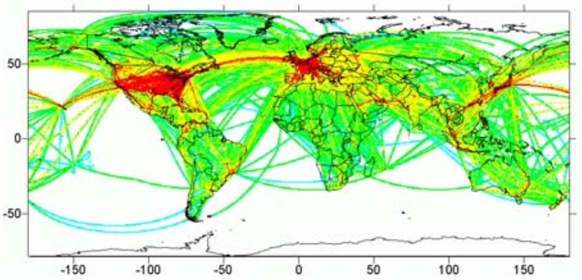
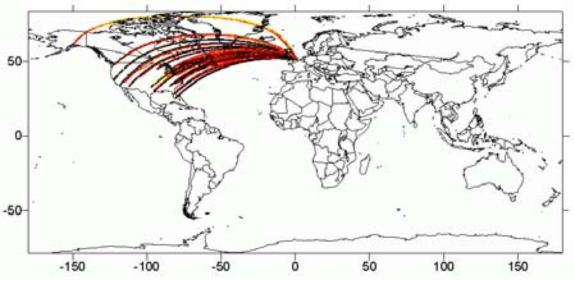
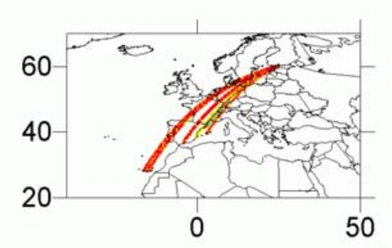
Study on the Allocation of Emissions from International Aviation to the UK Inventory – CPEG7

Final Report to DEFRA Global Atmosphere Division







Allocation of International Aviation Emissions from Scheduled Air Traffic – Future Cases, 2005 to 2050 (Report 3 of 3)

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Executive Summary

This report is the third of three, which examine options for allocation of international aviation emissions of carbon dioxide (CO_2) from scheduled air traffic as part of a study conducted by Manchester Metropolitan University for the UK Department of Environment, Food and Rural Affairs (DEFRA).

This study has used a global model of aircraft movements and emissions (FAST) to calculate future emissions for the time period 2000 to 2050 and to allocate international aviation emissions to Parties according to allocation options 3, 5, 6 and 8 of the United Nations Framework Convention on Climate Change's (UNFCCC) Subsidiary Body for Scientific and Technological Advice (SBSTA).

Future emissions were calculated with a sophisticated global aviation inventory model, FAST, by using external data on projections of revenue passenger kilometres (RPK) to 2050. Each aircraft type in the FAST model is defined by a seat-capacity banding, so that RPK data could be used to determine the necessary size of the global fleet and its subsequent emissions, incorporating future projections of fuel efficiency. Regional forecasts of RPK data to 2020 were used from the projections of the International Civil Aviation Organization's (ICAO) Forecasting and Economic Support Group (FESG) to calculate emissions in 2005, 2010, 2015 and 2020. After 2020, global RPK projections to 2050 were calculated using a non-linear Verhulst logistic model using the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (SRES) GDP projections, A1 and B2, to calculate emissions for 2030, 2040 and 2050. These particular SRES scenarios were chosen, as these are the 'baselines' against which current assessments of mitigation are being undertaken by the IPCC. These aviation scenarios were designated FAST-A1 and FAST-B2. International aviation emissions for all these projections were allocated according to SBSTA options 3, 5, 6 and 8.

The results presented here represent an update on aviation emissions scenarios of CO_2 to 2050 made in a consistent manner with those from the IPCC's 1999 Special Report '*Aviation and the Global Atmosphere*', which used the older IPCC IS92 GDP projections. Global aviation emissions of CO_2 in 2050 were calculated to be 2,971 Tg or 1,996 Tg according to scenarios FAST-A1 and FAST-B2, respectively. These results compare with the IPCC's previous estimates of 1,440 Tg CO_2 for Fa1 (mid) and 2,302 Tg CO_2 for Fe1 (high).

International and domestic emissions were calculated according to the SBSTA allocation options 3, 5, 6 and 8, and provided by individual country, Annex I countries, and the EU25. For the EU25, options 3, 5 and 6 gave rather similar results, generally within less than 15% of each other. For the largest emitters of aviation CO_2 across Europe, the variation was less than 5% between these allocation options. Allocation option 8 gave very different results as it is based on airspace.

In terms of the UK CO_2 budget in 2050, the contribution of aviation emissions represented approximately 43% of the UK's targeted emissions according to FAST-B2 and 65% according to FAST-A1, if international aviation emissions are included. The headline data for the UK and total European 25 Member States are given in the tables below for domestic and international emissions according to options 3, 5, 6, and 8.

Domestic and international allocated aviation emissions (methods 3, 5, 6 and 8) of CO_2 (Gg CO_2 yr^{-1}) 2005 – 2050, scenarios A1 and B2 for the UK

	Domestic Gg CO_2 yr^{-1}	Option 3 Gg CO_2 yr^{-1}	Option 5 Gg CO_2 yr^{-1}	Option 6 Gg CO_2 yr^{-1}	Option 8 Gg CO_2 yr^{-1}
UK 2005	2,479	22,339	22,429	21,984	4,517
UK 2010	3,102	28,874	28,996	28,429	5,668
UK 2015	3,977	38,494	38,654	37,985	7,116
UK 2020	4,526	45,177	45,359	44,544	7,909
UK 2030 (FAST-A1)	6,752	76,047	76,369	75,166	12,972
UK 2040 (FAST-A1)	9,209	107,045	107,517	105,845	18,179
UK 2050 (FAST-A1)	12,643	151,930	152,629	150,309	25,684
UK 2030 (FAST-B2)	5,570	62,739	63,004	62,012	10,702
UK 2040 (FAST-B2)	7,911	91,951	92,357	90,921	15,615
UK 2050 (FAST-B2)	8,496	102,097	102,567	101,007	17,260

Domestic and international allocated aviation emissions (methods 3, 5, 6 and 8) of CO_2 (Gg CO_2 yr^{-1}) 2005 – 2050, scenarios A1 and B2 for the EU25 total

	Domestic[1] Gg CO_2 yr^{-1}	Option 3 Gg CO_2 yr^{-1}	Option 5 Gg CO_2 yr^{-1}	Option 6 Gg CO_2 yr^{-1}	Option 8 Gg CO_2 yr^{-1}
EU25 2005	15,322	80,488	81,940	78,247	40,719
EU25 2010	18,847	103,662	103,530	79,027	41,300
EU25 2015	23,389	130,409	132,734	100,664	63,534
EU25 2020	27,086	155,595	155,419	118,183	75,965
EU25 2030 (FAST-A1)	40,409	256,197	255,865	194,622	116,439
EU25 2040 (FAST-A1)	55,111	357,638	357,222	271,559	160,729
EU25 2050 (FAST-A1)	75,682	503,276	502,761	382,299	223,539
EU25 2030 (FAST-B2)	33,337	211,363	211,088	160,564	96,062
EU25 2040 (FAST-B2)	47,340	307,211	306,853	233,269	138,066
EU25 2050 (FAST-B2)	50,858	338,202	337,855	256,905	150,218

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[1] Domestic in this case means the sum of domestic air traffic emissions from EU25 States, not intra-EU25 emissions

1 Introduction

This is the third of three final reports to DEFRA that consider the allocation of international aviation emissions of carbon dioxide (CO_2) to Parties and specifically, the UK and European Union (EU, in particular the enlarged EU25). The focus of this report is projections of aviation CO_2 emissions for the years 2005, 2010, 2015, 2020, 2030, 2040 and 2050.

Air traffic and its associated CO_2 emissions have been quantified for 1990 and 2000 by Owen and Lee (2005) and Lee *et al*. (2005) under a variety of allocation options suggested by the United Nations Framework Convention on Climate Change's (UNFCCC) Subsidiary Body on Science and Technological Advice (SBSTA) (see section 2).

For this study, scenarios of global emissions of CO_2 were created to the year 2050. Up until 2020, air traffic statistics of Revenue Passenger Kilometres (RPK) were taken from the International Civil Aviation Organization's (ICAO) Forecasting and Economic Support Group (FESG), who have provided detailed regional traffic forecasts (Wickrama *et al*., 2003) for the sixth quadrennial meeting of ICAO's Committee on Aviation Environmental Protection (CAEP). This is hereafter referred to as the FESG/CAEP-6 forecast.

After 2020, a different approach was required for providing predictions of traffic and emissions. The FESG had previously assisted the Intergovernmental Panel on Climate Change in formulating global aviation emission scenarios for the IPCC's Special Report '*Aviation and the Global* Atmosphere' (IPCC, 1999). The approach developed by the FESG (1998) was used in this work in order to provide updated aviation scenarios of CO_2 according to different GDP projections formulated by the IPCC in their 'Special Report on Emission Scenarios' (SRES) (IPCC, 2000).

From these forecasts of RPK, emissions can be calculated that account for changes in technology and efficiency of passenger management in the global fleet, and these emissions can be allocated via different SBSTA options.

In **Section 2**, an overview of the allocation options is given; in **Section 3**, the modelling approach is described. In **Section 4**, the results are presented for the years 2005 through to 2050 – in five-yearly intervals to 2020 and decadal increments to 2050. In **Section 5**, the results are discussed in terms of other aviation scenarios, the implications of the data for the UK inventory, and an analysis of some of the uncertainties in both the data and the modelling. Finally, in **Section 6**, conclusions are drawn and recommendations made.

2 Allocation methods and methodological approaches taken

Greenhouse gas (GHG) emissions from international aviation are not included in the Kyoto Protocol as no methodology for allocating emissions to Parties has been agreed. The Conference of the Parties (COP) to the UNFCCC adopted the Kyoto Protocol in 1997 and it entered into force on 16th February 2005 committing Annex I Parties to legally binding targets to limit or reduce their GHG[2]. Six greenhouse

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[2] See http://unfccc.int/essential_background/kyoto_protocol/items/3145.php

gases are included in the Kyoto Protocol; CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorcarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). The reduction targets are for the period 2008 – 2012 relative to the base year[3] and relate to emissions arising from economic activities that take place within national territories and are reported to the UNFCCC. The Kyoto Protocol was ratified by the EU on 31st May 2002 and overall, the EU (i.e. the EU15, as opposed to the enlarged EU25) has a target to reduce GHG emissions by 8 per cent. Under the EU's burden sharing agreement the UK has agreed to reduce GHG emissions by 12.5 per cent.

Parties that ratified the Kyoto Protocol are required to submit annual GHG inventories to the UNFCCC in order to monitor progress towards their targets. The IPCC has issued guidance on how to compile such inventories (IPCC, 1996). However, whilst quantification of aviation emissions is possible, the methodology for the *allocation* of international emissions from aviation and shipping to Parties is not yet resolved. Under Article 2, paragraph 2 of the Kyoto Protocol states; "*The Parties included in Annex I shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively*".

Domestic aviation emissions have no such problematic allocation since the emissions arising from a flight departing and arriving in the same country are allocated to that country and are included in national inventories. The difficulty of defining how international emissions are allocated was recognised early on in the UNFCCC process and the UNFCCC SBSTA was presented with a number of initial options for allocation of international aviation and marine bunker fuels (UNFCCC, 1996) as follows:

- Option 1—No allocation;
- Option 2—Allocation of global bunker sales and associated emissions to parties in proportion to their national emissions;
- Option 3—Allocation according to the country where the bunker fuel is sold;
- Option 4—Allocation according to the nationality of the transporting company, or to the country where an aircraft or ship is registered, or to the country of the operator;
- Option 5—Allocation according to the country of departure or destination of an aircraft or vessel; alternatively, emissions related to the journey of an aircraft or vessel shared by the country of departure and the country of arrival;
- Option 6—Allocation according to the country of departure or destination of passengers or cargo; alternatively, emissions related to the journey of passengers or cargo shared by the country of departure and the country of arrival;
- Option 7—Allocation according to the country of origin of passengers or owner of cargo;
- Option 8—Allocation to a party of all emissions generated in its national space.

In reviewing the options listed above, SBSTA recommended that options 1, 3, 4, 5 and 6 should form the basis of further work (UNFCCC, 1997).

Allocation allows a transparent and simple mechanism by which emissions can be assigned to Parties. It is important to draw a distinction between *allocation* of emissions to Parties and *assignment* or

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[3] The Kyoto base year is 1990 for CO_2, CH_4 and N_2O and, for the UK, 1995 for fluorinated gases.

distribution of emissions permits. Unfortunately, the two terms tend to be used differently by different communities, e.g. the EU refers to distribution of emissions permits in '*national allocation plans*' (Wit *et al*., 2004). In this report, the term '*allocation*' is used with reference to assignment of emissions to Parties in the UNFCCC sense of being responsible for them; not the assignment of emission permits in a trading scheme.

In terms of the emissions from aviation, CO_2 is the most important of the six GHG regulated under the Kyoto Protocol. Of the other five gases, only small amounts – if any – of CH_4 and N_2O are emitted by aircraft engines. This issue will be returned to in Section 5.2.

However, whilst aircraft emissions of CO_2 are considered in the context of Kyoto, there are other emissions and effects from aviation that are thought to impact upon climate change. This issue was reviewed in an IPCC Special Report, '*Aviation and the Global Atmosphere*', (IPCC, 1999) and updated quantitatively by Sausen *et al*. (2005). The implications of the non-CO_2 emissions for aviation are considered in more detail in terms of other allocation options (Lee *et al*., 2005).

3 Modelling

In this section, the modelling of future aviation CO_2 emissions is described. This was performed using the FAST model (Lee *et al*., 2005). It was also necessary to process and derive other data in order to use FAST in forecast/scenario mode, which is described in detail here. In this work, simple definitions of forecasts and scenarios are used, consistent with those of IPCC (1999) – a forecast is defined as an extrapolation of present day conditions under certain (given) assumptions, whereas a scenario is dependent on a top-down analysis of some global conditions, from which traffic and emissions can be calculated. This is equivalent to the definitions given by the IPCC (Henderson *et al*., 1999). The *modus operandi* for forecasts and scenarios are identical in the model but for scenarios, the input data are usually derived in a different way to forecasts.

3.1 FAST model and external data

The FAST model has been described in detail by Lee *et al*. (2005) so that only a short overview is necessary here. The model requires a global inventory of aircraft movements and their frequency, to which parameterisations of fuel flow are applied – the fuel flow being calculated from an external model, PIANO (Simos, 1993; 2004) – in order to derive gridded 3D emissions of CO_2/NO_x. Individual flight emissions are calculated on a 3D grid of variable resolution and built up to provide monthly and annual distributions. Gridded data of, e.g. NO_x and km travelled, whilst not necessary for this study, are required for chemistry calculations of aviation NO_x emissions on O_3 and CH_4, and distance-travelled used as input to contrail calculations.

In order to use FAST to generate a future forecast or scenario, representative aircraft are mapped to seat capacity bands to generate generic types of future aircraft. This then allows the fleet to be grown by specified factors across routes or regions (which may be defined) in line with traffic demand derived from external data on RPK, accounting for any improvement in fuel and traffic efficiency by factoring the fuel consumption on individual generic aircraft types.

The key external data to such an exercise are global RPK, fuel and traffic efficiency factors, and the regional breakdown of such data.

3.2 Overview of methodology for traffic projections

The objective of this exercise was to create global inventories of aviation emissions of CO_2 that were consistent with recognised, up to date, external data on RPK and GDP scenarios that could be used to calculate international emissions allocations according to SBSTA (1997) methodologies.

Global aviation CO_2 emissions have previously been calculated by the FESG (1998) for the IPCC (1999) Special Report by using forecasts of traffic and emissions to 2015 and thereafter applying a model of the relationship between RPK and GDP to 2050. At a global level, there is a good historical relationship between RPK and GDP. Thus, using a model of the historical relationship allows an extrapolation of this if GDP data are available, to obtain future global RPK. Previously, the FESG (1998) used GDP data from the IPCC's IS92 scenarios; specifically, IS92a, IS92c and IS92e, representing mid range, low and high growth rates, respectively (Henderson *et al*., 1999).

More up to date data have become available since the IPCC (1999) report such that the FESG (1998) scenarios could be updated in order to calculate international emission allocations. The same basic approach as that of the FESG (1998) was taken, except that instead of using a proprietary forecast of air traffic to 2015, a publicly available ICAO forecast of RPK to 2020 (Wickrama *et al*., 2003) was used. Thereafter, the same methodology of FESG (1998) to derive global RPK to 2050 was utilised, using more recent SRES-based GDP scenarios from the IPCC (IPCC, 2000). The resultant global RPK may then be translated to regional flows and converted to fuel usage and emissions of CO_2 according to similar methods as employed by FESG (1998).

In the following sections, the detailed data and approaches taken are described.

3.3 Methodology for traffic projections to 2020

3.3.1 Scheduled traffic to 2020

The Report of the FESG/CAEP-6 Traffic and Fleet Forecast Sub-Group (Wickrama *et al*., 2003) provides the basis of the forecast scenarios up to 2020. The FESG/CAEP-6 forecasts were kindly provided by the Sub-Group with a detailed spreadsheet (Larry Gray, personal communication) that gave forecast SKO (seat kilometres offered) and RPK up to 2020. A breakdown of RPK and SKO with regard to aircraft seat bandings and regional flows was also provided. The global data are summarised in Table 1 and shown in Figure 1. Regionalised RPK forecast data are given in Table 2. Figure 1 shows the difference between SKO and RPK, which reflects the assumed increased load efficiencies given in Table 1.

Table 1: Overview of FESG/CAEP-6 Long Term Global Forecasts

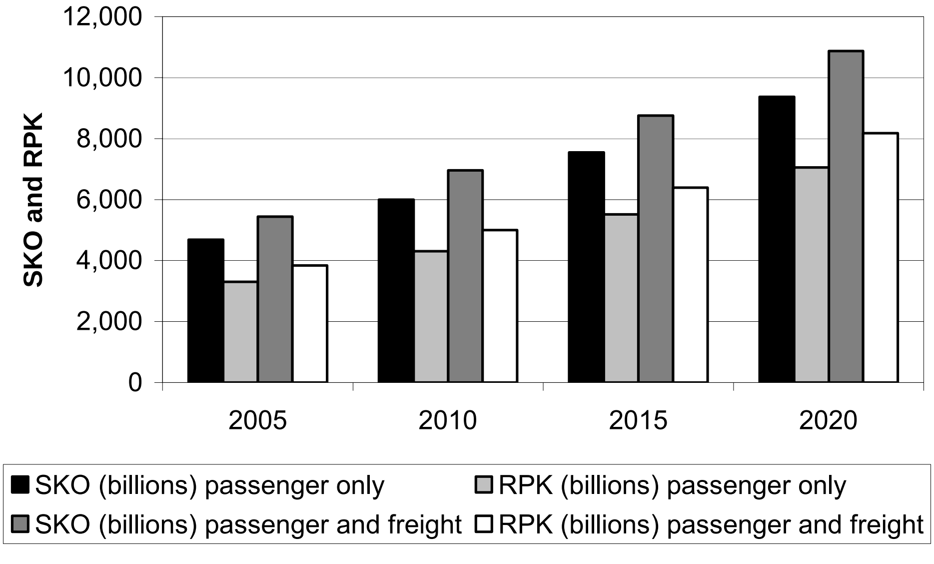
	2005	2010	2015	2020
Load factor (%)	71%	72%	73%	74%
SKO (billions*) Passengers only	4,685	5,998	7,542	9,365
RPK (billions) Passengers only	3,304	4,312	5,508	7,050
SKO (billions) Passenger and freight	5,434	6,958	8,749	10,863
SKO (billions) Passenger and freight	3,833	5,002	6,389	8,178

* billions = 1 × 10^9

Table 2: FESG/CAEP-6 Route Group Forecasts (billion RPK)

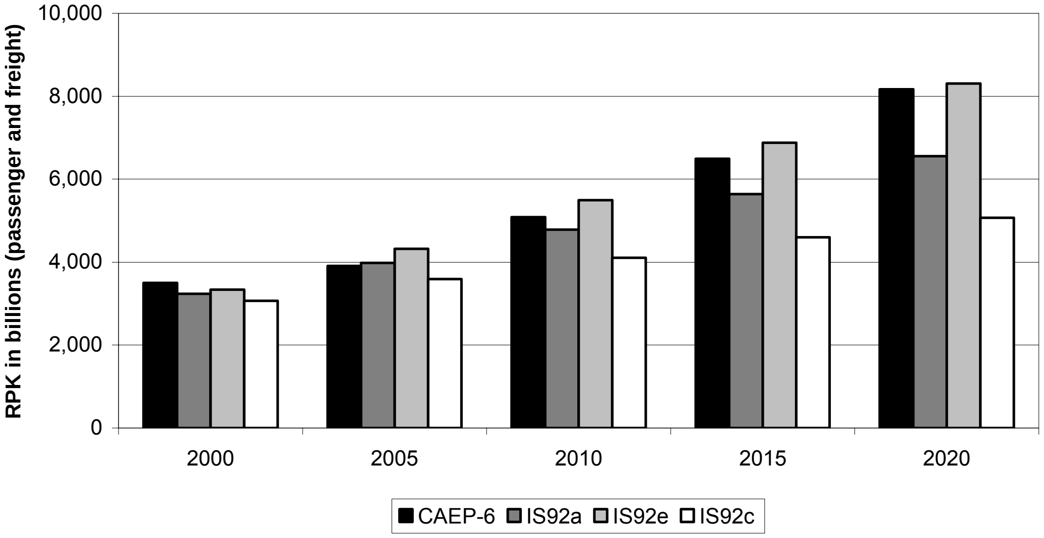
Route Group	Code	2002	2005	2010	2015	2020
Domestic Africa	XDA	14	15	18	23	28
Domestic Europe	XDE	86	92	119	151	191
Domestic Asia-Pacific	XDF	223	248	348	478	657
Domestic Latin America	XDL	62	64	80	96	117
Domestic Middle East	XDM	13	13	17	21	26
Domestic North America	XDN	802	809	958	1,112	1,292
Total domestic		*1,200*	*1,246*	*1,552*	*1,892*	*2,312*
Europe – Middle-East	XEM	57	59	75	94	116
Europe – Far East	XEP	228	256	361	499	691
Africa	XLA	14	15	19	25	31
Asia-Pacific	XLF	288	318	441	597	810
Middle East	XLM	11	12	15	20	25
North America	XLN	29	29	36	43	51
Latin America	XLS	23	25	33	42	55
South Atlantic	XSA	51	54	71	91	117
North Atlantic	XNA	388	408	519	646	805
North America – Central America	XNC	74	79	103	132	170
Europe – Africa	XNO	90	96	126	160	205
North America – South America	XNS	37	40	52	68	87
Other International Flows	XOI	89	95	124	159	204
Mid Atlantic	XMA	54	59	81	109	146
Trans-Pacific	XTP	224	248	344	467	634
Europe	XWE	236	256	343	449	590
Total international		1,894	2,054	2,751	3,607	4,738
Global		3,094	3,304	4,312	5,508	7,050

Figure 1: FESG/CAEP-6 Long Term Global Forecasts, SKO and RPK 2005 to 2020



The FESG/CAEP-6 forecasts were compared with the previous FESG (1998)/IPCC (1999) forecasts of RPK (which are discussed in more detail in the following section). The FESG/CAEP-6 forecasts were developed in May 2003 and accounted for the decline in growth rates, reflecting the impacts of industry downturn, 9/11 and SARS outbreaks. Thus, the estimated growth rates for the period 2000 – 2005 reflect these factors. This comparison (see Figure 2) shows that after 2005, the FESG expect growth to recover (as already witnessed post 2003) and that growth rates will be comparable with the IS92e (high) growth scenario to 2020.

Figure 2: Comparison of FESG/CAEP-6 Long Term Global Forecasts with IPCC forecasts (RPK in billions)



In the next step, the regional flows given in Table 2 needed to be related to the region-to-region flows in FAST, and the relationships given in Table 3 were used. FAST works on definitions of regional flows, i.e. 'region 1 to region 2'. These regions are in turn defined by the underlying country database. The 'codes' in Tables 2 and 3 refer to FESG/CAEP-6 forecast codes and how they have been used to correspond to FAST regions.

Table 3: Region to region and route group forecasts

Code	Region 1	Region 2
XLA & XDA	AFRICA	AFRICA
XWE & XDE	EUROPE	EUROPE
XLF & XDF	ASIA	ASIA
XLS & XDL	LATIN AMERICA	LATIN AMERICA
XLM & XDM	MIDDLE EAST	MIDDLE EAST
XLN & XDN	NORTH AMERICA	NORTH AMERICA
XMA	EUROPE	LATIN AMERICA
XNA	EUROPE	NORTH AMERICA
XNC & XNS	NORTH AMERICA	LATIN AMERICA
XNO	EUROPE	AFRICA
XSA	LATIN AMERICA	AFRICA
XTP	NORTH AMERICA	ASIA
XEM	EUROPE	MIDDLE EAST
XEP	EUROPE	ASIA
XOI	OTHER	OTHER

In order to utilise the region-to-region flows given in Table 3, they were assigned to aircraft seat bandings; i.e. the seat capacities of aircraft which reflect their size. Representative aircraft types were assigned according to each seat banding, which was based upon the prevalence of existing aircraft: this correspondence is given in Table 4.

The required inputs to the model were forecasts of SKO, so that information on SKO and passenger capacity is also required and these data were provided in the underlying data to the FESG/CAEP-6 forecasts. The load factors increased from 70% in the base year of 2002 to 74% in 2020.

Table 4: Representative aircraft and seat bandings according to technology classes[4]

Seat Band	Tech. 1	Tech. 2	Notes, and other aircraft represented
20 – 49	PROP6		DHC8-100
50 – 99	F100	DC9	E145; BAE146; PROP7; CRJ100; J328; RJ85; TU134; BAC111; B707; B7272
100 – 150	B7375	B7372	A319; B717; B7376; B7377; A320; MD80; YK42
151 – 210	B7572	DC8	TU154B; TU154M; B7378; MD90; A321;B7673
211 – 300	A300		B7672; A310; B7674; L1011; DC10; B7573; A3402
301 – 400	B7772		MD11; A3405; A3403
401 – 500	B7474		B7471; B7472; B7473
501 – 600	B7473		NO B7473 in PIANO so use B7474 instead
601 – 650	B7473		NO B7473 in PIANO so use B7474 instead

3.3.2 Freight traffic to 2020

In order to provide future fleet predictions, the carrying capacity of freight also needs to be considered. The FESG/CAEP-6 forecast does not explicitly separate out freighter aircraft and freight carried in scheduled passenger aircraft but rather represents passenger SKO/RPK only. Reference is made in the FESG/CAEP-6 report (Wickrama *et al*., 2003) to freight forecasts made for the ICAO CAEP-5 meeting, but these show projections of aircraft being used for freight only and not the number of tonne kilometres. The 2000 OAG movement database used as the base data in this work includes freighter movements but does not identify them directly.

Thus, the following simplified method was devised. A comparison of the time series of RPK used in the FESG (1998)/IPPC (1999) work (1970 to 1995) was compared with the ICAO RPK (passenger movements only) for the same period. A linear relationship was found between the two data sets (see Figure 3) and a factor of 1.16 was derived that was taken to represent the freighter movements (in terms of RPK) in the FESG (1998)/IPCC (1999) data. This factor was applied for all years and all scenarios.

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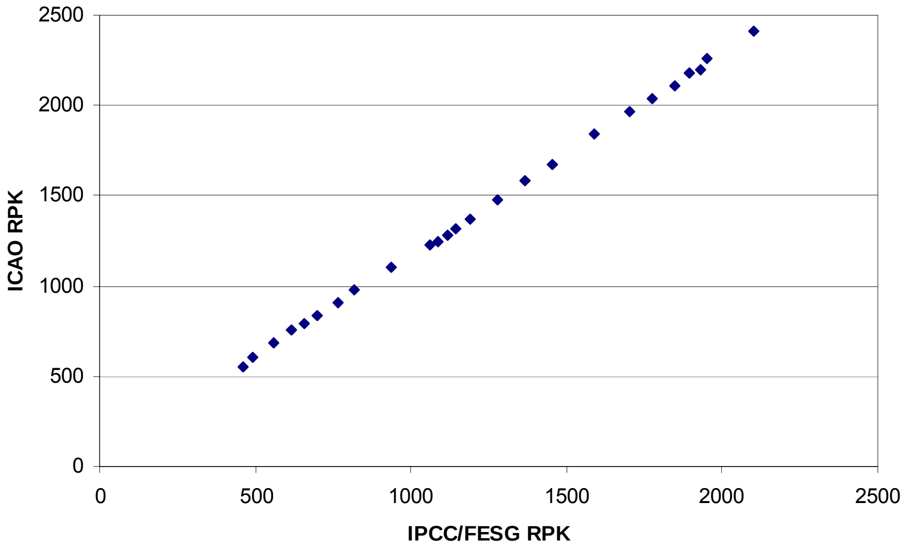
[4] A commonly employed method of discriminating technology classes for emissions forecasts (e.g. Gardner *et al*., 1998) is to designate newer technologies (Tech. 1) and older technologies (Tech. 2) according to ICAO noise discriminators (Chapter 2 and 3, equating to ‘old’ and ‘new’, respectively)

Figure 3: Scatter plot of RPK (in billions) statistics (ICAO passenger only, IPCC passenger and freight)



3.4 Methodology for traffic projections from 2020 to 2050

3.4.1 Projections beyond 2020 to 2050

The FESG/CAEP-6 report (Wickrama *et al.*, 2003) and data provides forecasts of air traffic to 2020 only. However, projections for 2030, 2040 and 2050 were also required for this work. The approach taken to project traffic data to 2050 is similar to the methodology employed by FESG (1998) for the IPCC (1999) aviation Special Report and is detailed in this section.

3.4.2 IPCC projections

Global Demand Projections: The IPCC (1999) used forecasts from FESG (1998). A relationship was first derived between RPK and GDP using historical data from the period 1960 to 1995. A single global model of traffic demand per unit of GDP was then developed based on a non-linear regression model, a 'Verhulst' logistic function of the form:

$$y = \left[\frac{b_1}{1 + b_3 EXP(-b_2 x)} \right] \qquad [1]$$

where b_1, b_2 and b_3 are coefficients. The equation used by FESG (1998) was:

$$\frac{RPK}{GDP} = \left[\frac{26.24}{1 + 9.04 EXP(-0.073t)} \right] \qquad [2]$$

where t = time in years, GDP is in \$US, and RPK (10^9).

Growth rates from the model were applied to 1995 reported world traffic demand (Boeing, 1996) – together with GDP growth rates from the IPCC IS92a, IS92c and IS92e scenarios – to reproduce the FESG (1998) base case (Fa), low (Fc) and high (Fe) scenarios of traffic demand.

Regional distribution of projections: Global traffic from the model projections was apportioned over 45 regional traffic flows with a separate market share model (IPCC, 1999). The underlying assumption of this procedure was that each route group share of the total approaches its eventual share of the market asymptotically. Mature markets tend to have declining shares approaching an asymptotic value, whereas, developing markets tend to increase their shares. This procedure was undertaken using a Boeing proprietary model and the methods and assumptions used were not documented, which meant that this procedure could not be repeated in the context of this present study.

3.4.3 Scenario methodology 2020 to 2050

Ideally, the scenarios in this study were to draw upon the work undertaken in the IPCC Report (summarised above). That is, using the same basic methodology but updating the logistic growth curve with the most recent RPK statistics and then replacing the IS92 GDP growth assumptions with the more recent SRES (IPCC, 2000) GDP growth assumptions.

However, this proved to be not possible for a number of reasons. Firstly, problems were encountered in repeating the derivation of the logistics growth curve using available ICAO traffic statistics of RPK from 1960 to 1995. A similar, but not identical relationship was derived which provides a similar growth pattern. Using the same non-linear regression model, a second logistics growth curve was derived using published ICAO RPK statistics and UN GDP statistics (from 1970 to 2000)[5].

$$\frac{RPK}{GDP} = \left[\frac{0.134}{1 + 2.433EXP(-0.064t)}\right] \qquad [3]$$

Application of Equation 3 to the FESG/CAEP-6 2020 forecast together with the IS92a, c and e GDP growth assumptions produced projections similar to those of the FESG (1998) (see Table 5). This confirms that the recalculated function (Equation 3) produced a comparable outcome to the original function (Equation 2), when applied to the same base figure (the CAEP-6 2020 forecast) and using the same GDP growth assumptions (i.e. IS92a, c and e) and thus we are confident in using the new equation.

Table 5: RPK forecasts for 2050 using different source data

	Forecast RPK (10^9) using derived logistic function* and 2020 CAEP base year	Forecast RPK (10^9) using original IPCC logistic function and 2020 CAEP base year	Published FESG RPK (10^9) data (FESG, 1998)
2050, IS92a (2.3% growth)	15,039.2	15,212.6	13,933.5
2050, IS92e (3% growth)	18,453.2	18,666.0	21,978.2
2050, IS92c (1.2% growth)	10,873.5	10,998.9	7,817.2

** derived from ICAO statistics and UN GDP statistics from 1970 to 2000*

ICAO statistics http://www.airlines.org/econ/d.aspx?nid=8144 accessed July 2004

UN GDP statistics http://unstats.un.org/unsd/snaama/selectionbasicFast.asp accessed July 2004

Using the FESG/CAEP-6 forecast for 2020 as the starting point for extrapolation (rather than the Boeing 2015 forecast of RPK as in the previous FESG/IPCC work) provides a larger 2050 RPK figure than both the Fe and Fc FESG (1998) forecasts. It is, however, approximately 15% lower than the Fe FESG (1998) forecast for 2050. This is because although the FESG/CAEP-6 forecast is likely to follow the FESG Fe high growth scenario, the interruption in growth trends during the 2000-2003 period as a result of 9/11 and SARS etc. has meant that the 2020 forecasts have been adjusted downwards. Having determined that the logistic function [3] produces similar growth patterns to the original FESG/IPCC model, it was used to provide projections of RPK from 2020 to 2050, using the SRES GDP growth scenarios A1 and B2.

The SRES scenarios A1 and B2 were chosen as the main ones for calculation of emissions and their allocation as IPCC is currently using these as 'baselines' against which mitigation possibilities are being considered by its Working Group 3. Selection of other SRES scenarios would give different results. A wider range is explored in terms of RPK projections (including A2 and B1) but the step from RPK to emissions involves much computation and hence the two main scenarios focussed upon A1 and B2 in terms of their GDP projections.

3.4.4 Application of SRES GDP scenarios to projections of RPK to 2050

SRES global GDP scenarios for the four main 'families' of scenarios (IPCC, 2000), A1M[6], A2, B1 and B2, are given in Table 6 and compared with the IS92a, c and e scenarios.

Table 6: Annual average percentage growth factors for GDP for main SRES and IS92 scenarios

	SRES				IS92		
	A1B	A2	B1	B2	a	c	e
1990 – 2020	3.37%	2.24%	3.13%	3.01%	2.9%	2.0%	3.5%
(IS92 1990 – 2025)							
1990 – 2100	2.98%	2.26%	2.54%	2.23%	2.3%	1.2%	3.0%

The SRES GDP data are provided at 10 yearly intervals between 1990 and 2100 on a global and regional basis, and the global data are given in Table 7.

Table 7: Annual average percentage growth factors for global GDP growth forecasts (IPCC, 2000)

SRES	1990 –2000	2000 –2010	2010 –2020	2020 –2030	2030 –2040	2040 –2050	2050 –2060
A1B	2.51%	3.55%	4.07%	4.66%	3.52%	3.71%	2.60%
A2	1.92%	2.38%	2.41%	2.36%	3.52%	1.21%	2.25%
B1	2.52%	3.38%	3.49%	3.35%	3.26%	3.02%	2.39%
B2	3.09%	3.16%	2.76%	2.67%	2.62%	2.50%	2.11%

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[5] Unfortunately, the FESG (1998) document does not give details of the RPK or GDP data utilised, so known sources (ICAO, UN) were used in this work.

[6] A1B (or A1B-AIM, in full) is the SRES 'marker' scenario for the A1scenario storyline and was calculated by the National Institute for Environmental Studies, Japan with the AIM model (Asia Pacific Integrated Model) (IPCC, 2000)

The global SRES GDP data were applied for the 2020–2050 period (ten year average growth rates used) to provide global projections of RPK. These are shown in Figure 4 for the four main SRES scenarios selected (A1B, A2, B1, B2) and tabulated in Table 8.

Figure 4: RPK forecasts 2020 – 2050 using Verhulst logistic function and SRES GDP growth assumptions

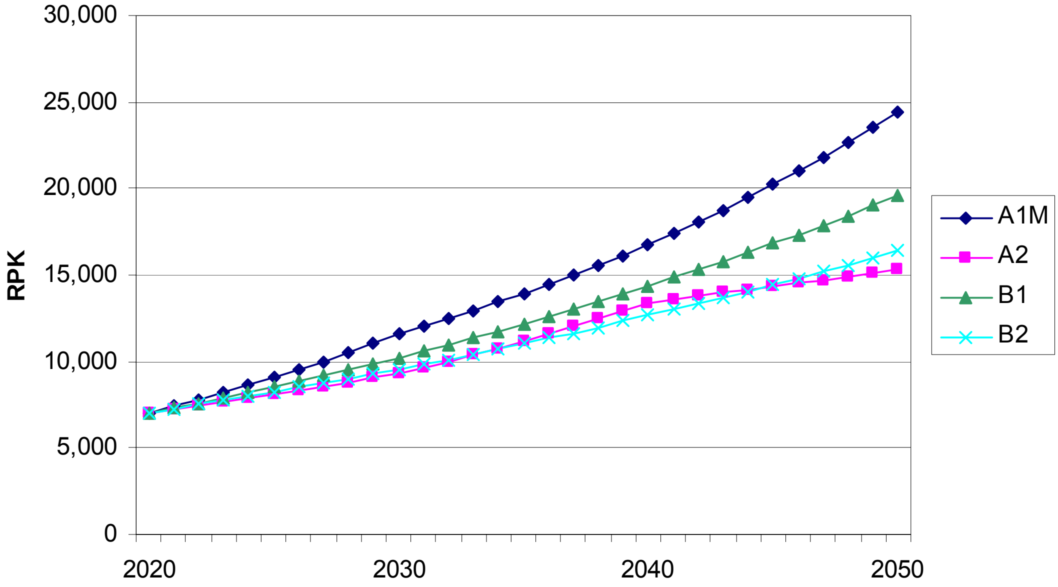


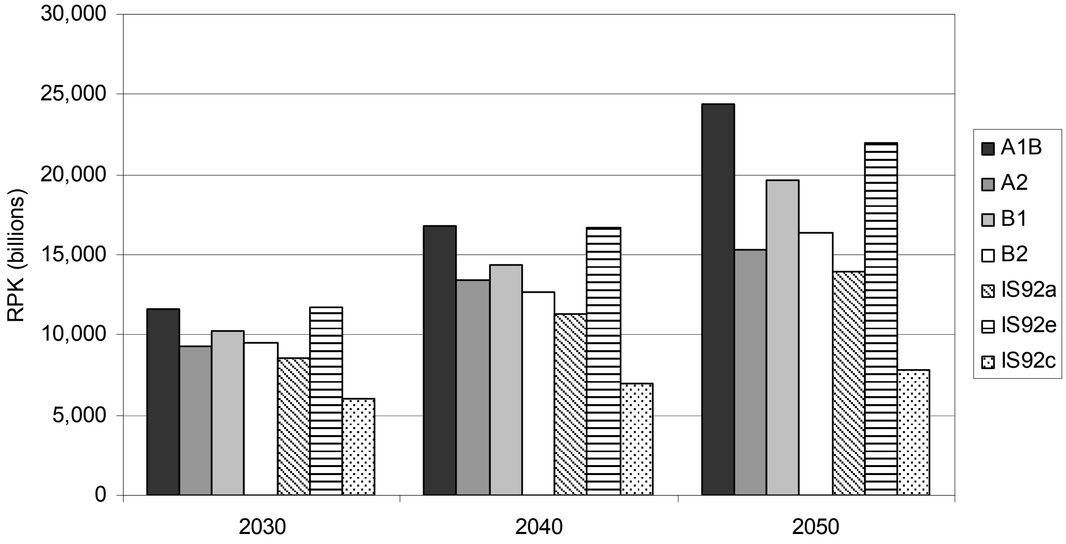
Table 8: SRES and IS92a, c, and e GDP growth forecasts for five and ten-year intervals [RPK in billions]

Year	A1B	A2	B1	B2	IS92a	IS92e	IS92c
2000	*3,017.9*	*3,017.9*	*3,017.9*	*3,017.9*	3,238.0	3,336.1	3,068.8
2005	*3,366.4*	*3,366.4*	*3,366.4*	*3,366.4*	3,981.4	4,322.4	3,591.9
2010	*4,381.1*	*4,381.1*	*4,381.1*	*4,381.1*	4,782.6	5,491.7	4,103.0
2015	*5,596.9*	*5,596.9*	*5,596.9*	*5,596.9*	5,638.6	6,876.2	4,596.1
2020	*7,041.6*	*7,041.6*	*7,041.6*	*7,041.6*	6,552.9	8,302.4	5,070.7
2030	11,583.1	9,279.7	10,209.3	9,557.1	8,592.7	11,727.0	5,981.4
2040	16,745.8	13,411.1	14,385.3	12,663.7	11,273.9	16,669.1	6,972.8
2050	24,406.6	15,310.2	19,601.1	16,401.1	13,933.5	21,978.2	7,817.2

The data in italics in Table 8 are from the FESG/CAEP-6 forecasts and are therefore the same for all four SRES scenarios to 2020. In Table 8, the projections made using the SRES GDP scenarios are compared with the published FESG (1998) scenarios. Up until 2020, the FESG/CAEP-6 forecasts are lower than the Fe (high GDP growth) scenario but, by 2020, higher than the Fa and c scenarios. After 2020, the A1 SRES scenario produces the highest growth with particularly strong GDP growth over the period 2020 – 2030 (see Figure 5).

Between 2020 and 2050, the projections made using the SRES GDP growth scenarios and the CAEP-6 2020 baseline show the A1M scenario overtaking the IS92e scenario to produce the highest 2050 projection. The A2 and B2 scenarios produce similar RPK projections to the Fa (medium growth) scenario in 2050. None of the selected SRES GDP scenarios resulted in projections as low as the Fc scenario.

Figure 5: Comparison of RPK (billions) forecasts using SRES and IS92 GDP growth assumptions



This comparison of the SRES-based traffic scenarios and the FESG (1998) IS92 scenarios is based upon different assumptions over and above the different implicit GDP growth assumptions. As discussed above, the SRES-based traffic scenarios were based on a newly derived Verhulst function and were applied to the FESG/CAEP-6 2020 baseline year. The FESG (1998) RPK data shown in Fig. 5 were derived from a different Verhulst function and applied to a 1995 baseline figure using IS92 GDP growth scenarios. Furthermore, the SRES 5 year growth projections were used in contrast to the average IS92 projections.

3.4.5 Regionalisation of scenario data

The FESG/CAEP-6 forecasts to 2020 were available on a regional basis. However, for 2030, 2040 and 2050 the global projections of RPK derived from the methodology described in section 3.4.3 also needed to be broken down into regional groups.

The RPK data that formed the basis for FESG/IPCC 2050 scenarios using the IS92 growth assumptions were available on a regional basis. These regional flows of RPK were determined using an in-house Boeing proprietary model and were therefore not transparent and could not be reproduced. In the absence of such a market-share model, the only course of action open was to disaggregate the global total regionally according to the proportions found in the original Wickrama *et al*. (2003) data for scenarios beyond 2020.

3.5 Fuel efficiency

Future trends in fuel efficiency improvements from the IPCC report (IPCC, 1999) are included in Table 9. Data to 2015 were based upon extrapolations of the results of analyses by Greene (1992) and Balashov and Smith (1992). These ‘efficiencies’ include improvements arising from the introduction of new aircraft into the fleet and changes to operating conditions and passenger management, i.e. not simply a change in engines but the overall operational efficiency of the engine/airframe/passenger management. A lower rate of fuel efficiency improvement for the period 2020 to 2050 was assumed based on the work of the DTI (Henderson *et al*., 1999).

The FAST model requires a fuel factor input that can be changed to account for future improvements in fuel efficiency of the aircraft. This is different to the *overall* fuel efficiency described above, as this relates only to the technological improvements and not changes in fleet or passenger management. However, the FESG/CAEP-6 forecast implicitly includes improvements in these latter effects.

Table 9: Fuel efficiency improvements assumed in percent per year

Period	Fuel efficiency improvement (percent yr^{-1})
2000 – 2010	1.3
2010 – 2020	1
2020 – 2050	0.5

For the purposes of this study, it was necessary to prescribe a fuel factor based on technological improvements independent of the operation of the fleet. A simplified approach has been taken based upon the estimates of new aircraft entering the fleet (Wickrama *et al.*, 2003) and assuming that these new aircraft have a 1% yr^{-1} improvement in fuel efficiency to 2020 (Henderson *et al*., 1999). Improvements to the fleet's fuel efficiency for existing aircraft (through modifications or in-life upgrades) are difficult to predict, but a constant global improvement value of around 0.4% yr^{-1} based on suggested improvements considered feasible up until 2025 was assumed by Eyers *et al*. (2004). These assumptions have resulted in the fuel efficiency assumptions, expressed as fuel factors, given in Table 10.

Table 10: Fuel factor assumptions applied to future periods

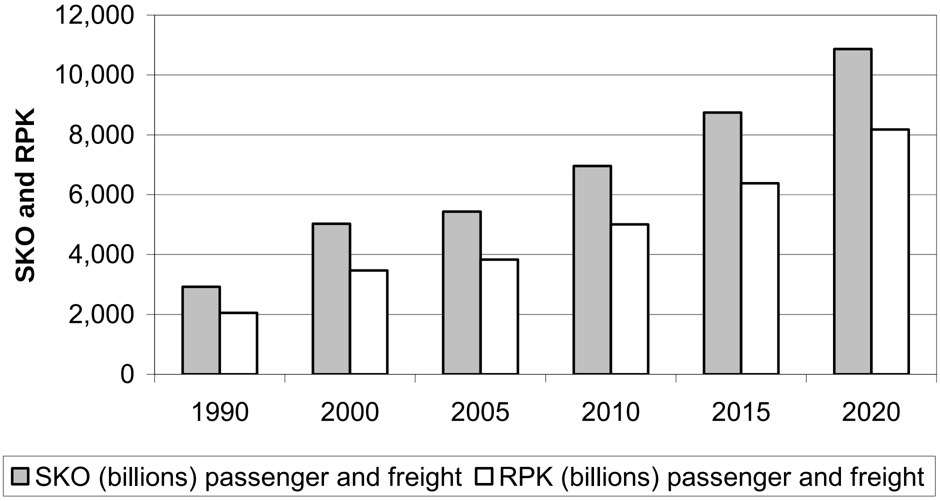
Period	Fuel factor
2000-2005	1
2005-2010	0.95
2010-2020	0.95
2020-2050	0.9

The overall improvements in fuel efficiency can be calculated from FAST output, which include improvements both from both technology (accounted for by the fuel factor input) and from air traffic management improvements and passenger capacity (accounted for by the FESG/CAEP-6 forecast data). These overall improvements are given in Table 11 and are comparable with the 'fuel efficiency' data given by IPCC (1999), although for the period 2000 – 2010 the resulting average annual improvements were lower because of the period of low growth experienced between 2000 – 2003. The fleet traffic efficiency in the base year 2000 was calculated to be 33.0 SKO per kg fuel. This is comparable with the previous DTI forecast for IPCC (1999) for 2002 of 34.1 SKO per kg fuel. The SKO and RPK forecasts are shown in Figure 6. The difference between the SKO and RPK represents the load factor, which is assumed to change over time from 70% to 74% from 1990 to 2020.

Table 11: Future trends in fuel efficiency improvements (percent per annum)

Period	Fuel efficiency from FAST (% yr^{-1})	Fuel efficiency from IPCC, 1999 (% yr^{-1})
2000 – 2010	1.1	1.3
2010 – 2020	1.0	1.0

Figure 6: SKO and RPK forecasts (billions), 1990 to 2020



4 Results

Having developed a method by which global air traffic emissions may be projected for various scenarios of GDP to 2050, this section of the report provides the results of the emissions calculations, and their allocation via SBSTA options 3, 5, 6 and 8.

4.1 Emissions projections: 2005 to 2050

The CO_2 emissions projections for 2005 through to 2050 via the different allocation methodologies are given in detail in a data appendix to this report (Owen and Lee, 2006) and are separately tabulated for all countries, EU25 States, and Annex I countries.

The data for the EU25 are given in Table 12 in terms of domestic and international emissions for 2005 through to 2050. In this table, allocation method 5 is the closest to ICAO, IEA and IPCC definitions of ‘international aviation’, and these data are utilised for this purpose.

The global totals are shown graphically in Figure 7 as a time series for domestic and international emissions (using the same definition of ‘international’ as above) for the scenarios A1 and B2.

Figure 7: Global emissions of aviation CO_2, split by domestic and international, SRES A1 and B2 scenarios, 1990 to 2050 (Tg CO_2 yr^{-1})

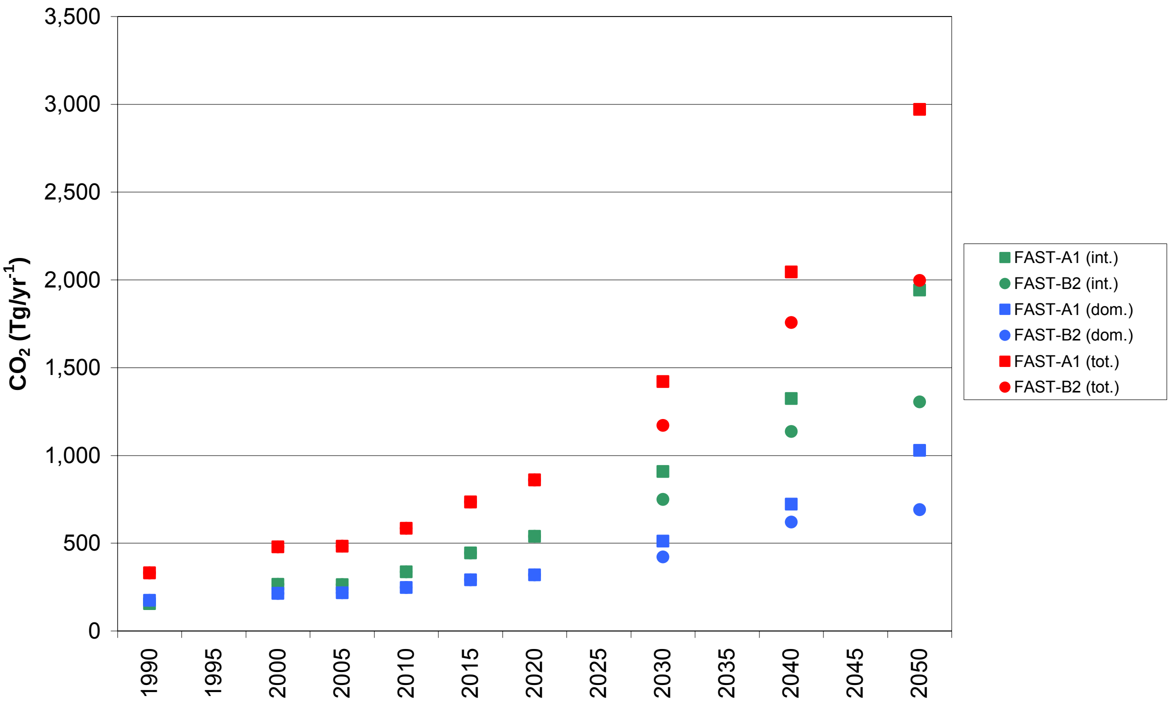
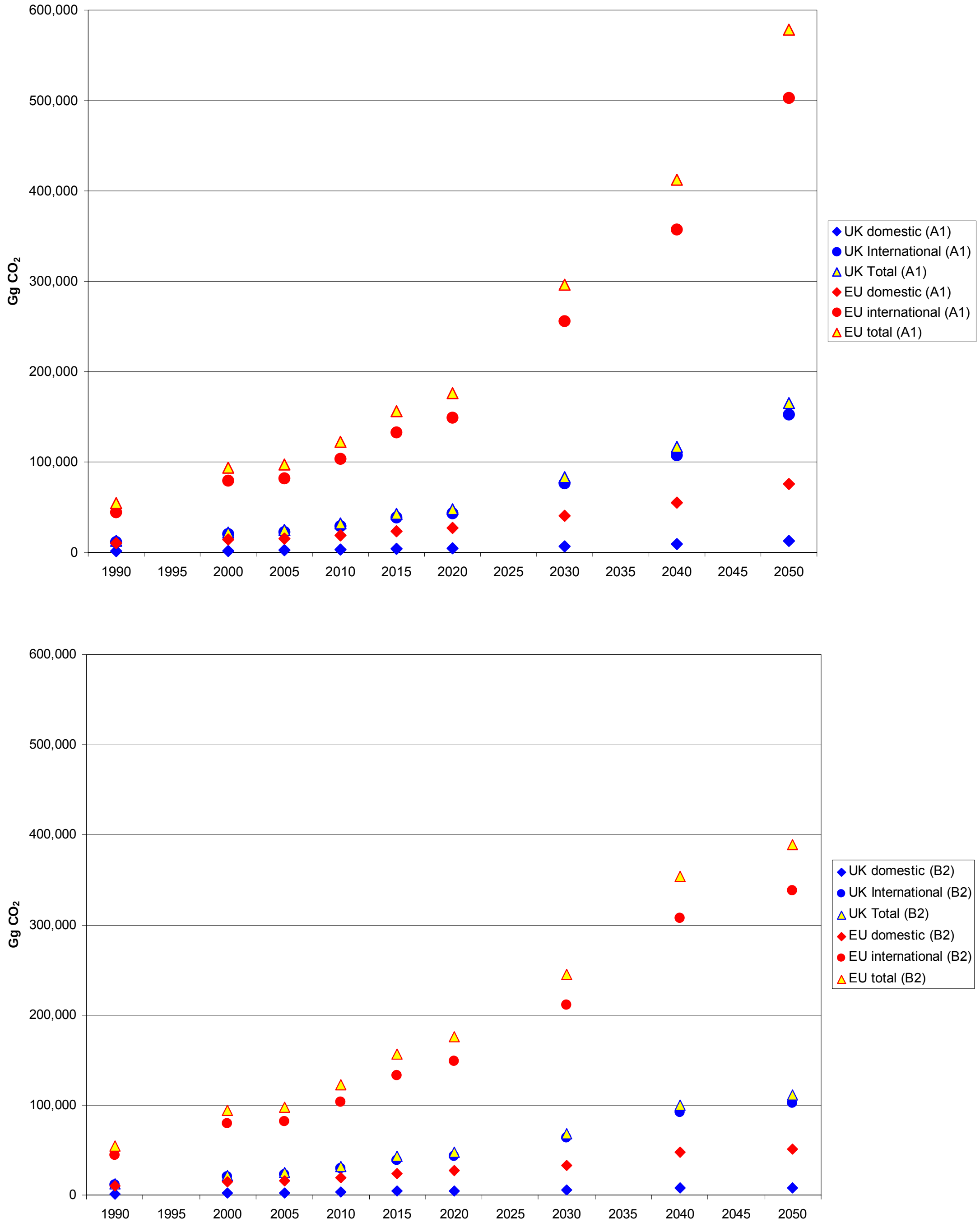


Table 12: Emissions of CO_2 from domestic and international aviation for EU25 countries, 2005 to 2050 (Gg CO_2 yr^{-1})

Basis→	FESG/CAEP-6								SRES A1						SRES B2					
	2005	2005	2010	2010	2015	2015	2020	2020	2030	2030	2040	2040	2050	2050	2030	2030	2040	2040	2050	2050
	Dom.	Int.	Dom.	Int.	Dom.	Int.	Dom.	Int.	Dom.	Int.	Dom.	Int.	Dom.	Int.	Dom.	Int.	Dom.	Int.	Dom.	Int.
Austria	92	1,920	112	2,351	133	2,713	150	3,033	223	5,125	305	7,033	418	9,720	184	4,229	262	6,042	281	6,532
Belgium	0	2,857	0	3,471	0	4,129	0	4,484	0	7,381	0	10,314	0	14,529	0	6,089	0	8,859	0	9,763
Cyprus	4	363	6	463	9	653	12	857	18	1,334	24	1,829	33	2,526	15	1,101	21	1,571	22	1,698
Czech Rep.	5	390	6	463	8	535	9	555	13	870	18	1,200	25	1,667	11	718	15	1,031	17	1,120
Denmark	234	1,519	290	1,885	362	2,479	399	2,900	595	4,801	811	6,618	1,113	9,190	491	3,961	697	5,685	748	6,176
Estonia	0	50	0	60	0	67	0	69	0	107	0	146	0	200	0	88	0	125	0	135
Finland	358	1,352	433	1,623	508	1,795	558	2,160	832	3,586	1,135	4,927	1,558	6,819	686	2,958	975	4,232	1,047	4,583
France	2,796	11,397	3,513	14,179	4,612	17,532	5,830	19,744	8,698	34,906	11,863	48,937	16,286	69,174	7,176	28,797	10,190	42,037	10,944	46,485
Germany	1,773	14,539	2,109	18,516	2,399	24,162	2,602	27,052	3,882	46,209	5,295	64,312	7,269	90,221	3,203	38,122	4,548	55,244	4,885	60,629
Greece	460	1,563	547	1,944	619	2,441	663	2,612	989	4,197	1,348	5,760	1,851	7,961	816	3,463	1,158	4,948	1,244	5,349
Hungary	0	460	0	558	0	655	0	675	0	1,094	0	1,502	0	2,078	0	903	0	1,290	0	1,396
Ireland	77	1,091	96	1,345	121	1,672	154	1,783	229	2,873	312	3,973	429	5,536	189	2,370	268	3,413	288	3,720
Italy	2,464	6,278	2,962	7,849	3,472	9,789	3,856	10,836	5,753	18,433	7,846	25,653	10,771	35,984	4,746	15,207	6,740	22,036	7,238	24,181
Latvia	0	62	0	74	0	86	0	90	0	140	0	192	0	265	0	116	0	165	0	178
Lithuania	5	66	6	78	8	88	8	89	13	138	17	189	23	259	11	114	15	162	15	174
Luxembourg	0	382	0	494	0	661	0	803	0	1,439	0	2,034	0	2,899	0	1,187	0	1,747	0	1,948
Malta	0	159	0	188	0	216	0	225	0	350	0	481	0	666	0	289	0	413	0	447
Netherlands	30	6,389	37	8,138	44	10,422	50	11,907	75	21,156	102	29,683	140	41,990	62	17,454	88	25,498	94	28,218
Poland	65	445	79	535	94	627	105	658	157	1,039	215	1,426	295	1,972	130	857	185	1,225	198	1,325
Portugal	246	1,049	325	1,326	484	1,789	759	2,234	1,133	3,503	1,545	4,807	2,121	6,644	935	2,890	1,327	4,129	1,425	4,465
Slovakia	6	29	7	36	8	45	9	48	13	75	17	102	24	141	11	61	15	88	16	95
Slovenia	0	64	0	76	9	87	0	89	0	138	0	189	22	259	0	114	0	162	15	174
Spain	3,141	5,698	3,882	7,171	4,886	9,319	5,608	10,432	8,366	17,006	11,410	23,470	15,665	32,637	6,902	14,030	9,801	20,161	10,527	21,932
Sweden	1,084	1,389	1,334	1,712	1,637	2,119	1,788	2,277	2,668	3,596	3,639	4,926	4,995	6,795	2,201	2,967	3,126	4,231	3,357	4,566
UK	2,479	22,429	3,102	28,996	3,977	38,654	4,526	43,527	6,752	76,369	9,209	107,517	12,643	152,629	5,570	63,004	7,911	92,357	8,496	102,567
EU25 Total	15,322	81,940	18,847	103,530	23,389	132,734	27,086	149,139	40,409	255,865	55,111	357,222	75,682	502,761	33,337	211,088	47,340	306,853	50,858	337,855

Figures 8a and 8b show domestic and international emissions for the UK and the EU25 as a whole until 2050 for scenarios FAST-A1 and FAST-B2. This illustrates the dominance of UK international traffic over domestic (the latter being 8 – 10% depending on year), whereas in Europe as a whole, domestic traffic represents a larger fraction at 13 – 16% (depending on year). Note that 'domestic European traffic' is not intra-EU but the sum of individual 25 Member States' domestic traffic.

Figure 8: UK and EU25 domestic, international and total emissions 1990 – 2050, FAST-A1 (upper panel) and FAST-B2 (lower panel) scenarios (Gg CO_2 yr^{-1}): 1990, 2000 data from Lee et al. (2005)



5 Discussion

5.1 Comparison of FAST-A1 and FAST-B2 scenarios with other projections

Global emissions of CO_2 from aviation in the early 1990s and 2000s as calculated with FAST were found to compare well with other inventory estimates (Lee *et al*., 2005). The FAST-2000(OAG)[7] estimate of global fuel usage and distance travelled was shown to be very similar to a prior forecast made with FAST, based on 1991/1992 traffic projected to 2000, and that of an independent inventory, AERO2K (Eyers *et al*., 2004), for 2002.

Section 3 provides details as to how estimates of global RPK compared with previous estimates, based upon various GDP assumptions, i.e. SRES and IS92. This showed that the methodology utilised was robust in the sense that it was able to reproduce prior estimates and that differences, where present, were explicable. The differences found between RPK projections appeared to be related to the input RPK data, which were unfortunately not adequately traceable for the FESG (1998) projections. For this work, published and traceable data for RPK and GDP were used.

The projections of CO_2 emissions thus calculated with the FAST model between 2005 and 2050 according to the SRES scenarios A1 and B2 may be compared with other independent scenario studies for 2050. The IPCC (1999) scenarios compiled by FESG (1998) are the most widely used data on global aviation emissions for 2050, which were based upon IS92 GDP assumptions. Recently, an EU project, 'CONSAVE 2050' has also provided scenario data for aviation emissions up to 2050 according to different 'story lines' (see below). The FAST-A1 and –B2 data calculated for this study are shown alongside the original IPCC (1999) data and the CONSAVE 2050 data (Berghof *et al*., 2005) in Figure 9.

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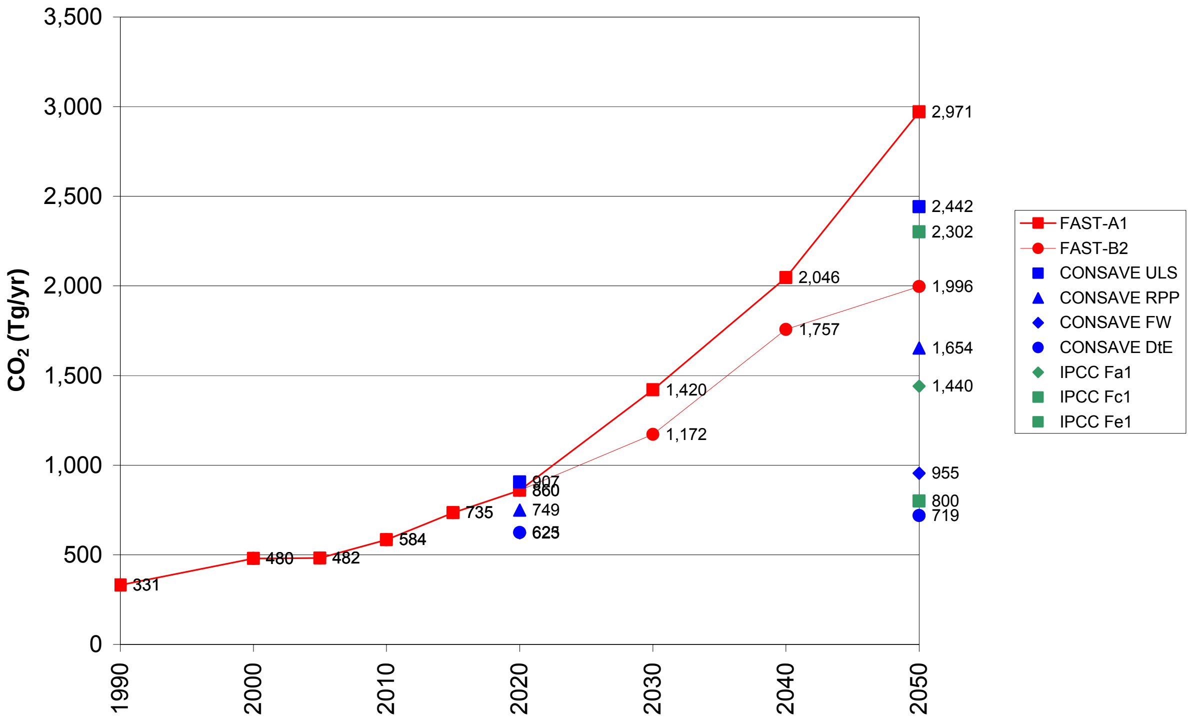
[7] 'FAST' is the model, '2000' refers to the year, 'OAG' refers to the underlying movement database, the Official Airline Guide

Figure 9: Comparison of global aviation CO_2 emissions (Tg yr^{-1}), 1990 to 2050 using FAST and showing other estimates for 2020 and 2050



It was not possible at the time of writing to make a detailed comparison with the CONSAVE 2050 results as only a high-level executive summary was available (Berghof *et al*., 2050). The CONSAVE scenarios 'ULS' (Unlimited Skies), 'Regulatory Push and Pull' (RPP) are both reported to be consistent with SRES A1, whereas 'FW' (Fractured World) and 'DtE' (Down to Earth) are consistent with SRES A2 and SRES B1, respectively (Berghof *et al*., 2005. Both the CONSAVE 2050 FW and RPP scenarios may, to some degree, be compared with FAST-A1 and FAST- B2 but both CONSAVE scenarios provide lower 2050 total values. However, this is not surprising as the CONSAVE approach differs to that taken in this work, in that we used RPK to 2020 from Wickrama *et al.* (2003), whereas CONSAVE generate their own differing RPK scenarios from 2005 to 2020. Thus, the CONSAVE scenarios have a range of starting RPK values at 2020.

The FAST-A1 and FAST- B2 2050 results bracket the IPCC (1998) Fe1 (high) scenario, whilst FAST- B2 is greater than the mid-range Fa1 scenario. The technology assumptions in FAST-A1 and –B2 are very similar to those of FESG (1998)/IPCC (1999) but the GDP data are different, which are the main 'drivers' of the scenarios, the technology assumptions having a second-order effect on the totals (Henderson *et al*., 1999). The formulation of 'scenarios' is clearly a difficult area in that there are no 'right' or 'wrong' answers: only transparent assumptions can be provided and on the basis of such assumptions, the scenarios can then be subjectively judged on their 'plausibility'. Such was the case for the IPCC scenarios (Henderson *et al*., 1999), who judged that some of the higher scenarios reviewed (Eah and Eeh, Vedantham and Oppenheimer, 1998) to be "*probably less plausible*". The EDF scenario Eah projected 6,578 Tg CO_2 and Eeh, 7,177 Tg CO_2 for 2050, the lesser of which is still 2.2 times greater than FAST-A1.

5.2 Emissions allocation projections

Full results for the allocation options 3, 5, 6 and 8 over the period 2005 – 2050 for FAST-A1 and FAST-B2 scenarios are provided in the accompanying data appendix (Owen and Lee, 2006). Domestic and allocated international aviation emissions of CO_2 are provided here in Tables 13 and 14 for the UK and EU25, respectively.

Table 13: Domestic and international allocated aviation emissions (methods 3, 5, 6 and 8) of CO_2 *(Gg* CO_2 yr^{-1}*) 2005 – 2050, scenarios FAST-A1 and FAST-B2 for the UK*

	Domestic Gg CO_2 yr^{-1}	Option 3 Gg CO_2 yr^{-1}	Option 5 Gg CO_2 yr^{-1}	Option 6 Gg CO_2 yr^{-1}	Option 8 Gg CO_2 yr^{-1}
UK 2005	2,479	22,339	22,429	21,984	4,517
UK 2010	3,102	28,874	28,996	28,429	5,668
UK 2015	3,977	38,494	38,654	37,985	7,116
UK 2020	4,526	45,177	45,359	44,544	7,909
UK 2030 (FAST-A1)	6,752	76,047	76,369	75,166	12,972
UK 2040 (FAST-A1)	9,209	107,045	107,517	105,845	18,179
UK 2050 (FAST-A1)	12,643	151,930	152,629	150,309	25,684
UK 2030 (FAST-B2)	5,570	62,739	63,004	62,012	10,702
UK 2040 (FAST-B2)	7,911	91,951	92,357	90,921	15,615
UK 2050 (FAST-B2)	8,496	102,097	102,567	101,007	17,260

Table 14: Domestic and international allocated aviation emissions (methods 3, 5, 6 and 8) of CO_2 *(Gg* CO_2 yr^{-1}*) 2005 – 2050, scenarios FAST-A1 and FAST-B2 for the EU25 total*

	Domestic[8] Gg CO_2 yr^{-1}	Option 3 Gg CO_2 yr^{-1}	Option 5 Gg CO_2 yr^{-1}	Option 6 Gg CO_2 yr^{-1}	Option 8 Gg CO_2 yr^{-1}
EU25 2005	15,322	80,488	81,940	78,247	40,719
EU25 2010	18,847	103,662	103,530	79,027	41,300
EU25 2015	23,389	130,409	132,734	100,664	63,534
EU25 2020	27,086	155,595	155,419	118,183	75,965
EU25 2030 (FAST-A1)	40,409	256,197	255,865	194,622	116,439
EU25 2040 (FAST-A1)	55,111	357,638	357,222	271,559	160,729
EU25 2050 (FAST-A1)	75,682	503,276	502,761	382,299	223,539
EU25 2030 (FAST-B2)	33,337	211,363	211,088	160,564	96,062
EU25 2040 (FAST-B2)	47,340	307,211	306,853	233,269	138,066
EU25 2050 (FAST-B2)	50,858	338,202	337,855	256,905	150,218

5.3 Comparison of allocation options

A simple method to examine the differences between results of the allocation options is to compare the statistical variability. For this, a coefficient of variation[9] (COV) has been calculated for each of the EU25

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[8] Domestic in this case means the sum of domestic air traffic emissions from EU25 States, not intra-EU25 emissions

[9] The standard deviation divided by the mean, expressed as a percentage

countries for options 3, 5 and 6 since they are favoured by SBSTA, and the resulting COV statistics are presented in Table 15.

The data in Table 15 show that most countries show variability between allocation options of less than 15%. Only 5 countries (Denmark, Ireland, Latvia, Lithuania and Slovakia) show variation above this (arbitrary) level of 15%. Of the countries with the most traffic, e.g. Germany, France, The Netherlands, Italy and the United Kingdom, the variability tends to be small, generally less than 5%, similar to the results for 2000 (Lee *et al*., 2005).

Table 15: Coefficient of variation statistics (%) for EU25 States, allocation methods 3, 5 and 6, 2000 to 2050

	2000	**2005**	**2010**	**2015**	**2020**	**2030 A1**	**2040 A1**	**2050 A1**	**2030 B2**	**2040 B2**	**2050 B2**
Austria	1.17	6.51	6.66	7.14	6.65	6.41	6.48	6.54	6.43	6.48	6.54
Belgium	1.57	2.85	3.00	3.09	2.83	2.77	2.70	2.62	2.78	2.70	2.62
Cyprus	1.63	3.68	3.87	4.52	5.17	4.97	4.86	4.76	4.93	4.86	4.77
Czech Republic	5.83	8.73	8.99	8.84	9.02	9.14	9.09	9.04	9.08	9.12	9.07
Denmark	6.49	8.15	4.56	16.31	22.40	40.66	48.03	53.87	40.66	48.03	53.87
Estonia	2.26	9.50	9.20	10.12	10.55	11.12	11.30	11.14	11.22	11.15	11.48
Finland	3.90	0.69	0.69	0.53	0.87	1.01	0.98	0.96	1.02	0.99	0.95
France	0.15	1.88	1.95	1.99	1.89	1.68	1.65	1.62	1.68	1.65	1.62
Germany	0.40	2.51	2.40	2.07	1.91	1.83	1.83	1.83	1.83	1.83	1.83
Greece	1.90	1.80	1.85	1.70	1.44	1.74	1.83	1.92	1.74	1.83	1.92
Hungary	5.34	9.05	9.08	8.87	8.76	8.98	9.01	9.05	8.99	8.98	9.05
Ireland	2.04	15.05	15.57	16.15	16.09	15.73	15.66	15.57	15.71	15.65	15.56
Italy	2.02	4.46	4.43	4.40	4.16	3.86	3.82	3.77	3.86	3.82	3.77
Latvia	12.86	18.97	19.58	20.02	20.70	21.00	20.95	20.89	21.00	21.00	20.64
Lithuania	6.04	13.84	13.94	14.57	15.78	15.54	15.70	15.78	15.61	15.86	15.65
Luxembourg	7.03	4.52	4.25	3.70	3.31	2.99	2.94	2.90	2.98	2.96	2.89
Malta	1.02	1.54	1.78	2.17	2.51	2.41	2.26	2.20	2.35	2.34	2.23
the Netherlands	0.99	0.90	0.80	0.68	0.60	0.37	0.37	0.35	0.38	0.37	0.35
Poland	2.88	9.38	9.50	9.33	9.35	9.51	9.54	9.58	9.54	9.55	9.59
Portugal	1.49	2.09	1.97	1.36	0.63	0.74	0.80	0.85	0.74	0.80	0.85
Spain	9.59	12.37	12.86	12.55	12.30	13.04	12.58	12.51	12.99	12.86	12.41
Slovakia	13.34	18.62	18.47	18.37	18.77	19.13	19.06	18.91	18.91	18.91	18.83
Slovenia	0.12	2.95	2.88	2.66	2.35	2.38	2.43	2.48	2.38	2.43	2.48
Sweden	5.52	8.84	8.79	8.58	8.72	8.53	8.52	8.49	8.52	8.52	8.49
United Kingdom	0.86	0.86	0.85	0.74	0.78	0.67	0.66	0.64	0.67	0.66	0.64

5.4 Implications of allocation methodology to UK inventory

The addition of CO_2 to the UK inventory from international aviation emissions is given in Table 13 and illustrated in Figure 8. In terms of 'CO$_2$ equivalents', which are the mass of CO_2 multiplied by the 100 year Global Warming Potentials (GWP) of the trace gas considered, the uncertainties of the emission factors for CH_4 and N_2O from gas turbines has been discussed in detail by Lee *et al*. (2005). It was concluded that there was no reliable emission factor for CH_4 (Lee *et al*., 2005), a view that is endorsed by the current considerations of the IPCC in their revision of greenhouse gas emission guidelines. For N_2O, an emission factor of 0.15g/kg fuel (Wiesen *et al*., 1994) was adopted by Lee *et al*. (2005). These were calculated to be 1.4% of CO_2 emissions, a fraction that is well within the uncertainties of other calculations, including the basic engine fuel-flow calculations such that these emissions are neglected here, given the uncertainty over the emission factor.

The aviation emissions projections presented here for the UK may be compared with those from other sources, particularly the UK Energy White Paper (DTI, 2003) and the Aviation White Paper (DfT, 2003).

Table 16: Comparison of UK aviation emissions with other UK Governmental estimates

Year	UK Aviation emissions	Source/notes
2000	5.5 Mt C (international) 0.5 Mt C (domestic)	Lee *et al*. (2005), FAST modelling, scheduled traffic only
2002	8 Mt C (international) 9 Mt C (domestic + international)	DTI (2003) para. 5.22 cites DfT (2003, only a graph is given)
2020	14 – 16 Mt C	DTI (2003) para. 5.22 cites DfT (2003, only a graph is given)
2030	16 – 18 Mt C	DfT (2003), domestic + international
2020	13.6 Mt C (domestic + international	This work, FAST modelling, scheduled traffic only
2030	18.7 (FAST-B2) to 22.7 (FAST-A1) Mt C (domestic + international)	This work, FAST modelling, scheduled traffic only
2050	15.7, 17.4, 29.1 (DfT best, central and worse cases, domestic + international)	DfT (2004), domestic + international
2050	30.3 (FAST-B2) to 45.1 (FAST-A1) Mt C (domestic + international)	This work, FAST modelling, scheduled traffic only

The emissions data given in Table 16 suggests that FAST modelling results for the UK are in reasonable agreement with other estimates, despite different methodologies and data used, up until 2020. For emissions between 2000 and 2020, the known underestimation of FAST because of the usage of scheduled traffic only explains the lower estimates. For 2030 onwards, where a different projection model comes into usage, utilising SRES GDP, the FAST projections are higher than the DfT (2003) projections for the UK. It is unclear whether the DfT (2003) projections for 2030 to 2050 consider SRES-type assumptions.

The UK Energy White Paper (DTI, 2003) provides the basis for a target of UK CO_2 emissions reduction of 60% in 2050 from 1990 emissions. This target of 60%, adopted by the Government (2003), originates from the recommendations of the Royal Commission on Environmental Pollution's report '*Energy, the Changing Climate*' (RCEP, 2000). This target results from the application of a reduction in emissions to achieve a 550 ppm stabilisation of CO_2 concentrations in the global atmosphere. Several stabilization scenarios have been widely considered at various CO_2 concentration levels: typically, 450 ppm, 550 ppm, 750 ppm etc. The stabilisation level recommended by RCEP (2000) was the 550 ppm level. The emissions required to produce stabilisation at 550 ppm imply reductions of the order 60% for Annex I parties.

Whilst international aviation emissions are explicitly excluded from the UK's declared CO_2 emissions targets (Evidence presented to the Environmental Audit Committee, 2004[10]) it is instructive to calculate the fraction of UK CO_2 emissions that international aviation might constitute under the different allocation options. However, one must first add the 1990 international aviation emissions of 11.5 Tg CO_2 (Lee *et al*., 2005) to the NAEI UK national total of 579.3 Tg CO_2, as this will similarly exclude international aviation emissions, which results in ~591 Tg CO_2 as a 1990 total estimate. On this basis, a like-with-like comparison can be made. Thus, for the lower B2 scenario, international aviation emissions constitute approximately 43% of UK total emissions for allocation methods 3, 5 and 6 (and 7% for allocation method 8): for the higher A1 scenario, international aviation emissions constitute approximately 64% of UK total emissions for allocation methods 3, 5 and 6 (and 11% for allocation method 8). The FAST-A1 scenario indicates a larger fraction than that calculated by the DfT (DfT, 2004) for their 2050 'worst case' (45.1 *cf* 29.1 Mt C) but the FAST-B2 scenario is rather similar to the DfT 'worst case' (30.3 *cf* 29.1 Mt C). That a potentially higher fraction is found is not of particular note: the simple point is made here that a range of projections can be made, according to the scenario assumptions and that it is necessary to provide a range of projections for 2050 to capture plausible outcomes.

A detailed comparison between the DfT methodology and that presented here is not possible: however, the DfT methodology has complex assumptions about future traffic but highly simplified emissions calculations, as no inventory model underlies the projections. By contrast, the projections made in this work have simpler assumptions on traffic growth but complex calculations of emissions. Clearly, the inventory method will be superior for emissions calculations, when detailed assumptions regarding traffic and technology are applied. The application of more complex assumptions of traffic to FAST is an approach that should probably be pursued in the future.

5.5 Uncertainties

Uncertainties in scenarios are difficult – if not impossible, given their speculative nature – to evaluate.

Certainly, whatever uncertainties are present in the base-case inventory are present in any projections derived from it and are magnified by other assumptions necessary in the scenario methodology. For example, there are significant uncertainties in the way traffic may develop and the technologies applied to that traffic.

The IPCC undertook some limited plausibility checks (Henderson *et al*., 1999) of the FESG (1998) scenarios and found that they were all within the range of qualitative plausibility. The scenarios provided here bracket the RPK and global emissions of the highest FESG (1998) scenario (Fe1). However, it has been shown (section 3) that the more recent FESG/CAEP-6 forecast of Wickrama *et al.* (2003) of RPK to 2020 is consistent with this higher Fe1 scenario such that neither of the scenarios (FAST-A1, FAST-B2) presented here might be considered on this basis as 'outliers'.

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[10] http://www.publications.parliament.uk/pa/cm200304/cmselect/cmenvaud/uc233-iv/uc23302.htm

There is potentially a systematic bias in the data presented here that results from the assumptions, which may give an *underestimate* of RPK and emissions: the FESG 2020 RPK forecast (Wickrama *et al.*, 2003) presents only data for *scheduled* traffic. Lee *et al*. (2005) estimated that this might cause a global underestimate of the order 9% in 1991/1992 where comparable data of scheduled versus total traffic were available. However, no data for a comparison of scheduled and total traffic were available for a more recent year.

The purpose of this study was not to provide an extensive analysis of potential scenarios as such but rather to reproduce the methodology devised by FESG (1998) and apply updated SRES-based GDP assumptions. Clearly, the subject of scenarios is a topic in its own right, worthy of further study, asides from allocation issues.

6 Conclusions and recommendations

- Future international aviation emission allocations of CO_2 have been calculated up to 2020 by using published ICAO projections of traffic (RPK) statistics at 5 yearly intervals. Thereafter, emissions and their allocation have been calculated with scenarios that use an updated application of the FESG (1998) methodology, incorporating SRES A1 and B2 GDP assumptions.
- In order to compare the older FESG (1998) scenarios as used by the IPCC (1999) with the updated scenarios based upon SRES A1 and B2 GDP scenarios, it was attempted to reproduce the FESG (1998) projections. This proved to be impossible because of a lack of transparency over the sources of input data of RPK and GDP from FESG (1998). However, a similar logistic Verhulst model was derived which satisfactorily predicted RPK (using the same IS92 assumptions). When the FESG (1998) model was compared with the model derived here (for the same updated data used here), differences of only 1 to 2% were found.
- Using the A1 and B2 scenarios as ‘marker’ scenarios, global emissions from aviation were found to be in the same range and a little greater than the previously published IPCC scenarios based upon IS92 GDP assumptions
- The contribution of international aviation to UK CO_2 emissions was calculated for the period 2005 to 2050, firstly at 5 yearly intervals to 2020 and at 10 yearly intervals, thereafter. The emissions of CO_2 in 2020 calculated here were found to be a little lower than DfT estimates but were based on scheduled traffic only: it is likely that incorporation of non-scheduled traffic would yield rather similar or greater emissions. After 2030, where a different projection model was used which was consistent with SRES A1 and B2 GDP assumptions, emissions from international aviation were greater than DfT estimates, representing either of the order 43% of total UK emission for FAST-B2 or 65% for FAST-A1 by 2050 for allocation options 3, 5 and 6.
- The different allocation options that could be calculated for future cases across Europe do not show great variation, generally of the order less than 15% (excluding option 8, the ‘airspace’ option, which generally gives very different results). For the largest emitters, e.g. UK, France, Germany, Italy and the Netherlands, the variation between allocation options 3, 5 and 6 was less than 5%.

- It is recommended that additional useful data could be gained from refining the study and approaches developed here. For example, a better 'base year' would be generated from one that incorporates non-scheduled traffic. In addition, a wider range of GDP driving scenarios could be explored, combined with different technology scenarios, e.g. such as implementation of ACARE targets etc. Moreover, it is possible to apply more complex assumptions on traffic projections to produce a range of scenarios for the UK.

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