UK Aviation Demand and Emissions

Model Methodology

Technical Note for Committee on Climate Change

16 October 2009

mvaconsultancy

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1 Introduction

1.1 Introduction

1.1.1 The Committee on Climate Change (CCC) commissioned MVA Consultancy (MVA) to construct a user-friendly **reduced form UK aviation demand and emissions model** for projecting passenger demand and CO_2 emissions under a range of scenarios, formed according to a range of inputs and assumptions such as economic growth and policy levers.

1.1.2 This note describes how the model functions in terms of its structure, the purpose of each step and the interactions between different functions. However, the note is not intended to cover very detailed model workings and coding, nor is it a record of user inputs and assumptions.

1.1.3 To illustrate the model's functionality, basic equations used in the model are provided where applicable.

1.1.4 The note structure is as follows:

- **Section 2: Model Overview**
  - overview of the model, its scope and expected applications
- **Section 3: Model Flow Chart**
  - flow chart illustrating interactions between inputs, calculations and outputs
- **Section 4: Description of User Inputs**
  - description of each user input, including sources and units
- **Section 5: Economic Growth Impact**
  - description of how economic growth is reflected and how this affects demand
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- **Section 9: Unconstrained Forecasts**
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  - description of how the biofuels and non-CO_2 multiplier inputs are applied
- **Section 15: Outputs**
  - description of the model outputs produced

2 Model Overview

2.1 Model Purpose, Scope and Form

2.1.1 The purpose of the model developed for this study is to forecast UK aviation passenger demand and emissions in future years to 2050, in response to a wide range of user-variable inputs. This will help the CCC to assess how emissions could be reduced below 2005 levels by 2050, under a range of scenarios.

2.1.2 The scope of the model is to forecast:

- Aviation passenger demand within, from and to the UK
- Associated commercial air traffic movements (ATMs), both passenger and freight
- Resulting CO_2 emissions

2.1.3 The model is uni-modal, forecasting only for aviation demand, movements and emissions (though demand abstraction by high-speed rail can be input). Forecasts of demand are projected from a base-year (2005) as a function of economic growth and changes in ticket prices. Sensitivity of demand to these factors is expressed as elasticities. Changes in ticket prices are driven by user-input levels of pass-through of changes in aircraft operating costs (fuel, non-fuel, and carbon prices) and APD. These processes lead to forecasts of demand and ATMs that are unconstrained by airport capacities; these forecasts are then constrained as necessary with reference to assumed future airport capacities.

2.2 User-Defined Inputs

2.2.1 The model forecasts vary depending on the scenario. The model scenarios are defined according to the range of user-defined economic and policy inputs that will or could impact on the future course of passenger demand, ATMs and CO_2 emissions. These user-inputs are discussed further in section 4.

2.3 Base Data

2.3.1 The base data[1] used in the model includes ATMs (passenger and dedicated freighters), passenger demand and total seats provided from all UK airports for 2005, the base year in the model. The data is disaggregated across over 13,000 individual traffic lines, each representing a unique combination of airport pair, carrier, carrier type (network, charter or low-cost) and aircraft type.

2.3.2 Given that demand response to economic and other policy changes is likely to vary according to journey purpose and the passenger's origin, it is helpful that the demand data provided to MVA was already disaggregated by **passenger type** as follows:

- UK business
- UK leisure

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[1] raw data supplied by DfT based on CAA data

- Foreign business
- Foreign leisure

2.3.3 For each traffic line, the great circle distance between the two airports is also provided. This is used to calculate fuel usage (see section 13).

2.3.4 Freight is represented in the model by grouping base year freight ATMs by distance band (km): 0 to 499; 500 to 999; 1,000 to 2,499; 2,500 to 4,999; 5,000 to 7,499; 7,500 to 9,999; and 10,000+.

2.4 Calculations

2.4.1 The model functionality discussed in this report generally operates at the individual traffic line level and is relative to the base year data. For some processing steps, aggregation is necessary, e.g. the capacity constraint mechanism is aggregated by UK airport and fuel usage is aggregated by aircraft type.

2.5 Outputs

2.5.1 The model outputs provide both unconstrained and constrained forecasts of passenger demand, ATMs and CO_2 emissions. These are provided at five-year intervals from 2010 to 2040 inclusive and also for 2050.

3 Model Flow Chart

3.1 Model Flow Chart

3.1.1 The model contains different calculators operating independently or in conjunction with each other to achieve the desired outputs. Figure 3.1 illustrates the high level interactions and interdependencies between the user-defined inputs, base data, calculations and outputs.

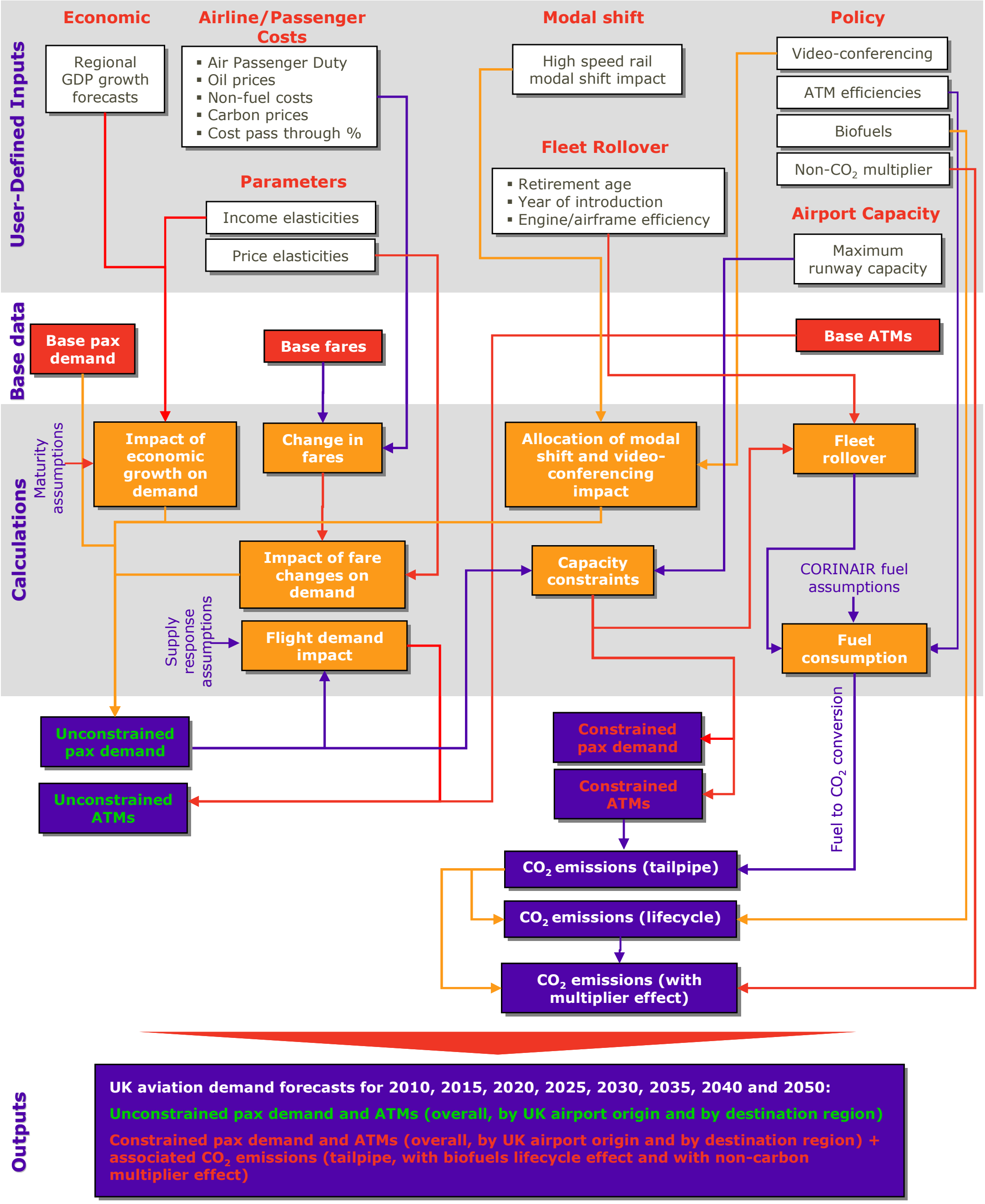

Figure 3.1 Model flow chart

3.1.2 The model functionality illustrated in Figure 3.1 is summarised as follows:

- The impact of economic growth on the base demand is determined by applying the economic growth user-inputs; the sensitivity of demand to economic growth is dependent on the income elasticity (a user input) and market maturity assumptions (DfT-based).
- The % change in fare relative to base fare is calculated according to the airline and passenger costs user inputs. This fare change has an impact on the base demand according to the price elasticity user input.
- Demand may also be impacted by the modal shift and videoconferencing user inputs.
- The combined impact of economic growth, fare changes, modal shift and videoconferencing on the base demand generates the unconstrained passenger demand in the forecast year. This then determines the unconstrained ATMs according to capacity to demand elasticity assumptions.
- The unconstrained forecasts are constrained using a capacity constraint mechanism which takes into account the airport runway capacity user input.
- Forecasts of fuel consumption are determined by applying the effects of the fleet rollover and air traffic management efficiency user inputs. This is then converted into CO_2 emission forecasts. The effects of the biofuel penetration and non-carbon multiplier user inputs are also reflected in the CO_2 forecasts.
- The model outputs show unconstrained and constrained forecasts at five-year intervals for passenger demand, ATMs and CO_2 emissions.

3.1.3 This functionality is described in greater detail in the subsequent sections of this note.

4 Description of User Inputs

4.1 User-Defined Inputs

4.1.1 The user-defined inputs in the model are grouped into seven categories as follows:

- Economic
  - GDP Growth
- Factors affecting Airline/Passenger Costs
  - Air Passenger Duty
  - Non-Fuel Cost Growth
  - Oil Prices
  - Oil Price Increase Pass-Through to Kerosene Prices
  - Airline Cost Increase Pass-Through to Passenger Fare
  - Carbon Prices
- Elasticities
  - Price & Income Elasticities
- Modal Shift
  - High-Speed Rail Modal Change Impact
- Policy Levers
  - Video-Conferencing
  - Penetration of Biofuels
  - Lifecycle Emission Reduction Effect from Biofuels
  - Non-CO_2 Multiplier
  - Air Traffic Management Efficiency Improvements
- Airport Capacity
  - Maximum Runway Capacity
- Fleet Rollover
  - Aircraft Retirement Age
  - Year of Introduction of New Aircraft Generations
  - Efficiency Improvement Associated with New Aircraft Generations

4.1.2 Each of these demand and policy levers is represented in the model as a selectable user input. Each input has a range of levels, generally up to four. These levels allow for variation within each input. For example, for economic growth, there are four levels (central, low, high and DfT GDP growth forecasts). Scenarios are therefore created by the user selecting a combination of input levels.

4.1.3 'Advanced' model users are also able to define new sets of inputs as required.

4.1.4 Table 4.1 indicates in which section of this report each input is described along with its units and from where the input values were sourced or derived. A description of the various levels used in the model as of summer 2009 is given in MVA's Final Report[2].

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[2] "Final Report Scenarios of UK Aviation Demand and Emissions to 2050", MVA, September 2009

Table 4.1 User-Defined Inputs

Input	Section of report	Units	Source from which input levels are based
GDP Growth	5.1	% p.a. (real)	HM Treasury (UK); IMF (other regions)
Price & Income Elasticities	5.1 (income), 7.1 (price)	-	MVA literature review/DfT
Air Passenger Duty	6.5	£/return flight	2008 HM Treasury Pre-Budget Report
Non-Fuel Cost Growth	6.2	% p.a. (real)	DfT
Oil Prices	6.2	$/barrel (2008 prices, real)	DECC
Oil Price Increase Pass-Through to Kerosene Prices	6.2	Range 0 to 100%	Test assumptions
Cost Increase Pass Through to Passenger Fare	6.3	Range 0 to 100%	Test assumptions
Carbon Pricing	6.2	€/tonne CO_2 (2009 prices, real)	CCC
Maximum Runway Capacity	10.3	ATMs/year	DfT
High-Speed Rail Modal Change Impact	8.1	% abstraction in forecast year relative to base	SDG
Video-Conferencing	8.2	%	MVA literature review
Penetration of Biofuels	14.1	%	E4Tech
Lifecycle Emission Reduction Effect from Biofuels	14.2	%	EU Emissions Trading System
Non-CO_2 Multiplier	14.3	-	Test assumptions
Air Traffic Management Efficiency Improvements	13.1	% p.a.	CCC
Aircraft Retirement Age	12.2	years	MVA literature review/assumptions
Year of Introduction of New Aircraft Generations	12.2	year	MVA literature review/assumptions
Efficiency Improvement Associated with New Aircraft Generations	12.2	% improvement relative to 2005	MVA literature review/assumptions

5 Economic Growth Impact

5.1 GDP and Income Elasticities Inputs

5.1.1 The impact of global economic growth on aviation demand is reflected in the model through **income elasticities** (the measure of the responsiveness in the level of demand of a product to a change in the income of the people demanding the product) and regional[3] **GDP growth forecasts**.

5.1.2 The impact of changes in income is likely to affect business and leisure passengers differently. Therefore, the income elasticities inputted in the model vary by passenger type.

5.1.3 To reflect the variation in economic growth in different parts of the world, the destination airport on each traffic line is classified by world region (Table 5.1). GDP growth forecasts[4] (in % per annum) are inputted in the model by year and world region.

Table 5.1 World Regions

Australia & New Zealand	North America
Caribbean & Central America	Other Europe
Central Asia & Caucasus (Turkey & neighbours)	Pacific Islands & South-East Asia (Thailand & Indonesia)
East Asia (China & Japan)	South America
EU	South Asia (India & Pakistan)
Middle East	Sub-Saharan Africa
Non-EU EEA & Switzerland	UK
North Africa (Morocco – Egypt)	

5.2 Impact on Demand

5.2.1 Aviation demand growth by airline type and destination region in a forecast year is then calculated by applying the relevant income elasticity to the average of the GDP growth in the UK and the destination region.

5.2.2 So, the aviation demand growth due to economic growth in forecast year x and for passenger type y, $\mathbf{Q(E)_{xy}}$ (% p.a.), is given by the following equation:

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[3] world region

[4] this takes into account both per capita growth **and** population growth

$$Q(E)_{xyz} = [\{1+ [½ * (GDP_{xUK} + GDP_{xz})]\}^{\wedge}YED_{y}] - 1$$

where:

GDP_{xUK} = UK GDP growth in forecast year x (% p.a.); GDP_{xz} = GDP growth in forecast year x and world region z (% p.a.); and YED_{y} = the income elasticity of demand for passenger type y.

5.2.3 These annual growths are compounded to derive a **cumulative demand growth relative to 2005** as a function of GDP for each forecast year at the level of individual traffic lines by passenger type.

5.2.4 These economic growth impacts are combined with the effects of any change in fares (sections 6 and 7), as well as modal shift to high-speed rail and video-conferencing impact (section 8), to estimate unconstrained forecasts of demand, as described in section 9.

5.2.5 The forecasts are "unconstrained" pending application of the airport capacity constraint mechanism (section 10). Market maturity effects that moderate the sensitivity of demand to economic growth are included in the unconstrained forecasts, however, as described in section 9.

6 Changes in Fares

6.1 Inputs Affecting Fares

6.1.1 There are six user inputs in the model that influence fares[5]:

- Crude oil prices
- Carbon prices
- Crude oil price pass-through to kerosene price
- Non-fuel airline operating cost change
- Operating cost change pass-through to fares
- Air Passenger Duty (APD)

6.2 Carrier Costs

6.2.1 Of the six user inputs above, the first four affect the carrier's costs (oil prices, carbon prices, oil price pass-through to kerosene and non-fuel cost change).

Crude oil prices

6.2.2 Crude oil prices are inputted in the model in $/barrel for each year to 2050.

Carbon Prices

6.2.3 Carbon prices are inputted in the model in €/tonne CO_2 for each year to 2050. Since CO_2 emitted is a simple factor of fuel consumed, the impacts of kerosene price increases and carbon prices have been combined by expressing the latter as a proportion of base fuel price: using a series of factors, carbon prices are converted into an equivalent carbon cost per oil barrel in $/barrel and represented in the model as a proportion of base year (2005) fuel cost ($66/barrel). For example, a $10 rise in oil prices to $76/barrel would equate to an increase in crude oil prices of 15% (76/66). To achieve the same increase through carbon pricing alone, the carbon price would need to be approximately €21/tonneCO_2 (which on conversion is the equivalent of $10/barrel).

Crude oil price pass-through to kerosene price

6.2.4 The crude oil price pass-through to kerosene is inputted in the model as a % and represents the proportion of the change in oil prices that is passed on to the cost of kerosene (this need not necessarily be 100%).

6.2.5 The three inputs affecting fuel costs are combined to create a fuel cost change in forecast year x relative to the base year 2005, $\Delta \mathbf{Fuel}_x$ (%), as given by the following equation:

$$\Delta Fuel_x = (\Delta OilPrice_x * OilKerosene\%_x) + CarbonPrice\%_x$$

where:

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[5] or more strictly costs to passengers

$\Delta OilPrice_x$ = % change in crude oil price in forecast year x relative to 2005 ($/barrel); $OilKerosene\%_x$ = % crude oil price increase pass-through to kerosene in forecast year x; and $CarbonPrice\%_x$ = carbon price in forecast year x as a % of the base year fuel cost.

Non-Fuel Costs

6.2.6 Changes in non-fuel costs are inputted in the model as a per annum % change in each year to 2050. This data is inputted by carrier type (to reflect that network carriers have significantly different cost structures to low-cost carriers for example) and whether the destination is within or beyond Europe (again to reflect the different cost structures of those carriers serving only short-haul destinations within Europe and those serving medium and long-haul destinations as well as European destinations).

6.2.7 The cumulative non-fuel cost change in forecast year x, for carrier type y and destination zone z relative to the base year, $\Delta NonFuel_{xyz}$ (%), is calculated by compounding the per annum % changes in non-fuel costs.

6.2.8 The overall impact on a carrier's costs in forecast year x, for carrier type y and destination zone z, $\Delta CarrierCost_{xyz}$ (%), is determined by combining the fuel cost and non-fuel cost changes to give an overall carrier cost change. This starts from in-built assumptions regarding the proportion of fuel and non-fuel costs in a carrier's cost base in the base year.

$$\Delta CarrierCost_{xyz} = [(\Delta Fuel_x * Fuel\%_{yz}) + (\Delta NonFuel_{xyz} * NonFuel\%_{yz})]$$

where:

$\Delta Fuel_x$ = fuel cost change in forecast year x relative to 2005 (%); $\Delta NonFuel_{xyz}$ = non-fuel cost change in forecast year x relative to 2005 for carrier type y and destination zone z (%); $Fuel\%_{yz}$ = fuel proportion of costs for carrier type y and destination zone z (%); and $NonFuel\%_{yz}$ = non-fuel proportion of costs for carrier type y and destination zone z (%)

6.3 Fare Change

6.3.1 The passenger fare is determined by considering the carrier cost increase pass through to fares and the change, if any, in APD.

6.3.2 The cost increase pass-through user input allows the user to vary how much of the change in the carrier's costs is passed onto the passenger via fares. This is inputted in the model as a %.

6.3.3 APD values for forecast years are inputted in the model according to distance band and class of travel in £/return flight. These rates are converted into $[6] and halved (given the base fares represent single journeys rather than the fare for the return journey).

6.3.4 The fare in forecast year x, $Fare_x$ ($), is calculated as follows:

$$Fare_x = \{Fare_{2005} * [1 + (\Delta CarrierCost_{xyz} * PassThrough_x)]\} + (APD_x - APD_{2005})$$

where:

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[6] based on exchange rates supplied by CCC

$\mathbf{Fare_{2005}}$ = base year fare including APD (\$); $\mathbf{\Delta CarrierCost_{xyz}}$ = change in carrier's costs in forecast year x, for carrier type y and destination zone z (%); $\mathbf{PassThrough_{x}}$ = cost pass-through to passenger fare in forecast year x (%); $\mathbf{APD_{x}}$ = APD single leg rate in forecast year x (\$); and $\mathbf{APD_{2005}}$ = APD single leg rate in 2005 (\$).

6.3.5 The overall fare change in the forecast year relative to 2005, $\mathbf{\Delta Fare_{x}}$ (%), is then calculated:

$$\mathbf{\Delta Fare_{x} = (Fare_{x} / Fare_{2005}) - 1}$$

7 Fare Change Impact

7.1 Price Elasticities

7.1.1 The impact of fares changes on aviation demand is calculated using **price elasticities** (a measure of the responsiveness in the level of demand for a product to a change in price of the product).

7.1.2 The price elasticities are inputted in the model according to passenger type (UK business, UK leisure, foreign business and foreign leisure) and airline type (network, low-cost and charter).

7.2 Impact on Demand

7.2.1 Once the fare change relative to 2005 in forecast year x (section 6.3) has been calculated, the change in aviation demand relative to 2005 due to change in fare in forecast year x for passenger type y and carrier type *z*, $Q(P)_{xyz}$ (%), is given by the following equation:

$$Q(P)_{xyz} = [(1 + \Delta Fare_x)\wedge PED_{yz}] - 1$$

where:

$\Delta Fare_x$ = % change in fare in forecast year x relative to 2005; PED_{yz} = the price elasticity of demand for passenger type y and carrier type z.

7.2.2 Demand by passenger type on individual traffic lines in the forecast year is then calculated by applying this fare change demand impact, $Q(P)_{xyz}$, to the 2005 base demand.

8 Modal Shift & Video-Conferencing Impact

8.1 Modal Shift

8.1.1 The modal shift input data shows the proportion of air passengers estimated to be abstracted from air to rail due to future high-speed rail (HSR) links, in both the UK and Europe, under different levels of HSR coverage[7]. The data is inputted for specific airport-pairs e.g. Heathrow – Manchester for each forecast year. The abstraction is restricted to domestic and UK-continental Europe city pairs.

8.1.2 The input value represents the percentage of air demand lost to HSR. The model input structure is set up to allow variation in the level of abstraction across the four passenger types.

8.1.3 The reduction in demand due to HSR (if any) is applied by looking up the modal shift abstraction input according to the forecast year, the traffic line airport pair and passenger type. This is then applied to determine the unconstrained demand in the forecast year, along with economic growth (section 5), fare changes (section 6) and video-conferencing (see below).

8.2 Video-Conferencing

8.2.1 MVA conducted a literature review to assess the likely substitution of flights by the use of video-conferencing technology and the subsequent impact this may have on aviation demand. The inputs are expressed terms of the overall % change in demand due to video-conferencing in each year. The model is structured so that the inputs can vary by passenger type (since leisure travellers are unlikely to be affected). So, for example an input of -2% for UK business in 2030 indicates that in this year, total demand from UK business travellers is reduced by 2% as a result of video-conferencing.

8.2.2 The change in demand due to video-conferencing (if any) is applied by looking up the demand change according to forecast year and passenger type and then adjusting the unconstrained demand in that year.

8.3 Impact on Demand

8.3.1 If applicable, the effect of modal shift and videoconferencing reduces the unconstrained passenger demand on the traffic line. This can result in fewer ATMs (as per the mechanism described in section 11.2).

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[7] modal shift input data from “Potential for Air – Rail Mode Shift” , Steer Davies Gleave, July 2009

9 Unconstrained Forecasts

9.1 Unconstrained Forecasts

9.1.1 The unconstrained forecasts (passengers and ATMs) are calculated without reference to the airport capacity inputs. There is therefore no suppression of demand due to airport capacity constraints at this stage of model calculation.

9.2 Passenger Demand

9.2.1 After applying the impact of economic growth (section 5), change in fares (section 6) as well as modal shift allocation and video-conferencing impact (section 8) relative to the base year, the initial estimate of **unconstrained passenger demand** for each traffic line in a given forecast year is calculated. This is then modified for market maturity effects, using the approach employed in DfT's model, which reflects DfT's expectation that there will be "some product cycle in aviation demand, with rapid early demand growth giving way to steadier growth in later years"[8].

9.2.2 Using the DfT approach, the model applies a multiplier to the initial estimate of unconstrained demand, for each of several demand segments. This multiplier has the form:

$$\left(\frac{\text{initial estimate of unconstrained demand in forecast year}}{\text{unconstrained demand in year in which maturity effect begins}}\right)^{x}$$

where x is a DfT-reported value, as shown below:

Business (short and long-haul) = -0.1 (applied from 2020)
Leisure (short-haul) = -0.3 (applied from 2015)
Leisure (long-haul) = -0.2 (applied from 2020)

9.2.3 These values are then mapped to the model passenger types: the business values were mapped to UK business and foreign business; the average of leisure (short-haul) and leisure (long-haul) was mapped to UK leisure and foreign leisure.

9.2.4 The unconstrained forecasts reported by the model include this market maturity effect.

9.2.5 Total unconstrained passenger demand is then determined by summing across traffic lines and displayed in the outputs. Unconstrained demand by UK origin airport and by region of destination is also shown.

9.3 Passenger ATMs

9.3.1 The unconstrained passenger demand is converted into passenger ATMs using the demand into flights process described in section 11.

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[8] "UK Air Passenger Demand and CO_2 Forecasts", DfT, January 2009, pp113-114.

9.3.2 Total unconstrained passenger ATMs is calculated by summing ATMs across all traffic lines and is shown in the outputs along with unconstrained passenger ATMs by UK origin airport and by region of destination.

9.4 Forecasting Movements by Dedicated Freighter Aircraft

9.4.1 Each freight distance band is assigned an assumed destination region based on the distance and the dominant destination region(s) observed in the base data (Table 9.1).

Table 9.1 Freight Distance Bands

Freight Distance Band (km)	Assumed Destination Region(s)
0 to 499	UK
500 to 499	Europe
1,000 to 2,499	Europe
2,500 to 4,999	Central Asia & Caucasus (Turkey & neighbours)/Middle East/ North Africa (Morocco – Egypt)
5,000 to 7,499	North America/Sub-Saharan Africa
7,500 to 9,999	East Asia (China & Japan)
10,000+	South America

9.4.2 The impact on freight ATMs due to economic growth in the forecast year is determined by applying the freight income elasticity of demand (as inputted in the model) and the average of the GDP growth in the UK and the assumed destination region(s) in the forecast year (as per section 5.2). These annual changes are compounded to derive a cumulative growth relative to 2005.

9.4.3 The impact on freight ATMs due to changes in carrier costs in the forecast year is determined by applying the freight price elasticity of demand (as inputted in the model) and the change in carrier costs in the forecast year (as per section 6.2).

9.4.4 The total number of freight ATMs in the forecast year is determined by applying the impact of both economic growth and changes in carrier costs to the base year freight ATMs, and summing across the distance bands.

9.5 Constrained Forecasts

9.5.1 Constrained passenger demand and passenger ATMs forecasts are calculated in the same way as for unconstrained forecasts but take into account the suppression of demand resulting from the capacity constraint mechanism discussed in section 10.

9.5.2 The proportional reduction in passenger ATMs in forecast year x resulting from the capacity constraint mechanism is applied to the unconstrained freight ATMs to determine the constrained freight ATMs.

10 Capacity Constraints

10.1 Introduction

10.1.1 The unconstrained forecasts discussed in section 9 do not take into account airport capacity. However, the model contains a capacity constraint function to accommodate the situation where unconstrained growth would exceed capacity at individual UK airports. For this purpose, capacity is expressed in units of ATMs per year[9,10].

10.1.2 If an airport's capacity does not increase or grows less rapidly than the unconstrained growth in demand for it, it can be expected that carriers using the airport will increasingly focus their own growth on their most profitable markets. Routes and individual departures that are relatively less profitable will be grown less rapidly or even reduced.

10.1.3 The net effect of an airport's capacity growing less rapidly than unconstrained demand for it will thus be:

- Some suppression of growth in demand
- Some realignment of realised demand such that growth focuses on more profitable operations

10.1.4 The model emulates these effects.

10.2 Capacity Constraint Mechanism

10.2.1 Passenger demand and capacity (i.e. number of seats) are forecast for each traffic line. This allows the traffic line average load factor to be computed. To implement the capacity constraint mechanism, the load factors for individual movements on the traffic line are assumed to be distributed around this average. Then, if there is a need to suppress ATMs at an airport to meet a constraint, it should be those movements on the traffic line that have relatively low load factors (and thus relatively low profitability) that are suppressed.

10.2.2 An equally important underlying concept is that the suppressed movements should be not only those that have relatively low profitability for the individual traffic line but also relatively low profitability of ***all*** movements (from/to other origins/destinations, of different movement-types and aircraft types) at the airport concerned. In this way, the capacity constraint mechanism:

- Ensures that the constraint is satisfied
- Increases average load factors (implying that demand is suppressed to a less extent than movements)
- Tends to suppress short-haul movements to a greater extent than long-haul movements (because the latter can be expected to more profitable ***per airport slot***)

10.2.3 The mechanism is applied as follows, and also illustrated in Figure 10.1:

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[9] maximum runway capacity input data supplied by DfT, June 2009

[10] the scope of the model does not extend to express capacity in terms of terminal passenger numbers

- A background assumption is that load factors on individual flights on each traffic line vary around the average with a distribution that accords with "k-factors"; these are the values that airlines themselves use to express the variability of load factors when planning aircraft-fleet deployment.
- On this distribution for each traffic line there will be a "threshold" load factor that corresponds to a "threshold" profit-level; this is determined within the capacity constraint mechanism, as described shortly. The proportion of movements on a traffic line that have load factors below the threshold are suppressed. Totalling suppressed movements over all traffic lines at the airport in question meets the constraint.
- The profitability of a flight on a traffic line at any given load factor is estimated from the "aspirational" load factor for the traffic line and a simple formula that relates the operating-cost of a single flight to traffic line distance and aircraft seat-count[11]. The "aspirational" load factor is a concept employed in the fleet rollover component of the model to trigger consideration of increasing the size of aircraft operated on a traffic line (see section 12). For the purpose of imposing capacity constraint, it is assumed that the "aspirational" load factor for a traffic line is related to the break-even level, and that revenue for a single flight on the traffic line varies proportionally with load factor. These assumptions allow the relationship of revenue to costs – and hence profitability – for any load factor to be estimated.
- These assumptions also permit the threshold load factor on the traffic line to be determined for a specified (threshold) profit-level. This profit-level is itself estimated by forming an equation across all the traffic lines at an airport, in which the profit level is the "unknown" variable by which the extent of suppressed movements can be matched to the difference between the unconstrained forecast of movements at the airport and its capacity.
- The threshold profit-level is then applied to traffic lines individually to establish the number of movements and associated volume of demand that must be suppressed on each traffic line. As noted above, the suppressed movements are assumed to be those with load factors below the threshold for the traffic line, implying that demand is suppressed less than capacity.
- Year by year, if the constraint is not relaxed and there is continued growth in the unconstrained forecasts, the severity of the constraint mechanism will suitably increase as the threshold profit-level rises. On the other hand, if the constraint is relaxed (the effect of inputting an assumed increase in airport capacity), the threshold profit-level will fall and the constrained forecasts will from then on be a higher proportion of the unconstrained levels than they would otherwise have been.

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[11] derived from Swan W M and N Adler, "Aircraft trip cost parameters: a function of stage length and seat capacity", Transportation Research, Part E 42 (2006) 105-115

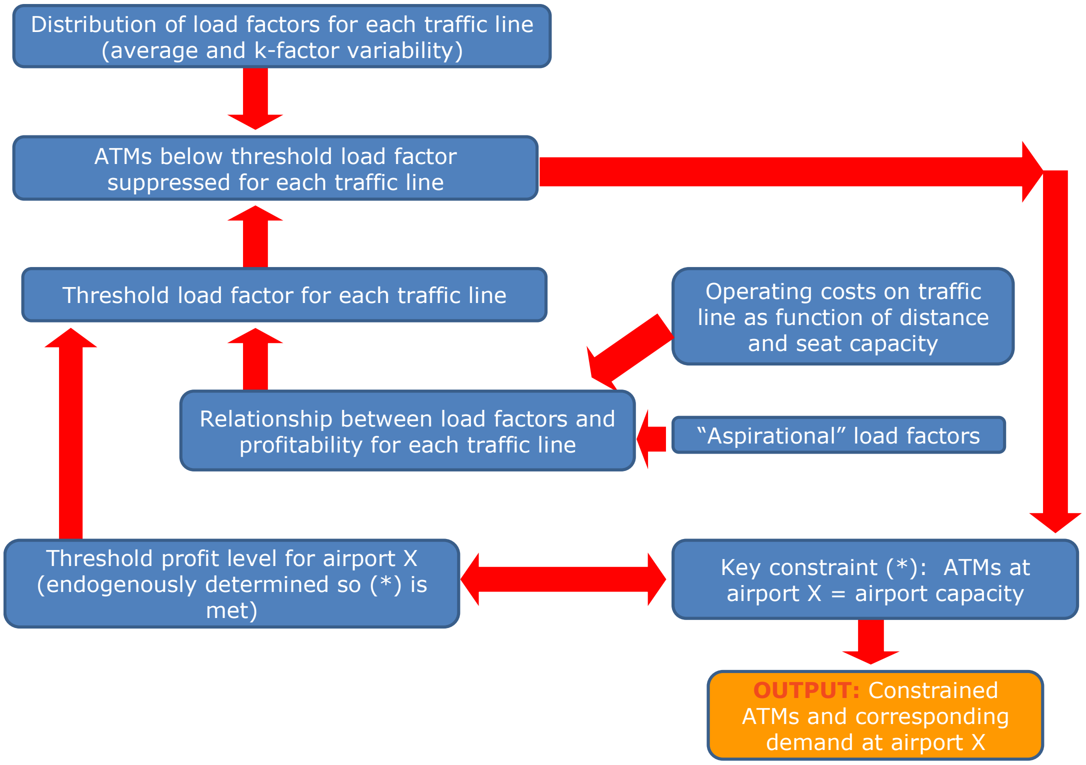

Figure 10.1 Capacity constraint mechanism

10.3 Airport Capacity Inputs

10.3.1 The model user is able to specify the constraints at airports in terms of the maximum ATMs allowed per year at the following ten airports: **Birmingham, Bristol, Edinburgh, Glasgow, London City, London Gatwick, London Heathrow, London Stansted, Luton** and **Manchester**.

10.3.2 For all other airports, no constraint is applied. Thus in these circumstances demand will grow at the unconstrained rate. The model however does allow the user to input the maximum runway capacity for forecast years for these unconstrained airports. The model then merely reports in the outputs for which unconstrained airports the forecast ATMs exceeds the runway capacity limits and the number of excess ATMs.

11 Demand into Flights

11.1 Demand into Flights

11.1.1 As demand on a traffic line grows through time, additional capacity is likely to be provided. This will be through a combination of:

- Frequency of flights (as described in this section)
- Capacity of aircraft employed (as described in section 12, Fleet Rollover Mechanism)

11.1.2 The impact of growing demand on capacity is estimated from elasticities of capacity to passenger demand growth: that is, the proportional change in capacity provided (available seat km, ASKs) divided by the proportional change in demand (revenue seat km, RPKs).

11.1.3 Elasticities were estimated from Association of European Airlines (AEA) time-series data for flows within Europe and from Europe to major world regions. The elasticities range between 0.81 and 0.86, indicating that seats offered tend to rise appreciably more slowly than demand grows.

11.1.4 For a given size of aircraft on a traffic line, a proportional growth in ASKs implies the same proportional growth in service frequency. With this condition, the elasticities can also be used to estimate the increase in ATMs for the traffic line, as set out below.

11.1.5 However, that the elasticity values are less than 1 also implies that load factors increase. As described in section 12, the fleet rollover component of the model responds to increasing load factors by potentially increasing the size of aircraft. This reduces load factors because service frequency remains as estimated from the elasticities as just described.

11.2 Application of Elasticities

11.2.1 Once the unconstrained passenger demand in a forecast year on a traffic line has been calculated (i.e. after taking into account impact of economic growth, videoconferencing, fare changes and modal shift), the number of unconstrained flights in the forecast year x and destination zone z, $\mathbf{ATMs_{xz}}$ is calculated as follows:

$$\mathbf{ATMs_{xz} = ATMs_{2005z} * [(Q_{xz}/Q_{2005z})\hat{}CED_z]}$$

where:

$\mathbf{ATMs_{2005}}$ = total traffic line ATMs in base year 2005 for destination zone z; $\mathbf{Q_{xz}}$ = total traffic line unconstrained passenger demand in forecast year x for destination zone z; $\mathbf{Q_{2005z}}$ = total traffic line unconstrained passenger demand in 2005 for destination zone z; and $\mathbf{CED_z}$ = elasticity of capacity to demand for destination zone z.

11.2.2 $\mathbf{ATMs_{xz}}$ is then used to calculate the average load factor in the forecast year and so is used in the fleet rollover mechanism (section 12).

11.2.3 $\mathbf{ATMs_{xz}}$ feeds into the capacity constraint mechanism to calculate the constrained ATMs on the traffic line.

12 Fleet Rollover Mechanism

12.1 Sub-systems of Fleet Rollover Mechanism

12.1.1 The fleet roll-over mechanism comprises two distinct sub-systems to determine when and how the base year aircraft type on a traffic line will change through time:

- A capacity succession, replacing the "incumbent" aircraft type with a higher-capacity type with the appropriate range capability for the traffic line, when load factors for the incumbent type can justify the shift to the higher-capacity type.
- A generational succession, replacing the "incumbent" aircraft type (at any particular point in time) with a younger and (possibly) more fuel-efficient successor having the ***same*** mission (capacity and range) capabilities.

12.2 Capacity Succession

12.2.1 For the capacity succession sub-system, each base year aircraft type has a potential successor type of higher capacity, with the obvious exception of the largest types. Capacity of the base year types is the average within movement-type (scheduled, charter and low-cost) implied by the base year data of seats offered and ATMs. For each traffic line, the potential successor type is the next largest that operates within the movement-type of the traffic line and has adequate range capability for the traffic line.

12.2.2 Under certain conditions, the potential successor type is assumed to replace the base year type. (It is important to appreciate that – for capacity succession – "base year type" relates only to its capacity and range capabilities, and not to its "generation", for which see the following sub-section.) These conditions are next described.

12.2.3 For each successive modelled future year, ATMs on a traffic line are forecast to grow more slowly than demand (with an elasticity of between 0.81 and 0.86: see section 11), giving rise to higher load factors for the incumbent aircraft type on the traffic line. An "aspirational" load factor is defined as that load factor at which consideration of replacing the incumbent type by a higher-capacity type is triggered. Given the forecast demand and ATMs, the corresponding "aspirational" aircraft capacity can be established. These range from 70 to 100%.

12.2.4 If the potential successor type to the incumbent type has capacity not larger than the "aspirational" capacity, its load factor with the forecast demand and ATMs will be at least as high as the "aspirational" load factor. It is therefore deemed to replace the incumbent type for the forecast year in question. It will become the incumbent for the next forecast year.

12.2.5 On the other hand, if the potential successor has a higher-than-"aspirational" capacity, the incumbent type will not be changed in this forecast year, from the capacity-succession point-of-view. (It may be replaced with a more-efficient successor having the same capacity, as described in the following sub-section.)

12.2.6 Whether an incumbent aircraft type is replaced by its capacity-successor depends upon several factors:

- The greater the disparity in capacity between an incumbent and its successor, the less likely that replacement will occur in any given forecast year.
- The higher that the “actual” (i.e. base year or forecast) load factor for the incumbent type is compared to the “aspirational” load factor, the more likely that replacement will occur.
- The faster that demand on a traffic line is forecast to grow, the more likely that replacement will occur.
- The higher the elasticity of growth in movements to the growth in demand, the less likely that replacement will occur.

12.3 Generational Succession

12.3.1 The generational succession sub-system models the penetration of improvement in aircraft (airframe and engine) efficiency (reduced fuel-burn and hence CO_2 emissions) as a function of the growth in ATMs and the following user-inputs:

- The extent to which a new generation of an aircraft type (defined by its capacity and range capabilities) is more efficient than the previous generation having the same capabilities.
- The year in which new generations are introduced, and hence the elapsed time between successive generations.
- The retirement ages of aircraft types.

12.3.2 For computational efficiency, the generational succession operates at the level of aircraft type rather than traffic line where aircraft type is at the level of disaggregation implied by, for example, “Boeing 737-500”. The process nonetheless implicitly retains the detail of the fuel-burn and emission estimates calculated at the traffic line level.

12.3.3 In addition to the user-inputs as just defined, the main data requirements are:

- The time-profile of aircraft production for each base year aircraft type[12], in units per year, as obtained from global delivery date of new units by aircraft type.
- For each traffic line in the base year data, the number of ATMs and the aircraft type.

12.3.4 In the base year, ATMs are aggregated within aircraft type. It is assumed that the age-profile of an aircraft type is reflected *pro rata* in the ATMs that it operates. The base year ATMs for each aircraft type are therefore partitioned into five-year “age-bands” using the proportions of aircraft of the type that were built up to 5 years, 5-10 years, etc before the base year. The default oldest age-band is nominally 35-40 years, though it includes all aircraft older than 35 years. Table 12.1 shows the age profile of aircraft aggregated by seat class in the base year (2005).

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[12] based on CAA data

Table 12.1 Age profile of base year aircraft by seat class

Seat class	0 – 5 years	5 – 10 years	10 – 15 years	15 – 20 years	20 – 25 years	25 – 30 years	30 – 40* years
Narrow Body	32%	30%	19%	15%	3%	0%	1%
Regional Jet	3%	5%	18%	48%	24%	1%	1%
Wide Body	18%	39%	24%	13%	4%	1%	1%
Turboprop	18%	11%	26%	40%	5%	0%	0%

*due to the low numbers involved, the 30 – 35 years and 35 – 40 years bands are combined

12.3.5 Since forecasts are prepared for five-year intervals, in each successive forecast year ATMs (aggregated within aircraft type) are stepped backward into the next older five-year age-band, except for those in the oldest band, which are stepped forward to the youngest (0-5 years) band. If the user specifies a retirement age for an aircraft type, that will determine the oldest age-band in place of the default assumption.

12.3.6 A logical result of the "stepping back" is that the generation operating the ATMs in all except the oldest age-band does not change from one forecast year to the next. The fuel-burn and CO_2 emissions per flight for these ATMs also do not change, therefore.

12.3.7 Another outcome is that the aircraft operating the ATMs in the oldest age-band are replaced by new-build aircraft of the latest ***available*** generation for the type in question. Whether these aircraft are of a new generation, with therefore different fuel-burn and CO_2 characteristics, depends upon the input assumption regarding the interval between introducing successive generations.

12.3.8 The user can also specify a retirement age for an aircraft type, in which case that will determine the oldest age-band in place of the default assumption.

12.3.9 If there is growth in ATMs between forecast years for an aircraft type, the additional movements will be added to the youngest age-band. They will therefore also be operated by the latest ***available*** generation of aircraft of the type concerned.

13 CO_2 Calculations

13.1 Fuel Usage

13.1.1 The fuel usage of a traffic line in a forecast year is initially calculated as a function of the forecast number of ATMs, traffic line distance and fuel consumption estimates from the 2007 CORINAIR Emission Inventory Guidebook. The CORINAIR fuel-consumption data relate to the total of all phases of flights (take-off, climb, cruise, descent and landing) for "standard"[13] flight distances.

13.1.2 This initial calculation estimates fuel consumption in the forecast year as if there had been no improvement in fuel-burn rates since the base year. The following steps in the model then compute the effects of such improvements for the forecast year in question:

- Fuel usage is aggregated across traffic lines within each combination of aircraft type and age-band (see section 12.2).
- These totals of "as if base-year technology" fuel consumption are then adjusted for the percentage improvements (if any) in engine/airframe efficiencies since the base-year applicable to the different age-bands within each aircraft type.
- There is further adjustment in fuel consumption to account for the efficiency gains arising from traffic management improvements between the base-year and the forecast year.

13.1.3 The total fuel usage (in Mt) from all flights to/from the UK is calculated by summing across all aircraft types.

13.1.4 As only the UK allocation of CO_2 emissions is reported, the fuel usage resulting from **domestic and departing international flights** only is required.

13.1.5 The proportion of total fuel usage attributed to domestic flights is assumed to remain constant over the forecast period and is based on the 2005 base year proportion. This assumption is required because (for reasons of computational tractability) fuel usage is calculated by aircraft type rather than on an individual traffic line basis, and it is therefore not possible to distinguish fuel usage between domestic and international flights.

13.1.6 The proportion of total fuel usage attributed to departing international flights is then calculated by taking 50% of the difference between total fuel usage and domestic flights fuel usage (the remaining 50% is attributed to inbound international flights).

13.1.7 Forecast year fuel usage is reported in the outputs (total i.e. all flights to/from the UK, domestic flights only and departing international flights only).

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[13] "standard" flight distance is not defined by CORINAIR, though there are indications in the CORINAIR documentation that (a) it is taken from Official Airline Guide schedules and is therefore Great Circle Distance (GCD), and that (b) relating emissions to the actual distance flown is one of the "areas of improvement" for CORINAIR calculations, implying that deviations from GCD are not as yet included.

13.2 CO_2 Emissions

13.2.1 Tailpipe[14] CO_2 emissions are directly derived from fuel usage by applying the carbon to fuel use conversion factor of 3.15 (as assumed by the CORINAIR Emission Inventory), i.e. for every tonne of fuel used, 3.15 tonnes of CO_2 are emitted from the aircraft engines.

13.2.2 This factor is applied to the fuel usage from domestic flights and departing international flights to determine the CO_2 emissions from both.

13.2.3 Additionally, as in the DfT's model, a bunker fuel adjustment is required to ensure that CO_2 forecasts are consistent with the DECC's estimates of aviation CO_2 emissions[15]. These are based on the amount of aviation fuel actually distributed from bunkers as per the UN Framework Convention on Climate Change reporting method. To ensure consistency with the DECC estimate of the total UK allocation of aviation emissions in 2005 of 37.5 $MtCO_2$[16], the model's initial 2005 forecast of 29.6 $MtCO_2$ (based purely on fuel *usage*) was therefore uplifted by 7.9$MtCO_2$[17]. In forecast years, this bunker fuel adjustment of 7.9$MtCO_2$ is increased in line with the increase in total ATMs (passenger + freight) relative to 2005.

13.2.4 The total UK allocation of aviation CO_2 emissions reported in the outputs is therefore the sum of emissions from domestic flights, departing international flights and the bunker fuel adjustment.

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[14] CO_2 emissions based solely on fuel-burn

[15] "UK Air Passenger Demand and CO_2 Forecasts", DfT, January 2009, p62.

[16] "UK Air Passenger Demand and CO_2 Forecasts", DfT, January 2009, p82.

[17] uplift includes base year freight emissions

14 Biofuels & Non-CO_2 Multiplier

14.1 Biofuels Penetration Inputs

14.1.1 The biofuels data inputted in the model shows the cumulative biofuels penetration of jet kerosene for each year up to 2050[18]. So, for example a value of 35% in 2030 indicates that by this year, biofuels comprise 35% of total aircraft fuel used, with the remaining 65% still kerosene.

14.1.2 The model assumes that the CO_2 emissions per unit mass of biofuels is identical to that of jet kerosene. Therefore CO_2 emissions from the aircraft tail-pipe are unchanged. However, considering the overall carbon lifecycle, it is assumed that aircraft CO_2 emissions are off-set to some extent if biofuels are used instead of kerosene. The user inputs into the model a percentage value showing the net lifecycle effect of biofuels compared to kerosene.

14.2 Biofuels Impact on Emissions

14.2.1 The reduction in CO_2 emissions due to biofuels in any forecast year is calculated by applying the level of biofuels penetration expected in that year and the net lifecycle effect to the total tailpipe CO_2 emissions in that year. This value, the total CO_2 emissions with biofuels lifecycle effect, is displayed in the outputs.

14.3 Non-CO_2 Multiplier

14.3.1 The non-CO_2 multiplier value in year x, M_x is inputted in the model for each forecast year. The total CO_2 emissions in forecast year x (with multiplier effect), $CO_{2withmultiplierx}$ (Mt) is then given by the equation:

$$CO_{2withmultiplierx} = (CO_{2withbiofuelsx} * M_x) + [(CO_{2tailpipex} - CO_{2withbiofuelsx}) * (M_x - 1)]$$

where:

$CO_{2withbiofuelsx}$ = total UK allocation CO_2 emissions with biofuels effect in forecast year x (Mt);
and $CO_{2tailpipex}$ = total UK allocation CO_2 emissions (tailpipe) in forecast year x (Mt).

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[18] biofuels input data supplied by E4Tech, July 2009

15 Outputs

15.1 Model Outputs

15.1.1 Two sets of outputs are generated by the model for every scenario created:

- **Unconstrained demand** forecasts which do not take into account airport capacity constraints
- **Constrained demand** where airport capacity constraints potentially suppress demand

15.1.2 Results are provided for the forecast years 2010, 2015, 2020, 2025, 2030, 2035, 2040 and 2050. The 2005 base year data is also presented for comparison.

15.1.3 The following outputs are provided:

- **Passenger Demand (m)**
- **ATMs ('000s)**
  - Passenger ATMs
  - Freight ATMs
  - Total ATMs
- **Fuel Usage (Mt)**[19]
  - all flights to/from UK
  - domestic flights only
  - departing international flights only
- **CO_2 Emissions (Mt)**[19]
  - all flights to/from UK
  - domestic flights only
  - departing international flights only
  - bunker fuel adjustment
  - total UK allocation
  - total UK allocation with biofuels effect
  - total UK allocation with multiplier effect

15.1.4 Additionally, the following more detailed forecasts are provided:

- Seat km/tfuel and Revenue Passenger km/tfuel and associated efficiency measures[19]
- Passenger demand and ATMs forecasts for the 10 constrained UK origin airports
- Passenger demand and ATMs forecasts by destination region.

15.1.5 Figure 15.1 shows examples outputs from the model.

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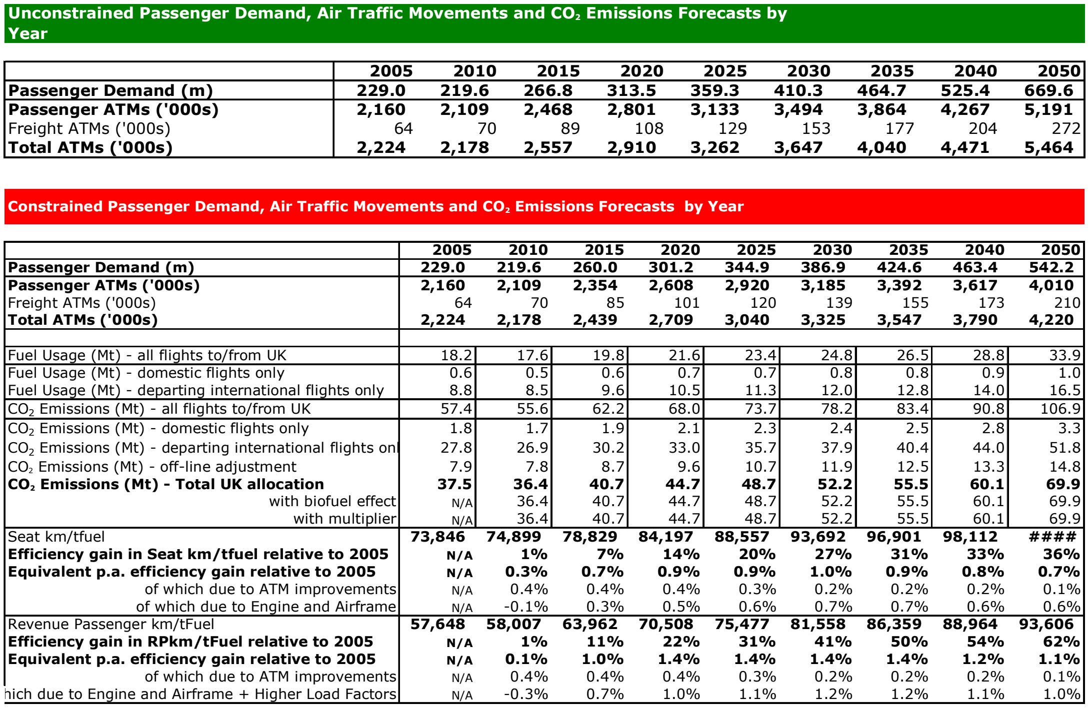
[19] only reported for constrained forecasts



Unconstrained Passenger Demand, Air Traffic Movements and CO_2 Emissions Forecasts by Year

	2005	2010	2015	2020	2025	2030	2035	2040	2050
Passenger Demand (m)	**229.0**	**219.6**	**266.8**	**313.5**	**359.3**	**410.3**	**464.7**	**525.4**	**669.6**
Passenger ATMs ('000s)	**2,160**	**2,109**	**2,468**	**2,801**	**3,133**	**3,494**	**3,864**	**4,267**	**5,191**
Freight ATMs ('000s)	64	70	89	108	129	153	177	204	272
Total ATMs ('000s)	**2,224**	**2,178**	**2,557**	**2,910**	**3,262**	**3,647**	**4,040**	**4,471**	**5,464**

Constrained Passenger Demand, Air Traffic Movements and CO_2 Emissions Forecasts by Year

	2005	2010	2015	2020	2025	2030	2035	2040	2050
Passenger Demand (m)	**229.0**	**219.6**	**260.0**	**301.2**	**344.9**	**386.9**	**424.6**	**463.4**	**542.2**
Passenger ATMs ('000s)	**2,160**	**2,109**	**2,354**	**2,608**	**2,920**	**3,185**	**3,392**	**3,617**	**4,010**
Freight ATMs ('000s)	64	70	85	101	120	139	155	173	210
Total ATMs ('000s)	**2,224**	**2,178**	**2,439**	**2,709**	**3,040**	**3,325**	**3,547**	**3,790**	**4,220**
Fuel Usage (Mt) - all flights to/from UK	18.2	17.6	19.8	21.6	23.4	24.8	26.5	28.8	33.9
Fuel Usage (Mt) - domestic flights only	0.6	0.5	0.6	0.7	0.7	0.8	0.8	0.9	1.0
Fuel Usage (Mt) - departing international flights only	8.8	8.5	9.6	10.5	11.3	12.0	12.8	14.0	16.5
CO_2 Emissions (Mt) - all flights to/from UK	57.4	55.6	62.2	68.0	73.7	78.2	83.4	90.8	106.9
CO_2 Emissions (Mt) - domestic flights only	1.8	1.7	1.9	2.1	2.3	2.4	2.5	2.8	3.3
CO_2 Emissions (Mt) - departing international flights onl	27.8	26.9	30.2	33.0	35.7	37.9	40.4	44.0	51.8
CO_2 Emissions (Mt) - off-line adjustment	7.9	7.8	8.7	9.6	10.7	11.9	12.5	13.3	14.8
CO_2 Emissions (Mt) - Total UK allocation	**37.5**	**36.4**	**40.7**	**44.7**	**48.7**	**52.2**	**55.5**	**60.1**	**69.9**
with biofuel effect	N/A	36.4	40.7	44.7	48.7	52.2	55.5	60.1	69.9
with multiplier	N/A	36.4	40.7	44.7	48.7	52.2	55.5	60.1	69.9
Seat km/tfuel	**73,846**	**74,899**	**78,829**	**84,197**	**88,557**	**93,692**	**96,901**	**98,112**	**####**
Efficiency gain in Seat km/tfuel relative to 2005	**N/A**	**1%**	**7%**	**14%**	**20%**	**27%**	**31%**	**33%**	**36%**
Equivalent p.a. efficiency gain relative to 2005	**N/A**	**0.3%**	**0.7%**	**0.9%**	**0.9%**	**1.0%**	**0.9%**	**0.8%**	**0.7%**
of which due to ATM improvements	N/A	0.4%	0.4%	0.4%	0.3%	0.2%	0.2%	0.2%	0.1%
of which due to Engine and Airframe	N/A	-0.1%	0.3%	0.5%	0.6%	0.7%	0.7%	0.6%	0.6%
Revenue Passenger km/tFuel	**57,648**	**58,007**	**63,962**	**70,508**	**75,477**	**81,558**	**86,359**	**88,964**	**93,606**
Efficiency gain in RPkm/tFuel relative to 2005	**N/A**	**1%**	**11%**	**22%**	**31%**	**41%**	**50%**	**54%**	**62%**
Equivalent p.a. efficiency gain relative to 2005	**N/A**	**0.1%**	**1.0%**	**1.4%**	**1.4%**	**1.4%**	**1.4%**	**1.2%**	**1.1%**
of which due to ATM improvements	N/A	0.4%	0.4%	0.4%	0.3%	0.2%	0.2%	0.2%	0.1%
hich due to Engine and Airframe + Higher Load Factors	N/A	-0.3%	0.7%	1.0%	1.1%	1.2%	1.2%	1.1%	1.0%

Figure 15.1 Example Model Outputs

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