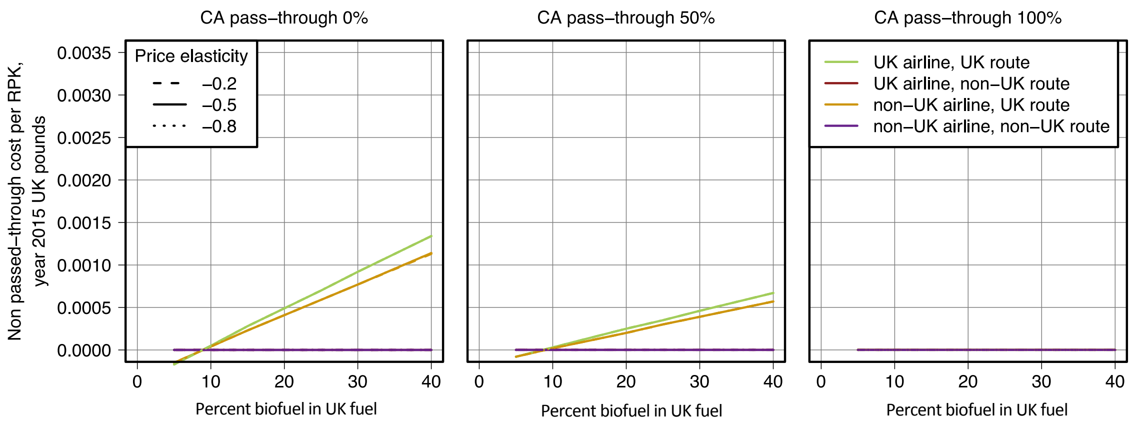

Figure 34. Non passed-on cost per RPK in the case of a hypothetical biofuel uptake policy applied under year-2015 conditions, with fleet swapping assumed.

In the case with fleet swapping, there is a slight decrease in costs for UK routes at the lowest biofuel percentage assumed. This is due to the cost saving from fleet swapping being marginally larger than the cost increase from biofuel use. Cost increases for non-UK flights are assumed fully passed on, so there is not a corresponding change in non passed-through cost for non-UK routes.

For airport-level demand, results are similar to, but smaller in magnitude than, the carbon pricing case. Demand at Heathrow airport reduces by up to 0.6 mppa in the case of 50% pass-through at congested airports and a price elasticity of -0.5. Demand at non-UK airports remains broadly constant or shows a small decrease, suggesting costs are not high enough to produce enough itinerary change for the demand increase due to passengers changing from UK hub routes to cancel out the demand decrease from passengers starting and ending their journeys in the UK.

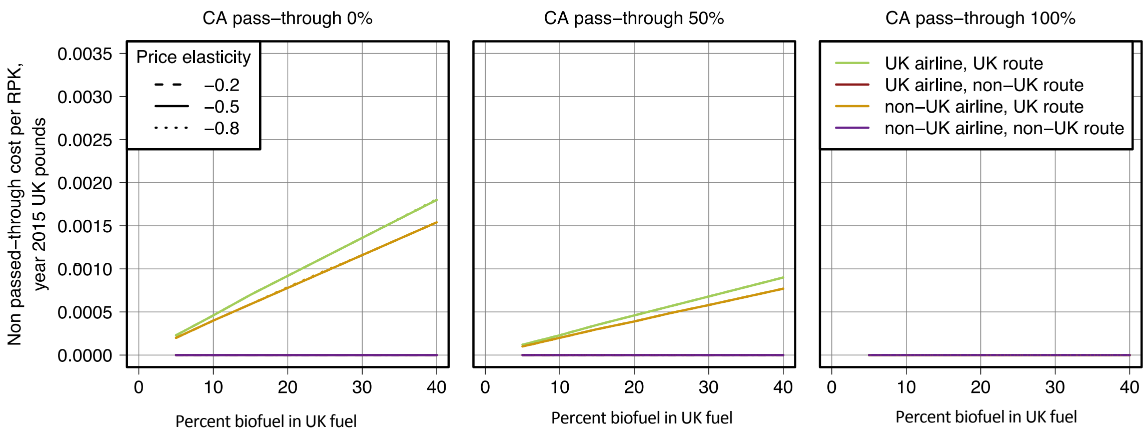

Figure 35. Non passed-on cost per RPK in the case of a hypothetical biofuel uptake policy applied under year-2015 conditions, without fleet swapping assumed.

5.2.3 Environmental landing changes

For the third hypothetical policy case, we look at making changes to UK airport landing charges to encourage the use of lower-emission aircraft. As with many existing environmental landing charge schemes (e.g. Roy, 2007) the changes are designed to be overall cost-neutral, with an increase in cost for older aircraft balanced out by a decrease in cost for younger aircraft. We choose age thresholds of 5 and 15 years to define younger, mid-aged and older aircraft. The older aircraft are assumed to have an increase in landing charge of a given amount (for example, £1,000/landing) at all UK airports across all aircraft sizes. The younger aircraft are assumed to have a decrease in landing charge of the same amount. Mid-aged aircraft are assumed to have no landing cost change. For comparison, current landing charges at UK airports can reach up to around £10,000 for large aircraft at Heathrow. The structure of landing charges can be complex, with factors like noise, number of passengers carried, international or domestic status and airline potentially affecting the exact value. However, usually landing charges for smaller aircraft are lower. Using thresholds of 5 and 15 years means that the policy is roughly cost-neutral with current fleets. However, airlines can make overall cost savings by changing their fleets.

Changes in landing charges have a fundamentally different impact on airline costs than policies which change the effective price of fuel. Both the carbon pricing and biofuel uptake policies produce a cost increase which is greater for longer flights, larger aircraft and older aircraft. In contrast, changes in landing charges penalise older aircraft, but they also penalise aircraft that land in the UK more often. This is generally smaller aircraft on short-haul routes. A regional jet on a UK domestic route might land up to ten times a day at UK airports (e.g. FlightGlobal, 2017). A large, long-haul aircraft, which might land at UK airports only once or twice a day, has a much smaller relative cost burden.

The overall aim of the hypothetical policy is to produce airline response to reduce emissions without substantial passenger response. Given that airline response in the previous hypothetical policy test cases has been associated with positive leakage, it is likely that it will also occur in this case. Leakage is shown in Figure 36, for the case where fleet swapping is assumed. Since the policy is aimed at prompting airlines to make fleet changes, running the model without fleet response produces very little change from the baseline system. There are some small demand shifts associated with different age distributions in the different aircraft size classes. For £2000/year increases in landing charge without fleet swapping, there are also up to 60 new aircraft purchases projected; these are nearly all regional jets, and result from the policy's larger impact on smaller aircraft on domestic and short-haul routes. However, emissions reductions from the purchase of new aircraft are balanced out by demand increases. This is because the policy is designed to be broadly cost-neutral under the current age distribution of aircraft using UK airports. Therefore if airlines can reduce the average age of their fleet using UK airports, they can make cost savings. If these are passed on to ticket price, there is a demand rebound effect, i.e. demand on UK routes increases. The net impact on emissions if no fleet swapping is assumed is small and, because it is composed of positive and negative terms, the absolute value of leakage is highly variable. In this case leakage is not a useful metric to use.

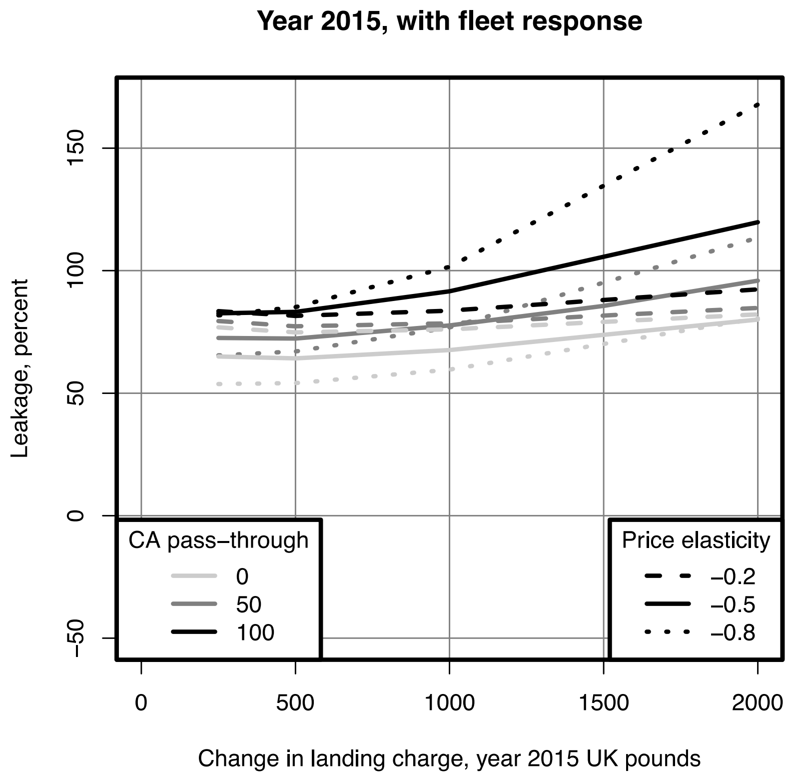

Figure 36. Carbon leakage in the case of environmental landing charges applied at UK airports under year-2015 conditions, with fleet swapping.

In the case that fleet swapping is assumed, leakage is positive and varies between around 50 and 150%. The main factors leading to leakage in this case are:

- Airlines swapping fleet between UK and non-UK routes. This moves around 2 $MtCO_2$ from routes to and from the UK to routes not associated with the UK.
- A demand impact on UK routes. As airlines are able to reduce their overall costs by swapping fleet and/or buying new aircraft, demand may increase on UK routes. This has the effect of reducing the overall emissions reduction on a UK departing flights scope, so tends to increase leakage. This demand effect is greater on short-haul routes, because short-haul aircraft usually land more times per day.
- A demand impact on non-UK routes. This arises from increased fuel use on those routes, because older aircraft have been switched to them from UK routes. This acts to decrease demand on non-UK routes and hence to reduce leakage.
- Airlines buying new aircraft. Because of the large increase in costs for regional jets, this policy can make it cost-effective to sell older regional jets and buy newer ones. This reduces emissions on UK routes, but also results in a small increase in non UK route emissions, because the sold aircraft are added to the non-UK fleet and they are usually older than the average age of the non-UK fleet.

The corresponding changes in demand by geographical scope are given in Figure 37. This shows the case where fleet swapping is included. The absolute emissions changes from the landing charge policy in the case without fleet swapping are close to zero, as discussed above.

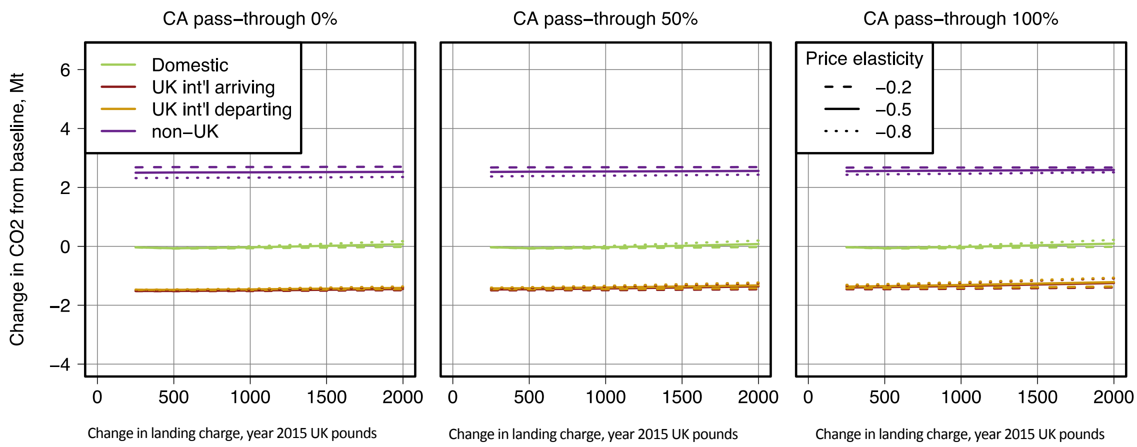

Figure 37. Changes in CO_2 by scope for a hypothetical policy in which landing charges are increased for older aircraft and decreased for younger aircraft, under year 2015 conditions with fleet swapping.

Net leakage is higher in the case that the change in landing charge is greater and/or cost pass-through at congested airports is greater. The relationship between leakage and price elasticity is more complex. If passengers are assumed to be more price-sensitive, the amount of leakage varies more around central values. The highest-leakage case is when cost pass-through is high and passengers are more price-sensitive. In this case, airlines are able to reduce their overall costs by putting as many aircraft onto UK routes as possible that are in the reduced landing charge category. This decrease in cost is passed on to passengers, leading to a demand increase on UK routes. Figure 38 shows the change in passenger numbers by airline and route type. In the most extreme case, demand on UK routes increases by 4 mppa, primarily on short-haul routes. This increase in demand causes a rebound in emissions. The reduction in emissions on a UK departing flights scope is smaller than anticipated, leading to leakage that is greater than 100%. If demand were even more price-sensitive, it is possible that the UK route demand increase would lead to an actual increase in emissions on a UK departing flight scope, i.e. leakage would be apparently negative because emissions within and outside scope both increase.

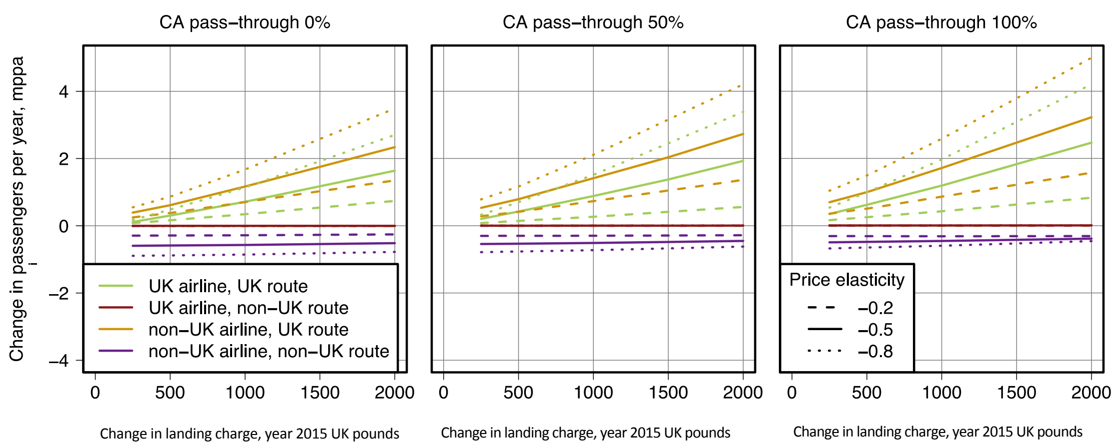

Figure 38.Change in passenger demand by airline type and scope for the landing charge policy, under year 2015 conditions with fleet swapping.

As shown in Figure 38, the demand increase is greater for non-UK airlines, for greater values of cost pass-through at congested airports, and for passengers who are more price-sensitive. However, demand changes are less sensitive to congested airport cost pass-through than for the other policies investigated. This is because short-haul routes from non-congested airports are the most affected. For non-congested airports 100% pass-through is assumed throughout. It is likely that domestic flights and flights by low-cost carriers are seeing the majority of this demand increase. For example, up to 1 mppa of the passenger demand increase is at London Stansted airport, and in the central, 50% pass-through and -0.5 price elasticity case, the demand increase at Stansted is greater than that at Heathrow.

The demand impact at non-UK hub airports is mixed. Demand increases mainly on short-haul routes from the UK to smaller European airports. Major non–UK hub airports are more likely to see demand remain flat or decrease slightly. One exception is Amsterdam Schiphol airport, where demand increases by up to 0.24 mppa.

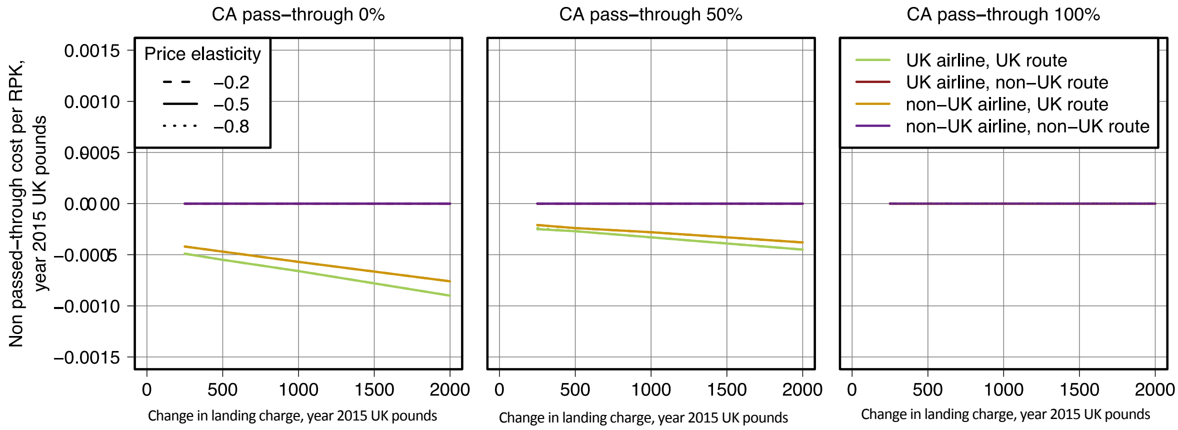

Figure 39. The change in non passed-through operating cost per RPK for the landing charge policy, for year-2015 conditions in the case that fleet swapping is assumed.

Figure 39 shows the corresponding change in costs not passed through per RPK for the landing charge policy, in the case that fleet swapping is assumed. As noted above, these costs are negative, i.e. airlines are able to reduce their overall costs by fleet swapping to get as many aircraft as possible into the lower landing charge category. Because this policy has the largest impact on smaller airports, where costs are assumed to be fully passed through in all cases, the total costs not passed through are small in comparison to airline revenues per RPK of around £0.1, and are similar for UK and non-UK airlines.

5.3 Policies applied in 2030

The total UK central-case aviation demand in terms of passenger movements in 2030, with no extra policy applied, is projected to be 321 mppa. This is consistent with DfT (2017)'s capacity-constrained central case scenario of 315 mppa. Total UK departing flight CO_2 is projected to be 38 Mt, in comparison to 37.3 $MtCO_2$ from DfT (2017). At a system-wide level, therefore, outcomes are broadly reproduced. Because we use system-wide growth rates, however, growth is assumed to be evenly distributed across all airports. Therefore, for example, demand growth at Heathrow is greater than in the DfT 2030 forecast case without capacity expansion, and demand growth at Stansted is smaller (at 116 and 21 mppa respectively, they are close to DfT (2017)'s ENR Heathrow expansion case). Because of this divergence, we concentrate on system-wide metrics rather than airport-level metrics for the 2030 model runs.

As well as changes in passenger demand, 2030 differs in several other characteristics from 2015:

- Baseline fuel prices are around 50% higher (£0.6 per kg compared to £0.4). This increases the importance of fuel as a component of airline costs.
- Baseline carbon prices are much higher (£77/tCO_2 compared to £5/tCO_2). As shown in Figure 13, this increases the effective fuel price by around 40%, to £0.84, before any of the policies applied in this study are applied.
- There are changes in the age structure, emissions and costs of UK and non-UK aircraft fleets. Because demand growth is relatively slow, these tend towards the fleet being older on average than the current one. However, fuel use per flight and maintenance costs per flight are typically lower than in 2015.

These factors change leakage and competitive disadvantage in several ways. Greater demand means that the absolute values of demand reduction, tankering potential, swappable fleet and other system totals are greater than in the year-2015 case. The changes in fleet age structure also mean that there is a greater potential to reduce policy costs through fleet swapping between routes. However, the overall change in output metrics compared to the year-2015 case is small. This is because the policy metrics examined largely rely on relative rather than absolute changes.

Table 16. Scheduled passenger demand and CO_2 by itinerary type for central year-2030 baseline conditions.

	Itinerary passengers, mppa	**CO2 in UK departing flight scope, tonnes**	**CO2 outside UK departing flight scope, tonnes**
UK domestic direct itineraries	24.125	1.777	0.000
UK international departing direct itineraries	88.187	18.006	0.000
UK international arriving direct itineraries	87.590	0.000	17.879
UK departing via UK hub	1.089	0.660	0.034
UK arriving via UK hub	1.113	0.070	0.646
UK departing via non-UK hub	14.360	6.385	5.694
UK arriving via non-UK hub	15.530	0.006	12.893
International-international transfer via UK	13.410	6.194	6.401
International-International transfer via non-UK	57.712	0.000	52.455
International-International direct	38.178	0.000	24.984

Additionally, because demand is assumed to grow at different rates per region-pair, the balance between demand for different itinerary types changes. This in turn affects the overall demand response. Table 16 shows scheduled passenger demand by itinerary type for year-2030 central conditions, and the associated emissions within and outside a UK departing flights scope. The corresponding table for year-2015 conditions is Table 13. As in Table 13, the totals are not adjusted for freight or non-scheduled flights.

The main shift in itinerary type to 2030 is between domestic and international direct itineraries, where passenger numbers grow more slowly (under 30% total growth), hubbing itineraries starting or finishing in the UK, which grow faster (around 40-45% total growth) and international-international itineraries hubbing via the UK, which grow the fastest (54% total growth). This reflects the balance of region-pair demand growth rates assumed (Table 3). Itineraries hubbing via the UK are more likely to be for faster-growth region-pairs. This slightly increases the importance of itinerary choice in determining the amount of leakage. This raises the risk of positive leakage. However, under year-2030 conditions UK origin and destination direct flights are still the dominant source of CO_2 within a UK departing flight scope. Additionally, because UK departing and arriving flights which travel via a non-UK hub have also grown by more than average, the negative leakage from this group of itineraries, which can be in excess of 100%, is greater. These factors tend to cancel each other out, leading to total leakage which is not much different from the year-2015 case.

Because outcomes are similar to those for the 2015 model runs, we show a more limited range of output below. However, the full range of other outcomes are included in Appendix 3.

5.3.1 Increased carbon price

Carbon leakage in the case of an increased carbon price is shown in Figure 40 (in the case that fleet swapping is assumed to occur freely) and Figure 41 (in the case the fleet swapping is not assumed). These outcomes are similar to those seen under year-2015 conditions. This is because leakage relies on relative changes rather than absolute ones. One exception is that leakage is more positive that in 2015 when passengers are assumed to have low price sensitivity. This is because of the larger number of transfer passengers switching itineraries under 2030 conditions; this arises because transfer passengers are a larger proportion of total passengers in 2030. Although the amounts of emissions reduction within and outside a UK departing flights scope change between 2015 and 2030, they do so in a way that is generally proportional and driven by the same interactions as the year-2015 case. The absolute values of emissions reductions in each case are shown in Appendix 3.

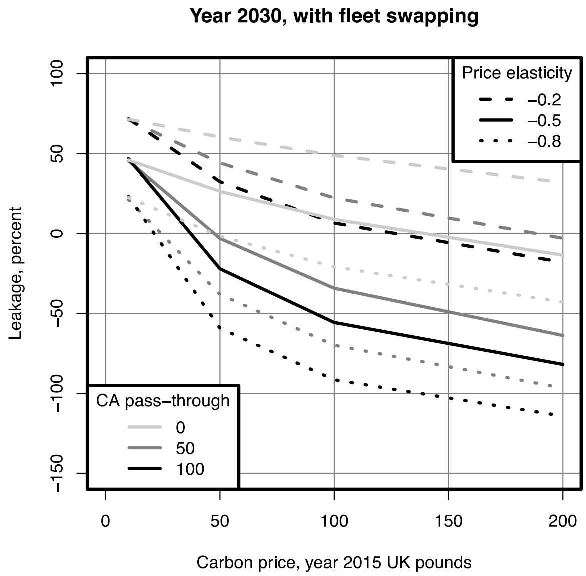

Figure 40. Carbon leakage for a hypothetical carbon price policy applied in 2030, with fleet response.

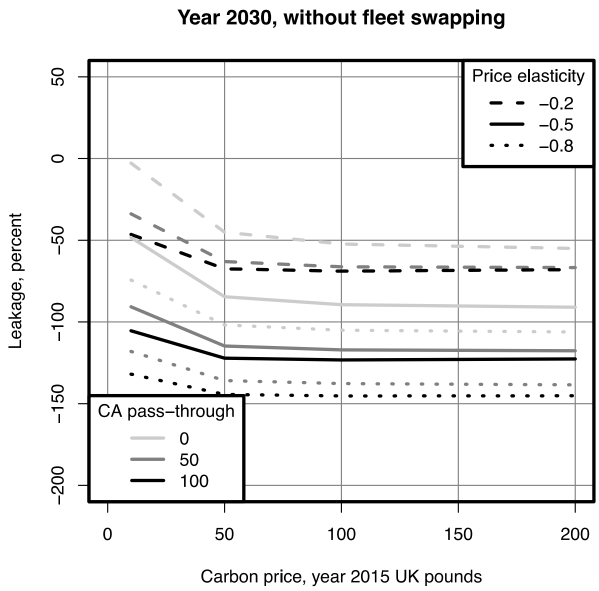

Figure 41. Carbon leakage for a hypothetical carbon price policy applied in 2030, without fleet response.

The corresponding changes in passenger numbers by scope are shown in Figure 42 (with fleet swapping) and Figure 43 (without fleet swapping). As discussed above, absolute values of emissions reductions are slightly higher than in the year-2015 case. This is because total demand and total emissions are higher than in the year-2015 case. However, in general the same factors interact in the same way as in 2015 and produce a response that is proportionally similar.

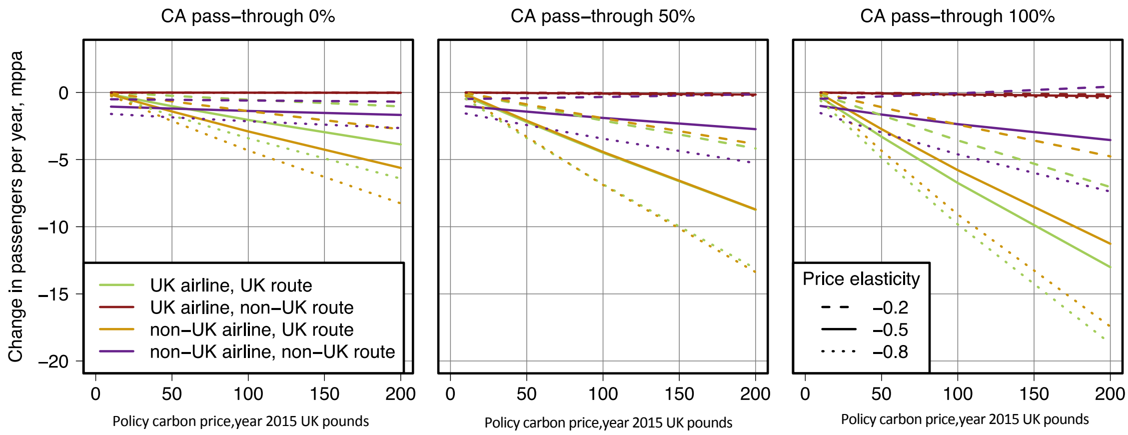

Figure 42. The change in demand with scope and airline type for a hypothetical carbon price policy applied in 2030, with fleet response.

The change in non-passed through cost per RPK by policy type is very close to that in the year-2015 carbon price case; as in the year-2015 case, UK airlines on UK routes are somewhat more affected than non-UK airlines, primarily due to the different structure of their networks, the airports that they operate out of, and the extent to which they can carry out fleet swapping. Figures for non passed-through cost are given in Appendix 3.

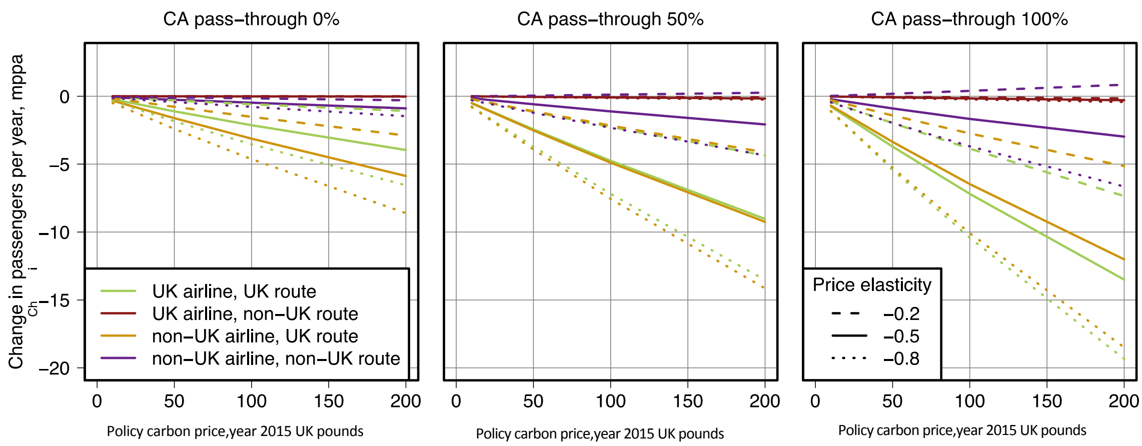

Figure 43. The change in demand with scope and airline type for a hypothetical carbon price policy applied in 2030, with no fleet swapping assumed.

5.3.2 Increased use of biofuel

As in 2015, the year-2030 biofuel policy requires airlines to use a set percentage of biofuel when refueling at UK airports. It is specified on a fuel uptake basis, so airlines may decide to tanker fuel as a response to it. We assume the same reduction in CO2 for biofuel compared to Jet A as in 2015. However, the price of biofuel is higher, as is the price of Jet A. Although the background carbon price is also higher, the biofuel price in 2030 is large enough that biofuel is still substantially more expensive than Jet A, as shown in Figure 13. Carbon leakage for the biofuel policy applied in 2030 is shown in Figure 44 (in the case that fleet swapping is assumed) and Figure 45 (in the case that it is not).

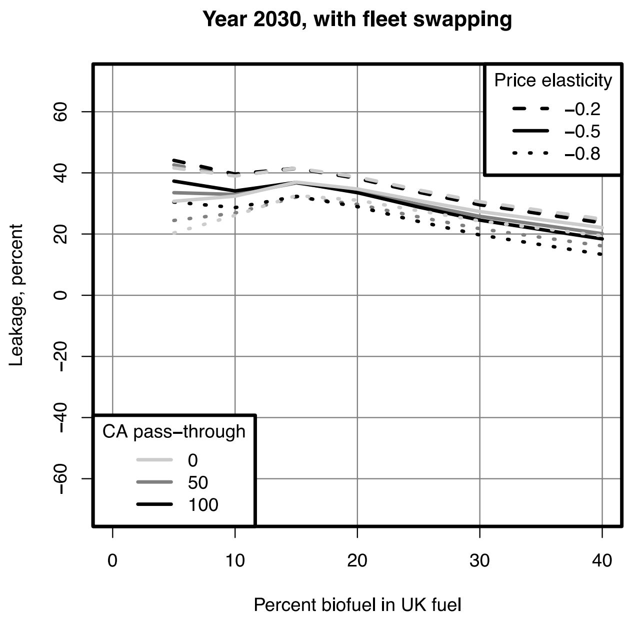

Figure 44. Carbon leakage from the biofuel uptake policy applied in 2030, with fleet swapping.

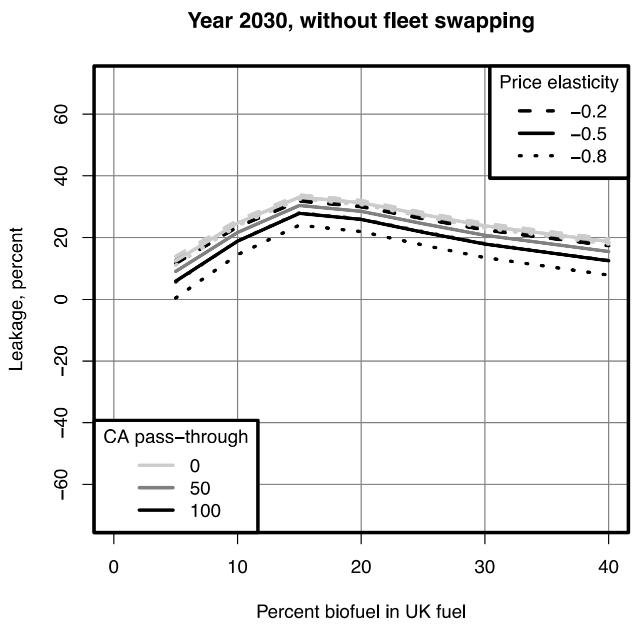

Figure 45. Carbon leakage from the biofuel uptake policy applied in 2030, without fleet swapping.

In general, outcomes match closely to those seen in 2015. Leakage is mainly in the positive 10-40% range and peaks at around 15% biofuel use. As in 2015, this is because airlines tanker more fuel as the required biofuel percentage in UK departing fuel increases. However, the potential for tankering saturates at around 20% biofuel. After this point there are no more flights on which it is physically possible to tanker fuel. After this point, leakage decreases as more costs are passed on to ticket prices and negative-leakage passenger demand effects take over. The amount of CO_2 tankered is shown in Figure 46. Tankering potential is around 0.5 $MtCO_2$ greater than in 2015. This is due to demand increases on tankerable routes, which are mainly short-haul international ones.

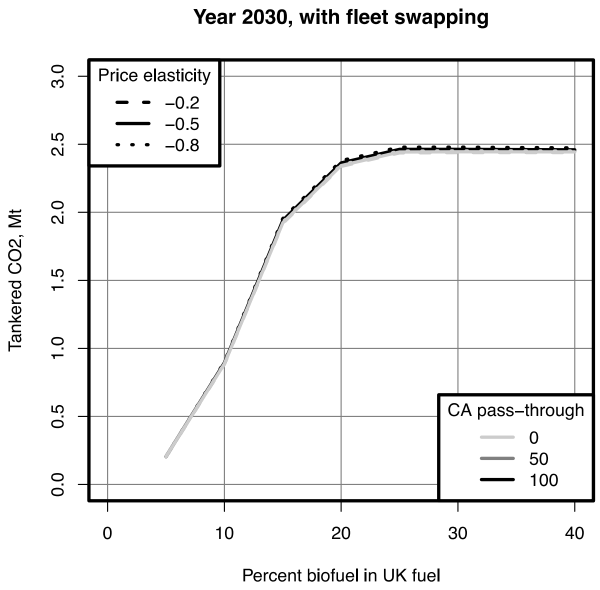

Figure 46. Amount of CO_2 tankered, for the biofuel uptake policy under year-2030 conditions.

Leakage is generally slightly smaller than under year-2015 conditions, but by an amount which is less than the amount of variability due to other uncertain parameters. This is mainly the result of a shift towards longer-haul flights, which cannot be tankered on, due to greater demand growth between longer-haul region pairs. Additionally, the range of uncertainty at low biofuel percentages is greater. This is due to the larger number of transfer passengers and the way that they interact with cost pass-through at congested airports.

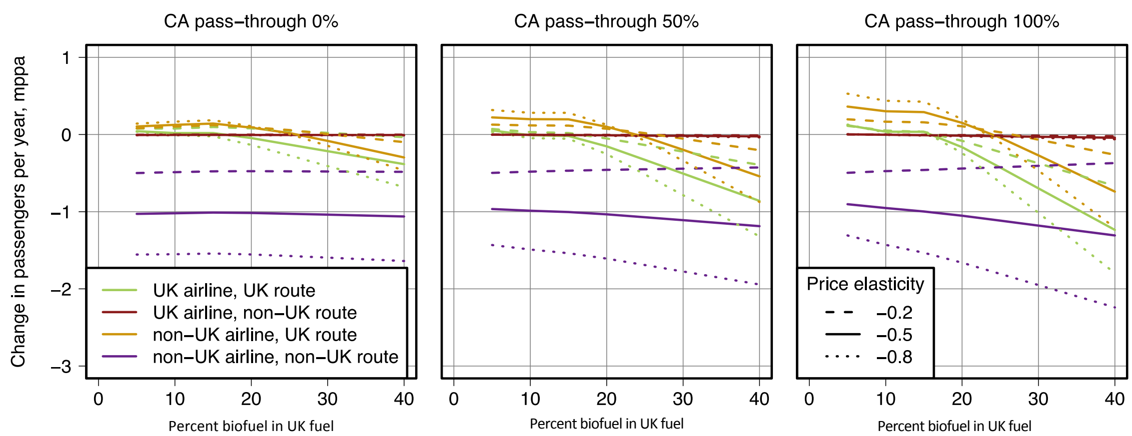

Figure 47. Change in number of passengers by scope and airline type, for the biofuel uptake policy under year-2030 conditions with fleet swapping.

The change in demand by airline type and scope for the biofuel uptake policy in 2030 is shown in Figure 47 (in the case that fleet swapping is assumed) and Figure 48 (if fleet swapping is not assumed). Demand reduction is greater than in 2015 for a comparable level of policy. There are two reasons why this occurs. First, as discussed above, total demand is higher. Second, the assumed difference in price between biofuel and jet A is higher in 2030 than in 2015 when using the DfT (2017) and Ricardo (2017) jet A and biofuel projected price trends (Table 7), so the same amount of biofuel use leads to greater costs for airlines. This also means that tankering has a larger impact on airline costs and on demand. Similarly, fleet swapping older aircraft onto non-UK routes produces a greater cost increase on those routes than in 2015, and hence a larger reduction in demand.

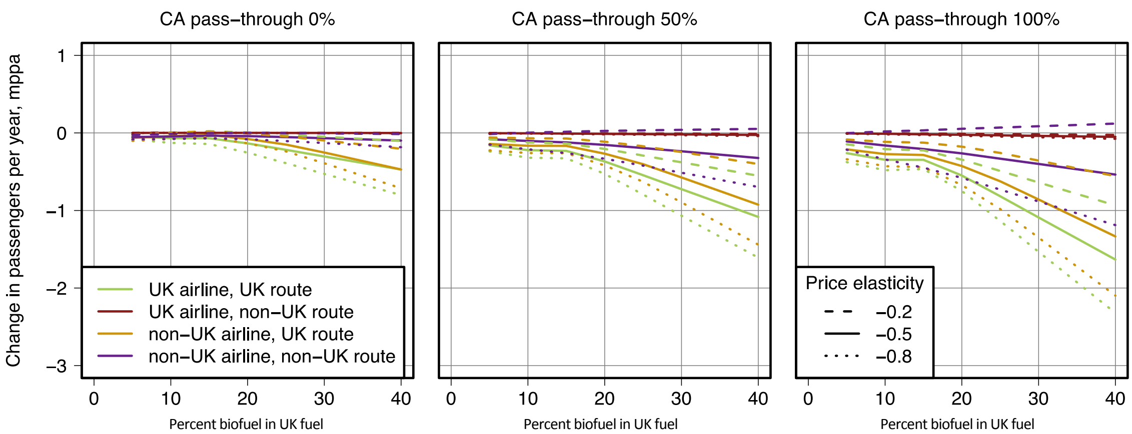

Figure 48. Change in number of passengers by scope and airline type, for the biofuel uptake policy under year-2030 conditions without fleet swapping.

5.3.3 Environmental landing charges

As with the year-2015 case, we show results for the landing charge policy only when fleet swapping is assumed. Without fleet swapping, airline response to the policy is very small; the policy is roughly cost-neutral, leading to only small changes in demand and fleet; and as a result, leakage is not meaningful as an output metric.

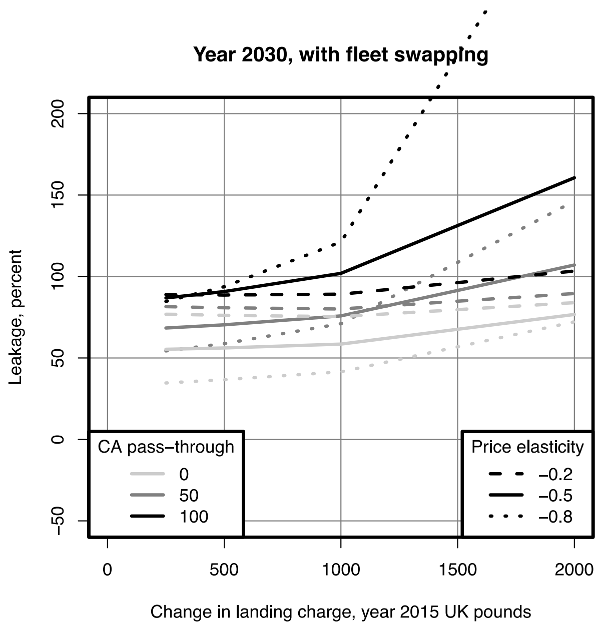

Figure 49. Carbon leakage in the case of the landing charge policy applied in 2030, with fleet swapping.

Carbon leakage in the case of the environmental landing charge policy is shown in Figure 49. As in 2015, the hypothetical policy is applied to aircraft in three age bands. Aircraft older than 15 years have an increase in landing costs of the given amount. Aircraft younger than five years have a decrease in landing costs of the same amount. Airlines therefore have an incentive to fly a younger fleet on UK routes. The policy is broadly cost-neutral if there is no change in fleet. However, by swapping their fleet between UK and non-UK routes or buying new aircraft, airlines are able to reduce their overall costs. If this happens, they may choose to reduce ticket prices, leading to a demand rebound effect.

Leakage outcomes are generally similar to those seen under 2015 conditions. For this policy, the main differences between 2015 and 2030 are that the total fleet is larger; the aircraft age distribution is slightly older, due to slow rates of growth; and the increased baseline carbon price adds an extra incentive to buy new aircraft (although not to swap fleet, because it is assumed to be the same on UK and non-UK routes). Fleet swapping, and to a lesser extent demand rebound effects and new aircraft purchases, produce leakage that is positive and significant, potentially being greater than 100%. Leakage greater than 100% occurs when within-system benefits are reduced by a demand rebound, whilst emissions for flights outside a UK departing scope are increased by older aircraft swapped from UK routes. Compared to 2015, a larger demand rebound effect is seen. This is because fuel and carbon prices are higher, so the impact on ticket prices of reducing fuel-related costs is greater. This effect is particularly noticeable in the case where all costs are passed through and passengers are more price-sensitive. In this case, the demand rebound at landing charge changes of over £1000/landing is enough to cancel out most of the CO_2 emissions reductions due to fleet change. Within-system emissions decreases are much smaller than emissions increases outside the system, leading to leakage well in excess of 100%. The absolute values of CO_2 emissions changes by scope are shown in Appendix 3.

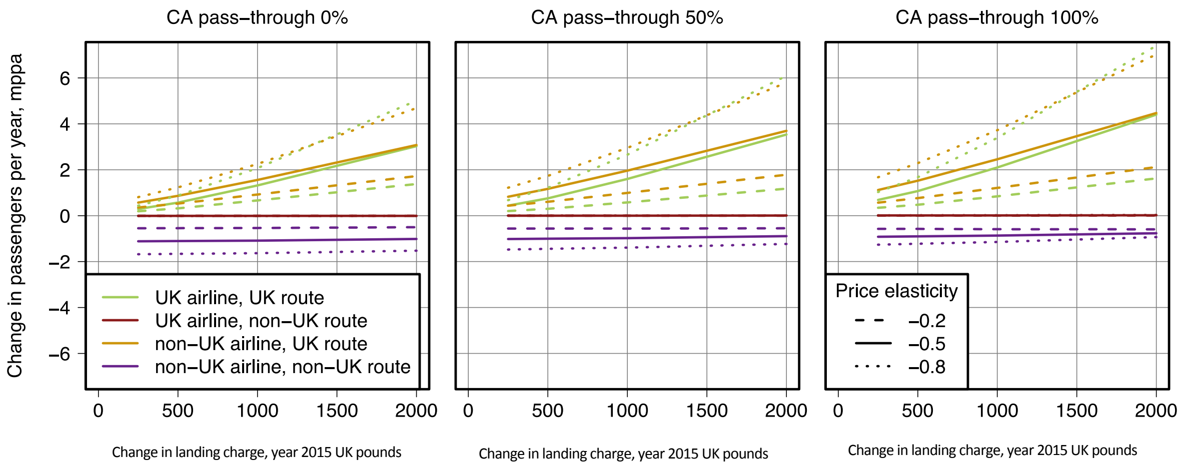

Figure 50. Change in passenger demand by scope and airline type, for the landing charge policy applied under year-2030 conditions, with fleet swapping.

Figure 50 shows the corresponding change in passenger demand by airline type and scope. As with the other policies examined under year-2030 conditions, outcomes are similar to the year-2015 case but totals are slightly larger, reflecting the larger total number of passengers in 2030.

6. Conclusions

This study investigated the impact of UK-specific aviation policy on carbon leakage and the competitive position of UK airlines and airports. To do so, a network model of city-pair aviation demand, routing and fleets was developed, based on components from the global aviation systems model AIM. The model outcomes were assessed for three hypothetical policies under a range of values for uncertain input parameters. This allowed the uncertainty in outcomes to be assessed as well as typical behavior in response to policy.

The main general conclusion is that there are two main components to aviation policy carbon leakage. One component is associated with airline response to policy. This component is generally positive leakage: emissions decrease within the policy area, but increase outside the policy area. It is caused by airline strategies to reduce policy costs, for example swapping fleet between policy and non-policy routes, selling older aircraft to airlines outside the policy region, or tankering fuel. The second component is associated with passenger response to policy. On a whole-network basis, this component is negative: an emissions reduction within the policy area is matched by an emissions reduction outside the policy area. This passenger effect arises because, even if a policy applies a cost increase on a single flight segment, this will be experienced by passengers as a cost increase across their entire round-trip itinerary. This effect has been neglected in previous studies due to a focus on individual route case studies rather than examining leakage on a whole-system basis. It is robust across a range of values for uncertain parameters, including cost pass-through at congested airports and the price elasticity of demand.

A second conclusion is that policies may differ substantially in the mix of passenger and airline response that they produce. In turn, this leads to substantial differences in typical leakage. In this study, increasing the carbon price led primarily to negative leakage. This was because the dominant effect of doing so was to increase ticket prices. Although some international-international transfer passengers were projected to change routing away from UK hubs in response, the primary impact of this ticket price change was to reduce demand for the much larger cohort of passengers starting or ending their journeys in the UK. This resulted in net negative leakage of typically between -50 and -150%. In contrast, a policy to increase landing charges for older aircraft and reduce landing charges for younger aircraft led primarily to an airline-based response, and resulting positive leakage.

Finally, the majority of the policies examined here have roughly the same impact on UK and non-UK airlines operating on UK routes, with some small differences caused by the different route networks and hub airports used by different airline types. One exception may be the case of changes in landing charge. If airlines swap fleet between UK and non-UK routes to try and reduce environmental landing costs, non-UK airlines will be at an advantage because they have a larger pool of non-UK aircraft to choose from, even after the impact of airline group fleet commonality is accounted for.

References

Adler, T., Falzarano, C. and Spitz, G., 2005. Modeling service trade-offs in air itinerary choice. *Transportation Research Record*, 1915, 20-26.

Airbus. Global Market Forecast 2018-2037. Airbus: Toulouse, 2018.

Airports Council International, 2018. Year to date passenger summary. https://aci.aero/data-centre/monthly-traffic-data/passenger-summary/year-2017/year-to-date/.

Albers, S., Bühne, J.-A. & Peters, H., 2009. Will the EU-ETS instigate airline network reconfigurations? *Journal of Air Transport Management*, 15(1), 1-6.

Aldy, J. & Pizer, W., 2015. The competitiveness impacts of climate change mitigation policies. *Journal of the Association of Environmental and Resource Economists*, 2(4), 565-595.

Al Zayat, K., Dray, L. & Schäfer, A., 2017. A first-order analysis of direct operating costs of battery-electric aircraft. 21st ATRS World Conference, Antwerp, July 5-8 2017.

Anger, A. & Köhler, J., 2010. Including aviation emissions in the EU ETS: much ado about nothing? Transport Policy, 17(1), 38-46.

ATA & Ellondee, 2018. Understanding the potential and costs for reducing UK aviation emissions. Report to the Committee on Climate Change and Department for Transport.

Behrens, C. & Pels, E., 2012.Intermodal competition in the London-Paris passenger market: High-Speed Rail and air transport. *Journal of Urban Economics*, 71(3), 278-288.

BEIS, 2017. 2015 UK Greenhouse gas emissions, final figures. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/604350/2015_Final_Emissions_statistics.pdf

Babiker, M. H., 2005. Climate change policy, market structure, and carbon leakage. *Journal of International Economics*, 65(2), 421-445.

BEIS (2016). Fossil fuel price assumptions: 2016. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/576542/BEIS_2016_Fossil_Fuel_Price_Assumptions.pdf

Boeing. Current Market Outlook 2018-2037. Boeing: Seattle, 2018

Boeters, S. & Bollen, J., 2012. Fossil fuel supply, leakage and the effectiveness of border measures in climate policy. CBP discussion paper 215. Netherlands Bureau for Economic Policy Analysis, Den Haag.

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

Brons, M., Pels, E., Nijkamp, P. Rietvald, P., 2001. Price elasticities of demand for passenger air travel. Tinbergen institute discussion paper 01-047/3. http://hdl.handle.net/10419/85990

BTS, 2018. Form 41 financial data. https://www.transtats.bts.gov/Tables.asp?DB_ID=135.

Burniaux, J. & Oliveira Martins, J., 2000. Carbon Leakages: A General Equilibrium View. *OECD Economics Department Working Papers*, No. 242, OECD Publishing, Paris.

CAA, 2017. Operating license holders. http://www.caa.co.uk/Commercial-Industry/Airlines/Licensing/Licence-types/Airline-licence-holders/

CAA, 2017. UK Airport Data. https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Airports/Datasets/UK-airport-data/

CE Delft, 2005. Giving wings to emissions trading: Inclusion of aviation under the European emissions trading scheme (ETS): design and impacts.

https://www.cedelft.eu/en/publications/334/giving-wings-to-emission-trading, Delft, 2005.
CE Delft and MVA (2007). Implications of EU Emission Trading Scheme for Competition Between EU and Non-EU Airlines. CE Delft, Delft.
Chi, C. & Qu, H., 2008. Examining the structural relationships of destination image, tourist satisfaction and destination loyalty: an integrated approach. *Tourism Management*, 29(4), 624-636.
Chi, J. & Baek, J., 2012. Price and income elasticities of demand for air transportation: empirical evidence from the US airfreight industry. *Journal of Air Transport Management*, 20, 18-19.
Coldren, G., Koppelman, F., Kasturirangan, K. and Mukherjee, A., 2003. Modeling aggragate air-travel itinerary shares: logit model development at a major US airline. *Journal of Air Transport Management*, 9(6), 361-369.
Cosbey, A. and Tarasofsky, R., 2007. Climate Change, Competitiveness and Trade. Chatham House Report, Royal Institute of International Affairs, London.
Derigs, U. & Illing, S., 2013. Does the EU ETS instigate Air Cargo network reconfiguration? A model-based analysis. *European Journal of Operational Research*. 225(3), 518-527.
DfT, 2016. Department for Transport Statistics Table TSGB0607: Channel Tunnel, traffic to and from Europe.
DfT, 2017. UK Aviation Forecasts. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/674749/uk-aviation-forecasts-2017.pdf
Di Maria, C. & van der Werf, E., 2008. Carbon leakage revisited: unilateral climate policy with directed technical change. *Environ. Resource Econ.*, 39, 55-74.
Department of Energy. US Billion-Ton Update. ORNL/TM-2011/224. Oak Ridge National Laboratory, 2011.
Dray L., Evans A., Reynolds T.G., Schäfer A., Vera-Morales M., Bosbach W., 2014. Airline fleet replacement funded by a carbon tax: an integrated assessment, *Transport Policy, 34,* 75-84.
Dray, L., 2013. An analysis of the impact of aircraft lifecycles on aviation emissions mitigation policies. *Journal of Air Transport Management*, 28, 62-69.
Dray L., Krammer P., Doyme K., Wang B., Al Zayat K, O'Sullivan A., Schäfer A., 2017. "AIM2015: Validation and Initial Results from an Open-Source Aviation Systems Model", 21st ATRS World Conference, July 5-8.
Dray, L., Schäfer, A. & Al Zayat, K., 2018. The global potential for CO_2 emissions reduction from jet engine passenger aircraft. *Transportation research Record*, in press.
EC, 2008. European Commission Directive 2008/101/EC.
EC, 2018. Carbon Leakage. https://ec.europa.eu/clima/policies/ets/allowances/leakage_en
EC, 2018a. Monitoring, reporting and verification of EU ETS emissions. https://ec.europa.eu/clima/policies/ets/monitoring_en.
EIA, 2018. Spot prices for crude oil and petroleum products. https://www.eia.gov/dnav/pet/PET_PRI_SPT_S1_D.htm.
Ernst & Young and York Aviation (2008). Inclusion of aviation in the ETS: Cases for Carbon Leakage. https://www.verifavia.com/bases/ressource_pdf/112/AN-EY-FULL-TEXT-OCT08.pdf
Eurocontrol, 2018. CODA Delay Analysis. https://www.eurocontrol.int/articles/coda-publications.

European Climate Exchange, 2017. Carbon prices on the European Climate Exchange. http://www.ecx.eu/
Faber, J. & Brinke, L., 2011. The inclusion of aviation in the EU Emissions Trading System. ICTSD Programme on Trade and Environment, Issue Paper No. 5. ICTSD, Geneva.
FlightGlobal, 2016. Ascend Online Fleet Database. http://www.ascendworldwide.com/what-we-do/ascend-data/aircraft-airline-data/ascend-online-fleets.html.
Gardiner, J., Ison, S. and Humphreys, I., 2005a. Factors influenceing airlines' choice of airport: an international study. *Journal of Air Transport Management*, 11(6), 393-399.
Gardiner, J., Ison, S. and Humpherys, I., 2005b. Freight choice operators' choice of airport: a three-stage process. *Transport Reviews*, 25(1), 85-102.
Gerlagh, R., & Kuik, O., 2007. Carbon leakage with international technology spillovers. FEEM Working Paper No. 33.2007. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=979915
Givoni, M, & Rietveld, P., 2009. Airline's choice of aircraft size - Explanations and implications, Transportation Research Part A, Elsevier, vol. 43(5), 500-510.
Google, 2018. Google maps navigation tool. http://maps.google.com.
IATA, 2007. Estimating air travel demand elasticities. https://www.iata.org/whatwedo/Documents/economics/Intervistas_Elasticity_Study_2007.pdf
IATA, 2018. Airline and airport code search. https://www.iata.org/publications/Pages/code-search.aspx.
ICAO, 2009. Available capacity and average passenger mass. ICAO Working Paper STA/10-WP/5. https://www.icao.int/Meetings/STA10/Documents/Sta10_Wp005_en.pdf
ICAO, 2014. ICAO Annual Report, 2014: Appendix 1. https://www.icao.int/annual-report-2014/Documents/Appendix_1_en.pdf
ICAO, 2016. ICAO Annual Report, 2016. http://www.icao.int/about-icao/Pages/annual-reports.aspx.
IEA, 2017. World Energy Statistics, 2016. http://www.iea.org/statistics/
IPCC, 2007. IPCC Climate Change 2007: Mitigation. Contrbution of Working Ground III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Eds. Metz, B., Davidson, O., Bosch, P., Dave, R. and Meyer, L., Cambridge University Press, Cambridge, 2007.
Krammer P., Dray L., Köhler M., 2013. Climate-neutrality versus carbon-neutrality for aviation biofuel policy, *Transportation Research Part D,* 23, 64-72.
Kuik, O. & Hofkes, M., 2010. Border adjustment for European Emissions Trading: competitiveness and carbon leakage. *Energy Policy*, 38(4), 1741-1748.
LAWA, 2016. United airlines launches first-ever jet biofuels initiative at LAX with flight to San Francisco. https://www.lawa.org/en/News%20Releases/2016/News%20Release%20122.
Lissys, 2017. The PIANO X Aircraft Performance Model. www.piano.aero.
Lurkin, V., Garrow, L., Higgins, M., Newman, J. and Schyns, M., 2017. Accounting for price endogeneity in airline itinerary choice models: an application to continental U.S. markets. *Transportation Research Part A*, 100, 228-246.
Mayor, K. & Tol, R. The impact of the UK aviation tax on carbon dioxide emissions and passenger numbers. *Transport Policy*, 14(6), 507-513.
Martin, R., Muûls, M., de Preux, L., & Wagner, U., 2014. On the empirical content of carbon leakage criteria in the EU Emissions Trading Scheme. *Ecological Economics*, 105, 78-88.

Mitra, S. and Leon, S. 2014. Discrete choice model for air-cargo mode selection. International Journal of Logistics Management, 25(3), 656-672.
Nero, G., & Black, J. A., 2000. A critical examination of an airport noise mitigation scheme and an aircraft noise charge: the case of capacity expansion and externalities at Sydney (Kingsford Smith) Airport. Transportation Research Part D, 5(6), 433-461.
Ohashi, H., Kim, T.-S., Oum, T. and Yu, C., 2005. Choice of air cargo transhipment airport: an application to air crago traffic to/from Northeast Asia. *Journal of Air Transport Management*, 11(3), 149-159.
ONS, 2016. Travel Trends, 2015. https://www.ons.gov.uk/peoplepopulationandcommunity/leisureandtourism/articles/traveltrends/2015
Porter, M., & van der Linde, C., 1995. Towards a New Conception of the Environment-Competitiveness Relationship. *Journal of Economic Perspectives*, 9(4), 97-118.
Quinn, J. C., and Davis, R., 2015. The potentials and challenges of algae based biofuels. *Bioresource Technology*, Vol. 184, pp. 444-452.
Reinaud, J., 2008. Issues behind competitiveness and carbon leakage. IEA Information Paper. OECD/IEA, Paris.
Reynolds, T. G., 2009. Development of flight inefficiency metrics for environmental performance assessment of ATM. 8th USA/Europe Air Traffic Management Research and Development Seminar, Napa, CA, June 29 - July 2.
Ricardo, 2017. Carbon Abatement in UK Aviation. Report for Department for Transport. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/653776/carbon-abatement-in-uk-aviation.pdf.
Roy, R., 2007. A cost-effectiveness analysis of local air quality charges at Zurich and Stockholm airports. In ICAO Environmental Report 2007, ICAO, Montreal, 2007.
Sabre, 2017. Market Intelligence database. https://www.sabreairlinesolutions.com/home/software_solutions/product/market_competitive_intelligence/
Schäfer, A., Evans, A. D., Reynolds, T. and Dray, L. M. Costs of Mitigating CO2 Emissions from Passenger Aircraft. *Nature Climate Change*, Vol. 6, 2016, pp. 412-417.
Scheelhaase, J. & Grimme, W., 2007. Emissions trading for international aviation – an estimation of the economic impact on selected European airlines. *Journal of Air Transport Management*, 13(5), 253-263.
EC, 2011. Impact assessment of revisions to regulation 95/93. Final report, Brussels, 2011. https://ec.europa.eu/transport/sites/transport/files/modes/air/studies/doc/airports/2011-03-impact-assessment-revisions-regulation-95-93.pdf
SEC, 2006. Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community, SEC(2006) 1684 SEC(2006) 1685 COM/2006/0818 final - COD 2006/0304
Sustainable Aviation, 2015. The SA Noise Roadmap. http://www.sustainableaviation.co.uk/wp-content/uploads/2015/09/SA-Noise-Road-Map-Report.pdf.
US DoT, 2018. Average Freight Revenue per Ton-Mile. https://www.bts.gov/content/average-freight-revenue-ton-mile.

Vivid Economics, 2007. A study to estimate ticket price changes for aviation in the EU ETS. http://www.vivideconomics.com/wp-content/uploads/2015/03/Vivid_Econ_Aviation_Tickets.pdf.
Vivid Economics, 2008. A study to estimate the impacts of emissions trading on profits in aviation. http://www.vivideconomics.com/wp-content/uploads/2015/03/Vivid_Econ_Aviation_Profits.pdf.
Vivid Economics & Ecofys, 2014. Carbon leakage prospects under phase III of the EU ETS and beyond. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/318893/carbon_leakage_prospects_under_phase_III_eu_ets_beyond.pdf
Wai Wang Lo, W., Wan, Y., & Zhang, A., 2015. Empirical estimation of price and income elasticities of air cargo demand: The case of Hong Kong. Transportation Research Part A, 78, 309-324.
Wang B., O'Sullivan A., Dray L., and Schäfer A., 2018. Modelling airline cost pass-through within regional aviation markets. *Transportation Research Record,* in press.
Warburg, V., Bhat, C. and Adler, T., 2006. Modeling demographic and unobserved heterogeneity in in air passengers' sensitivity to service attributes in itinerary choice. *Transportation Research Record*, 1951, 7-16.
Yuen, A., Zhang, A., Van Hui, Y., Leung, L. and Fung, M., 2017. Is developing air cargo airports in the hinterland the way of the future? Journal of Air Transport Management, 61, 15-25.

Appendix 1: Quality Assurance

A quality assurance process was also carried out for the model by an independent reviewer (Dr Ilkka Keppo). This involved:

- Running the model numerous times with different policy inputs and assessing whether model responses correspond with the top level rationale of the tool,
- Reviewing model inputs and equations for errors (note however that whilst all equations were reviewed on some level, the QA process did not involve a line-by-line audit), and
- Assessing the documentation, transparency and usability dimensions of the tool.

The final model implements the recommendations that followed from this process.

Appendix 2: Parameters for the itinerary choice model

For further discussion of this model and the parameters included, see section 4.3.2. Pax_{origin} and Pax_{dest} refer to the parameters for total airport passenger numbers in the previous year. Major route groups are shown below.

Table 17. Parameters for major route groups for the itinerary choice model.

Route group	Intercept	Fare	Time	Freque-ncy	N_{legs}	Pax_{origin}	Pax_{dest}	R^2
Intra North America	0.86 (0.004)	-3.9e-03 (5.9e-05)	-5.5e-03 (4.6e-05)	0.74 (0.004)	-1.99 (0.01)	2.75e-08 (4.1e-10)	2.79e-08 (4.1e-10)	0.59
Intra Europe	0.76 (0.006)	-5.1e-03 (8.6e-05)	-2.8e-03 (4.4e-05)	0.84 (0.004)	-3.43 (0.02)	3.9e-08 (8.8e-10)	4.0e-08 (9.0e-10)	0.65
Intra Asia	0.95 (0.01)	-2.1e-03 (1.1e-04)	-1.3e-03 (4.7e-05)	0.82 (0.009)	-3.51 (0.02)	3.5e-08 (9.9e-10)	3.6e-08 (1.0e-09)	0.58
Intra South America	0.81 (0.02)	-8.2e-03 (4.1e-04)	-1.5e-03 (1.9e-04)	0.88 (0.02)	-2.50 (0.06)	1.2e-07 (6.7e-09)	1.1e-07 (6.7e-09)	0.60
Intra Central America	0.91 (0.03)	-2.2e-03 (5.4e-04)	-1.7e-03 (1.2e-04)	0.48 (0.03)	-1.84 (0.08)	1.4e-07 (1.1e-08)	1.3e-07 (1.1e-08)	0.43
Intra Middle East	0.67 (0.04)	-3.4e-03 (4.8e-04)	-2.7e-03 (2.4e-04)	0.60 (0.03)	-2.88 (0.08)	5.2e-08 (4.6e-09)	5.2e-08 (4.5e-09)	0.91
Intra Africa	0.97 (0.03)	-1.6e-03 (1.5e-04)	-3.6e-04 (6.6e-05)	0.53 (0.03)	-1.30 (0.07)	3.9e-07 (4.0e-08)	3.5e-07 (4.3e-08)	0.85
North America-Europe	0.84 (0.006)	-8.5e-04 (4.3e-05)	-3.7e-03 (4.8e-05)	0.72 (0.006)	-2.24 (0.02)	8.2e-08 (9.7e-10)	8.1e-08 (9.8e-10)	0.91
North America - Asia	1.13 (0.01)	2.7e-04 (4.6e-05)	-2.6e-03 (5.5e-05)	0.78 (0.02)	-2.47 (0.03)	2.4e-08 (1.2e-09)	2.2e-08 (1.3e-09)	0.80
Europe - Asia	1.00 (0.01)	-5.7e-04 (3.6e-05)	-2.3e-03 (3.4e-05)	0.79 (0.009)	-2.36 (0.02)	1.9e-08 (9.2e-10)	2.1e-08 (9.6e-10)	0.90
North - South America	0.76 (0.01)	-3.2e-04 (5.2e-05)	-3.4e-03 (7.8e-05)	0.76 (0.01)	-1.81 (0.03)	8.7e-08 (2.1e-09)	8.4e-08 (2.1e-09)	0.92
Europe - Middle East	0.94 (0.01)	-2.2e-03 (7.8e-05)	-2.5e-03 (6.5e-05)	0.72 (0.09)	-2.58 (0.03)	5.6e-08 (1.8e-09)	5.6e-08 (1.8e-09)	0.91
Asia - Middle East	0.91 (0.15)	-1.8e-04 (1.2e-04)	-2.6e-03 (7.0e-05)	0.69 (0.17)	-1.91 (0.03)	3.2e-08 (2.0e-09)	3.3e-08 (1.9e-09)	0.93
Africa - Europe	1.01 (0.01)	-7.9e-04 (4.9e-05)	-1.6e-03 (3.7e-05)	0.66 (0.01)	-2.27 (0.03)	6.3e-08 (2.3e-09)	6.6e-08 (2.5e-09)	0.74
South - Central America	0.85 (0.02)	-7.25e-06 (1.5e-04)	-4.8e-03 (1.3e-04)	0.46 (0.02)	-1.01 (0.07)	1.7e-07 (9.5e-09)	1.2e-07 (9.2e-09)	0.82

Appendix 3: Additional results from the 2030 model runs

Because model outcomes under year-2030 conditions are similar to those under year-2015 conditions, we include these outcomes as an appendix to the report.

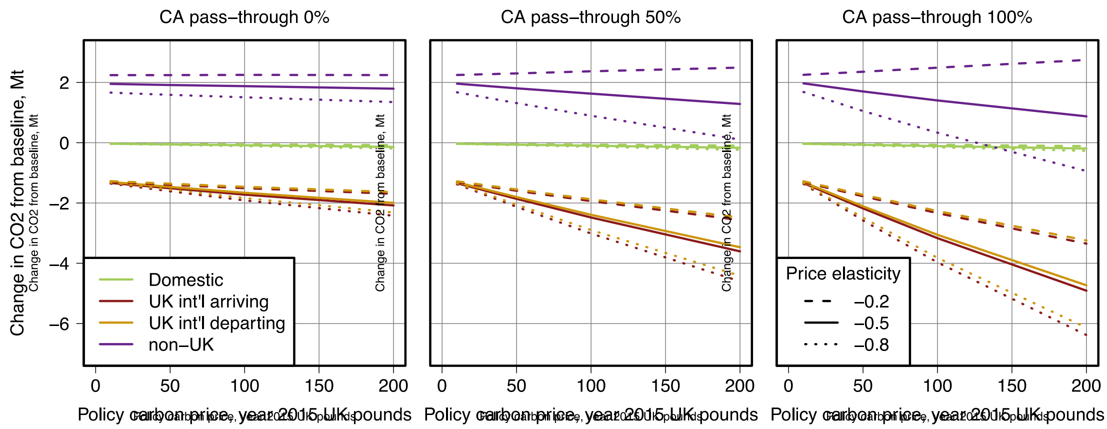

Figure 51. Absolute change in emissions by scope for the increased carbon price policy, in the case that no airline fleet swapping is assumed.

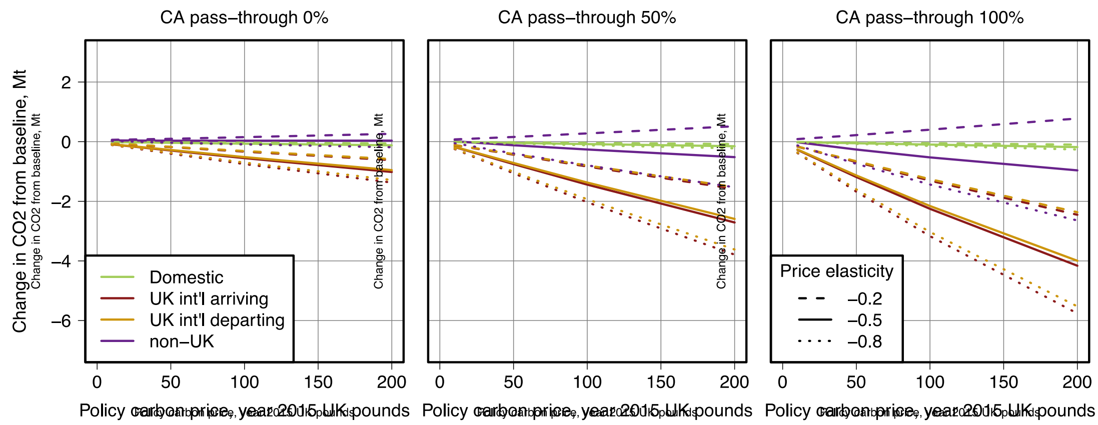

Figure 52. Absolute change in emissions by scope for the increased carbon price policy in 2030, in the case that airline fleet swapping is assumed.

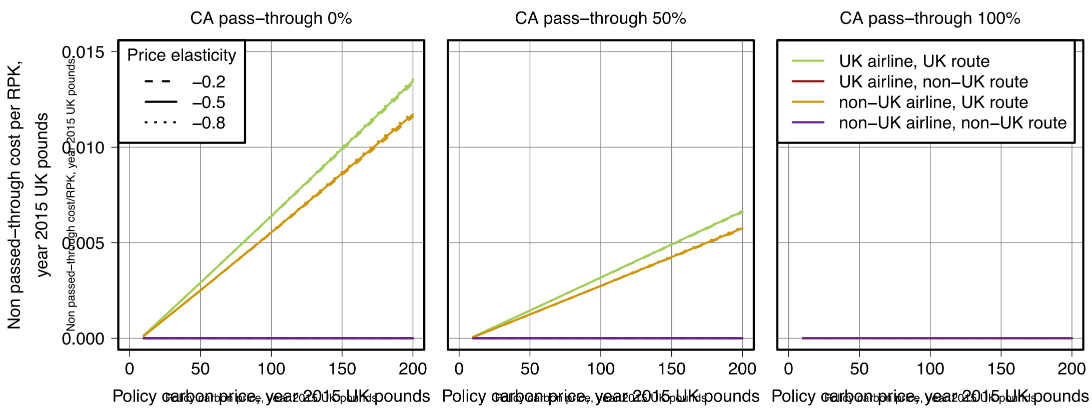

Figure 53. Change in non passed-on cost per RPK by airline type and scope for the increased carbon price policy, in the case that airline fleet swapping is assumed.

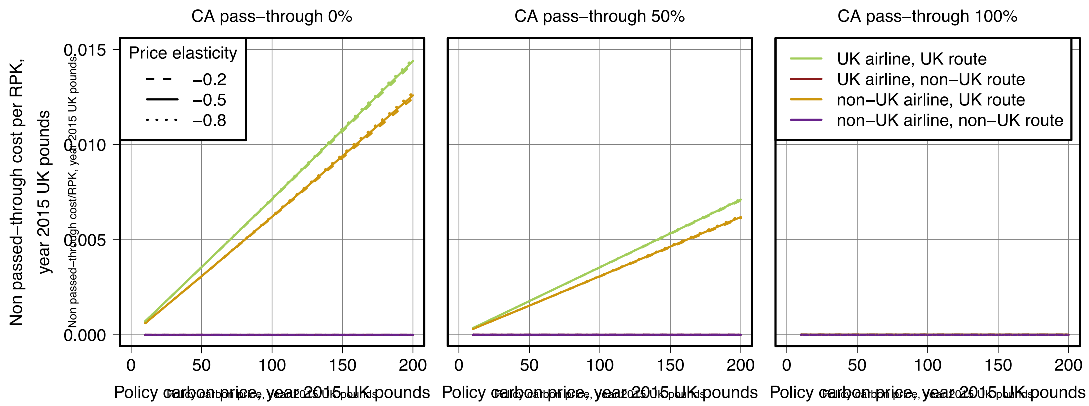

Figure 54. Absolute change in emissions by scope for the increased carbon price policy in 2030, in the case that no airline fleet swapping is assumed.

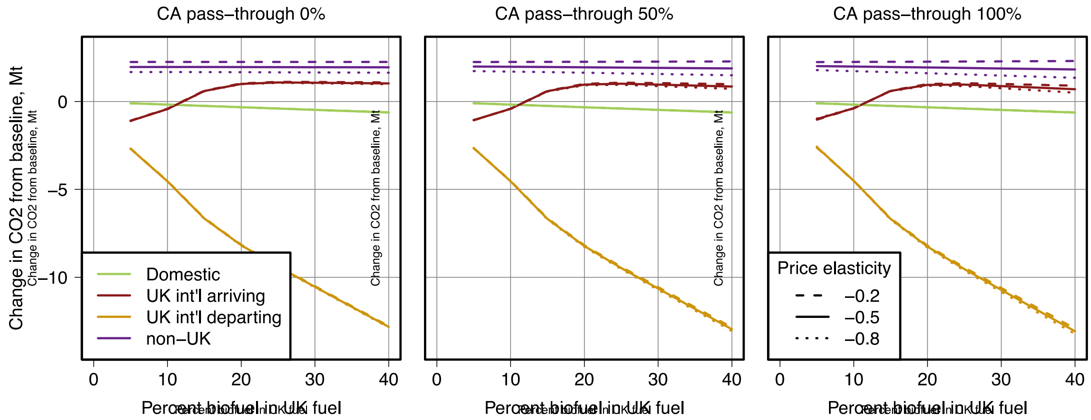

Figure 55. Absolute change in emissions by scope for the biofuel uptake policy, in the case that airline fleet swapping is assumed.

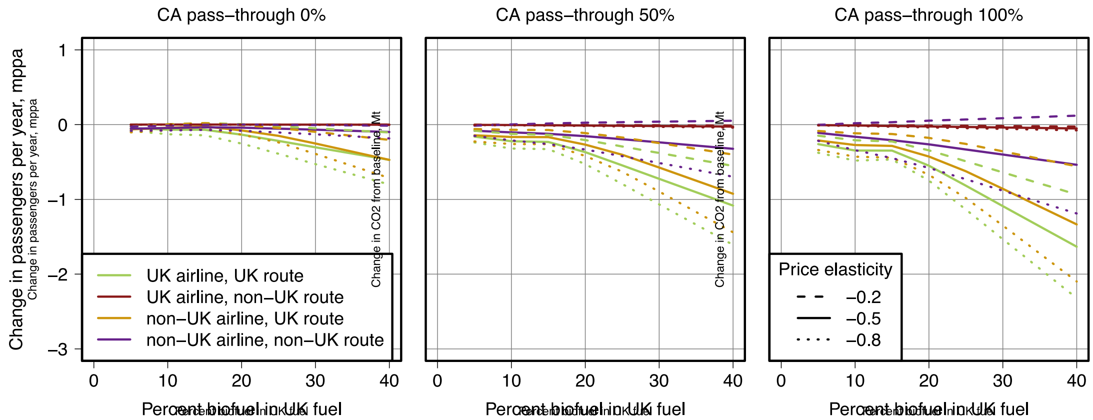

Figure 56. Absolute change in emissions by scope for the biofuel uptake policy, in the case that no airline fleet swapping is assumed.

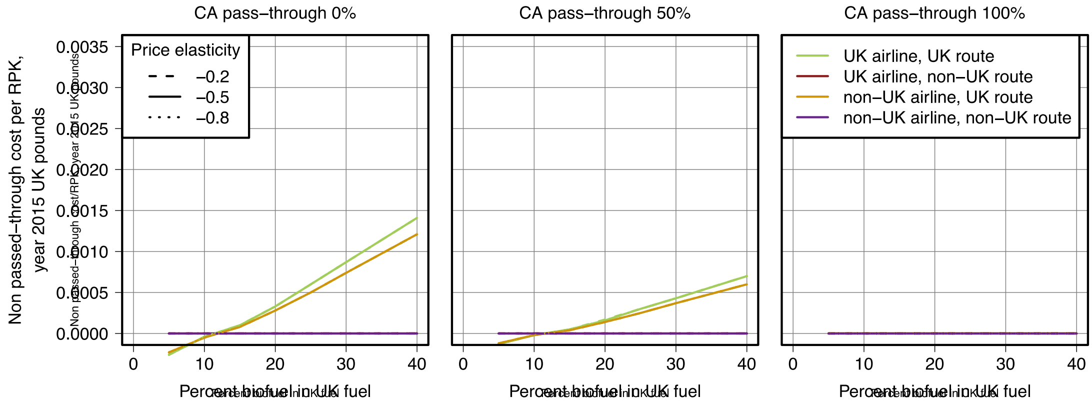

Figure 57. Change in non passed-on cost per RPK by airline type and scope for the biofuel uptake policy, in the case that airline fleet swapping is assumed.

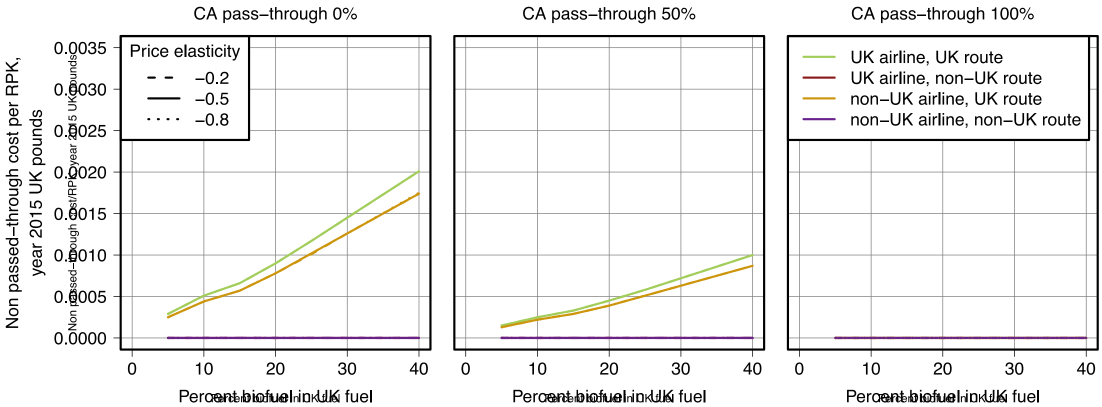

Figure 58. Change in non passed-on cost per RPK by airline type and scope for the biofuel uptake policy, in the case that no airline fleet swapping is assumed.

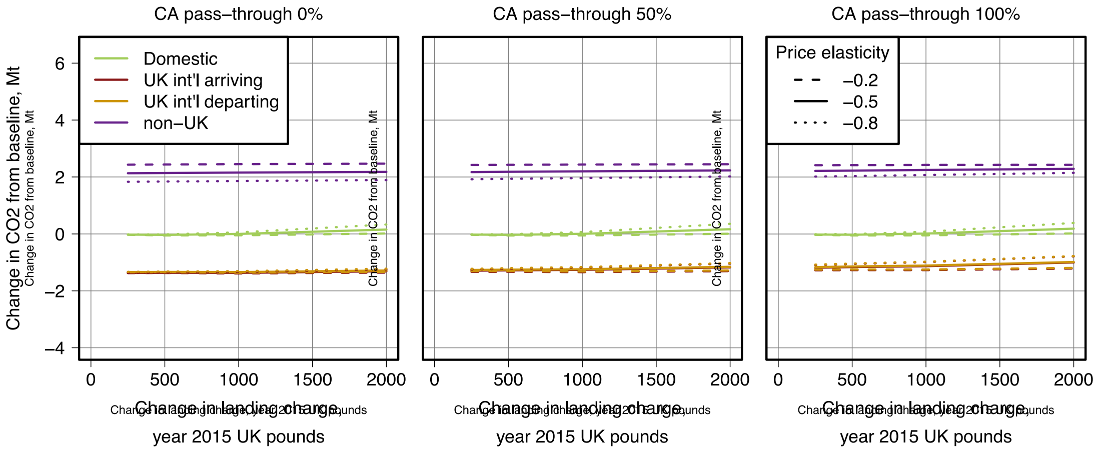

Figure 59. Absolute change in emissions by scope for the landing charge policy, in the case that airline fleet swapping is assumed.

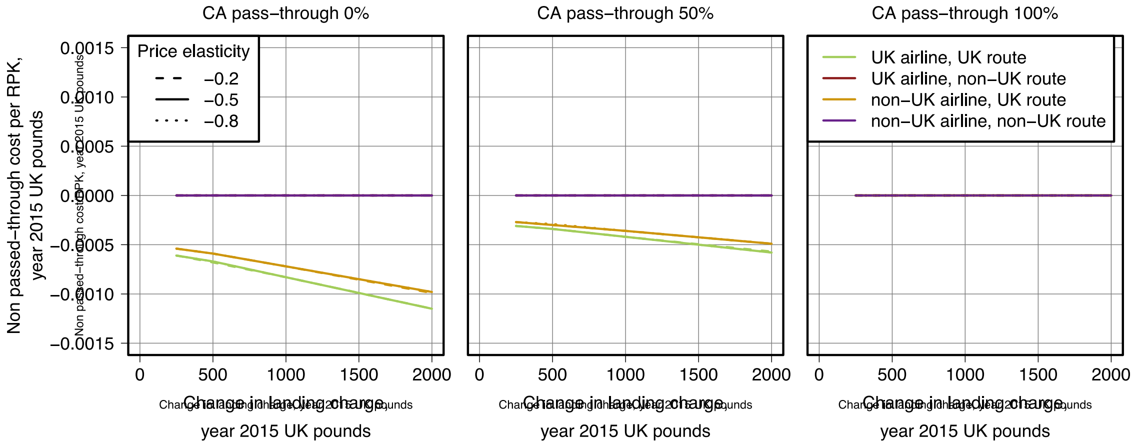

Figure 60. Change in non passed-on cost per RPK by airline type and scope for the landing charge policy, in the case that airline fleet swapping is assumed.