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Valuation of the Global Warming Impacts of UK Aviation

By

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A report submitted in partial fulfilment of the requirements for
the MSc and/or the DIC.

September 2003

DECLARATION OF OWN WORK

I declare that this thesis

'Valuation of the Global Warming Impacts of UK Aviation'

is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced and/or with appropriate acknowledgement given.

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ABSTRACT

The UK Government is due to publish a white paper, in late 2003, setting out its policy in relation to the expansion of airport capacity in the UK and the use of economic instruments to deal with aviation's environmental impacts. The Government has conducted cost benefit analysis (CBA) of capacity expansion. However, the CBA covers a narrow range of economic impacts in relation to the south east and east of England only (plus selected projects elsewhere), and does not monetarise the environmental impacts of airport capacity expansion within the CBA.

The present thesis seeks to fill some of the above gaps by valuing the global warming impacts of capacity expansion (arguably the most significant environmental impact) and presenting that valuation on a basis which can be compared directly with the economic benefits of capacity expansion. This also entails adjusting the CBA valuations performed by the Government.

Using the Government's own recommended values for valuing carbon dioxide emissions, the net present value (NPV) of the incremental emissions associated with capacity expansion is found to represent approximately 60-70% of the benefits of expansion. However, values to be found in some of the more recent academic literature suggest much lower percentages.

The valuation of emissions is subject to substantial uncertainty, both scientific and economic. A single number (such as NPV) cannot convey adequate information for policymakers to make an informed decision on capacity expansion. This thesis is therefore based both on deterministic and stochastic analysis. It is found that the former systematically understates the expected value of emission damages; however, the more important results of the stochastic analysis are to present valuations for any given confidence level as a tool for policymaking.

In addition to analysing the NPV of capacity expansion, aviation's global warming damages are also presented for illustrative journeys, as a possible basis for calculating the level of environmental taxes to be charged on aviation. The impact on demand (and, in turn, damage) of internalising such costs is explored. It is found that the effect of a tax would be a moderate reduction in demand (circa 10%). This reduction would not be sufficient to eliminate the requirement for additional capacity to be built.

ACKNOWLEDGEMENTS

Acknowledgements are gratefully extended to the following individuals and organisations:

- Susana Mourato of Imperial College, for her supervision and guidance throughout the project;
- The Parliamentary Office of Science and Technology for their sponsorship of the project and for providing a stimulating and convivial environment in which to work, and in particular to Gary Kass whose suggestions, guidance and comments were invaluable;
- Eric Lewis of the House of Commons Environmental Audit Committee, for the stimulating discussions which prompted a number of the ideas in this thesis;
- David Lee (Manchester Metropolitan University), David Lister (QinetiQ), Wieger Fransen (Ministry of Transport, Public Works and Water Management, Netherlands), Professor Helen ApSimon (Imperial College), Professor Jo Haigh (Imperial College), Professor David Pearce (University College London) and Nicholas Eyre (Energy Saving Trust) for their advice on particular issues raised in section 5 of the thesis;
- Anne and Geoff for their kind hospitality and forbearance at a crucial stage in the preparation of the thesis;
- Finally, and most important of all, Nicola, Chloë and Joshua, for their patience, love and moral support during the long hot summer of 2003.

Notwithstanding the input of the above individuals, all errors and omissions are the sole responsibility of the author.

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1. INTRODUCTION

1.1 Overview

In recent decades, aviation has been the fastest growing mode of transport in the United Kingdom. The growth in aviation has contributed to trade and economic growth, and the sector is an important employer. However, the growth in aviation places an increasing burden on the environment, in terms of climate change, air quality, noise pollution and other impacts associated with airports and their supporting infrastructure.

If substantial further growth in aviation is to be accommodated, then additional runway capacity will be needed in the years ahead. In 2000 the present Government launched a consultation exercise regarding the long-term development of the aviation sector, and is due to publish its conclusions in a White Paper in late 2003. This will potentially pave the way for planning applications in respect of additional runway and terminal capacity.

The White Paper will also include proposals for economic instruments addressing the environmental impacts of aviation. In March 2003 HM Treasury (HMT) and the Department for Transport (DfT)[1] launched a consultation document entitled "Aviation and the Environment: Using Economic Instruments" (HMT / DfT, 2003a). Whilst not prejudging the form or quantum of economic instruments, that document sets out monetary estimates of the environmental damage caused by UK aviation for the years 2000 and 2030.

From an economic perspective, the documentation prepared by the Government raises three sets of issues which will be addressed in this thesis. First, despite DfT having commissioned cost benefit analysis (CBA) work, there is no indication of the net benefits of capacity expansion taking account of the environmental costs. Second, the HMT / DfT damage estimates cited above are based upon valuation exercise which is inherently uncertain; however, no attempt is made to quantify, or consider the policy implications of, such uncertainty either for capacity expansion or for the use of economic instruments.

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[1] In this thesis, the abbreviation "DfT" also encompasses DfT's predecessor departments, namely DoT, DETR and DTLR (see Appendix II for a glossary of abbreviations).

Section 1 below sets out the background to the foregoing. It then goes on to describe the objectives of this thesis, in the light of the problems identified, and provides a guide as to how and where they are addressed in the ensuing sections.

1.2 Growth of Aviation

Over the period 1970-2000, the number of passengers using UK airports increased from 32 million to 180 million (source: DfT, 2003a, page 38), an increase well in excess of 400%. With a compound annual growth rate (CAGR) of ~6% per annum, the growth of aviation outstripped that of other modes of transport and indeed of the overall economy.

There is some evidence that the rate of growth of aviation is declining, as the industry has started to mature[2], and the Government forecasts that (assuming no capacity constraints) the CAGR for the period 2000-2030 will, at 3.5% p.a., be lower than for the preceding three decades (DfT, 2002a). Nonetheless, with UK airport passenger levels of 500 million forecast for 2030 (*ibid*), the increase in traffic over the next 30 years will, in absolute terms, be more than twice as large as the increase during the preceding 30 years. This level of demand would place an increasing strain on airport infrastructure, unless significant new runway and terminal capacity is constructed. Indeed, the Government estimates that if no further runways are built, then approximately 15% of the potential demand in 2030 will be suppressed (based on figures in DfT, 2003a).

The Government's forecasts for aviation growth pre-date the terrorist attacks of September 2001, which had an immediate and material impact on aviation demand. However, it is assumed in this thesis that this impact will not be long-lasting and that, in general, the Government forecasts represent a reasonable forecast of the industry's long-term growth (in the absence of capacity constraints and demand management).

1.3 Environmental Impacts of Aviation

The principal environmental impacts of aviation are shown in Table 1 below. These range from global issues (climate change) to site-specific issues (airport development).

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[2] The CAGR in the 1990s was 5.8% compared to 6.1% in the 1970s (DfT 2003a, page 38). The growth rate for the 1990s was bolstered by the emergence during that decade of the low cost airlines (LCAs), suggesting that the underlying deceleration in the growth of demand may have been sharper than indicated by these figures.

Table 1: Environmental Impacts of Aviation

Climate change and global atmosphere:	➢ Greenhouse gases (GHGs) released by aircraft[3] ➢ GHGs released by surface transportation (principally CO_2) ➢ Depletion of stratospheric ozone (formation of N_20 by supersonic aircraft flying at high altitude)[4]
Local and regional air pollution:	➢ Human health impacts (NO_x, SO_2, PM_{10}, VOCs, CO, O_3)[5] ➢ Acidification and eutrophication (NO_x, SO_2) ➢ Crop yields (O_3) ➢ Damage to buildings (SO_2, smoke) ➢ Nuisance (odour)
Noise and vibration:	➢ Nuisance to residents from aircraft and surface transport ➢ Nuisance to non-residents (loss of peace and tranquillity) ➢ Physical and psychological impacts on health ➢ Impacts on learning and productivity ➢ Disturbance of fauna in affected habitat ➢ Loss of land use due to noise zoning (an impact of mitigation) ➢ Vibration damage to civil structures
Local impacts at airports:	➢ Loss of habitat, and impact on flora, fauna and biodiversity ➢ Loss of land use ➢ Visual intrusion, light pollution ➢ Use and contamination of water ➢ Waste generation at airports
Surface transportation:	➢ Construction impacts of surface transportation infrastructure ➢ Environmental impacts of airport traffic (see above)
Indirect impacts:	➢ Supply chain (fuel extraction/refining, aircraft manufacture) ➢ Induced development at airports (housing, commercial, etc.) ➢ Additional traffic induced by surface transport infrastructure ➢ Environmental impacts of tourism

1.3.1 Local Impacts

The issues identified in Table 1 have received varying degrees of attention in recent decades. Local issues have tended to dominate, reflecting the strength of local opposition to airport development, and regulatory regimes have developed (notably under the auspices of the International Civil Aviation Organisation - ICAO) governing emissions of local air pollutants and noise.

The result of successive rounds of regulation is that, on a per aircraft or per passenger basis, major reductions have been achieved in emissions of local air pollutants and noise. The impact on the overall exposure of populations in the vicinity of airports is less clear-cut, owing to the rapid increase in aviation and also the surface traffic which it generates. In general, exposure to severe noise disturbance (measured by the number of

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[3] The principal GHGs emitted by aircraft are CO_2 - carbon dioxide; CH_4 – methane; NO_x – oxides of nitrogen (indirect effect); and H_20 – water.

[4] N_20 – nitrous oxide.

[5] SO_2 -sulphur dioxide; PM_{10}, - particulate matter with a diameter of 10 microns and below; VOCs – volatile organic compounds; CO – carbon monoxide; O_3 – ozone.

people living within the 57 dB LEQ noise contour) has declined, but noise nonetheless remains a major issue for local populations (Arthur D. Little, 2001). At the busiest airports, such as Heathrow, the impact of increasing aircraft traffic is that the ability to meet air quality standards to be introduced in 2010 is likely to be compromised, particularly in relation to NO_x and PM_{10} (Parliamentary Office of Science and Technology, 2003).

1.3.2 Global Warming

Until recently, emissions by aircraft of global pollutants have received less attention than local pollutants and, except in so far as regulations pertaining to local pollutants indirectly affect GHG emissions, remain unregulated. CO_2 emissions from domestic flights are captured within national limits applicable under the Kyoto Protocol; however, in common with international maritime, CO_2 emissions from international flights (although subject to reporting requirements) are not limited.

Emissions of CO_2 from UK aviation have grown from 4 MtC[6] in 1990 to 8 MtC in 2000 – a CAGR of 7.1% (AEA Technology, 2003). This growth is less than the growth in aviation traffic over the equivalent period (5.8% p.a., based on figures in DfT, 2003a), reflecting the progressive modernisation of the UK's aircraft fleet. The Government forecasts that aviation's CO_2 emissions will be in the range 18 – 21 MtC by 2030, representing a CAGR from 2000 of 3.1 – 3.6% (HMT / DfT, 2003a). Given that the Government is targeting a reduction in the UK's total carbon emissions to 64 MtC by 2050 (Department of Trade and Industry, 2003, page 25), this potentially means that aviation will account for 20 – 22% of the UK's CO2 emissions in 2030[7], compared to just 2.3% in 1990 and 4.9% in 2000. In practice, the level of aviation emissions in the future will depend not only on underlying demand growth, but also on such factors as technological and operational developments, and indeed the extent to which airport infrastructure is developed to meet demand.

The relative global warming effect of GHGs other than CO_2 is thought to be more significant for aviation than for other industrial activities, mainly because of the impact of contrails and, to a lesser extent, emissions of NO_x. The overall contribution of aviation to global warming is in the region of two to four times the impact of aviation's CO_2 emissions alone (Intergovernmental Panel on Climate Change, IPCC, 1999). This

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[6] Million tonnes of carbon (equivalent to 3.67 million tonnes of CO_2).

multiple (which is referred to as the Radiative Forcing Index, or RFI) is a relatively broad range, since the impact of these other GHGs is not yet well understood. Using a central estimate of three for the RFI, and assuming that the RFI of human activities as a whole is in the region of 1.5 (IPCC, 1999), this implies that aviation's share of the UK contribution to global warming would be in the range of 32 – 35% by 2030, based on the 20 – 22% share of CO_2 emissions quoted in the previous paragraph.

The foregoing suggests that aviation has the potential to become a major (or even, if the Government's CO_2 targets are considered plausible, the largest) contributor to the UK's GHG inventories over the decades to come. In view of this, and indeed the apparently high proportion of total aviation damage accounted for by global warming impacts (see Table 2 below), this thesis focuses only on the global warming impacts of UK aviation[8].

1.4 Government Policy Towards Aviation

The rapid growth in aviation means that new capacity will be required if demand is to be met. According to DfT, modelling work suggests that if no new capacity is permitted then "by 2019, all the principal UK airports would effectively be full" (DfT, 2002a). Whilst this date is clearly some way in the future, increasing bottlenecks are likely to drive up fares in the meantime, and the controversies surrounding recent airport projects (such as Heathrow Terminal 5) suggest that the project development process needs to be initiated far in advance of commencement of construction.

Accordingly, in 2000, DfT launched the first of a series of consultations regarding development of the aviation sector (DfT, 2000a), supported by a series of technical, economic and environmental studies examining options for the development of airport capacity. The consultation process is due to culminate, in late 2003, in a white paper setting out the Government's policy on further capacity development (the White Paper). This will potentially pave the way for developers to submit planning applications in respect of those runway developments which are supported by the Government in the light of its analysis and feedback from the consultation process.

The economic analysis performed by DfT includes CBA of a series of capacity expansion options in the south east. The largest option analysed comes close to meeting

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[7] This assumes a constant rate of reduction in CO_2 emissions over the period 2000 to 2030, in order to meet the 64 MtC target by 2050.

[8] It should be added that, since the climate impacts of aviation are not dependent upon the precise location of emissions, these impacts lend themselves well to evaluation at a national level.

unconstrained demand forecasts whereas the smallest entails no new capacity development. The net present value (NPV) of the former, compared to the latter, is estimated to be approximately £50 bn (discount rate of 3.5% p.a.); however, this takes no account of externalities such as wider benefits to the UK economy or environmental impacts.

In its Integrated Transport White Paper (DfT, 1998a) the Government stated that "aviation should meet the external costs, including environmental costs, which it imposes". To this end, HMT and DfT recently published a consultation document entitled "Aviation and the Environment: Using Economic Instruments" (HMT / DfT, 2003a), and it is proposed that the Government's ideas on economic instruments will be included in the forthcoming White Paper.

As well as seeking views on the application of economic instruments to aviation's environmental impacts, the HMT / DfT document provides an estimate of the main impacts (see Table 2). Other environmental impacts listed in Table 1 were excluded from the valuation, and it is understood that the Government considers these to be more appropriately addressed via regulation than via economic instruments.

Table 2: Government Estimate of the Environmental Costs of UK Aviation

Year	**2000**	**2030**[9]
Climate change	£1,400m	£4,800m
Local air quality	Up to £236m	Not valued
Noise	£25m	Not valued
Total	**Up to £1,661m**	**£4,800m**

Based on HMT / DfT, 2003a

"Aviation and the Environment: Using Economic Instruments" does not explicitly anticipate the level of any tax (or other economic instrument) which might be proposed in the forthcoming White Paper. However, the Government has stated (see House of Commons Environmental Audit Committee, 2003, page EV 2) that it views the purpose of any environmental tax on aviation as being to internalise environmental costs, and thereby create incentives for supply side improvements in technology and operations, rather than to achieve any particular environmental targets or demand side responses. The Government has suggested that the impact of an aviation tax reflecting external costs would be to suppress demand by up to 10%, which reduction would be at least partially offset by supply side responses (DfT, 2003a, Chapter 5).

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[9] All values in this table are understood to be at year 2000 prices.

1.5 Issues Raised by Government Studies and Consultations

A number of important issues arise from the work performed by the Government in relation to capacity development, valuation and economic instruments.

The first issue is that, whilst DfT and its consultants have prepared CBA studies of various development options (particularly in the south east), they have not conducted CBA into policy options at a national level and they have excluded from the CBA many of the wider impacts of capacity development (not only environmental costs but also other externalities). This is particularly troubling because, based upon the figures presented in Table 2, the environmental costs (and in particular global warming damage) are, *prima facie*, likely to account for a significant proportion of the economic benefits set out in DfT's CBA work. Thus, the first problem is that the net benefits of capacity development at a national level not been quantified in the economic analysis.

In part, DfT's reluctance to attempt an all-embracing CBA reflects its concern that many of the costs and benefits cannot be reliably monetarised, owing to the substantial uncertainties associated with valuation of those impacts. Indeed, the climate change damage estimates quoted in Table 2 are based upon an underlying valuation of CO_2 published by the Government Economic Service (Clarkson and Deyes, 2002) which has caused some controversy (Pearce, 2003) and is inevitably subject to a high degree of uncertainty. In addition, the valuation takes account not only of CO_2 released by aircraft but also other climate impacts related to aircraft emissions, and these are subject to considerable scientific uncertainty. Furthermore, even leaving aside the scientific uncertainties, the use of the RFI as a metric for monetarising non-CO_2 emissions introduces a number of conceptual and economic difficulties which are not fully recognised.

Thus, the second problem is that the valuation of aviation's environmental impacts is highly uncertain. A single point estimate, such as shown in Table 2, is therefore not very helpful from a policymaking perspective unless accompanied by an analysis of the uncertainties surrounding that estimate.

The manner in which these issues are addressed by this thesis is described below.

1.6 Objectives of Thesis

1.6.1 Objective One: Quantifying the Net Benefits of Capacity Expansion

The first objective is to attempt to estimate the NPV of certain of the capacity expansion options identified by DfT, taking account of the environmental - and in particular global warming - costs. This involves a number of tasks:

- Identifying the analysis which has been performed by DfT and the framework within which that analysis has been conducted;
- Estimating the approximate economic benefits of national capacity expansion options as a basis for comparison with environmental damage estimates;
- Quantifying the environmental (global warming) damage caused by UK aviation on a basis which is comparable to the estimated benefits. This entails modelling emissions over a period comparable to the economic analysis and then monetarising those emissions using values to be found in the literature;
- Comparing the costs and benefits and drawing conclusions for national policy.

Of the above tasks, the main emphasis is on valuing global warming impacts. The estimate of economic benefits is a “quick-and-dirty” approximation, based upon an adjustment of DfT’s own figures. Despite these limitations, such an exercise is necessary in order to infer policy implications of the global warming valuation.

1.6.2 Objective Two: Assessment of Uncertainties of Global Warming Damage

The second objective is to take explicit account of the uncertainties associated with the damage estimates derived as described above. This involves:

- Identifying and estimating uncertainties associated with the key variables used in the model;
- Running Monte Carlo analysis (under which those variables are randomised and multiple repetitions of the model calculations performed) so as to derive a probability distribution for the results of interest;
- Comparing the results of the Monte Carlo analysis with the results of deterministic analysis;
- Considering the implications of the analysis, and in particular the uncertainties identified, both for decisions regarding capacity expansion and economic instruments.

The tasks associated with the second objective are performed in parallel with the first objective. In other words, at each stage of the quantitative analysis of environmental damage, results are presented both on a deterministic and probabilistic basis.

1.7 Exclusions

There are a number of areas relevant to the topic of aviation and the environment which this thesis does not attempt to address.

First, certain categories of aviation are excluded. These are: military aviation; "general aviation" (e.g. small-scale private aircraft); and supersonic flight. Supersonic flight is excluded because it presents a somewhat different range of climate impacts to (lower flying) subsonic aircraft. Furthermore, following the retirement of the Concorde fleet in 2003, subsonic aircraft are not expected to be a significant feature of the civil aircraft fleet over the period for which emissions have been modelled.

Second, no further discussion is included of environmental impacts other than global warming, except for an illustrative allowance (based on Table 2) of damage from local air pollutants and noise. There is a significant body of literature in relation to these particular issues and a number of sources have criticised the Government's estimate of noise damage in particular (see House of Commons Environmental Audit Committee, 2003). There is, perhaps, a gap in the literature relating to the valuation of site-specific impacts such as habitat loss, etc.; however, this gap is not addressed in this thesis.

Third, suppression of air travel (via capacity restrictions) will entail a certain amount of diversion to other transport modes which are themselves environmentally damaging. This thesis does not consider the external costs of such other modes, and the implicit assumption is therefore made that the external costs of such other modes will be addressed in parallel to those of aviation. (For a comparison of aviation with alternative modes of transport, see Commission for Integrated Transport, CfIT, 2001).

Finally, no attempt is made to quantify the wider external benefits of aviation over and above those included in DfT's CBA, although some discussion of the subject is included in section 3.

1.8 Outline of Thesis

The ensuing sections are organised as follows:

- Section 2 sets out the overall methodology used in this thesis, including some of the limitations of the approach taken. Detailed aspects of the methodology are presented throughout the document;
- Section 3 supplements the policy background presented in this introduction. It reviews the approach adopted by DfT in relation to analysing options for airport capacity, including a discussion of the differing approaches towards CBA of DfT and HMT. The CBA work performed by DfT is presented, and adjustments made so as to derive an estimate of economic benefits to be compared with environmental damage;
- Section 4 presents the methods used to forecast CO_2 emissions, and the results obtained. Comparison is made throughout the section with the equivalent work performed by DfT's consultants;
- Sections 5 reviews some of the scientific issues, and associated uncertainties, surrounding aviation's atmospheric impacts and how these relate to economic analysis. It also reviews the relevant literature pertaining to valuation of global warming damage. The section concludes by placing a range of values upon the emissions estimates derived in section 4;
- Section 6 brings the findings of the preceding sections to a logical conclusion by comparing the economic benefits of capacity expansion with the environmental costs. The implications for capacity expansion are discussed, taking account of the uncertainties identified. The damage estimates are also presented on a basis which could potentially be used to quantify an environmental tax, and the consequences of such a tax are considered. The section concludes with a discussion of wider implications of the findings of this thesis, including with regard to stochastic methods in economic valuation, further research needs and conclusions on the extent to which the thesis has fulfilled its objectives;
- Finally, section 7 briefly summarises the findings of the thesis.

A number of appendices are provided to supplement the document:

- Appendix I provides list of references;
- Appendix II provides a glossary of abbreviations and defined terms;

- Appendices III, IV and V provide some supplementary material for sections 3, 4 and 5 respectively. Although not essential to the thrust of the discussion, this information (together with Appendices VI and VII) is intended to make the details of the work undertaken transparent to subsequent researchers in this area;
- Appendix VI describes the detailed assumptions used in the model;
- Appendix VII presents the model, including a CD-ROM containing the spreadsheet and brief instructions for navigating the model.

2. METHODOLOGY

2.1 Overview

This section gives an overview of the methodology employed in the project. Further details are provided throughout the thesis. In brief, the methodology involved:

- Reviewing, in the light of economic theory and HM Treasury guidance, DfT's approach to appraising airport capacity expansion;
- Identifying national capacity expansion scenarios to be evaluated, and estimating the net economic benefits of those scenarios;
- Valuing the global warming impacts of UK aviation under the scenarios identified, both in absolute and relative terms;
- Using Monte Carlo simulation, as well as sensitivity and scenario testing, to assess the robustness of the above estimates;
- Analysing the implications of the above valuation work for airport expansion and for economic instruments dealing with aviation's environmental impacts.

2.2 Review of Government Studies

DfT and its consultants have prepared a number of studies in preparation for the forthcoming aviation White Paper. These studies have an important gap from the perspective of economic theory and environmental valuation, viz. they do not systematically monetarise the economic costs and benefits of the national policy scenarios identified, nor do they monetarise the environmental costs associated with such scenarios. Economic and environmental valuation work has been conducted but it does not amount to a CBA of national policy scenarios.

The first part of this project (section 3) therefore involved reviewing the work prepared by and on behalf of DfT, and the wider policy context in which it was undertaken, so as to understand the evaluation approach used by DfT. This approach was then contrasted with economic theory and with the approach recommended by HMT in the "Green Book" (HMT, 2003).

For purposes of the quantitative analysis, it was then necessary to identify policy scenarios (in terms of capacity expansion) to be evaluated. Whilst the main emphasis of the thesis is to value the environmental costs of the selected scenarios (specifically global warming impact), an estimate of the net economic benefits of those scenarios was also made so as to give a basis for comparison with environmental costs. The estimate of net economic benefits is based entirely on DfT estimates pertaining to specific development options, with some (relatively crude) adjustments made to reflect the national policy scenarios identified and deficiencies identified in the DfT estimates.

2.3 Valuation of Global Warming Damage

A computer model was compiled which monetarises the global warming costs of three alternative airport capacity expansion options, broadly reflecting a “high case” and two alternative versions of a “low case”. In each case, the model takes as its starting point DfT’s demand projections for passenger and freight traffic over the period 1998 to 2030, converts these into a forecast of aircraft movements, calculates emissions from those aircraft movements and then applies a value per unit of emissions to derive damage estimates. These estimates are presented as an aggregate (discounted) amount, and also in other relevant metrics such as cost per passenger mile, etc. Although emissions are only forecast until 2030, a valuation is given for the period 2000 to 2060 (applying the valuations for 2030 to the years 2031 to 2060), so as to allow comparison with the net economic benefits of capacity expansion.

The comparison of a high and low capacity case not only serves as a comparator for the CBA but also generates, in effect, an estimate of the marginal environmental cost of capacity expansion (albeit averaged over a relatively substantial change in capacity). The comparison enables non-linear effects of expansion to be explored. For example, while higher passenger volumes are to be expected to generate higher total emissions under a high capacity case, the magnitude of the increase will be affected by such factors as the higher levels of aircraft occupancy that can be expected if capacity is constrained or, conversely, the more rapid fleet modernisation achievable if capacity is less constrained. These effects are explored quantitatively, using assumptions drawn from secondary data and (in some cases) personal judgment.

One weakness of the comparison between alternative levels of capacity is that it does not consider the indirect effects of suppressed air travel, e.g. the diversion of a proportion of the suppressed demand to other (potentially environmentally damaging) forms of transport. To the extent that damage valuation techniques are used as the basis for economic instruments, the implicit assumption is made that environmental externalities will also be internalised for alternative modes of transport.

2.3.1 Traffic and Emissions

The detailed steps used to convert demand forecasts into estimates of emissions are described in Section 4. The general approach taken was to replicate, to the extent feasible and using a simplified methodology devised for this project, the results produced in DfT's own analysis and then to vary certain of the assumptions (e.g. regarding technological and operational developments), in light of supplementary analysis, in order to give independent estimates of emissions.

Given that many of the details of DfT's analysis have not been published, and given the differences in methodology employed, the exercise of calibrating the model against DfT's analysis was inevitably imperfect. A key obstacle was that DfT's analysis is not a single body of work but is scattered across a number of studies, whose methods and findings are not always consistent. Thus, the calibration exercise was viewed as a process for "sanity checking" the modelling process and deriving a certain amount of comfort in the results obtained, but not an infallible process.

2.3.2 Valuation of Emissions

The approach to valuing the CO_2 emissions quantified in section 4 is described in detail in sections 5. Four alternative valuation profiles were selected from the literature, representing valuations which are reasonably up-to-date, representative of the range of academic opinion and amenable to Monte Carlo simulation. In addition, two composite profiles were created from certain of those valuations. All of the valuations were based on the damage cost method rather than the abatement cost method. The rationale for this is that the abatement cost method is only considered reliable under the rather artificial assumption that environmental limits have been set at a level coinciding with the socially optimum level of emissions (see 5.5.1).

Aviation is responsible for a number of other greenhouse gases besides CO_2, the climatic effects of which are generally less well understood than those of CO_2. The Government's approach is to multiply the damage caused by aviation's CO_2 emissions by the RFI (which is intended to reflect the impact of other GHGs relative to CO_2). This approach raises a number of conceptual difficulties which are discussed in section 5. Despite these difficulties, there was little alternative within the scope of this thesis to using RFI as the metric for valuing non-CO_2 GHGs; however, the uncertainties were, to the extent possible, taken into account in the analysis.

For purposes of calculating NPVs of emissions, a discount rate of 3.0% was chosen. This was consistent with the discount rates used in DfT's most recent CBA work and reflects the recommendations of the Green Book. CO_2 valuations were chosen which were, as far as possible, consistent with the 3.0% discount rate.

2.4 Approach to Uncertainty

A model inevitably represents a simplified version of a system and is inherently prone to uncertainties. These include uncertainties as to the values assumed for variables, the precise relationships between those variables and the influence of variables (known and unknown) which are not modelled. In modelling the environmental damage caused by aviation's future emissions, the key uncertainties relate to:

- Future levels of demand and traffic (reflecting economic factors, consumer preferences and the development of alternative modes of transport, as well as the extent to which demand can be accommodated by future levels of capacity);
- Technological and operational factors (e.g. fuel consumption of the aircraft fleets of the future, passenger load factors, flight paths, etc.);
- The values assigned to aircraft emissions (reflecting scientific uncertainties as to the impact of those emissions, and economic uncertainties as to their valuation)[10]; and
- Demand and supply side responses to policies introduced to reduce or mitigate the environmental impacts of aviation.

Since the uncertainties arise throughout a chain of calculations, the range of damage estimates is potentially broad. This calls for a formal analytical approach to dealing with uncertainty, and indeed potentially calls into question the applicability of economic instruments aimed simply at internalising aviation's external costs. In this project, the following techniques were employed for dealing with uncertainty:

- Specific scenarios were constructed, so as to be able to assess the impacts of assumptions linked to a specific "storyline"[11].
- Specific assumptions used in scenarios were subjected to individual sensitivity analysis so as to assess the sensitivity of the results to individual variables;

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[10] The continuing controversies over the valuation of a tonne of CO_2 are magnified by the uncertainties, which are specific to aviation, relating to the valuation of non-CO_2 GHGs.

[11] In each scenario, two alternative levels of infrastructure capacity (a "high case" and a "low case") were assumed. A distinction is therefore made between the words "scenario" and "case". The scenarios are introduced throughout the document. See Table 28 on page 142 for an overview.

- Monte Carlo simulation was performed, i.e. key variables were randomised and multiple model runs (up to 2,000 recalculations) performed, so as to analyse the distribution of results and derive an expected value (i.e. arithmetic mean of the Monte Carlo simulations) for the results of interest.

Randomisation was performed by assigning a probability density function (PDF) to key variables. Where possible, the PDF was based on published estimates; in other cases, personal judgement (albeit informed by the literature) was used. PDFs used included:

- Where only upper and lower estimates were available or the central estimate has no greater probability than other points within the range, a uniform distribution;
- Where the central estimate is viewed as having a greater probability than other points within the range but without a precise indication of the distribution within the range, a triangular distribution[12];
- Where assumptions were generated from large databanks of information (e.g. aircraft fuel burn characteristics) a normal or lognormal distribution;
- In one specific case (one of the valuation profiles of carbon emissions) a PDF was created by manually recreating a histogram published in the literature.

The uncertainty analysed via the above techniques almost inevitably fails to capture the full range of uncertainties. In particular, while the uncertainties associated with some of the key assumptions are analysed, the analysis does not take account of the uncertainties relating to: exogenous factors; the relationships between variables (and the modelling thereof); the shape of the probability density functions assumed; or indeed the adoption of particular scenarios/cases (in particular airport capacity)[13].

The approach adopted towards randomising individual variables is explained throughout the text and also in the detailed model assumptions set out in Appendix VI.

2.5 Computer Software

The spreadsheet package employed for the quantitative analysis was Microsoft Excel. In order to perform Monte Carlo simulation, a macro was created in Microsoft Visual Basic for Applications, enabling the automation of multiple calculations utilising

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[12] The term ‘triangular distribution’ refers, in this thesis, to a distribution with a gradient between the lowest, central and highest estimates. It is therefore distinct from ‘three-point analysis’ which considers only the lowest, central and highest figures (sometimes on a weighted basis).

[13] In effect, the latter point means that the probability distributions of results are calculated from the perspective of a policymaker who has control over the policy decisions to be made.

different "draws" from key random variables. The random variables themselves were generated within Excel, utilising (in certain cases) an add-in for statistical techniques known as SIMTOOLS. A CD-ROM containing the spreadsheet is included, together with brief instructions for using the model, in Appendix VII.

2.6 Policy Implications

The policy implications of the quantitative results were analysed in a number of ways (see section 6). First, the NPV of global warming damage estimates for particular levels of capacity expansion were compared with the NPV of the benefits of expansion so as to identify whether or not the damages, calculated at different levels of probability, outweigh the damages. The policy implications of the results were then considered.

Second, the damage estimates were calculated for a range of illustrative journeys as the basis for quantifying an environmental tax on aviation. Again, the focus was on the impact of uncertainty on such a tax, including uncertainty as to the demand side response to a tax (supply side responses were not analysed). An illustrative sensitivity case was run under which the demand side response was analysed and, based on that demand side response, the economic damage re-computed.

Finally, although the structuring of economic instruments is beyond the scope of this thesis, some of the implications of the findings of this report for the structuring of economic instruments were briefly considered.

2.7 Strengths and Weaknesses of the Quantitative Approach Used

The quantitative approach employed for this project offered two potentially significant advantages over the approach used by the UK Government to value emissions for the years 2000 and 2030 (as shown in Table 2):

- First, by considering an extended period of time rather than just a "snapshot" of damages at a particular point in time, the resulting valuation would be directly comparable with the result of the CBA work;
- Second, by attempting to deal systematically with uncertainty, the exercise imparts information about the range and spread of estimates which should be more meaningful for evidence-based policymaking than a single, deterministically derived, figure.

It is recognised, however, that the extent to which the above two advantages are realised is qualified by a number of caveats:

- First, the approach taken, for many of the variables considered, was to make assumptions for the years 2000 and 2030, and to interpolate assumptions for intervening years. Not all assumptions were interpolated in this way and indeed interpolation was not necessarily simply a case of assuming a straight-line progression from 2000 to 2030. Nonetheless, this is still likely to be a source of inaccuracy in the computations;
- Second, all figures and values for the period 2031 to 2060 were assumed to be exactly as per 2030, given the difficulties of forecasting half a century into the future. Thus, the impacts of traffic growth, technology and changes in damage valuations beyond 2030 are not taken into account. Whilst this would not be a significant issue at a relatively high discount rate (e.g. the 6% recommended, until recently, by HMT), the years 2031-2060 have a reasonably high weighting in the overall value at a discount rate of 3%. This, then, is a further source of inaccuracy;
- Third, the incremental value of a probabilistic model over a deterministic model depends on the extent to which the PDFs assigned to variables stand up to scrutiny and cover the full range of uncertainties. As noted above, the approach adopted is subject to a number of limitations, which may result in a range of model results which is either too narrow or too broad. Accordingly, pending more rigorous estimates of PDFs associated with the variables covered in the model, the results of the Monte Carlo simulation should be considered only as illustrative of the range of uncertainty associated with the modelled results. Nonetheless, the framework adopted here can help to prioritise further research into particular variables, by highlighting the relative sensitivity of the results to those variables and the degree of uncertainty assigned (transparently albeit, in some cases, subjectively) to them.

The limitations of the work are discussed further in section 6.

3. THE UK GOVERNMENT'S APPROACH

3.1 Overview

The Government is due to publish, in late 2003, a White Paper setting out its policy on aviation, including the development of further runway capacity and the role of economic instruments in managing aviation's environmental impacts. This section sets the ensuing sections on environmental valuation in context by:

- Briefly introducing the policy background to the forthcoming White Paper;
- Discussing the framework used by DfT to assess the impacts of transportation projects in the context of economic theory and HMT guidance;
- Presenting and adjusting components of the economic analysis performed by DfT, so as to give a valuation of benefits which can be compared with the environmental costs presented in later sections; and
- Briefly reviewing issues associated with environmental taxation, by way of introduction to the discussion in section 6.

3.2 Background to Government Aviation Policy

The Labour Party included in its 1997 election manifesto a commitment to "put concern for the environment at the heart of policy-making" and to "safeguard our environment, and develop an integrated transport policy to fight congestion and pollution" (Labour Party, 1997). A strategic review of the roads programme was promised, but no specific commitments were made on aviation. The manifesto also alluded to the potential for the tax system to be used as an instrument to discourage environmental pollution.

Since gaining power in 1997, the Government has undertaken a number of initiatives in the above areas, including:

- Publication of the Integrated Transport White Paper (DfT, 1998a). As well as emphasising sustainability and integration of transport and of the environment, this document announced a "New Approach to Appraisal" (NATA – see 3.3.1 below), which was subsequently carried forward from roads to other modes of transport;
- Undertaking a strategic review of the roads programme. The resulting policy document (DfT, 1998d) acknowledged that a "predict and provide" approach to accommodating growing demand via road building was not a viable solution – a conclusion with potentially important implications for other modes of transport;

- Formulating policy in relation to environmental taxation (HMT, 1997, 2002) and implementing a number of such taxes (e.g. climate change and aggregates levies);
- Launching a policymaking process towards the aviation sector. The outcome will be an Air Transport White Paper, due to be published in late 2003;
- Launching a consultation process (following publication of HMT / DfT, 2003a), which will form the basis for proposals for economic instruments to be included in the White Paper (see 3.5).

Figure 1 below maps out some of the key documents leading up to the White Paper. Besides documents specific to aviation, these include DfT documents on transport project appraisal (see 3.3.1), HMT's guidance on appraisal (see 3.3.3) and HMT documents addressing environmental taxation (see 3.5).

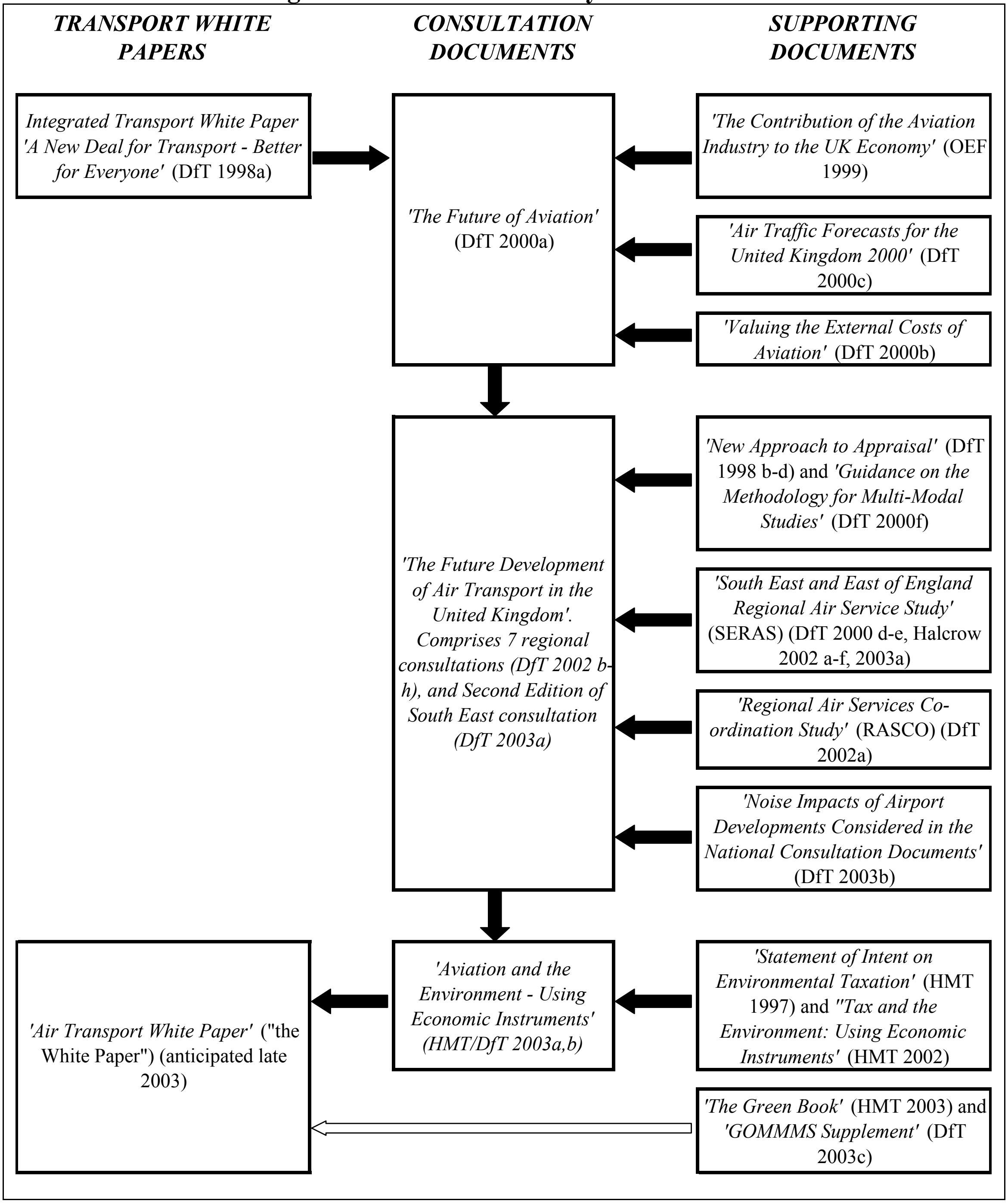
The studies specific to aviation include documents prepared by DfT (in relation to traffic forecasting and external environmental costs) and studies commissioned from third parties. The latter category includes the SERAS and RASCO studies (relating, respectively, to the south east and east of England and to the remainder of the UK). The various studies were summarised in a high-level consultation launched in 2000 (DfT, 2000a) and more detailed regional consultations in 2002 and 2003 (DfT, 2002 b-h, and DfT, 2003a), feedback from which will inform the policy-making process.

The studies for the south east and east of England (SERAS) and the rest of the country (RASCO) were carried out separately, owing to the complex issues related to the former regions (size, scale of demand, diversity and status of airports, etc. – see DfT, 2003a, page 163). Although both studies were prepared within the NATA framework described in 3.3.1 below, there is a somewhat differing emphasis between the two:

- RASCO identifies national policy scenarios reflecting different levels of support for the development of aviation. It then considers, for the different regions, the levels of demand and adequacy of capacity, thereby identifying capacity requirements under each of the different policy scenarios. Certain projects meeting such capacity requirements are deemed to be of national or regional significance and are considered in further detail, whilst other projects are deemed to be incremental investments not needing to be considered within a national policy framework.
- SERAS, by contrast, does not consider national policy scenarios (although certain environmental policy sensitivity cases are performed – see 3.3.1 below) but

considers a number of development options at each of the major south east airports. These options are then aggregated into "packages" for purposes of overall appraisal.

Figure 1: Overview of Policy Framework



3.3 DfT's Methodology

3.3.1 NATA, GOMMMS and the Aviation Studies

DfT's approach to appraising transport investment programmes is set out in "Guidance on Methodologies for Multi-Modal Studies" (GOMMMS) (DfT, 2000f). GOMMMS builds on the NATA methodology (see DfT, 1998b,c), which emerged from the roads review (DfT, 1998d). The NATA/GOMMMS approach has been adopted (with some adjustments – see DfT, 2000e) in the RASCO and SERAS studies.

The NATA/GOMMMS approach is a form of multi-criteria analysis (MCA), requiring investment options to be evaluated according to five criteria, viz. safety, economy, environment, accessibility and integration. The impacts on these criteria are to be presented in an Appraisal Summary Table (AST) utilising indicators which are either quantified in monetary or physical terms or described qualitatively. The AST is not intended to allow impacts to be compared or prioritised in a mechanistic way, requiring judgement on the part of decision-makers in order to decide on the best way to proceed.

As part of the airport studies, the Government and its consultants have prepared a CBA of a series of options, mainly in the south east. Consistent with the GOMMMS framework (see DfT, 2000f) only a narrow range of economic impacts is included in the CBA. Wider economic impacts (e.g. on employment, competitiveness, etc.) and non-economic impacts (i.e. the other evaluation criteria) are excluded from the CBA, and are presented (in many cases for illustrative years only) either in the ASTs or elsewhere in the documentation. Thus, the CBA is just one constituent of one of the criteria within the MCA framework, and has not in any case been conducted for many of the projects underpinning the RASCO policy scenarios.

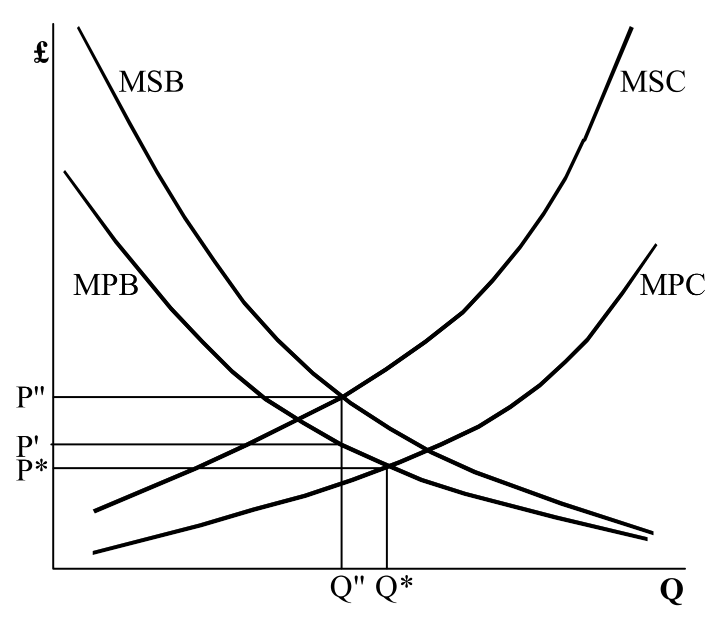
Although not included in the CBA, DfT has attempted to value certain of the environmental impacts of aviation (DfT, 2000b and HMT / DfT, 2003a). However, DfT's analysis presents a "snapshot" of the impacts of total UK aviation in one or two years only, rather than a time series analysis of the incremental impacts of specific development options. The monetary values presented by DfT are therefore not readily comparable with the economic benefits calculated as part of the CBA.

DfT has also, as part of the CBA, performed environmental sensitivity cases. These introduce an aviation fuel tax (based on the estimated environmental costs) and assess the impact of the resulting reduction in demand on the net economic benefits. Only those items included in the base case analyses (see 3.4) are considered, and the monetarised environmental impacts themselves are excluded from the calculation. The tax itself has no net impact on the calculations (a reduction in consumer and/or producer surplus, matched by an increase in government revenue), and the only impact on net benefit is via reduced demand. The environmental sensitivity cases cannot therefore be seen as incorporating the environmental impacts of aviation within the CBA result.

3.3.2 Economic Theory

According to economic theory, the socially optimal level of an activity such as aviation (Q'') will be found at the point where the Marginal Social Benefits (MSB) and Marginal Social Costs (MSC) of that activity intersect[14]. MSB and MSC include external benefits (e.g. employment, facilitation of trade) and external costs (e.g. environmental impacts, safety considerations) which are additional to the Marginal Private Benefits (MPB) and Marginal Private Costs (MPC) accruing to the economic actors directly involved in supply or demand of that activity. See Figure 2 below.

Figure 2: Socially Optimal Level of Aviation



DfT's CBA of investment options, as described in 3.3.1 above in effect considers discrete points along the X-axis in Figure 2, ranging from no additional capacity (other than that for which planning permission is in place) to a level of capacity (nearly) meeting DfT's unconstrained demand forecasts[15]. The analysis can be viewed as a form of multi-party private economic analysis, in that it aggregates the benefits and costs of the economic actors directly involved in aviation (passengers, freight users, airport operators and Government, as a recipient of taxation). However, no account is taken of externalities accruing to society at large, and no common yardstick is provided

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[14] Distributional considerations may affect the level of welfare associated with MSB and MSC, and a distributionally weighted approach may result in a socially optimal level different from Q".

[15] In practice, the options vary in a number of respects (e.g. location) and cannot solely be differentiated in terms of additional capacity provided.

weighing up the MSB and MSC for each option. The option providing the highest NPV under the CBA (i.e. the option closest to Q* of capacity) may entail positive or (as in Figure 2) negative net external benefits and may or may not be socially optimal. Indeed, it is not even obvious that the impacts considered in the CBA represent a significant proportion of the overall costs and benefits (see 3.4.5 below).

It can be argued that DfT's MCA approach has the benefit of not allowing impacts to be double-counted in decision-making. However, the main reason for avoiding monetarisation of wider impacts appears to stem from valuation uncertainties. On the subject of environmental valuation, for example, DfT stated in 2001:

> "Steady progress is being made, but will vary between different environmental impacts, with more promise in securing reasonable valuations on vehicle emissions affecting health and on noise than on the effects of climate change and effects of transport on landscape and landtake. In all these areas, however, robust monetary values are some way off." (DfT, 2001)

Whether the above concern is justified is addressed (in the context of global warming) in the later sections of this thesis. However, it is worth noting that, if the external benefits of aviation are considered substantial but cannot be effectively measured (see 3.4.5), then the usefulness to policy formulation of valuing external costs may be limited, since the policy decision becomes a matter for qualitative judgement.

3.3.3 The Green Book

In 2003, HMT published the latest version of "The Green Book: Appraisal and Evaluation in Central Government" (HMT, 2003). The Green Book advocates monetarising as many impacts as possible via CBA, but recognises that impacts which cannot be monetarised need to be taken into account qualitatively. As the following quotations from The Green Book show, impacts to be considered include social and environmental costs, even where there is uncertainty as to valuations.

> "Wider social and environmental costs and benefits for which there is no market price also need to be brought into any assessment. They will often be more difficult to assess but are often important and should not be ignored simply because they cannot easily be costed."
>
> "In the absence of an existing robust (i.e. reliable and accurate) monetary valuation of an impact, a decision must be made whether to commission a study … Where it is concluded that a research project to determine valuations is not appropriate, a central estimate, together with a maximum and minimum plausible valuation, should be included. These figures should be included in sensitivity analyses to give assurance that benefit valuation is not critical to the decision to be made."

Annex 2 of The Green Book refers to climate change, air quality, landscape, water, biodiversity, noise and disamenity as environmental impacts to be valued. 'Investment appraisal for long-term planning and infrastructure projects' is singled out as an area where valuation of climate change impacts is particularly relevant, and HMT cites a specific paper as a source of valuing CO_2 (Clarkson and Deyes, 2002 – see 5.5.1).

It is apparent from the foregoing that there are differences between the MCA approach of NATA/GOMMMS and the economically orientated Green Book approach. In the light of the revised Green Book, DfT has announced a number of changes to GOMMMS. On the subject of monetarisation, DfT has stated:

> "The emphasis on quantification in monetary terms is clearly an important issue for the appraisal of transport investment, where several significant environmental and other impacts are identified but not, currently, valued. The Department is committed to extending valuation to a wider range of the impacts of transport investment. Valuation is planned for impacts such as noise, local air quality and global emissions, but is further off for 'land take' impacts such as landscape, heritage, biodiversity and so on. The Department's ambition to extend monetary valuation to more of the impacts of transport investment will bring the NATA closer to the [Green Book] ideal, bringing greater transparency to decision making." (DfT, 2003c)

DfT has also adjusted the CBA undertaken in SERAS and RASCO in light of the Green Book. Specifically, the discount rate has been reduced from 6% p.a. to 3.5% p.a.[16], and sensitivities addressing optimism bias have been introduced. However, no attempt has been made to incorporate environmental impacts into the revised CBA or to present values for those impacts on a basis which can be compared with the economic NPVs.

3.4 Economic Analysis

Sections 3.4.1 to 3.4.4 below attempt to derive, based upon the CBA work performed by DfT and its consultants, the net economic benefits of particular scenarios whose environmental costs are analysed in later sections.

By way of background, the regional aviation markets are highly inter-dependent. Indeed, DfT's "SPASM" passenger allocation model (see Box 1 on page 35) allocates demand from districts to particular airports on a national basis. Thus, it was necessary for both SERAS and RASCO to take account of developments being considered in the counterpart study. The RASCO scenarios allow for alternative levels of development in

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[16] In fact, the years beyond 2030 should be discounted at 3.0%, according to the Green Book.

the south east whereas SERAS, for most purposes, assumes that there will be no capacity constraints in the regions. This is shown in Table 3.

Table 3: RASCO/SERAS Capacity Combinations

	Level of capacity	RASCO scenario	SERAS package
A.	South east: high Regions: unconstrained	RASCO Reference Case (RRC)	Packages 14-21 (3/4 new runways)
B.	South east: low Regions: unconstrained	South East Constrained (SEC)	Packages 1-2 (no new runways)
C.	South east: high Regions: constrained	N/A	N/A
D.	South east: low Regions: constrained	UK-Wide Constrained (UKC)	N/A[17]

3.4.1 SERAS Packages

Under SERAS, options were considered at the major airports in the south east and bundled together into over twenty "packages" of options. For the purposes of this discussion, the most relevant packages are:

- Package 1: no incremental development over and above that for which planning permission has already been granted;
- Package 2: maximum use of existing runways, facilitated where necessary by construction of new terminal capacity and (at Luton) extension of the existing runway, but no additional runways. Of all the packages, this package ranks second lowest in terms of NPV, but second highest in terms of Benefits Cost Ratio (BCR, i.e. the ratio of NPV to investment costs);
- Package 18: one new runway at Heathrow and two new runways at Gatwick. Of all the packages, this package ranks third in terms of additional capacity and traffic, first in terms of NPV, and second in terms of Benefit Cost Ratio (BCR)[18].

In the studies, the consultants originally used Package 2 as the comparator against which all packages were evaluated. However, in the presentation of the figures in the public consultation documents, Package 1 has been used as the comparator. The costs and benefits of the above packages (through to 2060) are shown in Table 4 below.

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[17] In fact, the SERAS studies considered one scenario which assumed no new runways in the south east or regionally, for purposes of estimating CO_2 emissions (Halcrow, 2002d, pages 93-113, described further in 4.3 below). However, this scenario was not appraised in other respects.

[18] Although coming slightly closer to meeting unconstrained demand than Package 18, Packages 19 and 21 have lower NPVs. This is primarily because they do not include an additional runway at Heathrow and therefore fail to generate the higher consumer surplus associated with business travel at this airport. Package 19 has the highest BCR, since construction costs are lower at Stansted than at Heathrow.

Table 4: Discounted costs and benefits

	Package 2 *versus* Package 1	**Package 18 *versus* Package 2**	**Package 18 *versus* Package 1**
Additional capacity	**47.5 mppa**	**110.5 mppa**	**158.0 mppa**
Passenger benefits:			
- Generated/UK users	n/d	£8,458m	n/d
- Generated/foreign users	n/d	£3,706m	n/d
- Existing/UK users	n/d	£1,614m	n/d
- Existing / foreign users	n/d	£1,022m	n/d
Freight user benefits	n/d	£214m	n/d
Airport operator benefits	n/d	£2,952m	n/d
Government revenue	n/d	£572m	n/d
Total benefits	**£6,730m**	**£18,537m**	**£25,267m**
Costs (capex + opex)	**-£1,770m**	**-£5,155m**	**-£6,925m**
NPV	**£4,960m**	**£13,382m**	**£18,342m**
BCR	**3.8**	**3.60**	**3.65**
NPV / add. Capacity	**£104**	**£121**	**£116**
NPV (@3.5% p.a.)	**£14,670m**	**£36,750m**	**£51,420m**

Adapted from Halcrow, 2002a, Table 14.8, and from DfT, 2003d, Table 1.
All values are expressed in 2000 prices and, except where indicated, discounted at 6% p.a.

3.4.2 RASCO Projects

Under most national policy scenarios, RASCO (DfT, 2002a) identified a large number of investment requirements across the regions over the period to 2030. Most of these are incremental investments, and CBA has only been undertaken for the projects large enough to be considered of "national significance". In other cases forecast traffic levels have been proposed as an indicator of economic efficiency.

The two RASCO national policy scenarios considered here are the RASCO Reference Case (RRC) and the UK-Wide Constrained (UKC) scenario (see Table 3). Although not the largest capacity option, the RRC assumes continuing provision of capacity (albeit subject to some constraints in the south east) in order to (nearly) satisfy DfT's unconstrained traffic forecasts. The RRC predicts passenger traffic in 2030 of 471 mppa (nationally) and 270 mppa (for the regions). The major projects which are relevant to the RRC are shown in Table 5[19]. The UKC reflects a relatively stringent environmental policy stance and assumes that, other than projects for which planning

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[19] Different locations and/or configurations are also under consideration. Where possible, the option with the highest NPV has been shown here. A number of other major national projects have been identified (e.g. a new airport at Bristol) but are more relevant to the South East Constrained scenario (since demand spills over from the south east) than to the RRC.

permission is in place[20], no expansion of capacity will take place. The UKC predicts passenger traffic in 2030 of 260 mppa (nationally) and 116 mppa (for the regions)

Table 5: Regional Projects of National Significance (RRC)

	Additional capacity	**NPV @ 6% p.a. (2000 £)**	**NPV (6%)/ add. Capacity**	**NPV @ 3.5% p.a. (2000 £)**
Birmingham runway	~20 mppa	£720m	~£36	£2,360m
Manchester terminal	~30 mppa	£462m	~£15	N/A
Edinburgh runway	~25 mppa	£680m	~£27	£2,240m

With the exception of Manchester, these NPVs are drawn from DfT, 2003d. The NPV for Manchester (from DfT, 2002a) may not be directly comparable with the other NPVs (e.g. based on a shorter appraisal period).

3.4.3 NPVs of National Capacity Scenarios

The principal national capacity configurations (reflecting rows A and D of Table 3) evaluated in this thesis are:

- A high capacity scenario, such as RRC (RASCO) or Package 18 (SERAS). For purposes of reconciliation with DfT figures, this is modelled in a number of ways (see 4.3) but can essentially be thought of as one scenario;
- A low capacity scenario, reflecting maximum use of existing runway capacity but no further runway capacity. Although it does not correspond to any of the RASCO scenarios or SERAS packages, it coincides with a case used by Halcrow for modelling CO_2 emissions (see 4.3.1);
- A very low capacity case, reflecting the UKC. Although arguably the scenario least likely to be adopted in the White Paper, the UKC represents the *status quo* and, as such, is perhaps the most appropriate comparator for other development options.

Quantifying the NPVs of the above capacity scenarios is not just a question of adding the amounts shown for the south east and regions shown in Table 4 and Table 5; however, a broad estimate of the NPVs of the high and low capacity case (relative to the very low capacity case) can be derived by making a number of (somewhat *ad hoc*) adjustments to the above figures:

- In the high capacity case, this entails adding an additional amount to the NPV for Package 18 shown in Table 4, to reflect the fact that Package 1 (which assumes no regional capacity constraints) assumes higher traffic levels in the south east than the UKC, and extrapolating from the NPVs shown in Table 4 and Table 5 to derive the

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[20] This is analogous to, but not quite consistent with, assumptions for the south east in SERAS Package 1. The latter assumed, in common with all SERAS packages, that capacity would be unconstrained in the regions.

value of incremental capacity in the regions. This gives an NPV, relative to the very low capacity case, of approximately £26 or £75 billion (6% and 3.5% discount rates respectively);

- In the low capacity case, this entails a similar process, except that Package 2 is the relevant case to be adjusted in the south east. This gives an NPV, relative to the very low capacity case, of approximately £14 or £41 billion (6% and 3.5% discount rates respectively).

Details of the above calculations are provided in Appendix III. It should be stressed that the adjustments made are subject to a high degree of uncertainty, and do not take account of the fact that the marginal benefits of different expansion options, per unit of additional traffic liberated, are unlikely to be constant[21] across different levels of capacity addition. However, at least in the case of the high capacity scenario, the overall level of error introduced by the above adjustments is likely to be relatively modest, given that a high proportion of the aggregate NPV is represented by the DfT figures (ex-adjustments).

3.4.4 Further Adjustments to NPVs

Aside from the fact that the values given in 3.4.3 take no account of externalities, and incorporate some relatively crude adjustments to which a high degree of uncertainty applies, the underlying numbers prepared by DfT are subject to a number of criticisms.

First, the net benefits include consumer surplus accruing to foreigners. DfT maintains that, because aviation is an international business involving reciprocity, this is appropriate. In contrast, the Green Book states:

> "All impacts … on non-UK residents and firms should be identified and quantified separately where it is reasonable to do so, and if such impacts might affect the conclusions of the appraisal. Generally, proposals should not proceed if, despite a net benefit overall, there is a net cost to the UK (for instance, after taking into account environmental costs)." (HMT, 2003, page 21.)

There is an inconsistency and/or an ambiguity here, which is directly relevant to environmental valuation. The valuation of CO_2 emissions advocated in the Green Book represents the valuation of global, not national, damage. It is not clear whether HMT is consciously recommending that global environmental costs be taken into account as an

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[21] The relationship is unlikely to be straightforward: note, from Table 4 that the net benefit per passenger is actually higher for the high capacity option (Package 18) than for the lower capacity option (Package 2).

exception to the guidance only to consider UK costs and benefits, or whether (unlikely) HMT believes that only the proportion of climate change damage incurred by the UK should be reflected in CBA. For purposes of this study, a global valuation of climate change is used, and therefore DfT's inclusion of consumer and producer surplus accruing to foreigners is not challenged.

Second, the net economic benefits include producer surplus accruing to airport operators (e.g. £3.0 billion in the case of SERAS Package 18 versus Package 2). This is derived using the societal discount rates (i.e. 6% p.a., for the number just quoted, or 3.5% p.a.). However, financial viability is separately analysed utilising private financial analysis, based on a nominal discount rate of 12.5% p.a. (Halcrow, 2002a) – equivalent to a real rate of approximately 10% p.a. This analysis generates a negative NPV, implying that airport charges would need to increase in order to enable airport operators to make the required investment. Unless the argument is made that society places a higher value on producer surplus than the producer itself places, then the inclusion of such surplus seems inappropriate and ought to be excluded[22].

Third, DfT's economic analysis has excluded a number of costs associated with airport development, such as public enquiry costs, legal costs and environmental mitigation costs. It is not clear why these "soft costs", which could potentially be material, have been excluded. Furthermore, the costs are based on prevailing cost levels and take no account either of the potential for construction prices to change in real terms by the time that construction commences or for these (very major) works to make an impact on prices in the construction market. If the construction market is resource-constrained at the time, then the works may lead to an increase in civil construction prices generally, and this would entail not only a higher cost of airport construction but also (as another example of an externality) an opportunity cost in the wider construction market generally. This has not been taken into account by DfT.

An illustrative allowance for producer surplus and for additional "soft costs" (totalling 25% of the net benefits, ex-adjustment) is deducted from the aggregate figures given in Table 6. The amount of the adjustment is based, in the high capacity scenario, on the proportion of the total NPV (6% discount rate) accounted for by producer surplus in

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[22] Indeed, there is an argument for subtracting the "producer deficit" calculated using a private sector discount rate. Alternatively, consumer surplus should be recalculated utilising the level of airport charges which would enable airport infrastructure providers to realise (based on a private sector discount rate) a marginally positive NPV.

Table 4 and (based upon the author's own experience of infrastructure projects) a relatively conservative allowance of 5% in respect of soft costs. A *pro rata* adjustment is then made to the other cases.

Table 6 shows the NPVs of the high and low capacity cases, relative to the very low capacity case, after taking account of the adjustments described above. These are taken forward to later sections of this document for comparison with environmental costs.

Table 6: Adjusted NPVs

Case (discount rate)	**High capacity (6.0%)**	**High capacity (3.5%)**	**Low capacity (6.0%)**	**Low capacity (3.5%)**
NPV (from 3.4.3)	~£26 bn	~£75 bn	~£14 bn	~£41 bn
Adjustments	(~£6 bn)	(~£17 bn)	(~£3 bn)	(~£9 bn)
Total	**~£20 bn**	**~£58 bn**	**~£11 bn**	**~£32 bn**

3.4.5 Wider Economic Benefits

It should be noted that no allowance has been made in the figures quoted in Table 6 for the wider external economic benefits associated with aviation, such as the impact on tourism, investment, employment, etc. There is considerable controversy in this area. The first issue is the conceptual difficulty of potentially double-counting social and private economic benefits, and indeed this is acknowledged by DfT (2003e).

The second issue relates to the disputed claims as to the net economic benefits, in practice, of aviation. For example, British Airways (BA) suggests that, at £67 bn, the NPV of the wider economic benefits of three additional runways in the south east is more than double its estimate (£28 bn) of the direct economic impacts (BA, 2003a). Conversely, other commentators (Whitelegg, 2003) contest these wider benefits, and argue that there are substantial negative economic externalities (e.g. outbound tourism). (See also Ecotec, 2000 and Berkely Hanover, 2000.)

Research commissioned by the Government (Oxford Economic Forecasting, 1999) suggests that aviation directly contributes around 1.4% of GDP and 0.8% of employment and has wider, indirect benefits to the UK in terms of employment, investment and competitiveness. However, it is not clear that an analysis of aggregate benefits is particularly useful in the context of analysing the marginal economic benefits of specific expansion options. Conceptually, for instance, it is possible that a low level of aviation activity is consistent with keeping "the wheels of commerce" turning and that the marginal economic benefits of additional activity are relatively modest.

An appraisal of the marginal social benefits of airport expansion is therefore required, to complete the analysis. Such an appraisal is beyond the scope of this thesis, however.

3.5 Background on Policy Towards Economic Instruments

The Integrated Transport White Paper (DfT, 1998a) stated that "aviation should meet the external costs, including environmental costs, which it imposes". To this end, HMT and DfT initiated a consultation exercise by releasing a consultation document entitled "Aviation and the Environment: Using Economic Instruments" (HMT / DfT, 2003a).

The HMT / DfT document does not quantify the level of any tax (or other economic instrument) which might be proposed in the White Paper. However, the Government has stated (House of Commons Environmental Audit Committee, 2003, page Ev2) that it views the purpose of a tax as being to internalise environmental costs, and thereby create incentives for supply side improvements in technology and operations, rather than to achieve any particular environmental targets or demand side responses. The Government has suggested that the impact of an aviation tax reflecting external costs would be to suppress demand by up to 10%, which reduction would be at least partially offset by supply side responses (see DfT, 2003a, Chapter 5).

In proposing economic instruments, the Government will need to consider a number of constraints. The first is the possibility that the competitiveness of the UK aviation industry, and to some extent of the economy in general, may be adversely affected by the imposition of economic instruments which are not matched in other countries.

A second constraint is the existence of over 2,000 international bilateral agreements exempting international flights[23] from taxation of aviation fuel (DfT, 2000a, page 38). Similarly, the fact that CO_2 emissions from international flights are not covered by the Kyoto Protocol creates an obstacle, for the time being, to an international tradable permit scheme. These institutional barriers are not considered further in this thesis.

Aside from fuel tax exemptions, the aviation industry enjoys various fiscal advantages. These include VAT zero-rating of air travel and duty-free retail status at airports and on-

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[23] There are no such restrictions on taxing aviation fuel used domestically, and it is possible that the European Union may have the ability to allow taxes to be levied on intra-European flights.

board aircraft (for travel outside the EU). It has been estimated that these concessions, together with fuel tax exemption, exceed tax revenues from Air Passenger Duty (APD) by around £9 bn p.a. (Sewill, 2003). Clearly, such fiscal advantages pull in the opposite direction to any economic instrument that might be aimed at mitigating aviation's environmental impacts. However, recent Ministerial statements suggest that the Government is not proposing to equalise the tax treatment of aviation relative to other forms of transport (see House of Commons Environmental Audit Committee, 2003).

It should be noted that preliminary feedback from the consultation exercise (HMT /DfT, 2003b) indicates that most consultees view an environmental tax as less desirable, at least ultimately, than a tradable permit system. In some quarters this reflects a concern that internalisation is less of an end in itself than the attainment of a particular level of emissions reductions (see section 6).

3.6 Conclusions

DfT has adopted its NATA/GOMMMS methodology for purposes of the RASCO and SERAS studies which will inform the forthcoming White Paper. The approach adopted is in some important respects at odds with the Green Book methodology in that it does not aim to monetarise all of the costs and benefits of the policies in question. This reflects departmental misgivings towards the validity of such an exercise, given the uncertainties associated with economic valuation of the externalities arising from major transport programmes. Nonetheless, some valuation work has been performed as part of the studies and it is possible to form a broad estimate of the net economic benefits of capacity expansion scenarios for purposes of comparison with environmental costs.

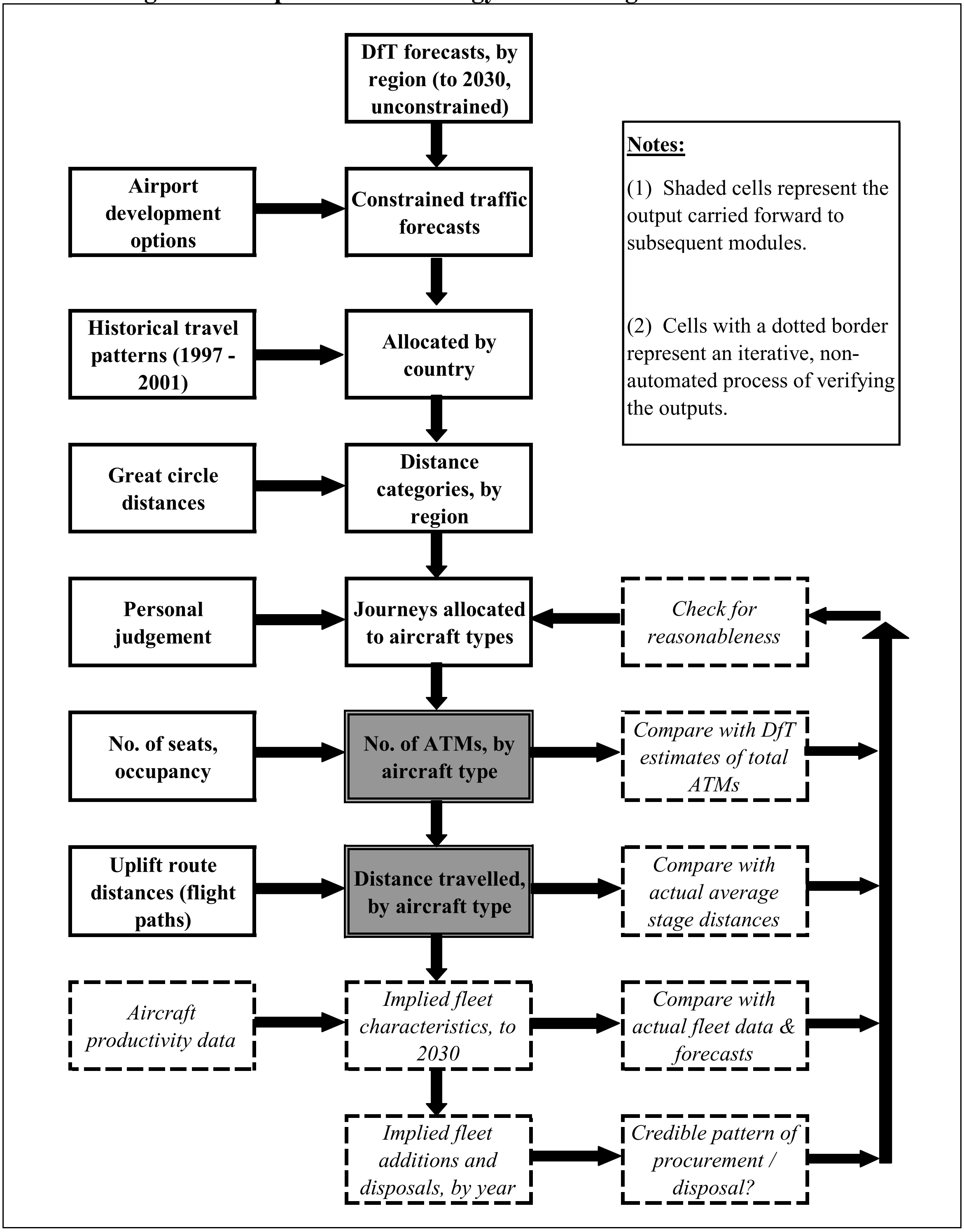
The documents underpinning the RASCO and SERAS work are extensive and detailed. Whilst combining two such studies would no doubt have created a daunting challenge, the separation of RASCO and SERAS appears to have led to some shortcomings in both studies. The lack of economic analysis in the RASCO studies (which may have been due to a timing issue – see Box 1on page 35) has been noted above. It can also be argued that the SERAS studies (notwithstanding the sophistication of the modelling work) do not address the policy scenarios presented in the RASCO studies and merely analyse a large number of capacity options in the south east, while apparently taking for granted national policy decisions yet to be made. The decisions regarding the structuring of the studies would perhaps benefit from further research.

4. MODELLING OF TRAFFIC, FUEL AND CO_2 EMISSIONS

4.1 Overview

This section presents the approach used to estimates aircraft movements and CO_2 emissions for the period to 2030. It is supplemented by Appendix IV (for points of methodology) and Appendix V (for detailed model assumptions).

Figure 3: Simplified methodology for deriving ATMs and AMTs



Notes:

(1) Shaded cells represent the output carried forward to subsequent modules.

(2) Cells with a dotted border represent an iterative, non-automated process of verifying the outputs.

DfT and its consultants have developed models (notably SPAM and SPASM[24] - see Box 1) for forecasting aviation traffic. They have also developed estimates of CO_2 emissions for 2030 (Halcrow, 2002d, pages 93-113), based on SPASM forecasts for that year[25]. Since DfT's data is only available for "snapshot" years, it was necessary for this project to model aviation activity, at a national level, over the period to 2030, in order to estimate fuel consumption and emissions. Such an exercise could not match the sophistication of the SPAM and SPASM models, and a simplified methodology was devised for estimating traffic. This is shown in Figure 3 above and is described below.

Box 1: Overview of DfT's SPASM model

The SPASM model[26] was used in the SERAS studies to generate forecasts of passenger and aircraft movements across the major UK airports. For this purpose, DfT's unconstrained demand forecasts (DfT, 2000c) were used as an input. The SPASM model allocates demand geographically across the UK, and then allocates that demand to different airports, taking into account the costs to the user of airport selection. Such costs include not only the monetary costs of travelling to airports, but also the time costs associated with reaching different airports and the differing level of flight frequencies between airports. There is therefore an interface with surface transport models developed by DfT.

The SPASM model takes into consideration the capacity limitations of airports under different development packages. To the extent that demand exceeds supply, a "shadow cost" is imputed to aircraft movements (runway capacity constraints) and/or users (terminal capacity constraints). Demand is then re-allocated between airports (and, at the limit, suppressed), taking account of the demand curve and costs (including shadow costs) of the sub-sectors of users (passengers and freight) considered within the model.

The SPASM model is also used to generate the estimates of consumer surplus associated with air travel, taking account of the above costs and the levels of travel calculated within the model. This was not possible with the earlier SPAM model – hence the lack of CBA for many of the RASCO projects (see 3.4.2).

Where possible, the model was compared with, and/or calibrated against, Halcrow's results. However, there were a number of practical limitations in such an exercise[27]. In some cases, where uncertainty as to assumptions was greatest, the assumptions were adjusted so as to improve convergence with Halcrow's results. In other cases, discrepancies were allowed to stand, reflecting either a decision to utilise different

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[24] The SPAM model was used in the RASCO study. The more recent, and more sophisticated, SPASM model was used in the SERAS studies.

[25] Quantification of CO_2 emissions was originally performed by QinetiQ for the south east only. This analysis was extended nationally by Halcrow, using a somewhat simplified methodology. Since it is the national calculations which are of relevance here, Halcrow's work is cited in this thesis, although their approach and assumptions are in many respects inherited from QinetiQ.

[26] For more details of SPASM, see Halcrow, 2002e, section 4.

[27] The SPASM runs have been prepared at different times for different purposes. This presents difficulties in, for instance, tracing back assumptions used in the forecast of CO_2 emissions to the remainder of the SERAS documentation.

assumptions or methods from Halcrow, or reservations towards Halcrow's results, or where the source of the discrepancy could not be identified.

4.2 Unconstrained Demand Forecasts

4.2.1 Passenger Demand

DfT's passenger demand forecasts for the period to 2020 are set out in "Air Traffic Forecasts for the United Kingdom" (DfT, 200c). The approach adopted by DfT was to divide the aviation market into 21 sub-sectors[28] and to use an econometric approach to derive a relationship between demand in each of those sub-sectors and four key variables (economic growth, air fares, international trade and exchange rates). Forecasts were made of those four variables for the period to 2020, and demand projected accordingly. High and low cases were generated by multiplying and dividing 2020 demand by 1.15, and interpolating for periods prior to 2020.

Total demand is estimated by DfT to increase from 160.2 mppa in 1998 to 400.7 mppa in 2020 (a CAGR of 4.3%). These projections were extrapolated to 2030, within the SERAS and RASCO studies, assuming demand growth of 2.3% p.a. These figures have also been adopted by this study[29]. It is assumed that probabilities are normally distributed around the mean, with the DfT high and low cases (extrapolated out to 2030) assumed to represent a 95% confidence interval.

An adjustment was made to the allocation of unconstrained demand between the domestic and international markets. This is explained in Appendix IV.

4.2.2 Freight Demand

The unconstrained freight forecasts used in RASCO and SERAS are set out in Halcrow (2002f) and are based on a study by MDS Transmodal (2000). Demand is calculated separately for "bellyhold" freight carried by passenger aircraft and freight carried on

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[28] There are three domestic sub-sectors: London, Channel Islands and the regions. The international market is divided into four regions - Western Europe, OECD, newly industrialised countries of Asia (NICs) and less developed countries (LDCs) - with each region sub-categorised between UK business travellers, UK leisure travellers, foreign business travellers and foreign leisure travellers. The low cost airlines are treated as a separate sub-sector. Finally, a "miscellaneous" category captures airside interliners, visitors to oil rigs, diplomats, etc.

[29] Although adopted in this study without revision, the DfT estimates are open to criticism on a number of grounds. One potential weakness is that, while the econometric approach captures an element of market maturation (i.e. slow-down in rate of demand growth relative to economic growth), the actual rate of maturation may be higher in the long-term. For example, the prospect of the average Briton wishing to make four flights per year in 2030 (versus just over one flight per year in 1998) may be unrealistic. On the other hand, DfT notes that its earlier estimates (based on a similar approach) have tended to underestimate demand growth.

dedicated freighter aircraft. The forecasts show unconstrained demand for these services increasing, respectively, from 1.5 and 0.6 million tonnes in 1998 to 7.9 and 5.7 million tonnes in 2030 (a CAGR of 5.4% and 7.2%)[30].

The above figures have been adopted in this study. For purposes of interpolation, a gradually declining rate of demand growth was identified which gave results consistent with DfT figures for 1998, 2015 and 2030. The same PDF and randomisation was applied to freight demand as to passenger demand, on the implicit assumption that the factors giving rise to variation from the median would be the same in each case[31].

The freight forecasts are of tonnages of freight moved through UK airports. These include not only international freight originating or terminating in the UK and domestic freight, but also international trans-shipment freight (i.e. cargo flown into the UK in order to be flown elsewhere on a connecting flight).

Unlike DfT's passenger forecasts, the freight forecast is not broken down by destination, nor is trans-shipment freight differentiated from other freight. It was therefore assumed that the geographic breakdown of freight terminating/originating in the UK would be as per the origin/destination of UK trade transported by air in 1998 (see DfT, 2000h)[32]. Similarly the proportion of total freight represented by trans-shipment traffic was estimated from analysis by DfT (*ibid*) and was assumed to be transiting between Europe and long-haul destinations (i.e. 50% allocated to international journeys up to 1,000 miles, and 50% allocated among journeys of more than 1,000 miles). No differentiation was assumed between the geographic composition of bellyhold and dedicated freighter service demand, although this merits investigation.

4.3 Constrained Traffic Forecasts

The next stage was to constrain demand to reflect capacity limitations. Three scenarios were created[33], each with two alternative levels of capacity ("hi" and "lo"):

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[30] The figure quoted for freighter demand excludes suppressed bellyhold demand diverted to freighter services. Since the 1998 figures quoted are actual figures, it is not possible to make a similar adjustment for 1998 figures. Note that mail traffic is generally analysed separately from the remainder of freight, and is not considered in this thesis.

[31] Despite relatively rapid growth, air freight represents a relatively small part of the overall aviation market. Accordingly, simplified methods were adopted for freight where practical.

[32] A preferable methodology would be to forecast demand separately for each region, as per the passenger demand forecasts. A regionally differentiated forecast of freight traffic is provided by Rolls Royce (Rolls Royce, 2001); however, see footnote 31.

[33] Table 28 on page 142 provides a reminder of the scenarios and cases used in this thesis.

- The "Calibration Scenario" (CS) is intended to recreate, to the extent possible, Halcrow's results. Halcrow's high capacity case is based on six new runways nationally. The low capacity case is based on maximum use of existing runways;
- The "Revised Calibration Scenario" (RCS) is based on the same cases but introduces revised assumptions, as described throughout this section;
- The RASCO Scenario (RS) is based on two of the national policy scenarios described in the RASCO study (DfT, 2002a), namely the RRC and UKC (see Table 3). Other assumptions are as per the RCS, except where consequential to differences in the level of capacity assumed.

In practice, the level of capacity associated with the high cases is very similar, and can be compared with the high capacity case evaluated in 3.4.3. The main difference is between the low cases, with the UKC (i.e. RS/lo) generating substantially lower passenger levels than Halcrow's low case. In part, this is because Halcrow's analysis is based on allowing maximum use of existing runways whereas the UKC assumes that other operating restrictions remain in force at those runways. It may also be the case that the UKC case is influenced by infrastructure constraints besides runways (e.g. capacity of terminals) whereas Halcrow's low case assumes that the only constraints are in relation to runway capacity[34].

4.3.1 Passenger Traffic

The method used to constrain passenger traffic was to assume a limit on the number of passengers consistent with the number of passengers calculated by Halcrow and DfT, in 2030, for the comparable case. For the high cases, this is approximately 470-480 mppa; for the low cases, 415 mppa (CS/lo and RCS/lo) or 260 mppa (RS/lo). Other adjustments were made, as described below.

First, it was assumed that unconstrained passenger growth would continue unabated until full capacity is reached. In practice, through a mechanism similar to SPASM's shadow pricing mechanism, there would perhaps be a "glidepath" approach to full capacity. However, since the eventual level of capacity allowed for in the scenarios modelled was in any case assumed to be available as soon as necessary (i.e. the timing

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[34] It should be noted, however, that the Halcrow high case is based upon the SPASM model whereas the UKC was created within the earlier SPAM model. It is possible that the choice of model, as well as underlying assumptions, may be material to the substantial difference in passenger volumes – 260 mppa (UKC) versus 415 mppa (Halcrow low case).

of construction of new capacity was not modelled), the greater sophistication associated with such a profiling of capacity utilisation was not considered necessary.

Given the different levels of demand elasticity and per passenger shadow costs borne by different segments of the market, accurate modelling of the allocation of capacity shortages between market segments was not attempted. However, the following, relatively crude method of prioritisation was adopted:-

- As described in Appendix IV, estimates of the proportion of total 2030 traffic represented by domestic passengers were made, for the various constrained scenarios, based on DfT sources;
- Domestic demand was assumed to grow at a constant rate from its (unconstrained) level in the year preceding full capacity to the level assumed for the year 2030, and this traffic was prioritised over other types of traffic[35];
- Remaining capacity was then allocated to non-LCA international demand;
- To the extent that further capacity was available, it was allocated to LCA traffic. The low priority afforded to LCAs rests on the assumption that they are marginal users of airport capacity, for which demand is relatively price-elastic[36].

The above methodology undoubtedly lacks the sophistication of SPASM (see Box 1). Crucially, where runways (rather than terminals) are the constraining factor, SPASM limits ATMs rather than passenger numbers, and the latter are the result of the number of ATMs permitted and the aircraft and journey characteristics prioritised by SPASM. To consider passenger numbers as the binding capacity constraint, and then to work back to ATMs, as in this case, is not entirely satisfactory. However, even if capacity is calculated in ATMs (as with SPASM), it is not easily represented by a single number in any case, owing to the distinction between operating and physical capacity (DfT, 2002a, Annex F). Also, technological developments may increase the physical capacity of a runway over time (Arthur D. Little, 2000). The fluidity of runway capacity was therefore reflected in the Monte Carlo simulation by assuming that the PDF for capacity is a uniform distribution of ±5% around the central estimate.

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[35] The reason domestic demand is prioritised over international demand is that, according to Halcrow's forecasts, 2030 domestic demand growth appears to be less affected by capacity constraints than international demand growth (possibly because it is lower in the first place).

[36] Almost certainly, the situation is much more complex – not least because LCAs tend to use remote airports which may perhaps be less close to full capacity than the major airports.

4.3.2 Freight Traffic

Constraints arise at two levels within the freight market. The first is that spare capacity on passenger aircraft may not be sufficient to accommodate bellyhold demand on the desired routes. A portion of this suppressed demand will be diverted to dedicated freighter traffic, although some will be lost to alternative modes (e.g. transported by road to mainland European airports). The second constraint is that there may be insufficient runway capacity to accommodate freighter aircraft (which tend to be the marginal users of runway capacity). The method used to constrain freight traffic in the model (based on Halcrow, 2002f, pages 5-37) was to:

- Calculate the proportion of bellyhold demand which could be satisfied from passenger aircraft ATMs (calculated as described further below), based upon an assumed level of overall bellyhold capacity utilisation[37];
- Calculate the amount of residual demand which would switch to dedicated freighters (assumed to be 50%);
- Constrain freighter traffic according to the capacity case in question. In the high capacity case, it was assumed that 100% of freighter demand could be accommodated. In the low capacity case, it was assumed that 150,000 ATMs could be accommodated annually[38];
- Prioritise runway capacity to freighters travelling long-haul distances, on the assumption that short-haul traffic would more readily be priced into alternative transport modes than long-haul traffic[39].

For purposes of Monte Carlo simulation, the capacity was assumed to vary from the central estimate in line with the PDF assumed for passenger capacity.

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[37] This level of utilisation will tend to be relatively low, since passenger aircraft destinations and frequencies do not necessarily coincide with the requirements of freight users. Since the level of bellyhold utilisation is uncertain, both now and in the future, this figure is randomised, using a triangular distribution, in the Monte Carlo simulation. In the low capacity case, the distribution is positively skewed, reflecting the likelihood that scarce bellyhold capacity is less likely to be inefficiently utilised than in the high capacity case.

[38] DfT has not prepared freight forecasts under the heavily constrained UKC scenario, on the argument that such a scenario would lead to freight traffic being largely displaced by passenger traffic (DfT, 2002a, page 6-31). However, it appears from other sources (see Halcrow, 2002f, pages 25-26) that, even if runway capacity were fully utilised by passenger aircraft, there would still be some residual capacity for night-time freight movements, particularly in the Midlands.

[39] Ideally, trans-shipment traffic would be prioritised separately, since long-haul and short-haul trans-shipment journeys would reduce *pro rata*. Also, a policy question to be investigated is whether trans-shipment traffic should be made to decline in priority to UK freight as capacity constraints arise, and what impact this would have on UK emissions.

4.4 Allocation of Distances to Journeys

The next step was to categorise journeys by distance, since journey distance is of course relevant to fuel consumption. The approach used involved the following steps:

- As noted earlier (see footnote 28), DfT's passenger traffic forecasts are broken down into geographic regions. It was assumed that, within these regions, the country-by-country break-down would remain constant, based on the average for the period 1997-2001 (taken from DfT, 2002i, Table 7.7);
- The distance to each country was calculated based on Great Circle distances, utilising online software (Byers, 2003). For domestic journeys, distances were calculated for the 70 most frequented routes (according to data from the Civil Aviation Authority – CAA, 2002b). The remaining 300 domestic routes account for just 10% of journeys and were simply assigned distances based on those of the 70 most frequented routes. All international distances were calculated with London as the origin/destination, and a separate adjustment was made to reflect the fact that a proportion of flights originate or terminate elsewhere in the country[40]. In countries where there are multiple, relatively dispersed destinations, representative destinations were selected and a weighted average distance (based on judgement as to popularity of precise destination) calculated[41];
- Five "distance bands" (0-500 miles, 501-1,000 miles, 1,001-2,000 miles, 2,001-5,000 miles, and over 5,000 miles) were created. Journeys to the geographic regions were assigned to these distance bands, based on the calculated distance, and a weighted average distance, for each year and for each distance band, was calculated.

The end result of the above process was that, for each year, passenger journeys were distributed among six representative journey types (representing each of the above distance bands for international journeys, plus domestic journeys), the distance of which

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[40] It was assumed that (based on data for 2000 – DfT, 2002a), 28% of international flights are to/from the regions. For the sake of simplicity, it was assumed that all such flights are to/from Manchester, and that the incremental distance is 80% of the distance from London to Manchester. For example, the average distance flown (in 2000) for international journeys of below 500 miles was uplifted from 333 miles by 10.2%, based on an average increment of 33.8 miles (28% x 80% x 151 miles).

[41] For example, in France, it appears that (for 2001, based on CAA 2002b), airports in the southern part of the country attracted approximately 20% of traffic. Marseilles (654 miles) was taken as being a representative distance from London for this traffic. Paris (213 miles) was taken as being representative both of the 50% of traffic that went to/from Paris itself and of the remaining 30% of traffic. Thus, a weighted average distance of 301 miles was chosen.

reflects the weighted average in that category for the year in question[42]. A similar process was undertaken in respect of freight carried aboard freighter aircraft.

4.5 Allocation of Aircraft to Journeys

4.5.1 Passenger Aircraft

Representative aircraft types were then allocated to the representative journeys. In the absence of published data as to the relationship between aircraft types and journey distances[43], the following approach was employed:

- The model incorporates a two-stage approach. The first stage allocates each of the six representative passenger journeys between up to three (of six) "seat bands"[44]. The second stage allocates journeys served by particular seat bands to aircraft types within those seat bands. This two-stage approach provides flexibility within the aircraft/journey mix over time, yet lends itself well to Monte Carlo simulation[45].
- Judgement was used in allocating seat bands and aircraft types. An iterative approach was used to settle on a combination which gives an aggregate number of ATMs comparable to Halcrow's forecasts[46], and implies a plausible fleet (see Box 2) serving a plausible range of journeys (in terms of average distance).

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[42] Since aircraft fuel consumption is not linear across journey distance, this simplified approach will have some impact on the accuracy of the overall result; however, the inaccuracy resulting from this non-linearity is not considered to be significant.

[43] The SPASM model employs "Larame graphs" relating passenger density on a route to aircraft size, an approach which cannot be applied in the simplified approach used in this project. Data are available regarding the average stage length served by aircraft types, but not regarding the range of journey distances served by aircraft types.

[44] The seat band classifications used were the same as those used by Halcrow, viz: Band 1 - up to 70 seats; Band 2 - 71-150 seats; Band 3 - 151-250 seats; Band 4 - 251-350 seats; Band 5 - 351-500 seats; Band 6 - >500 seats (see HMT/DfT, 2003, page 23).

[45] An unintended consequence of this approach is that a small number of flights are flown by aircraft flying beyond their maximum range. An adjustment was made to the model to remove the most obvious potential anomaly (Boeing 757s flying up to 5,000 miles); the remaining examples are not considered material to the overall results.

[46] The Calibration Scenario revealed that Halcrow's model generates a larger number of passengers per ATM in the high case than in the low case. This is counter-intuitive – first, because shadow costs per passenger will rise more sharply for small aircraft than for large aircraft as runway capacity is constrained and, second, because the impact of such shadow costs on long-haul passengers should be relatively small compared to the impact on short-haul passengers. For purposes of the Revised Calibration Scenario and RASCO Scenario, this assumption was therefore reversed, i.e. larger aircraft are employed when capacity is constrained. (This might also imply that total capacity, expressed in terms of passengers, would be higher than assumed in the low case; however, no adjustment was made in respect of this possibility.)

Box 2: Aircraft Fleet Composition

Twenty year forecasts of the global aircraft fleet are published by the major manufacturers (Airbus, 2002; Boeing, 2003b; Rolls Royce, 2001). The forecasts treat the smallest aircraft category (Band 1) differently, but it is possible to compare their analysis for Band 2 upwards.

Airbus anticipates a scenario in which airport capacity limitations worldwide will lead to a marked reduction in the share of Band 2 aircraft, and an increase in the share of larger aircraft, including very large aircraft of up to 1,000 seats. Boeing also anticipates a modest reduction in the share of Band 2, but anticipates that the need for flexibility will mean that growth is concentrated in the medium bands, with a reduction in the share of the largest aircraft. Rolls Royce (whose product range is arguably less tied to either scenario) lies between the two.

Based on CAA data (CAA, 2002a) it appears that the UK airlines already operate fleets of relatively large passenger aircraft corresponding reasonably closely (other than very large aircraft types which are not yet available) with the Airbus forecast for 2020. The future fleet profile adopted therefore corresponds somewhat more closely to the Airbus forecast than the Boeing forecast. In the low capacity case, the representation of larger aircraft was more pronounced, and a more aggressive penetration of Band 6 aircraft was assumed.

The model allows for 26 representative aircraft types, spread across the six seat bands. These are broadly the same as the aircraft types assumed by Halcrow. However:

- Some substitutions were made owing to availability of fuel and emissions data;
- Whereas Halcrow assumed that turboprop aircraft would be phased out as regional jets are introduced, an allowance was made for preserving turboprops, in light of their greater fuel economy and the prominence of environmental concerns;
- Other than the near-term introduction of the Embraer 170 and Airbus A380, Halcrow did not allow for future aircraft types. This is a conservative approach (cf IPCC 1999; Arthur D. Little, 2000; ACARE, 2002; and Greener by Design, 2002). It was therefore decided to provide for the introduction (circa 2018) of one new aircraft type, with improved fuel consumption, in each seat band;
- In common with Halcrow, it was assumed that some older aircraft types would be progressively phased out.

More details on the methodology used to allocate aircraft to journeys are provided in Appendix IV. Assumptions regarding fuel consumption are described in 4.7.

4.5.2 Freighter Aircraft

Six freighter aircraft types were allowed for in the model. In common with Halcrow, and with one exception, the aircraft types in service were assumed to remain constant (albeit in varying proportions) over time and no new types were introduced. In part this reflects the slower uptake of new technology in the freighter fleet (many of which are converted passenger aircraft – see Boeing, 2003b); in part it reflects a simplified approach to what is a relatively small proportion of the overall aircraft fleet[47].

4.6 Operational Factors

4.6.1 Aircraft Occupancy

In order to calculate the number of ATMs performed by aircraft, it was necessary to make assumptions as to the general level of occupancy of aircraft. It was assumed in Halcrow's analysis that passenger load factors (PLF) would increase from 70% in 2000 to 74% in 2030 (see HMT / DfT, 2003a, page 28), which corresponds with analysis performed by Rolls Royce of the global aggregate fleet PLF (Rolls Royce, 2001).

Analysis of data published by the Federal Aviation Authority (FAA, circa 1997) and Civil Aviation Authority (CAA 2001; CAA 2002a) reveals a generally higher PLF on large aircraft than on small aircraft[48], which likely reflects the relatively high employment of smaller aircraft on "thin routes".

The approach taken in this study, consistent with the above, was to assume a generally rising trend in PLFs over the period considered, but to stratify PLFs according to aircraft type. In the high capacity cases, the overall rise in PLFs was generally consistent with Halcrow and Rolls Royce. In the low capacity cases, a more marked rise in PLF was assumed (6% higher by 2030), reflecting the assumption that scarcity of capacity would give rise to more efficient utilisation. The PLFs were randomised for purposes of Monte Carlo simulation.

As regards freight, Halcrow's approach was to assume a constant load factor (assumed to be 50% - see Halcrow, 2002d, page 97) across all aircraft and routes for calculating 2030 emissions. The load factors assumed by Halcrow for bellyhold freight are not known. In this study, the approach taken was to assume a maximum bellyhold freight load factor which is differentiated by journey category and which increases over time. The dedicated freighter load factor is differentiated by aircraft type and increases over time. Both assumptions are randomised for purposes of Monte Carlo simulation.

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[47] There is an argument that it would have been appropriate to introduce the (very large) A380 family in the low capacity scenario to maximise freight's utilisation of limited runway capacity. Also the selected fleet arguably does not reflect the relatively large number of under-sized aircraft currently employed in the nascent freight market.

[48] However, the largest current aircraft have a moderately lower PLF than Seat Band 4.

4.6.2 Operational Adjustments

As noted in 4.4, distances are calculated from Great Circle distances (representing the shortest possible distance between points on the globe). In practice, aircraft seldom fly the shortest possible route, due to such factors as air traffic control requirements, avoidance of adverse meteorological conditions (or seeking favourable tailwinds), queuing in "stacks" prior to landing, etc.

In all but the Calibration Scenario[49], two separate adjustments were made to reflect such "flight extensions". First, an assumed level of distance uplift was input for each journey category. Based on estimates for intra-European flights (EUROCONTROL, 2003), an uplift of 8.9% was assumed for flights of up to 500 miles. Smaller percentage increments (based, in the absence of data, on personal judgement) were assumed for longer journeys. For purposes of Monte Carlo simulation, these were randomised using a lognormal distribution (to reflect the fact that flight extension cannot be negative).

Second, assumptions were made regarding the reductions that can be achieved over time in flight extensions as a result of CNS/ATM technology[50]. For modelling purposes, two alternative sets of assumptions were used, viz. a central estimate and, as part of a broader "Technology Scenario"[51], more aggressive assumptions. The former estimate was a reduction of 50%, implemented over the period 2013-2025 (with both the level of reduction, and the timing thereof, randomised in the Monte Carlo simulation). This broadly reflects EUROCONTROL's estimate of the potential for flight efficiencies of 2-5% (of total distance flown) via CNS/ATM measures. The assumed timing reflects the significant investment and international co-ordination required and the fact that, at present, there are no plans for "free flight" systems in the UK (Byrne, 2002). The Technology Scenario assumed a 70% reduction over the period 2010-2019.

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[49] It is understood that Halcrow's calculations do not allow for such Great Circle extensions.

[50] CNS/ATM is the abbreviation for Communications, navigation and surveillance/air traffic management systems. According to IPCC, 1999, CNS/ATM "has been defined as a system employing digital technologies, including satellite systems together with various levels of automation, applied in support of a seamless global air traffic management system."

[51] The Technology Scenario (TS) represents a scenario in which, whether because of policy measures or otherwise, relatively rapid technological innovation (albeit not including the longer term "breakthrough" technologies predicted for the industry) is experienced. In the main, the TS assumptions are equivalent to the most aggressive assumptions allowed under the PDF assigned to the RCS (and are not subject to further randomisation for purposes of Monte Carlo analysis). In specific cases, a separate PDF was assigned, based on the literature, and does not necessarily coincide with the range of probabilities allowed within the RCS.

4.7 Aircraft Fuel Consumption and CO_2 Emissions

4.7.1 Fuel Consumption –Existing and Planned Aircraft Types

Having estimated ATMs and distances travelled, the next step was to convert these into estimates of fuel consumed and emissions of CO_2. In general, the approach taken followed the detailed methodology for IFR[52] flights described in the EMEP/CORINAIR Emission Inventory Guidebook (European Environment Agency, EEA, 2002). This source provides information on fuel consumption and emissions per aircraft type for each phase of the landing and take-off (LTO) manoeuvre, based on the assumed level of engine thrust and number of seconds spent in each mode, and also for the cruise phase (based on different journey distances)[53].

In a small number of cases, fuel consumption data were not available from the above source, and it was necessary to rely on other (less detailed and potentially less objective) sources, such as manufacturer data. However, with the possible exception of the Airbus A380, the aircraft concerned have a small impact on overall fuel consumption. It was also necessary, in a small number of cases, to extrapolate fuel consumption for distances beyond the quoted range of aircraft (see footnote 45).

The fuel consumption data presented in EEA (2002) are not differentiated with respect to load factors. The PLF assumptions underpinning the model are therefore unlikely to be fully consistent with the fuel consumption data. Since the load factors underpinning the EMEP/CORINAIR data are not known, no adjustment was made for this factor.

Comparison of fuel consumption data within EEA (2002) with fuel consumption assumed in Halcrow's analysis (as presented, for a variety of aircraft types over two representative journey lengths, in HMT / DfT, 2003a, page 28) suggests that the former will tend to yield fuel consumption estimates around 10-15% higher, on average, than

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[52] Instrumental flight rules – in effect this excludes small-scale "general aviation".

[53] The LTO phase consists of the approach (from 3,000 feet altitude to landing), taxiing in to the terminal and idling, idling and taxiing out to the runway, take-off, and climb-out (to 3,000 feet). The cruise phase is deemed to include the ascent and descent between 3,000 feet and the final cruise altitude. Ideally, the "time in mode" for the different LTO phases would reflect operating conditions at UK airports, and a methodology for arriving at these times is provided by AEA Technology (AEA Technology, 2000, Appendix 2). In practice, the time periods adopted in EEA, 2002 were adopted (reflecting default times recommended by the International Civil Aviation Organisation for turbofan aircraft, and a slightly shorter period for turboprops).

the latter (with a more pronounced difference in the case of short-haul travel). For purposes of the Calibration Scenario only, fuel burn was therefore multiplied by 0.88[54].

Fuel consumption for freight aircraft was assumed to be the same as for passenger aircraft – again, reflecting the lack of data with regard to the relationship between operating weight and fuel consumption.

In view of the various uncertainties, the fuel consumption data were randomised for purposes of Monte Carlo simulation.

The EMEP/CORINAIR data are based on current aircraft, engines and modes of operation, whereas the present study is attempting to quantify future emissions. Aside from reductions in flight extensions (see 4.6.2) and the introduction of new aircraft types (see 4.7.2) there are additional reasons why fuel burn per aircraft mile should decline over time. Some of these are implicit within assumptions described elsewhere (e.g. increase in average aircraft size) but others are not. These include CNS/ATM improvements not directly related to flight extension (e.g. optimising cruise altitude), reducing operational weights (e.g. reducing reserve fuel margins) and improved management of aircraft on the ground (e.g. reduced taxiing times). Further potential improvements include reducing cruise speeds and, on the longest journeys, adding refuelling stops, although these clearly raise issues of market acceptance.

Various estimates have been made of the potential for such reductions[55]. These generally distinguish between CNS/ATM improvements and other operational factors. For example, IPCC (1999) suggests improvements of 6-12% and 2-6% respectively. Caution is required towards such assumptions, both because of the double-counting of improvements already captured within the model (e.g. Great Circle extensions) and because inroads may by now have been made into the potential quoted by earlier studies. Also, implementation of CNS/ATM is motivated as much by the need to enhance airport and/or airspace capacity as for environmental reasons, and the relationship between capacity and fuel efficiency is likely to be complex.

For modelling purposes, a relatively conservative reduction in fuel consumption was assumed for the scenarios described in 4.3, and a more optimistic set of assumptions for

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[54] Without an understanding of the differences in the fuel burn data between the two sources, it was not considered appropriate to apply this factor to other scenarios.

[55] See, for example: Liang and Chin, 1998; EUROCONTROL / FAA, 2000; ACARE, 2002; Arthur D. Little, 2000; Greener by Design, 2002.

the Technology Scenario (see footnote 51). For both, it was assumed that the level of reduction achieved would be slightly higher in the high capacity cases than the low capacity cases, reflecting the likelihood that increased congestion (of airspace and of airport infrastructure) would make reductions harder to achieve in low capacity cases[56].

4.7.2 Fuel Consumption – New Aircraft Types

A number of forecasts have been made of reductions in fuel consumption associated with future aircraft types[57]. These vary in their degree of optimism as to the reductions to be achieved over the period considered in this study. For example, IPCC (1999) suggests a reduction of 40-50% by 2050, whereas ACARE (2002) anticipates a similar level of reduction by 2020. It is generally acknowledged (see, for example, ACARE, 2002) that the scope for reductions achievable through incremental technologies is declining and that, in the long-term, major reductions will be dependent upon "breakthrough" technologies, such as blended wing body designs and laminar flow control. Some of the studies focus more on the timing of introduction of new technologies than the rate of deployment in the aircraft fleet.

The approach adopted in this study was to project the fuel savings that will be introduced into new aircraft types over time, relative to "state of the art" aircraft in the year 2000, and to assume that new aircraft types introduced in any given year will incorporate the level of reduction that is projected for that year[58]. A higher level of fuel reduction, and a more rapid rate of new aircraft type uptake, is assumed in the Technology Scenario than in the other scenarios.

A report prepared for DfT by Arthur D. Little (2000) was used as the source of the level of reductions to be achieved by 2015 and 2030 (with intermediate years calculated via interpolation). Whilst Arthur D. Little's overall forecast is at the optimistic end of the sources reviewed, their approach of quantifying the impact of technologies item by item enabled their forecast to be adjusted by removing the impact of some of the

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[56] While the difference between the Technology Scenario and the other scenarios broadly reflects the differing outlooks observed in the literature, the difference between the high and low capacity cases is conjectural and is intended to provide a relatively conservative illustration of asymmetries between the high and low capacity cases. Further research is needed in this area.

[57] See, for example: ACARE, 2002; Greener by Design, 2002; IPCC, 1999; Arthur D. Little, 2000.

[58] The overall impact on fuel consumption will be complex. The later a new aircraft type is assumed to be introduced (and, with one exception, only one new aircraft type is adopted for each seat band throughout the period considered), the greater the assumed fuel efficiency of that aircraft, but the lower the level of fleet penetration achieved by that aircraft by 2030.

technologies whose adoption is considered by Arthur D. Little to be relatively speculative. (See Appendix IV.)

The reductions in fuel consumption described in 4.7.1 also apply to new aircraft types.

4.7.3 Aircraft CO_2 Emissions

Fuel consumption data are converted (separately for LTO and cruise modes) to CO_2 emissions, based upon an emission factor of 3.15 tonnes CO_2 per tonne of kerosene (source: HMT / DfT, 2003a). Whilst emission factors of other pollutants are subject to some uncertainty, the CO_2 emission factor for kerosene is well understood and was therefore not subjected to randomisation. Small, gasoline-fuelled aircraft are not covered by this study, and it is assumed that alternative fuels (such as bio-fuels or hydrogen) will not be introduced into commercial aircraft prior to 2030.

In common with Halcrow, it is assumed that 100% of emissions from domestic flights, and 50% of emissions from international flights, are attributed to UK aviation. This is based on the premise that if a passenger (of any nationality) is travelling between countries A and B, then countries A and B share equal responsibility for the emissions.

4.7.4 Allocation of Fuel and Emissions between Passengers and Freight

Since passenger aircraft carry bellyhold freight as well as passengers, a method is required for allocating passenger aircraft fuel consumption between the two[59].

Two alternative methods were devised for this purpose. One of these is to attribute to bellyhold freight the same amount of fuel as would have been consumed had this freight been carried on a dedicated freighter, and to attribute the balance of passenger aircraft fuel consumption to passengers. The alternative method is to attribute to bellyhold freight only the marginal increment in fuel burn associated with the weight of the extra payload involved (i.e. bellyhold freight plus associated fuel).

These two methods inherently have an opposing bias. The first method potentially exaggerates bellyhold freight fuel consumption (and "cross-subsidises" passengers), since (because of the relatively low load factors of freighters compared to passenger

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[59] This issue is not addressed in Halcrow 2002f, since only aggregate emissions are considered. A potential method of allocation, not described here, is presented in Dings *et al* (2002, Annex V). This method was rejected, on the grounds that it is more applicable to "combi" aircraft (i.e. aircraft whose passenger capacity is reduced to accommodate additional freight, which are not considered in this thesis) than to passenger aircraft carrying bellyhold freight.

aircraft) it attributes to bellyhold freight a relatively high proportion of the fuel needed to move an entire aircraft (and not just its payload) over a given distance. The second method attributes all of the fuel efficiency savings associated with combined carriage of passengers and freight to the passengers. On a long-haul flight (where the proportion of bellyhold capacity utilised will be relatively high), it was calculated that the first method might result in a fuel allocation between passengers and bellyhold freight of circa 90:10, whereas 98:02 was calculated utilising the second method.

The second of the above methods was adopted here, the rationale being that bellyhold freight is in a sense “incidental” to the carriage of passengers and that the cost to be allocated to freight is therefore the marginal opportunity cost of the extra fuel involved. It is recognised that this approach is not without problems, particularly if bellyhold freight revenue influences airline decisions regarding passenger services offered (routes and frequencies) and aircraft specifications demanded from aircraft manufacturers. The approach taken has a modest impact on the calculation of emissions attributable to passengers, but a more significant impact on the calculation of emissions attributable to air freight. Details of the calculations are provided in Appendix IV.

4.8 Other Sources of CO_2 Emissions

Aside from ATMs, there are a number of activities associated with commercial aviation which consume energy and produce CO_2 emissions. These include:

- Non-commercial movements of aircraft, e.g. repositioning empty aircraft;
- Use of auxiliary power units (APUs) by stationary aircraft and engine start-up;
- Airport operations (terminal buildings, baggage handling, air traffic control, etc.);
- Surface transport to/from airports;
- Supply chain and life cycle activities.

Halcrow’s analysis of CO_2 emissions includes an estimate of CO_2 emissions associated with surface transport (travel by car and light goods vehicle only) but not the other activities[60]. Their estimate is based upon the surface access models underpinning SPASM (see Box 1) and therefore takes into account distance travelled from each district to the relevant airport for the SPASM scenario in question. Whilst Halcrow finds the contribution of surface transport to be modest compared to aircraft emissions

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[60] With the possible exception of airport operations, it may be that the activities excluded from Halcrow’s analysis are not material to CO_2 emissions.

(less than 5%), its analysis shows surface transport to be relatively more significant in a low capacity case than a high capacity case because passengers and freight need to travel further to reach an airport with available capacity.

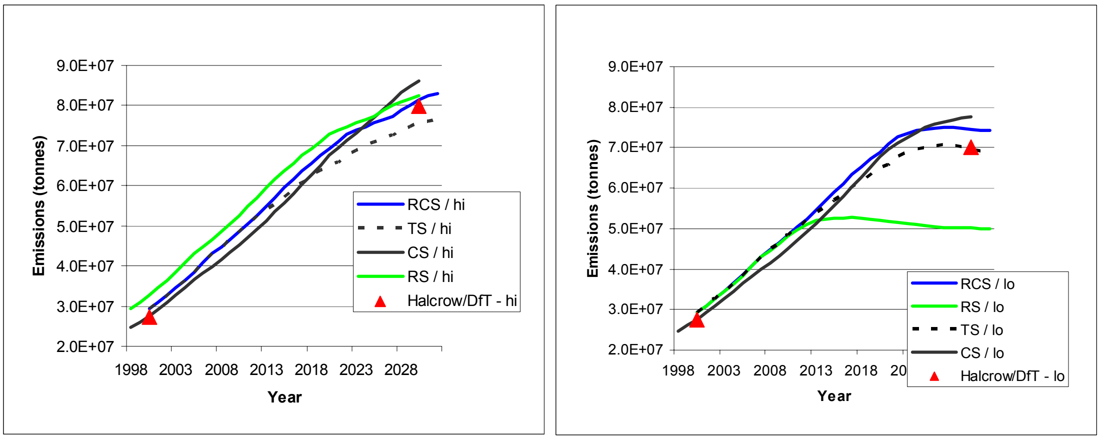
CfIT (2001) has analysed emissions for different modes of airport surface access, including rail and bus. Whereas Halcrow assumes that 90% of air passengers travel to airports by car, CfIT cite DfT statistics showing a greater proportion of travel by other modes (particularly in the south east). CfIT's analysis does not attempt to capture the mix of surface access journey distances, nor does it take into account future changes in surface access fuel consumption. Conversely (as reported in HMT / DfT, 2003a), Halcrow assumes 2030 levels of vehicle fuel efficiency for purposes of calculations applicable to both 2000 and 2030.

Rather than attempt a bottom-up estimate of surface transport emissions, the present study adjusted Halcrow's estimates in light of information contained in the CfIT report (see Appendix IV). Also, the model incorporates a switch allowing surface transport emissions to be included or excluded from the analysis. The reason for this is that, for purposes of designing economic instruments, it is arguably more appropriate to address the environmental impacts of surface transport directly (e.g. via road pricing) than to include these in economic instruments applied to aviation.

4.9 Results

Figure 4 below presents CO_2 emissions (as modelled deterministically) for the various scenarios over the period 1998 to 2030. The results of the scenarios are analysed in 4.9.1 and 4.9.2 below. Results of Monte Carlo simulation are then presented in 4.9.3.

Figure 4: CO_2 emissions 1998 – 2030 (all scenarios)



4.9.1 Comparison with DfT/Halcrow Figures

A comparison of the Calibration Scenario with DfT/Halcrow figures is provided in Appendix IV (see Table 20 on page 126). The results of the Calibration Scenario are of relatively little interest *per se*, except as indicators of possible differences in assumptions and methods between Halcrow's work and this study. The main points to be noted in this regard are that:

- Emissions from passenger aircraft travel are very similar between the two sets of figures and, in the case of international travel, virtually identical. Emissions from domestic travel show a discrepancy of ±25%, for reasons which are unclear;
- The emissions from freighter aircraft are significantly different between the two sets of figures, with the CS giving much higher total emissions (but lower in the case of domestic freight) in the later years than calculated by Halcrow.

Details of the discrepancies and possible explanations are presented in Appendix IV. It should be noted that, since (as shown in Figure 5 below) the large majority of emissions are from international passenger journeys (for which the two sets of results are closely aligned), the overall level of divergence is relatively modest.

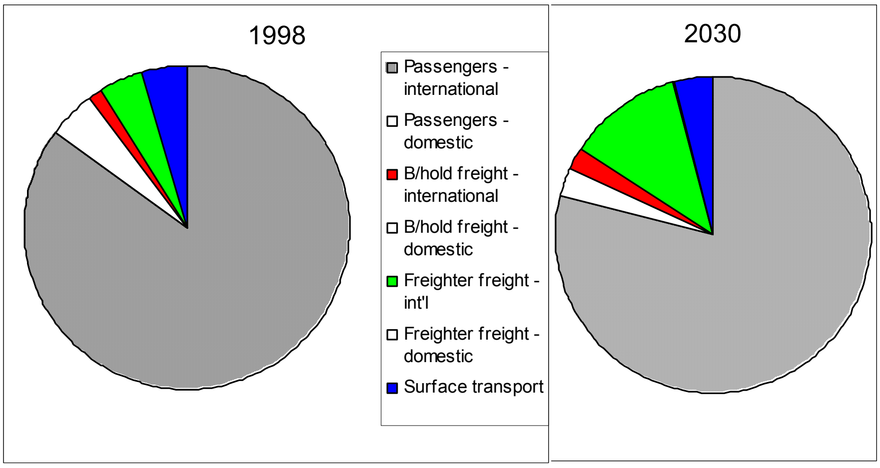
With one exception, the revised assumptions underpinning the RCS, RS and TS do not have a very clear impact on the degree of fit with Halcrow's results, although coincidentally they tend to give a result even closer to Halcrow's, for 2030, than the CS. Unsurprisingly, the RS/lo case (based on a lower level of capacity than assumed by Halcrow) results in a very much lower level of emissions than Halcrow's low case.

Overall, the calculations of emissions found by Halcrow and by this study are broadly consistent. But for the differences in underlying fuel burn data and assumptions regarding Great Circle extensions, it is likely that the present study would have generated somewhat lower emissions than Halcrow, because of the assumptions regarding new technology. However, in the context of the very sizeable increases in emissions forecast for the period studied, the differences are perhaps marginal.

4.9.2 Analysis of Emissions Growth

While the main drivers of emissions can be deduced via sensitivity analysis (as presented in Appendix IV), a clear picture can be gained from analysing the trends shown in Figure 4 and the differences between scenarios. This is analysed below from the standpoint of passenger emissions, since it is clear from Figure 5 that, despite the growing share of freight, passenger emissions will remain the dominant source.

Figure 5: Sources of emissions for 1998 and 2030 (RCS)



Note: emissions from domestic freight are too low to be clearly visible.

The factors determining the growth of emissions can be categorised into three components, namely demand, passengers per aircraft and technology. Conceptually, these can be represented by the equations shown in Box 3.

Box 3: Equations representing passenger CO_2 emissions

$$\textbf{(1)}\quad \text{Emissions} = PMT_{GC} \times \frac{ATM}{PAX} \times \frac{CO_2}{AMT_{GC}}$$

$$\textbf{(2)}\quad PMT_{GC} = PAX \times Dist_{GC}$$

$$\textbf{(3a)}\quad \frac{ATM}{PAX} = 1 \div \frac{PAX}{ATM}$$

$$\textbf{(3b)}\quad \frac{PAX}{ATM} = \frac{\text{Seats}}{\text{Aircraft}} \times PLF$$

$$\textbf{(4)}\quad \frac{CO_2}{AMT_{GC}} = \frac{CO_2}{SMT_{GC}} \times \frac{\text{Seats}}{\text{Aircraft}} \times (1 + \text{extension})$$

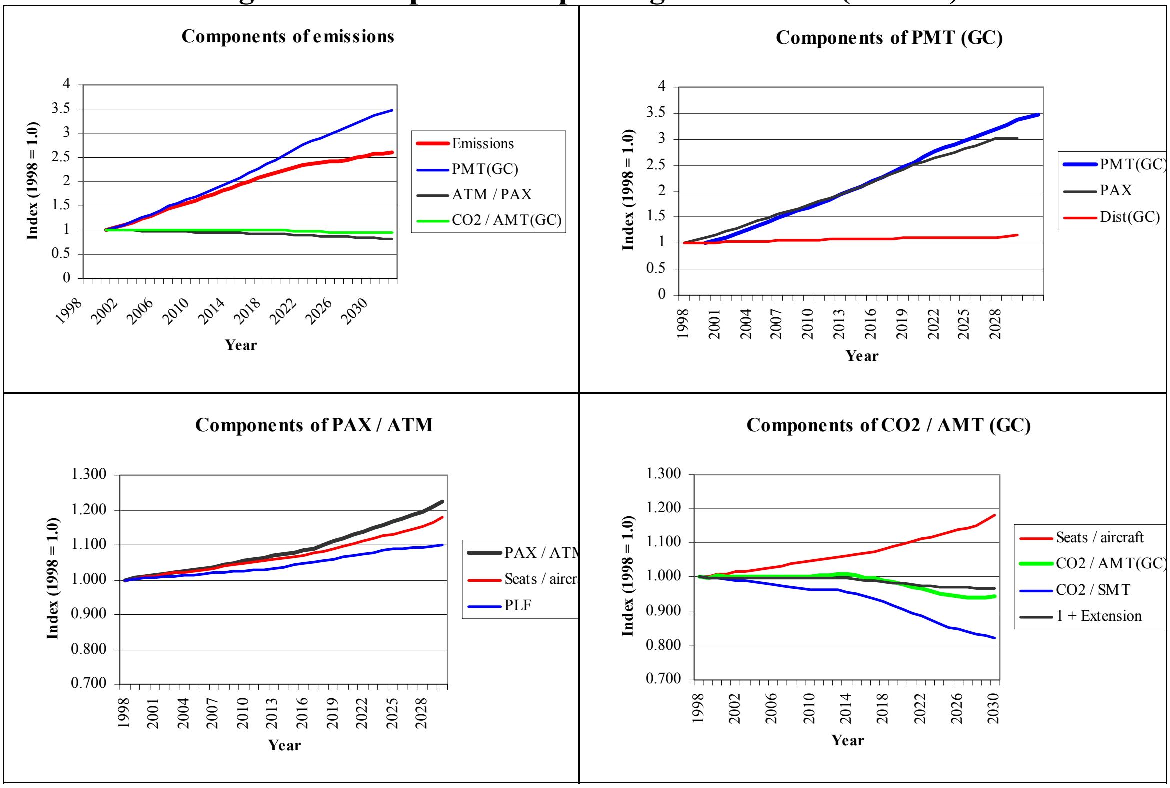
where:

PMT_{GC} = Passenger miles travelled (great circle distance)
ATM = Air transport movements
PAX = Passengers
AMT_{GC} = Aircraft miles travelled (great circle distance) = ATM x $Dist_{GC}$
$Dist_{GC}$ = Average great circle distance = PMT_{GC} / PAX
PLF = Passenger load factor
SMT_{GC} = Seat miles travelled (great circle distance)
Extension = (Distance flown - $Dist_{GC}$) / $Dist_{GC}$

The components of equation (1)[61] can be analysed, to understand what lies behind the projections. This is shown (for the RCS/hi case) in Figure 6, which reveals that:

- The major impact on emissions is demand growth, i.e. passenger numbers and a slight increase in distances travelled;
- The rising number of passengers per aircraft has a moderating influence on emissions, with progressive increases both in aircraft size and load factors;
- Emissions per aircraft mile are relatively constant. In effect, improved technology (from both aircraft and operations) allows larger aircraft to fly without increasing emissions per aircraft mile.

Figure 6: Components of passenger emissions (RCS/hi)



It is evident, from the above and from similar graphs for other scenarios (see Figure 14 and Figure 15 in Appendix IV) that the savings in fuel consumption via technology do not offset rising traffic; hence the increase in emissions for all scenarios[62].

The introduction of capacity constraints has a significant impact on emissions, once capacity is reached, although even in the relatively severe RS/lo scenario, 2030

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[61] In fact, equation (1) is truistic, or an "identity". It is in some respects analogous to the Kaya Identity which is sometimes used to project future trends in GHG emissions.

[62] The general conclusion that technological development is unlikely, within the early decades of this century, to counteract the impact on emissions of economic growth has been reached by a number of studies – see, for example, Arthur D. Little (2000) and IPCC (1999).

emissions are higher than 1998 emissions[63]. It is to be noted that capacity limitations have an impact not only on traffic levels but also on emissions efficiency (as measured by CO_2 per PMT – see 4.9.3). Emissions per PMT are lower in the RS/lo case in 2030 than in the RS/high case (see Table 23 in Appendix IV), reflecting the assumptions made regarding aircraft occupancy and/or size. However, not all assumptions work in the same direction (e.g. the rate of penetration of new aircraft types) and this effect is more muted in the RCS/lo case, and eliminated in the TS/lo case.

4.9.3 Uncertainty

Potentially, the spread of results shown by the above scenarios might be interpreted as a guide to the level of uncertainty associated with the estimates. However:

- One of the purposes of this thesis is to weigh the relative economic benefits and environmental costs of policy decisions regarding capacity. For this purpose, it is the uncertainty within a scenario, rather than between scenarios which is of interest;
- In other contexts (e.g. economic instruments), the uncertainty associated with the absolute level of emissions may be of less interest than, say, the level of emissions per passenger or PMT (or per freight-tonne or freight-tonne-mile);
- Other than reflecting differences in capacity and technology, the results presented above do not take into account the uncertainty of many other variables.

A Monte Carlo simulation was therefore performed on the various scenarios in order to quantify the uncertainty. Two indicators were used (namely total CO_2 emissions and passenger emissions per passenger-mile – g/PMT) over three time periods (average emissions per year over the period 2000-2030, and emissions in the years 2015 and 2030). The level of uncertainty was judged from the coefficient of variation (CV, the standard deviation as a percentage of the mean) and from the range between the 5th and 95th percentiles. These indicators are shown, for the RCS, in Figure 7 and Table 7. Figure 16, Figure 17, Table 23 and Table 24 in Appendix IV present equivalent graphs and figures for the RS and TS.

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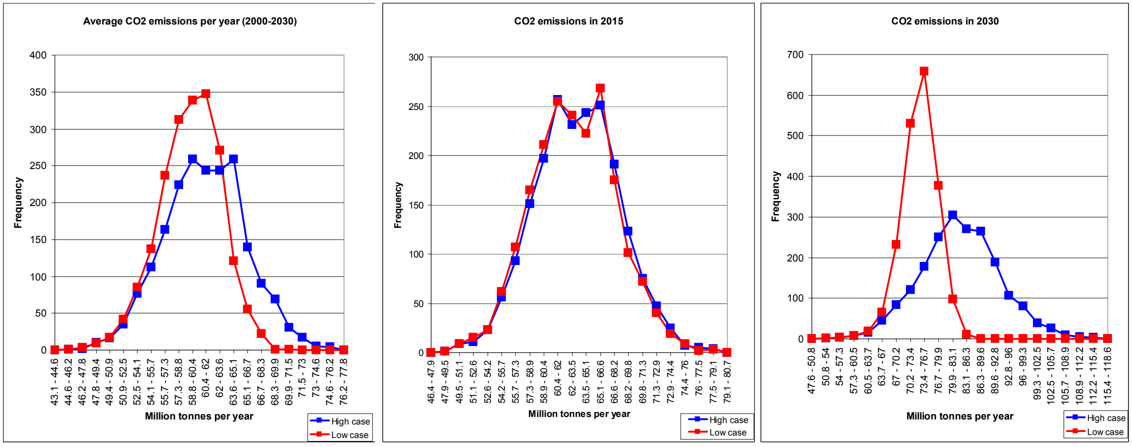
[63] As noted in 4.7.1, some of the reductions associated with the TS cases stem from the introduction of CNS/ATM technology – motivated in large part by the desire to maximise capacity. Although not modelled, it is possible in the TS/lo case (where capacity is assumed to be limited to maximum use of existing runways, as per the RCS/lo case) that the expansion in capacity associated with an aggressive CNS/ATM programme, would more than offset the reductions in emissions associated with the impact of technology on fuel burn.

Figure 7: Histogram of emissions for Revised Calibration Scenario

Emissions per year Average for 2000-2030 | Emissions per year 2015 | Emissions per year 2030



Emissions per PMT Average for 2000-2030 | Emissions per PMT 2015 | Emissions per PMT 2030

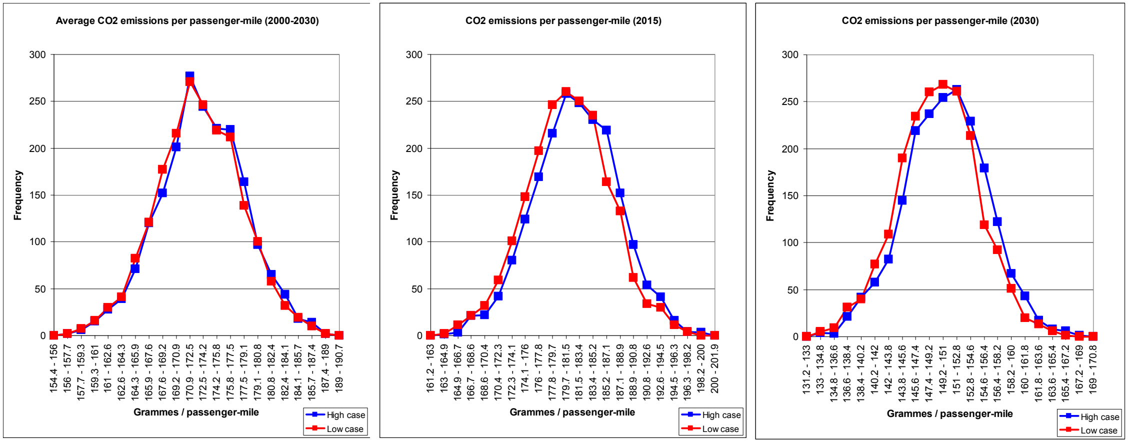


Table 7: Estimates of uncertainty of emissions for Revised Calibration Scenario

Scenario / indicator	High case			Low case		
	Result	**SD/mean**	**95th/5th %'ile**	**Result**	**SD/mean**	**95th/5th %'ile**
Average emissions 2000-2030	61.1 mt	7.6%	1.29	59.4 mt	6.0%	1.22
Total emissions 2015	63.3 mt	7.3%	1.27	63.0 mt	7.3%	1.27
Total emissions 2030	83.2 mt	10.9%	1.44	73.9 mt	5.5%	1.19
Average emissions / PMT 2000-2030	173 g/PMT	3.0%	1.11	173 g/PMT	3.0%	1.10
Total emissions / PMT 2015	182 g/PMT	3.1%	1.10	181 g/PMT	3.1%	1.11
Total emissions - / PMT 2030	150 g/PMT	3.6%	1.13	149 g/PMT	3.5%	1.12

A number of conclusions can be drawn from the Monte Carlo analysis of emissions:

- The level of uncertainty associated with emissions per PMT is low in all scenarios. This reflects the fact that, even though the rate of technological advance in future aircraft types is relatively uncertain, fleet turnover is slow and existing aircraft types are likely to remain an important part of the fleet over the period considered. Unsurprisingly, the level of uncertainty is highest in the later years;

- Uncertainty is of course higher for total emissions, since these are influenced by traffic levels. Even so, from a policymaking perspective, the level of uncertainty is relatively low. Over time, as would be expected, the level of uncertainty associated with the high capacity cases increases. The level of uncertainty associated with low capacity cases is lower than the high capacity cases (and generally reduces over time), reflecting the fact that capacity constraints set an upside limit to traffic and thereby reduce the uncertainty associated with traffic levels;
- The lowest individual result from all of the simulations (the 0th percentile in the RS/lo case) showed emissions of 41.7m tonnes in 2030. When compared with Halcrow's estimate of 27.4m tonnes for 2000, this suggests that an increase in emissions is inevitable. The highest individual result for 2030 (the 100th percentile in RS/hi) was a figure of 115m tonnes, over four times emissions in 2000.

4.10 Conclusions

This section has presented estimates of CO_2 emissions for a number of scenarios/cases. Three of these can be related directly to the three capacity cases evaluated in section 3. In deriving these estimates, a number of simplifying assumptions were made, and it was not possible to reproduce all of the sophisticated interactions of the SPASM model.

Nonetheless, the analysis gives a number of reasonably firm conclusions. First, an increase in aviation's CO_2 emissions seems inevitable over the next 30 years. There is little prospect that increases in traffic will be offset by technological progress. Adjusting for the conservatism towards technology inherent in Halcrow's forecasts for 2030 does not significantly change the results.

Second, policy decisions to be made in the forthcoming White Paper can play a significant role in stemming the rise in emissions. Even the most drastic capacity level theoretically under consideration, however, cannot prevent an increase in emissions.

Finally, although there are many sources of uncertainty, the overall quantum of emissions is reasonably predictable (for any given level of capacity) over a thirty year time horizon. In other words, uncertainty towards emissions should not present a significant barrier to policy making.

5. GLOBAL WARMING

5.1 Overview

This section estimates the value of GHG emissions from UK aviation. The approach used by the UK Government to value emissions is briefly summarised. This is followed by a discussion of the two issues which are crucial to the valuation, viz. the impact of non-CO_2 GHGs emitted by aircraft, and the economic valuation of global warming damage. Estimates are then made of the global warming damage associated with certain of the scenarios and cases introduced in section 4.

5.2 Summary of UK Government Approach

The Government has attempted to value the climate change damage from UK aviation, for the years 2000 and (for both a high and low capacity case – see 3.4 and 4.3) 2030. The approach taken for both years (as described in HMT / DfT, 2003a) was to:

- Distinguish between emissions released at altitude (i.e. the cruise phase of flights) and emissions released at or near the surface (i.e. LTO phase and surface transport);
- Multiply the releases at altitude by a factor of 2.7 (equivalent to a multiple of 2.5 on total emissions), reflecting the Radiative Forcing Index (RFI – see Box 5 and 5.4.3);
- Value the RFI-adjusted CO_2 emissions at £70 per tonne of carbon[64] (£70/tC) for 2000 and £100/tC for 2030.

The resulting estimates (in 2000 prices) were £1.4 bn (2000) and £4.8 bn (2030).

The above approach raises two areas of difficulty. First, there is the issue of whether the RFI fairly represents the damage of non-CO_2 GHGs relative to CO_2, and indeed whether 2.7 is the correct multiple. Second, there is the issue of whether the £70/tC and £100/tC valuations are appropriate.

5.3 Atmospheric Impacts of Aviation

Aviation is unique among industrial activities in that it involves combustion of fuels at high altitudes. Whilst this is irrelevant to the damage caused by CO_2 emissions (which are indistinguishable from other anthropogenic sources of CO_2), it causes a number of other atmospheric impacts (see Box 4). These have received significant attention in recent literature, notably “Aviation and the Global Atmosphere” (IPCC, 1999).

Box 4: Impact of aircraft emissions on the global atmosphere

CO_2:	Emissions of CO_2 (a weak, but long-lived GHG) are the inevitable product of the combustion of fossil fuels.
NO_x:	NO_x emissions are the result of oxidising nitrogen present in the air used to burn fuel and, to a lesser extent, in the fuel itself. Tropospheric releases of NO_x promote both the formation of ozone (O_3, a potent GHG) and the removal of methane (CH_4, also a GHG). The warming effect of the former is thought to exceed the cooling effect of the latter.
H_2O:	Another by-product of fuel combustion, water acts as a GHG. It is precipitated relatively quickly from the troposphere, although emissions from supersonic aircraft flying at higher altitudes have a much longer residence time.
Contrails:	Contrails are line-shaped clouds formed as water emitted from aircraft (and present in the atmosphere generally) nucleates around particles emitted from jet engines. Contrails reflect both incoming and outgoing radiation, although the net impact is understood to promote atmospheric warming.
Cirrus clouds:	Although the processes are not well understood, it is believed that the presence of persistent contrails and the emission by aircraft of water and particles may promote the formation of cirrus clouds. Cirrus clouds have, on average, a warming influence on the Earth’s surface.
Aerosols:	Aerosols form from particles emitted as a result of incomplete combustion of fuel (soot) or combustion of trace elements in the fuel (sulphate). The radiative impact is positive, in the case of soot, and negative, in the case of sulphate. These direct impacts are relatively minor; however, aerosols play a role in cloud formation and may also influence the radiative properties of clouds.

Aside from uncertainties relating to atmospheric chemistry and microphysics, estimating the climatic effect of aviation emissions is complex. Some of the emissions have short atmospheric residence times, are not well mixed in the atmosphere and have impacts which vary with prevailing conditions (including pre-existing concentrations of GHGs and other pollutants). This means that the relationship between emissions, atmospheric concentration and impacts is not straightforward, with impacts varying by region. Notably, the effects of ozone and contrails are likely to be most pronounced in the northern mid-latitudes, reflecting the geographic concentration of air traffic.

5.4 Estimating and Measuring the Atmospheric Impacts

5.4.1 IPCC Approach

In its 1999 report, IPCC estimated the radiative impact of aviation as at 1992, 2015 and 2050, under a variety of scenarios. This involved modelling the emissions scenarios

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[64] Converting from tonnes of CO_2 to tonnes of carbon involves dividing by 3.67.

developed in the IPCC's Second Assessment Report (IPCC, 1995) and superimposing perturbances from aviation emissions under comparable scenarios.

In order to quantify the impact, IPCC estimated the radiative forcing (see Box 5) caused by the various effects outlined in Box 4. Its best estimate, for example, of the combined RFs, as at 1992, was 0.048 W/m^2, of which 0.018 W/m^2 was accounted for by CO_2 and the balance of 0.030 W/m^2 from the other effects excluding cirrus clouds, implying an RFI of 2.7 (see Box 5). Based on its estimates of aviation's combined RFs, IPCC estimated that aviation would account for around 0.05ºK of a forecast 0.9ºK increase in global mean surface temperature between 1990 and 2050.

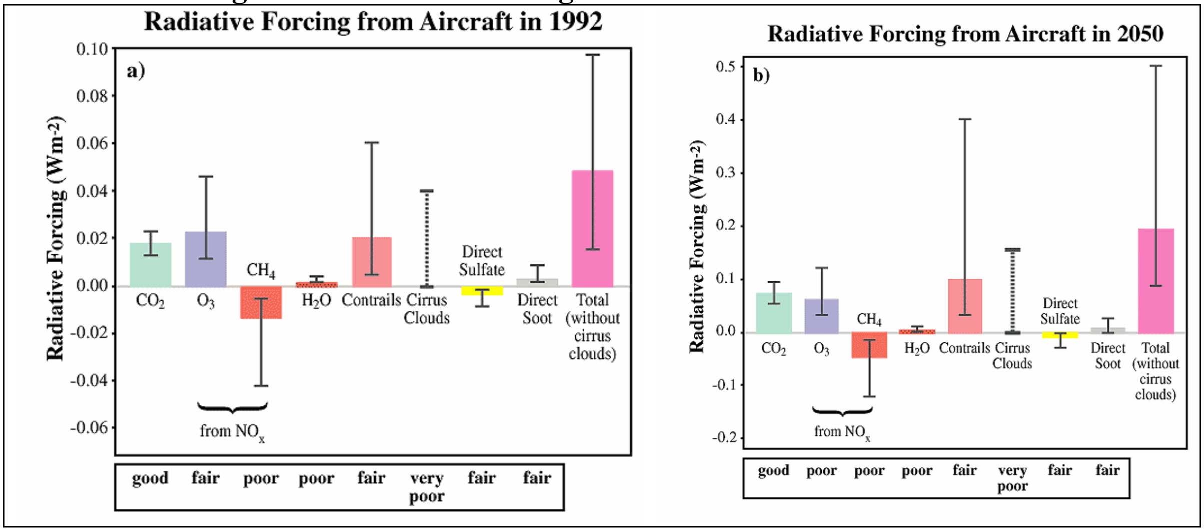
Box 5: Metrics used to describe climate change impacts

Radiative Forcing (RF):	When greenhouse gases or other radiative properties of the Earth are perturbed, the balance between incoming and outgoing radiation is affected. Eventually, radiative balance will be restored, but at a different equilibrium temperature for the Earth's surface atmosphere, troposphere and oceans. Radiative forcing represents the radiative imbalance (expressed in watts per square metre of the Earth's surface, W/m^2) prior to equilibrium being restored.
Climate change sensitivity (λ):	The relationship between the Earth's radiative balance and climate is complex. A simplified measure is given by the impact on global mean surface temperature, which can be related to RF via a constant, λ. As a first-order approximation, λ is considered appropriate for most types of perturbance.
Radiative Forcing Index (RFI):	RFI is the ratio of the sum of all the RFs caused by an activity (in this case, aviation) to the RF caused by CO_2 emissions from that activity. An RFI greater than 1.0 provides a first-order indication that the activity has a more serious climate impact than suggested by its CO_2 emissions alone. *Ceteris paribus*, the higher the RFI, the more serious the impact.
Global warming potential (GWP):	Whereas RF measures a perturbance (e.g. an emission) in terms of its net radiative impact per second, GWP integrates the impact over a defined period (e.g. 100 years) so as to take into account the longevity of the emission in the atmosphere relative to CO_2. The impact is expressed as an index relative to the integrated impact, over the same period of time, of a tonne of CO_2.

Based on IPCC, 1999, section 6.2.

IPCC makes a number of caveats regarding its estimates. These include uncertainties associated with: the size of the various RFs (see Figure 8); the simplified approach of relating summed RFs to global mean surface temperature; the regional nature of aviation's impacts; and the possibility of a unique "climate signature" for aviation.

Figure 8: Radiative forcing from aircraft in 1992 and 2050



Reproduced from IPCC, 1999.
Note that the bars represent "best estimates" whereas the whiskers represent 67% probability intervals. No best estimate is shown for cirrus clouds, and the dotted whiskers represent a range of possible estimates rather than a probability interval. The description beneath each item represents the level of scientific understanding.

The RF quoted for any year (e.g. 1992) is not just the result of aviation emissions during the year 1992; rather it represents the radiative imbalance, in 1992, caused by the emissions of all the aircraft that have ever flown. For some GHGs (e.g. tropospheric water emissions), the atmospheric residence time is so short that the continuing RF impact, in 1992, of prior year emissions is negligible or non-existent. However, for a long-lived GHG such as CO_2, a high proportion of the RF in 1992 is attributable to emissions from aircraft flying in previous years. This has implications for the use of the RFI to value emissions for a particular year (see 5.4.3 below).

Conceptually, a more appealing metric for valuing the emissions of a particular year would be Global Warming Potential (GWP – see Box 5). Although not ideal from the perspective of economic analysis[65], GWP has the advantage of taking into account the RF of a particular quantum of emissions over its atmospheric lifetime. However, IPCC rejects the use of GWP as a metric of aviation emissions, on the grounds that it is ill suited to short-lived gases and aerosols whose impacts are contingent upon atmospheric conditions. IPCC cites studies which have produced widely varying estimates of the GWP of aviation's Nox emissions and concludes:

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[65] GWP would imply equal weighting to CO_2 and to a GHG whose RF is ten times higher but which has a lifetime of one tenth of that of CO_2. However, the non-CO_2 GHG might be considered more damaging: first, because (for impacts such as biodiversity) the rate of climate change may matter, as well as the absolute level of eventual change; second, because the damage is incurred earlier. GWP does not take time value into account. A metric which does take time value into account ("global damage potential") is described in Eyre *et al*, 1999.

> "In view of all these problems, we will not attempt to derive GWP indices for aircraft emissions in this study. The history of radiative forcing, calculated for the changing atmosphere, is a far better index of anthropogenic climate change from different gases and aerosols than is GWP." (IPCC, 1999, page 200.)

5.4.2 Recent Developments

There have been some developments in scientific understanding of the impacts of aviation since publication of the IPCC report. As reported by the Royal Commission on Environmental Pollution (RCEP, 2002), these include indications that:

- The impact of CH_4 removal may be at the lower end of the range indicated by IPCC;
- Uncertainty as to the RF impact of contrails has increased rather than decreased, and some studies suggest that IPCC may have overestimated the impact of contrails;
- The relationship with cirrus cloudiness is now more robust than suggested by IPCC;
- Subsonic aircraft spend a higher proportion of time than previously thought flying above the tropopause, implying a lower incidence of contrails and cirrus cloud but a higher impact of stratospheric water vapour.

Taken together with more robust traffic growth than projected by IPCC, RCEP concludes that IPCC's "estimate of the climate impact of aviation is more likely to be an under-estimate than an over-estimate" (RCEP, 2002, page 19).

5.4.3 DfT Approach

DfT's valuation of the climate change impact of UK aviation is based on the 2.7 RFI quoted (for 1992) in 5.4.1. However, this raises a number of issues:

- First, given the uncertainties presented by IPCC (see 5.4.1), use of a single point estimate for the RFI inevitably gives an over-precise valuation of climate damage;
- Second, it would be desirable to take account of scientific developments subsequent to the IPCC report, notably the emerging evidence of a robust relationship between aviation and cirrus cloudiness (see 5.4.2). Indeed, however uncertain the science, it is arguable that some allowance should be made for this effect if the full range of possible estimates is positive;
- Third, use of the 1992 RFI as a multiple of annual CO_2 emissions is problematic on two counts. The minor point is that there are a number of factors which will cause

the RFI to vary over time[66] and the application of the 1992 RFI to 2030 emissions could potentially give the wrong result. In practice, linear interpolation between IPCC's RFI estimates for 2015 (3.0) and 2050 (2.6) gives an RFI of 2.8 for 2030, suggesting that any errors arising from the application of the 1992 RFI to 2030 emissions are likely to be inconsequential;

- More significantly, it follows from the discussion in 5.4.1 that there may be a conceptual problem with the use of the RFI to convert CO_2 emitted by aircraft in a particular year to a damage estimate. The RFI is a snapshot of the radiative impact, in a particular year (relative to some base year), of the history of aviation. It is not a measure of the lifetime impact of the aviation activities conducted during that year.

If the latter point is correct[67], then there are two implications. These can be illustrated by reference to aircraft journeys in 1992 and the (fictitious) assumption that all non-CO_2 climate change impacts are from highly potent, but very short-lived, GHGs:

- First, if damage is calculated by multiplying 1992 CO_2 emissions by the RFI, then the impact of the short-lived GHGs is understated – it is the 1992 CO_2 atmospheric concentrations attributable to (UK) aviation that should be so multiplied;
- At the same time, if the monetary estimate of the damage caused by a tonne of CO_2 emitted in 1992 reflects the RF that will be caused by that tonne of CO_2 over its atmospheric lifetime, then the use of the RFI as a multiple overstates the damage caused by non-CO_2 GHGs emitted by aircraft during 1992. Put simply, if all aviation were to have ceased on 31st December 1992, then the CO_2 hitherto emitted would continue to warm up the atmosphere, whereas other emissions would quickly have ceased to make any further impact on the environment. The RFI at a particular point in time does not take account of such subsequent difference in impacts.

It is possible that, as a very broad approximation, the above "errors" cancel each other out. This is because, in each case, the magnitude of the error is related to the

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[66] These include (i) the influence of pre-existing GHGs and pollutants (for example, a tonne of CO_2 emitted in 2050 will have a lower RF than a tonne emitted today, and the indirect effects of NO_x will depend on atmospheric pollution levels) and (ii) changing operational factors (for example, contrails are expected to increase faster than traffic due to developments in the aircraft fleet and flight routes). Also, since CO_2 concentrations will accumulate over time (see 5.4.1), the denominator of the RFI equation will increase over time. Indeed, the IPCC projections suggest that RFI would fall significantly between 1992 and 2050 but for the increase in contrails.

[67] Correspondence was initiated by the author with a number of climate experts and economists (see Acknowledgements) on this issue. The only conclusions drawn from the correspondence were (i) that the author's intellectual grasp of the underlying scientific issues is deficient but (ii) that the possibility that the point raised above is valid nonetheless merits further investigation.

atmospheric residence of CO_2. However, until such time as aviation traffic and CO_2 concentrations reach an equilibrium plateau, it is *prima facie* unlikely that the first effect would be as large as the second effect.

Just how significant the above point is in quantitative terms is not clear. Ultimately, it may be just one example of why, whilst λ and RFI are useful, they should be seen only as a first-order approximation of the link between RF and temperature change.

To synthesise the foregoing, the use of the RFI for purposes of valuing the emissions of a particular year is problematic. Whether or not conceptually correct, any resulting estimate is subject to considerable uncertainties. These uncertainties are not entirely captured by the probability intervals suggested by IPCC (see Figure 8). Indeed, one expert has commented, on DfT's use of the 2.7 RFI:

> "'About 3, ranging between 2 and 4' would be a more honest description in layman's terms." (Lee, D., 2003.)

5.4.4 Other Approaches

If the use of RFI is problematic, then an alternative approach might be to estimate and value separately each of the climate impacts of aviation. Indeed, a number of studies have considered specific emissions separately. For example:

- Pearce and Pearce (2000) calculated separate valuations for the climate impact of aviation's CO_2 and NO_x emissions;
- Dings *et al* (2002) consider the impacts of CO_2, NO_x and H_20 separately and also differentiate between situations in which contrails are and are not formed;
- Tol and Downing (2000) report the results of a (1999 draft) study by Grewe and Tol valuing the marginal costs of NO_x emissions by European aircraft[68];
- A number of the studies described in 5.5 below calculate values for CH_4 emissions (not specifically for aviation).

In fact, both Pearce and Pearce and Dings *et al* scale the radiative impacts of the non-CO_2 emissions to the relative RFs quoted by IPCC and the emissions for the years in question. Their approaches are therefore equivalent to the RFI approach used by IPCC and are subject to some of the same conceptual issues as are described in 5.4.3.

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[68] The Grewe and Tol study was not seen during the preparation of this thesis. Publication of that document could potentially fill a significant gap in the literature.

The description of the Grewe and Tol study reveals the importance, for economic analysis, of the regional and temporal impacts of NO_x emissions. The warming impact of resulting ozone in Europe is initially positive, in economic terms, but eventually gives rise to a negative economic effect, as the warming impact is succeeded by the cooling impact of CH_4. The sign of the net effect in Europe (in NPV terms) is dependent upon the discount rate chosen. However, at a global level, the NPV impact of European aircraft NO_x emissions is suggested to be damaging, at all discount rates, reflecting the warming impact of NO_x emissions at a global level[69].

5.5 Economic Valuation of GHG Emissions

5.5.1 Introduction and UK Government Approach

A review of the literature on valuation of CO_2 emissions is provided by Clarkson and Deyes (2002). This document (a 'Working Paper' of the Government Economic Service) forms the basis for the valuation of emissions in HMT / DfT (2003a).

Clarkson and Deyes distinguish between two approaches to valuation, one of which focuses on abatement costs, the other on direct estimation of damage caused by CO_2. They reject the former as it is only valid if the (artificial) assumption is made that emission targets have been set (e.g. in the Kyoto Protocol) at a level reflecting the optimum trade-off between the marginal cost of abatement and marginal damage cost. Within the damage cost approach, they describe two variants: the CBA method (to derive the shadow cost of carbon at the optimum level of emissions) and the marginal cost method (based on the damage associated with perturbing a defined emissions scenario). They express a preference for the latter method, on the grounds that the CBA approach depends on ambiguous assumptions relating to the private marginal damage curve. The marginal cost method tends to give higher values than the CBA method because it considers values under a business-as-usual, rather than optimum, scenario.

The studies cited by Clarkson and Deyes give a wide range of values (from \$1.4 to \$298.5/tC). The extent of variation is attributed to a number of factors, including underlying climate assumptions and damage estimates, but also economic assumptions relating to discount rates and equity weighting. Of the studies they survey, the approach

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[69] It is not immediately obvious why the impact at a global level is unambiguously damaging. The (warming) impact of ozone is predominantly at a regional level, whereas the (cooling) impact of CH_4 should be a global phenomenon, potentially implying a positive global impact in NPV terms. Caution is needed here, however, recognising the uncertainty towards regional climate impacts expressed by IPCC (1999).

of Eyre *et al* (1999) is recommended as the "most sophisticated". The strengths of Eyre *et al* are the use of dual models (FUND 1.6 and Open Framework), the detailed (and time-dependent) nature of the damage estimates and the sophistication of the modelling compared to some of the earlier studies. A later variant of the FUND model (FUND 2.0, described in Tol and Downing, 2000) was viewed as less reliable, despite a number of improvements over FUND 1.6, because it included more optimistic assumptions regarding adaptation and beneficial aspects of global warming and had not yet been peer-reviewed. Reservations were also expressed towards the method of equity weighting and the use by Tol and Downing of the value-of-life-years-lost (VLYL), rather than value-of-statistical-life (VSL), method of valuing mortality.

Clarkson and Deyes therefore base their recommended valuation (£70/tC for 2000, increasing by £1 per year) on Eyre *et al* (1999), subject to some adjustments so as to update values to 2000. They justify the fact that their recommendation is at the upper end of the range quoted in the literature not only on the sophistication of the Eyre *et al* approach but also on the observations that (i) the valuations surveyed do not include potential climate catastrophe or socially contingent events[70]; (ii) the disparity between valuations is diminished when equity weighting and discount rates are taken into account; and (iii) studies using stochastic analysis tend to find that the expected value exceeds the 'best guess' (see 5.5.2 below). Clarkson and Deyes' stance on these three issues is consistent with recommendations in the Green Book (HMT, 2003).

In view of the substantial uncertainty surrounding estimates, and the skewed results of probabilistic analysis, Clarkson and Deyes recommend that asymmetric sensitivities of £35 and £140/tC (i.e. halving and doubling) be used, as well as the £70 central estimate.

Pearce (2003) challenges Clarkson and Deyes' recommendations on a number of grounds. He points out that the later version of FUND described by Tol and Downing (2000) has subsequently been peer-reviewed and suggests that the more optimistic conclusions associated with adaptation and benefits of climate change are valid. He notes that climate catastrophe has indeed been taken into account in a number of studies omitted from Clarkson and Deyes' survey and that the results of one such study (Nordhaus and Boyer, 2000) fall within the range estimated by Tol and Downing.

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[70] Clarkson and Deyes could have added that most valuations tend not to allow adequately for a number of effects which are difficult to value, notably impact on ecosystems, extreme weather, tourism, recreation and amenity, etc. (see Tol, 2002a).

Pearce proposes that, taking account of equity weighting[71] and a time-varied discount rate, the social cost of CO_2 is within the range £4 – 27/tC.

Pearce goes on to evaluate the policy implications of carbon valuation and, in particular, the sub-optimal policy decisions arising from inconsistent valuations. Although aviation policy is not addressed by Pearce, this is clearly an example of an area where (if policy were formulated, implicitly or explicitly, on the basis of valuing global warming impacts) selection of a value which is inconsistent with the value used in other policy areas could lead to quixotic policy decisions regarding future capacity.

5.5.2 Other Relevant Literature

With a wide range of published estimates, the selection of a value per tonne of CO_2 has a profound impact on valuation results. Convincing justifications can no doubt be found for high and low values, and an attempt to out-guess other estimates (such as those of Clarkson and Deyes and Pearce) here is not necessarily constructive. There are, however, two areas where additional material is relevant:

- First, a number of studies are particularly relevant to Monte Carlo analysis;
- Second, it is also relevant to consider regionally disaggregated valuations.

As noted above, the range of published valuations of CO_2 is wide, reflecting a high degree of uncertainty. There are two ways of capturing this uncertainty within a PDF. One way is to use a PDF constructed from a particular study based on stochastic analysis; the other way is to use a PDF reflecting the range of published estimates. The former approach has the advantage of internal consistency, but has the risk of inheriting any bias in the underlying study. The second approach should avoid any such bias but, given that the majority of published estimates are 'best guesses', does not necessarily capture the range of uncertainty.

A number of probabilistic valuations of global warming have been attempted, one of the earliest being Frankhauser (1994). This study utilised mainly triangular distributions reflecting the availability of low / central / high estimates of underlying variables in the literature. The results were found to be positively skewed, reflecting the impact of low probability / high impact events, with the consequence that the expected value is higher

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[71] Pearce suggests that Clarkson and Deyes have doubled the Eyre *et al* valuation so as to allow for equity weighting. In fact, the equity weighting is performed by Eyre *et al* themselves, and it is not clear why Pearce makes this suggestion.

than the best guess. More recently, the FUND models (both 1.6 and 2.0, as described in 5.5.1) are based upon a more sophisticated array of distributions than Frankhauser. Again, a positive skew is observed in the results. The estimates are presented as a floor on the overall level of uncertainty since only parametric uncertainty is captured (see 2.4)[72]. Since Tol and Downing (2000) acknowledge the potential for over-pessimism in FUND 1.6 and over-optimism in FUND 2.0, the PDFs given by these two models can potentially be used as limiting cases or combined into a composite PDF (see 5.6.4).

A PDF constructed from a literature survey is provided by Tol (2003a). The purpose of Tol's analysis is to demonstrate how isolating various factors reduces the level of uncertainty. Discount rates and equity weighting are, unsurprisingly, shown to be important explanatory variables, not only for the average value but also for the level of uncertainty. It is also demonstrated that the level of uncertainty (and average value) is reduced when weighting is placed on the underlying estimates according to various quality scoring criteria or when only peer-reviewed studies are included.

As noted earlier, the regional climate impacts of aviation emissions are not uniform, with the (short-term, at least) impacts of NO_x and contrails concentrated in the northern mid-latitudes[73]. Potentially, therefore, these impacts should be valued by reference to regional, rather than global, valuations. The FUND and Open Framework models both value the impacts of climate change on a regionally disaggregated basis[74]. A comparison of results is far from conclusive. For example:

- According to Eyre *et al* (1999), FUND 1.6 indicates that the northern mid-latitudes account for approximately 6 – 9% of global damage (in NPV terms, no equity weighting) or less than 1% (with equity weighting);
- In contrast, the same source quotes respective shares, according to the Open Framework model, of approximately 100%[75] (no equity weighting) or 45-55% (equity-weighted). A significant proportion of these shares is accounted for by a strongly negative impact on water resources in CEE/FSU.

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[72] The underestimation of uncertainty is also shown by Tol (2003b), where it is demonstrated that the expected cost of global warming is potentially infinite. This arises because of the possibility that, if discount rates are endogenous within the model (via a component relating to economic growth), and potentially negative, then the overall weight attaching to increasingly high impact / low probability events may increase, despite the decay in probability.

[73] The "northern mid-latitudes" are construed here to refer to North America, Western Europe, Central and Eastern Europe (CEE) and the Former Soviet Union (FSU).

[74] In contrast, a number of the earlier studies are based on US impacts and are extrapolated to other regions of the world.

[75] A number of other regions are net beneficiaries of global warming.

The picture is further confused by the more recent work using FUND 2.0. With greater emphasis on benefits and adaptation, the net impacts are found to be beneficial for the OECD countries and detrimental elsewhere (Tol, 2002b). Tol and Downing (2000) find that global warming damage outweighs the benefits (albeit by a smaller margin than Eyre *et al*), with the incidence of damage accruing to the European Union anywhere between 0% and 90%, depending on the choice of mortality valuation method, equity weighting and discount rate.

5.6 Quantification of Damage – Methodology and Assumptions

5.6.1 Overall Methodology

The simplest method for valuing aviation's climate impacts, in common with the approach used by DfT and HMT, is to multiply emissions by the RFI (except for surface transport and LTO emissions) and then to multiply the adjusted total by the value of a tonne of CO_2. This can be done both deterministically and stochastically, utilising values for RFI and the value of CO_2 (and associated PDFs) selected from the literature.

The foregoing pages show that such an approach is fraught with difficulties. Even if it is correct to multiply annual emissions by the RFI to obtain equilibrium temperature change, RFI takes no account of the geographic and temporal aspects of the various impacts relative to those of CO_2. Indeed, it is conceivable (albeit unlikely) that, even if CO_2 emissions cause net damage in NPV terms (which is by no means undisputed), the short-term warming impacts of ozone in the northern mid-latitudes and the longer-term cooling impacts of CH_4 globally may even be shown by a disaggregated economic analysis of impacts to be beneficial[76].

Reliable answers to the above issues await further research into the regional incidence of aviation's climate impacts, a greater degree of consensus as to regionally disaggregated damage estimates and, perhaps, a conceptually sound method of calculating impacts per unit of aviation activity (e.g. per flight, aircraft-mile, etc.). In the meantime, for a study of this nature, an approach based on RFI is unfortunately "the only game in town", and the following analysis is based, with some modifications, on the simplified method described above. It follows that any quantification of uncertainty within the analysis fails to capture the uncertainty associated with the validity of the relationships underlying the calculations.

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[76] The only study which tackles this question does not support such a conclusion – see 5.4.4.

5.6.2 RFI Assumptions

Figure 8 showed IPCC's best estimates and 67% confidence intervals for the various sources of climate impact. These could potentially be used to derive central estimates and PDFs in this study. However, as summarised in Table 8, there are a number of factors which argue in favour of higher or lower estimates than IPCC.

Table 8: Potential adjustments to RFI estimates for purposes of valuation

Reasons for downward revision	Reasons for upward revision
➢ IPCC over-estimation of contrails. ➢ Total damage to regions lower than implied by globally averaged estimates? ➢ RFI an inappropriate multiple of annual emissions?	➢ IPCC over-estimation of CH_4 cooling. ➢ Cirrus effects increasingly robust. ➢ Time value and rate-dependent damage of relatively fast-acting non-CO_2 effects.

Note: a question mark denotes the possibility (judged to be less than 50% probable) that the potential adjustment may have been assigned to the wrong column.

Recognising the risks of spurious precision and the expert opinion elicited from Lee (see 5.4.3), 3.0 is used as the point estimate for deterministic analysis[77], and a uniform distribution between 2.0 and 4.0 is used in the Monte Carlo analysis. Recognising the modelling uncertainties associated with non-CO_2 effects, results are reported separately for CO_2 and non-CO_2 effects.

Stochastically derived estimates of CO_2 values (see 5.6.4 below) incorporate some amount of uncertainty in respect of the RF attributable to CO_2. Potentially, this double-counts an element of the uncertainty within the above PDF. The RFI should therefore be seen as comprising (and indeed is modelled as) an RFI of 1.0 for CO_2 (by definition) plus a uniform distribution of between 1.0 and 3.0 for non-CO_2 effects.

5.6.3 Discount Rate Assumptions

One of the purposes of this thesis is to provide a valuation which can be compared with the economic benefits of capacity expansion presented in section 3. For purposes of consistency, emissions have been valued (at 2000 prices) over the period 2000 to 2060[78] and discounted back to 2000. This raises the issue of which discount rate to use. This choice needs to be considered in conjunction with the discount rates used to derive the value per tonne of CO_2 (see 5.6.4) and the discount rates used in calculating the economic benefits of capacity expansion presented in section 3.

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[77] However, in the Calibration Scenario, 2.7 is used, for the sake of consistency with DfT figures.

[78] It is assumed that emissions in the years 2030-2060 remain constant at their 2030 level.

In fact, a relatively clear answer presents itself. Much of the literature reviewed in 5.5 employs the social rate of time preference (SRTP) as the discount rate, calculated according to (variants of) a formula such as $\text{SRTP} = \text{PRTP} + \theta g$, where "PRTP is the pure rate of time preference (the utility discount rate), θ is the negative of the income elasticity of marginal utility and g is the growth rate of per capita consumption" (Clarkson and Deyes, 2002). In fact, this is precisely the approach recommended in the Green Book and underpinning the 3.5% discount rate used in DfT's revised analysis. However, due to the impact of uncertainty on discount factors[79], the Green Book recommends that lower discount rates be used beyond 30 years (3.0% for years 31-75).

Given the long-term nature of climate impacts and the intent to derive a valuation which is comparable with other aspects of Government policy, a 3.0% discount rate is selected for the analysis which follows (and values per tonne of CO_2 chosen accordingly). Given that the literature generally supports utilising a discount rate greater than zero (see Pearce, 2003) and given that the 6.0% discount rate originally used by DfT for economic valuation has been overtaken by events, little value is derived from illustrating sensitivities based on discount rates which are significantly higher or lower.

5.6.4 Carbon Valuation Assumptions

The sources surveyed in 5.5 provide many values to choose from, depending on the desired combination of discount rate, equity weighting, etc. Rather than use one single value (or PDF), a variety of profiles have been chosen for the analysis, as follows:

- "Clarkson and Deyes" profile: £70 / tC (plus £1 per year, to 2030), for purposes of comparison with the HMT / DfT analysis[80]. For Monte Carlo analysis, a triangular distribution of £35 /£70 / £140 is used (and the annual increment similarly profiled);
- "Literature Survey" profile: a literature-based estimate of US$49 / tC[81]. This is the mean of a survey (Tol 2003a) for studies using a PRTP of 1% (broadly equivalent to a SRTP of 3%). For the Monte Carlo analysis, the PDF constructed by Tol was replicated. The range includes some negative values and is very broad. Since the literature suggests a value which grows in real terms over time, the assumed value is escalated at a CAGR of 2% p.a. (until 2030). This is the average CAGR for studies

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[79] See also Pearce (2003).

[80] The value selected by Clarkson and Deyes was explicitly predicated upon a 3% discount rate – see 5.6.3. Note that the £1/year increment is assumed to stop in 2030, so as to avoid extrapolating the relationship between time and value beyond the range originally intended.

[81] This is converted to £ at the 2000 average US$/£ exchange rate of 1.52 (Bank of England, 2003).

surveyed by Tol (in Eyre *et al*, 1999, Appendix 1), although it may not be representative of the sample surveyed in Tol (2003a);

- "FUND 1.6" profile: an estimate taken from Eyre *et al* (1999). The best guess estimate of US$60 / tC[82] is similar to Clarkson and Deyes. For Monte Carlo analysis, the PDF quoted by Eyre *et* al is a log-normal distribution (geometric mean of US$67, geometric standard deviation of 1.8). In common with Clarkson and Deyes, the value is escalated at £1/year until 2030, which is approximately the increase shown by Tol and Downing (albeit over a shorter period). A PDF similar to that used for the Clarkson and Deyes increment is applied to the increment;
- "FUND 2.0" profile: an estimate taken from Tol and Downing (2000). The best guess figure is US$8.9 /tC[83]. For Monte Carlo analysis, the PDF quoted by Tol and Downing is a log-normal distribution (geometric mean of US$9.6; geometric standard deviation of 1.7). In common with the Literature Survey profile, the assumed value is escalated at a CAGR of 2% p.a. (until 2030);
- "Composite (A)" profile: this is a composite of FUND 1.6 and FUND 2.0, created by alternating the random draws between those of the FUND 1.6 and 2.0 profiles. The resulting distribution exhibits bi-modal characteristics;
- "Composite (B)" profile: an alternative composite of FUND 1.6 and FUND 2.0, created by randomising the geometric mean and geometric standard deviation, with a uniform distribution between the levels quoted for the FUND 1.6 and FUND 2.0 profiles. This eliminates the bi-modal nature of Composite (A)[84]. The value is escalated at 2% per year until 2030.

With the exception of the Literature Survey figures (which include both weighted and unweighted values), equity weighting is implicit in all of the above values. This is consistent with Clarkson and Deyes, and with Green Book recommendations. The

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[82] The figures are multiplied by a factor of 1.17, so as to convert from (i) 1990 US\$ discounted to 1990 at 3% p.a. to (ii) 2000 £ compounded to 2000 at 3% p.a.. For converting 1990 US\$ to 2000 US\$ a consumer price index factor of 1.32 is used (US Bureau of Labour Statistics, 2003). The exchange rate is as per footnote 81.

[83] It is assumed that these values are expressed in 2000 prices, and they are therefore converted to £ at the exchange rate quoted in footnote 81. Note that the VLYL method of valuing mortality has been selected, since this profile is intended to illustrate the opposite extreme to the Eyre *et al* profile. The Green Book is not explicit with regard to UK Government policy in this area.

[84] It is argued in 5.5.2 that FUND 1.6 and FUND 2.0 potentially represent upper and lower valuation extremes. In other words, if the biases within each of them (exaggeration of damage and adaptation respectively) were removed, the resulting distribution would lie between the two and should exhibit a similar distribution to FUND 1.6 and 2.0. Thus, the bi-modal distribution of Composite (A) is considered an artificial consequence of the method used to derive it.

valuations chosen are based on a SRTP of 3% or PRTP of 1%. Histograms illustrating the PDFs of the various profiles are given in Figure 18 in Appendix V.

5.6.5 "Thought Experiment" Sensitivity

In addition to the above, a case has been prepared which attempts to capture some of the uncertainties which have not otherwise been modelled:

- Recognising that, other than CO_2 and CH_4, the impacts of aviation are primarily of a regional rather than global nature (albeit, perhaps, with 'leakage' to the global climate), non-CO_2 emissions have been split within the model between 'global' effects and 'regional' effects. A uniform distribution between 20% and 80% has been used for the percentage of non-CO_2 effects represented by regional effects;
- For the regional effects, the value per tonne of carbon, using the Composite (B) profile, is multiplied by a random factor (uniformly distributed between zero and one). This random factor reflects the enormous uncertainty regarding geographical impacts and also the halving (on average) of valuations so as to remove the impact of equity weighting (see Clarkson and Downing, 2002; Pearce, 2003). The rationale for de-weighting regional effects is that the countries of the northern mid-latitudes (where the regional impacts are largely concentrated) are relatively rich.

It should be emphasised that this approach is little more than a creative attempt to take account of considerations not otherwise catered for in the analysis, using a questionable methodology and somewhat arbitrary assumptions. Arguably, it amounts to little more than a semi-informed approach to placing a weighting factor on non-CO_2 effects. Nonetheless, it is offered as a "thought experiment" and could potentially stimulate more informed analysis at a later stage.

5.7 Quantification of Damage – Results

5.7.1 Deterministic Analysis

Results of deterministic analysis for the Calibration Scenario are shown in Table 9. Equivalent results for the other scenarios are presented in Table 25 in Appendix V.

Table 9: Deterministic Results: Calibration Scenario

Case		**High case**				**Low case**			
Valuation profile		**(1)**	**(2)**	**(3)**	**(4)**	**(1)**	**(2)**	**(3)**	**(4)**
NPV CO2	£ [2000] bn	42.6	23.4	42.7	4.9	40.4	22.1	40.5	4.7
NPV GHGs	£ [2000] bn	106.4	58.5	106.7	12.3	100.9	55.3	101.2	11.7
Weighted avg value /tC	£ [2000] /tC	91.3	50.2	91.6	10.6	90.9	49.8	91.2	10.5
Damage / PMT 2000	£ [2000] /PMT	0.8	0.4	0.8	0.1	0.8	0.4	0.8	0.1
Damage / PMT 2030	£ [2000] /PMT	1.1	0.6	1.1	0.1	1.1	0.6	1.1	0.1
Weighted avg damage / PMT	£ [2000] /PMT	0.9	0.5	0.9	0.1	0.9	0.5	0.9	0.1
Damage / PAX 2000	£ [2000] /PAX	6.8	3.2	6.9	0.7	6.8	3.2	6.9	0.7
Damage / PAX 2030	£ [2000] /PAX	10.0	5.9	10.1	1.2	10.2	6.0	10.3	1.3
Weighted avg damage / PAX	£ [2000] /PAX	8.4	4.4	8.4	0.9	8.4	4.4	8.4	0.9
Damage / FTM 2000	£ [2000] /FTM	2.5	1.1	2.5	0.2	2.5	1.1	2.5	0.2
Damage / FTM 2030	£ [2000] /FTM	5.0	2.9	5.0	0.6	5.2	3.1	5.3	0.6
Weighted avg damage / FTM	£ [2000] /FTM	3.8	2.0	3.8	0.4	3.9	2.0	3.9	0.4
Damage / tonne 2000	£ [2000] /tonne	84.8	39.2	85.2	8.3	84.9	39.2	85.2	8.3
Damage / tonne 2030	£ [2000] /tonne	173.1	101.4	173.6	21.4	187.5	109.8	188.0	23.1
Weighted avg damage / tonne	£ [2000] /tonne	132.3	70.1	132.7	14.8	134.8	71.4	135.2	15.0

Notes: The valuation profiles are labelled as follows: (1) Clarkson and Deyes; (2) Literature Survey; (3) FUND 1.6; (4) FUND 2.0. The Composite profiles and Thought Experiment sensitivity have not been modelled deterministically. Note also that damages expressed as a value per PMT, per FTM and per tonne are aggregate damages before apportioning only a proportion to the UK. Damages expressed in absolute terms and per PAX are the damages attributable to the UK.

The Calibration Scenario / Clarkson and Deyes profile mimics DfT’s analysis. The model shows an undiscounted value of £5.3 bn for emissions in 2030 (not shown), versus DfT’s projection of £4.8 bn. The 10% difference reflects the freight discrepancy referred to in 4.9.1. The NPVs of total emissions for 2000-2060 are £106 bn (high case) and £101 bn (low case). The delta of £5 bn is the marginal damage associated with an increase in capacity from maximum use of existing runways to a high capacity case (see section 6). The other noteworthy aspects of the CS are that:

- The increase over time in the value per tonne of GHGs outweighs the reduction in emissions per passenger-mile, i.e. the damage per PMT increases over time[85];
- The increase in damage per PMT is similar between the high and low cases;
- The NPVs are highly dependent on the valuation profile selected. The FUND 2.0 profile gives an NPV just over 10% of the Clarkson and Deyes profile, reflecting differences in initial values and the rate of increase. The FUND 1.6 profile gives similar NPVs to the Clarkson and Deyes profile. The Literature Survey profile represents a medium estimate. The weighted average damage per PMT varies between 0.1 pence (FUND 2.0) and 0.9 pence (Clarkson and Deyes, FUND 1.6).

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[85] This is even more pronounced for freight traffic, owing to the larger share of future traffic accounted for by dedicated freighter aircraft.

The values for the RCS, RS and TS (see Appendix V), relative to the CS, generally reflect the differences in emissions results discussed in section 4. It is to be noted that:

- Owing to the higher fuel burn assumptions, the RCS has damage estimates approximately 15% higher than the CS; consequently the marginal damage of capacity expansion is also higher, at £7 billion (Clarkson and Deyes profile);
- The RS/lo case results in damage of approximately 75% of the RCS/lo case in NPV terms, consistent with a higher aggregate amount of marginal damage associated with a larger difference in capacity (£33 billion, using the Clarkson and Deyes profile). The impact of capacity limitations on emissions efficiency (see 4.9.2) is evident in the relatively low weighted average damage per PMT;
- The fuel efficiency savings realised under the TS generate reductions in damage of approximately 5% in NPV terms.

5.7.2 Monte Carlo Simulation

Table 10 presents results for the Calibration Scenario using the Clarkson and Deyes valuation profile. Histograms are shown in Figure 9 below (high cases only).

Table 10: Monte Carlo: Calibration Scenario / Clarkson and Deyes Profile

	NPV (£ bn)		Damage / PMT (pence)	
	High case	**Low case**	**High case**	**Low case**
Base case (deterministic) *(CO_2 only)*	106 *(43)*	101 *(40)*	0.93	0.93
Expected value *(CO_2 only)*	125.8 *(50.5)*	117.7 *(47.2)*	1.08	1.08
Median	118.3	111.9	1.04	1.03
Standard deviation (SD)	0.52	0.46	0.38	0.38
SD / mean (CV)	41.4%	38.7%	35.0%	34.8%
5th percentile	57.4	56.8	0.56	0.56
95th percentile	224.2	204.5	1.80	1.79
Geometric mean	115.4	109.2	1.02	1.01
Geometric SD	1.52	1.48	1.43	1.42
NPV total damage / NPV CO_2 damage	5th %'ile: 3.30 95th %'ile: 1.70		N/A	N/A

Notes: All values are expressed in £$_{2000}$ terms. The weighted average damage in the two columns on the right are calculated as the NPV of passenger-related damage divided by the NPV of PMTs. 2,000 recalculations. Note also that damages expressed as a value per PMT, are aggregate damages before apportioning only a proportion to the UK whereas damages expressed in absolute terms are the damages attributable to the UK.

Two points are to be noted from the above table. The first is that the relatively high degree of uncertainty as to damage is apparent. For example, whereas Table 7 showed (albeit for a different scenario) a CV of approximately 3% for emissions per PMT, the CV of damage per PMT is over ten times as high. This uncertainty is manifested in a ratio of approximately four between the 95th and 5th percentiles of total damage.

The second point is that, whereas the distributions of emissions in section 4 were generally symmetrical, the distribution of values is skewed, reflecting the asymmetric high and low value estimates. This has the effect that the expected value is appreciably higher than the base case, as indeed is the delta between the high and low cases.

Figure 9: Histograms: Calibration Scenario / Clarkson and Deyes Profile

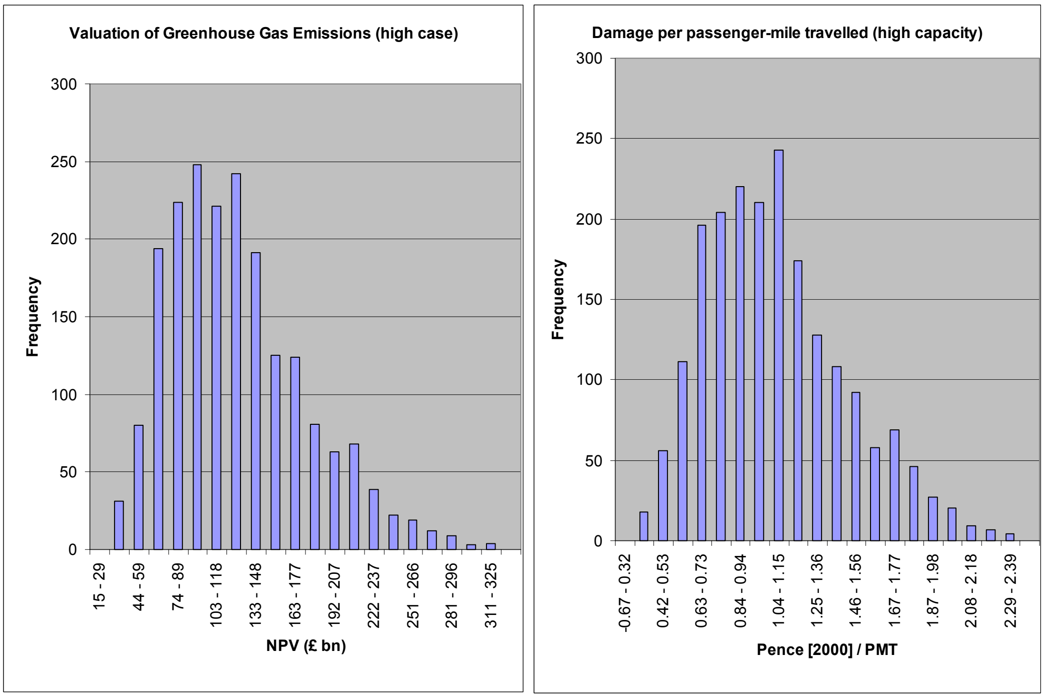


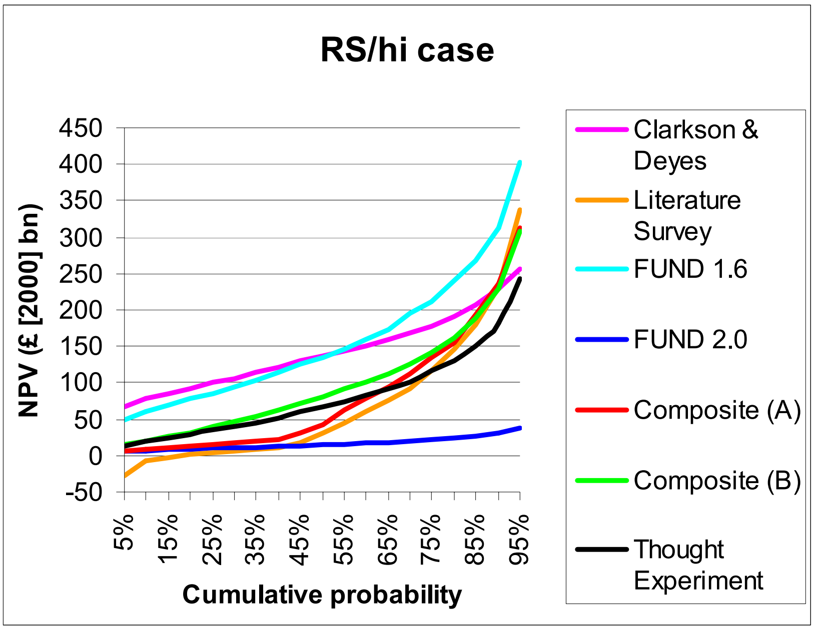
Table 26 and Table 27 in Appendix V show equivalent results for the RASCO Scenario under each of the valuation profiles. The following points are to be noted:

- In all cases, the expected value is higher than the deterministically derived damage estimate. In the case of the FUND 1.6 profile (which was the original source of the Clarkson and Deyes estimate), the expected value is 37% higher than the point estimate and 15% higher than implied by the Clarkson and Deyes PDF;
- The FUND 1.6 and 2.0 model profiles exhibit moderately wider distributions around the mean than the Clarkson and Deyes profile (geometric standard deviation of ~1.8 to 1.9 *verus* ~1.4 to 1.5 for Clarkson and Deyes). In contrast, the composite profiles (Literature Survey, Composite (A) and (B) and the Thought Experiment sensitivity) exhibit much wider distributions, with geometric standard deviation of ~2.5 to 5.5;
- The lowest damage estimate of the 5th percentiles of all of the profiles is given by the Literature Survey and is minus £27 bn (i.e. a net benefit, in NPV terms). The highest damage estimate of the 95th percentiles is the FUND 1.6 result of £402 bn;
- The Thought Experiment sensitivity shows a ~20% lower expected damage value than the Composite (B) profile (on which it is based). Clearly, CO_2 accounts for a

higher percentage of the total damage in this sensitivity. The distribution of results is broader by some measures than the Composite (B) profile (e.g. CV) but narrower by others (geometric mean, 5th and 95th percentiles as a fraction of the mean). It appears that the additional uncertainties introduced by this sensitivity are masked by the large underlying uncertainty with respect to valuation.

Figure 10 shows the cumulative PDFs of damage (for the high capacity case only) using the different valuation profiles. Such PDFs serve a potentially useful role by allowing policymakers to take a view on the value of the damage caused, based on their preferred valuation profile(s) and the level of confidence desired. For example, a policymaker favouring the FUND 1.6 profile and wishing to be 70% confident that damages are not underestimated would opt for a valuation of circa £200 bn.

Figure 10: RASCO Scenario: Cumulative PDFs of Damage



5.8 Conclusions

The conclusions to be drawn from this section are that whereas, over a thirty year time scale, the uncertainties associated with aviation emissions are moderate (section 4) there are significant uncertainties associated with the climate impact of those emissions and the valuation of those impacts. Nonetheless, it is possible to derive valuations which take account of parametric uncertainties, albeit that the extent of uncertainty within those valuations is almost certainly underestimated. Section 6 discusses the policy implications of these findings.

6. ANALYSIS AND DISCUSSION

6.1 Overview

This section brings together the analysis of the previous sections so as to draw conclusions. Specifically, it compares the damage estimates from section 4 with the economic benefits calculated in section 3 and draws conclusions for capacity expansion. It then considers the implications of the damage estimates (and associated uncertainty) for economic instruments. Wider implications are then discussed, viz. the application of the techniques used in this thesis and further research needs. Finally, observations are made regarding the extent to which this thesis has accomplished its objectives.

6.2 Benefits of Airport Capacity Expansion

6.2.1 Comparison of NPVs

By calculating the difference in costs and benefits for different levels of capacity development, the damage estimates derived in section 5 can be compared with the economic benefits of expansion quoted in section 3. This is shown in Table 11.

Table 11: Comparison of NPVs of Economic Benefits and Environmental Damage

Capacity comparison *All values are £$_{2000}$, discounted to 2000*	**High *vs.* low (£ bn)**	**High *vs.* very low (£ bn)**	**Low *vs.* very low (£ bn)**
Net benefits to compare with global warming damage estimates			
Adjusted benefits @ 3.5% (from Table 6)	~26	~58	~32
Env. damage – noise/air quality (illustrative)	(~0)	(~2)	(~2)
Net benefits	**~26**	**~56**	**~30**
Calibration Scenario / Clarkson and Deyes			
Base case value	5.5	N/A	N/A
Expected value	8.1	N/A	N/A
Revised Calibration and RASCO Scenarios	**RCS/hi *vs.* RCS/lo**	**RS/hi *vs.* RS/lo**	**Net**
Clarkson and Deyes – base case	6.8	33.2	26.4
Clarkson and Deyes – expected value	10.2	41.0	30.8
Literature Survey – base case	4.0	18.8	14.8
Literature Survey – expected value	4.5	22.3	17.8
FUND 1.6 – base case	6.9	33.2	26.3
FUND 1.6 – expected value	13.0	48.9	35.9
FUND 2.0 – base case	0.8	4.0	3.2
FUND 2.0 – expected value	1.1	4.9	3.8
Composite (A) – expected value	7.2	26.6	19.4
Composite (B) – expected value	9.3	33.7	24.4
Thought Experiment – expected value	7.4	27.2	19.8

Notes: "Very low" capacity refers to RS/lo; "low" capacity refers to CS/lo or RCS/lo; "high" capacity refers to CS/hi, RCS/hi or RS/hi. Expected values for RCS cases are based on 1,000 iterations rather than 2,000.

An illustrative amount has been allowed for the environmental damage caused by noise and local air quality. This has been derived simply by scaling up the Pearce and Pearce (2000) noise and Dings *et al* (2002) air quality damage estimates quoted by HMT / DfT (see Table 2) by the modelled increases in LTO fuel burn over time, and discounting back to 2000 at 3.5%. A discussion of these valuations (and indeed the crude approach used here to project them into the future) is beyond the scope of this thesis.

The question arises as to whether it is legitimate to compare a point estimate of economic benefits with an expected value of damage, given the possibility that a point estimate might understate (or exaggerate) benefits in the same way that such an estimate understates the expected value of damages. Ideally, stochastic estimates would be compared for both figures. In the absence of stochastic estimates of benefits (and of any *prima facie* reason to believe that benefits are distributed asymmetrically), benefits are compared here both with point and stochastic estimates of damages.

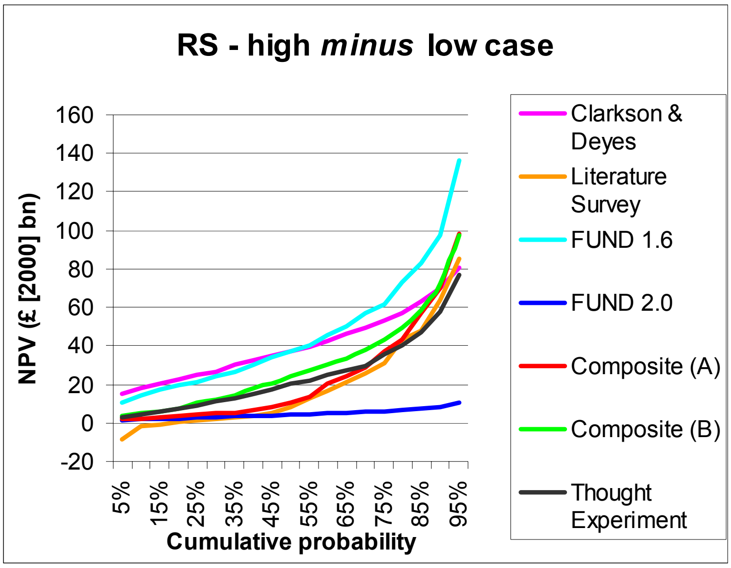
The conclusions to be drawn from Table 11 are the following:

- For some profiles, the damage caused by global warming is a significant proportion of the net benefits of incremental capacity. For example, the Government's own valuation profile (Clarkson and Deyes) suggests that the environmental costs of a large capacity increase (RS/hi minus RS/lo) represent 60% (point estimate) or 75% (expected value) of the economic benefits of expansion;
- Conversely, applying the FUND 2.0 profile to the same scenario implies that damage is an order of magnitude lower than the benefits of expansion;
- In all cases, the high capacity option results in benefits which exceed environmental costs. Counter-intuitively, this is not always the case under all valuation profiles for the low capacity option. This is not due to non-linearities within the economic damage function but rather reflects the increasing economic returns per unit of capacity increase implicit within DfT's economic analysis (see footnote 21).

6.2.2 Decision Making

Since the NPV of expansion is marginal in some cases, the results will be sensitive to assumptions in the economic and environmental analysis. A decision-maker will need to know the level of confidence associated with the economic benefits (which is beyond the scope of this thesis) and with environmental damage. This is a function both of the PDF of damage results (see Figure 11) and of the valuation profile selected.

Figure 11: Cumulative PDF for global warming damage from capacity expansion



The selection of the appropriate confidence level, and indeed valuation profile, is ultimately a political judgement. For example, a policymaker sceptical of the scope for adaptation may be inclined towards the FUND 1.6 profile. If s/he wished to be 70% confident that the costs do not outweigh the benefits, then Figure 11 suggests that s/he should rule out expansion, since the damage at that probability exceeds the £56 bn benefits indicated in Table 11. Conversely, a policymaker more convinced of the scope for adaptation might adopt the FUND 2.0 valuation profile, which suggests that capacity expansion is worthwhile at all realistic probabilities. The composite profiles are of course a compromise view taking account of both perspectives; this does not make them more correct than the other profiles, however. Indeed, a policymaker might prefer to take account of the results of multiple models rather than rely on a composite valuation.

Briefly, a policymaker might also take account of the following pieces of information:

- The break-even price of carbon. The value of carbon at which the NPV of capacity expansion is eliminated is in the region of £95 /tC (2000 value escalating at 2% in real terms; RS/hi minus RS/lo)[86];
- The effect of ignoring non-CO_2 GHGs. Whilst Monte Carlo simulation and the Thought Experiment sensitivity serve some use in factoring in the uncertainties associated with non-CO_2 impacts, it is also useful to distinguish between the NPVs

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[86] Interestingly, this result is not significantly different for deterministic analysis and stochastic analysis (i.e. with all variables other than the value of carbon randomised). This demonstrates the extent to which the difference between the base case value and expected value is accounted for by the uncertainty attributed to carbon valuation rather than other variables.

of CO_2 and other GHGs. These are, for example, £12.2 and £21.5 bn respectively for the Composite (B) profile (RS/hi minus RS/lo);

- The damage estimates under the Technology Scenario. In fact, based on a comparison of the high and low capacity case using the Composite (B) profile, the impact of the Technology Scenario assumptions is to reduce net damage from £9.3 bn to £8.2 bn. This does not have a major impact on the net results.

Finally, it is to be noted that benefit : cost ratios (BCR, a metric hitherto favoured by DfT) do not feature in the above analysis. BCRs are intuitively appealing because they give some *prima facie* indication of the extent to which options with apparently positive NPVs might be robust under adverse assumptions. However, BCRs are inherently prone to misinterpretation by policymakers and are a relatively poor guide to robustness. A tool explicitly demonstrating how decisions are affected by uncertainty, such as shown in Figure 11 provides a more reliable indication.

6.2.3 Conclusions for Capacity Expansion

The results presented in 6.2.2 provide a tool (in addition, of course, to the MCA prepared pursuant to NATA/GOMMMS) for policymakers to decide on the case for or against capacity expansion. A decision based solely on base case and expected values would be to build a high level of additional capacity. However, the higher valuation profiles suggest that the level of confidence associated with such a decision is not particularly high (less than 70%, for example, under the FUND 1.6 profile), particularly if there is concern that those valuations do not fully capture impacts such as potential climate catastrophe or that other environmental damage is underestimated.

This brings into focus the sensitivity of the net results with respect to valuation of the underlying economic benefits of aviation, the science associated with non-CO_2 impacts and the valuation of global warming, and indeed other environmental, impacts. If the Government's current valuation profile of carbon is to be retained, then it is conceivable that a more sophisticated approach to valuation of aviation's benefits (e.g. the use of SPASM, rather than SPAM, for appraising national policy scenarios) could lead to the conclusion that the benefits of additional capacity do not outweigh the environmental damage. Conversely, a more rigorous approach to valuing non-CO_2 impacts (see 5.4.3) or revision of the price of carbon in light of issues raised by Pearce (see 5.5.1) could increase the level of confidence associated with the positive NPV of capacity expansion.

The issues raised in the previous paragraph are not necessarily intractable. The use of SPASM for modelling national policy scenarios would involve an extension of consultancy work already performed for DfT. The issues raised in relation to the use of RFI for valuation would need to be discussed at a conceptual level between scientists and economists, accompanied by further modelling work. Scientific certainty as to the climate impacts of aviation and a greater degree of consensus as to the economic valuation of climate impacts (globally and regionally) will clearly take longer to achieve. In the meantime, scientific research has progressed since the IPCC report (see 5.4.2) and a review by the Government of the Clarkson and Deyes valuation recommendations is under way. The latter could perhaps take into account the prospects for adaptation and environmental benefits (per Tol and Downing) as well any other up-to-date GHG valuation work.

The question therefore arises whether the forthcoming White Paper should make a definitive decision as to future capacity expansion or whether a more flexible range of options could be considered such as:deferring a final decision on capacity expansion pending further analysis or a phased development programme which allows later tranches of capacity to be cancelled in the light of subsequent analysis. Clearly, the prospects for such outcomes depend on political factors beyond the scope of this thesis.

6.3 Economic Instruments

The use of economic instruments for internalising aviation's environmental impacts is receiving widespread attention as a result of the consultation accompanying publication of "Aviation and the Environment – Using Economic Instruments" (HMT / DfT, 2003a). For a review of the issues associated with the structuring of such instruments, the reader is referred to a recent report commissioned by CfIT (Wit *et al*, 2003).

This thesis focuses more on valuation issues than on economic instruments; however, a number of the findings are relevant to economic instruments, viz: the level of external costs to be internalised; the impact on demand of internalising such costs; and the implications of certain of the findings for the structuring of economic instruments.

6.3.1 Level of External Costs to be Internalised

A number of estimates of the global warming costs of illustrative aircraft journeys are to be found in the literature. For example, Dings *et al* (2002) quote estimates of €2.1,

€8.9, €16 and €35 for journeys of 200, 500, 1,500 and 6,000 kilometres respectively[87]. Estimates have also been made by Pearce and Pearce (2000), DfT (2000b – using values and a methodology which are superseded by HMT / DfT, 2003a) and others.

Table 12 below presents damage estimates, as modelled for the various journey categories identified in 4.4. Note that, since this discussion relates to economic instruments, and since it is argued that indirect effects are more appropriately addressed at source (see 4.8 and also Wit *et al*, 2003), surface transport damage is excluded. For the sake of brevity, figures are shown only for the RS/hi case with the Composite (B) valuation profile. The damage estimates quoted are for the total damage per passenger, i.e. international emissions are not divided by two. The rationale for this is that, if an environmental tax were to be imposed, then it would be cumbersome to apply separate charges in two countries. The figures can therefore be seen as an amount to be charged at (say) departure to cover the entire journey.

Table 12: Damage Estimates for Illustrative Journeys

All monetary values are expressed in £$_{2000}$.	**Domestic**	**Int'l (0-500 miles)**	**Int'l (501-1000 miles)**	**Int'l (1,001-2,000 miles)**	**Int'l (2,001-5,000 miles)**	**Int'l (>5,000 miles)**
Avg distance (miles)	~273	~333	~775	~1,277	~3,985	~6,560
Est damage						
• 2000	£2.2	£2.6	£4.6	£6.8	£22.4	£40.0
• 2030	£3.0	£3.8	£6.8	£9.6	£31.6	£52.4
Wtd avg damage						
• Base case	£2.7	£3.4	£6.0	£8.6	£27.4	£47.4
• Expected value	£3.6	£4.6	£8.0	£11.6	£36.6	£63.4
• 10th percentile	£0.8	£1.0	£1.7	£2.4	£7.8	£13.5
• 90th percentile	£7.3	£9.2	£16.2	£23.2	£73.9	£127.9
Illustrative journey						
Destination (from London)	Newcastle	Frankfurt	Vienna	Valletta	Delhi *(Chicago)*	Singapore
Distance (miles)	276	398	767	1,298	4,168 *(3,944)*	6,741
Airfare (Sep'03)						
• Low	£27	£40	£48	£84	£213 *(137)*	£215
• Average	£34	£50	£121	£112	£287 *(168)*	£284
• High	£150	£246	£312	£243	£492 *(495)*	£585

Notes: Damages per PAX represent total damage (and, in the case of international journeys, not just the UK share) divided by the total number of passenger journeys. The stochastic estimates have been approximated off-model by multiplying the point estimates by a suitable factor (based on Table 27) rather than by performing Monte Carlo analysis on a journey-by-journey basis. Distances quoted are Great Circle distances.

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[87] These estimates are within ±40% of the figures quoted in Table 12 below. When account is taken of the differences in the valuation of carbon, the discrepancies are reduced, except in the case of the long-haul journey. Dings *et al* use a literature-based valuation equivalent to approximately £74 / tC.

It can be seen from the table that the expected values vary between £3.6 (domestic journeys) and £63.4 (journeys over 5,000 miles). As noted previously, the value increases over time, since growth in the real value of CO_2 outweighs efficiency savings. (The significance of the airfares quoted in Table 12 is explained further below.)

6.3.2 Internalisation of Damage Estimates

Various studies have attempted to quantify the impact on demand of internalising environmental costs, based on estimates of the price-elasticity of demand (PED) for air travel. Wit *et al* (2003) provide a brief survey of published estimates of the PED. They point out that the market is highly segmented, with the PED varying significantly between short-haul and long-haul travel, and between business and leisure travel. They quote a literature survey by Gillen *et al* (2003) which suggests that the PED for long-haul business travel (at one extreme) is in the range -0.198 to -0.475 and for short-haul leisure travel (at the other extreme) is in the range -1.288 to -1.743.

As part of their economic analysis on behalf of DfT, Halcrow (2002a) performed an "environmental sensitivity test" (see 3.3) in which fuel costs were assumed to double over time as a result of an environmental charge. For this purpose, they assumed a PED of -1.0, consistent with assumptions made by DfT (DfT, 2000c). Wit *et al* (2003) quote empirical support for the -1.0 estimate, based on the reduction in demand for air travel which accompanied the introduction in the UK of APD.

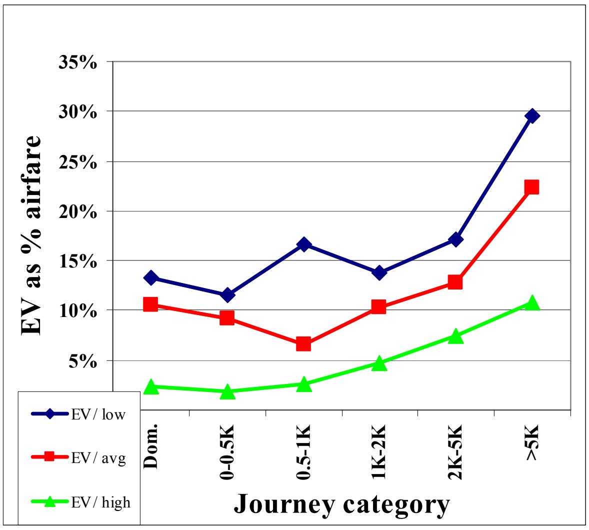
It is possible to model the effect of introducing an environmental charge equal to the external costs imposed by global warming. It is necessary, for this purpose, to make assumptions about supply side responses, both in terms of technical and operational performance, and also the extent to which charges are passed through to consumers or absorbed by the industry. (DfT / Halcrow assumed full pass-through, with no supply side response.) Table 12 raises two more basic questions for such an exercise, viz:

- Given the large uncertainty range associated with damage estimates, at what level would costs be internalised? It can be seen from the table that the 90th percentile damage estimate is approximately twice as large as the expected value (and ten times as large as the 10th percentile). Again, policymakers therefore need to decide the level of confidence they require that costs have been fully captured by an economic instrument, and the valuation profile they wish to adopt;

- Second, the market price of air travel is by no means obvious, not only in terms of the future but also current prices. Table 12 quotes high, average and low estimates for illustrative journeys with a distance very close to the average distance assumed for the relevant journey category. The prices quoted are not intended to be extremes: the low and average estimates were simply taken from a randomly chosen website quoting airfares (Expedia, 2003) whereas the high estimates were flexible economy fares quoted online by British Airways (2003b)[88]. The ratio of the high to low estimate varies between approximately two and six (and would clearly be significantly higher if the upper estimate were based on business class fares).

To put this another way, if an environmental charge were set at a level equal to the expected value of damage, then a (higher fare-paying) business traveller to Newcastle would face a fare increase of approximately 2% (see Figure 12). At the other extreme, if the charge were to be set at a precautionary level equal to the 90th percentile damage estimate, then a (low fare-paying) leisure traveller to Singapore would face a fare increase of approximately 60%. Clearly, even ignoring the differences in PED between the two travellers, the scale of their responses would likely be very different indeed. In the case of the former traveller, the fact that the traveller is prepared to pay a high fare[89] indicates a low PED and suggests that the demand response would be small.

Figure 12: Expected value of damage estimate *versus* airfares



Note: Delhi, rather than Chicago, is shown for the 2K-5K journey category.

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[88] The prices shown in the table are 50% of the price for return journeys in September/October 2003, deflated by the Retail Price Index to 2000 prices.

[89] The high fare likely reflects the success of airlines in capturing consumer surplus via product differentiation. It does not necessarily follow, however, that this entails a socially sub-optimal level of production or a distortion of economic signals associated with economic instruments.

The question therefore arises as to the purpose of an economic instrument such as environmental taxation when there is considerable uncertainty not only as to the value of the externalities to be internalised but also as to the long-term impact of internalisation on the behaviour of economic actors (both demand side and supply side) and a reasonable likelihood that the long-term impact of the tax will be scarcely discernible in the face of growing demand.

From the theoretical arguments presented in 3.3.2, a possible answer to the above question is that, so long as it is possible to set a tax based upon a reasonable estimate of the marginal damage costs at the optimum level of emissions (even if the optimum level is not known with precision), then it can be left to the economic actors to find the socially optimal level of emissions, through operation of the market. The socially optimal level of emissions may or may not entail a significant supply and/or demand side response. If not (e.g. because of inelastic demand and/or high marginal abatement costs), then the implication is that it may be more efficient to seek reductions from other sectors (with more elastic demand and/or lower abatement costs) than to seek to achieve particular targets from the aviation sector.

In this regard, it will be recalled (from section 3.5) that the Government views internalisation of environmental costs as a goal from the standpoint of economic efficiency and as a stimulus to supply side effects, rather than necessarily being a lever to engineer a reduction in the level of demand. Thus, the "fuzziness" of the market response to an environmental tax would not necessarily be viewed by the Government as problematic to policy. It is relevant to note, however, that the various consultation processes launched in 2003 suggested that consultees were generally in favour of limits-based approaches (specifically the inclusion of international aviation emissions under the Kyoto Protocol – see HMT / DfT, 2003b), with environmental taxes charges viewed (by some) as an interim measure pending international agreement.

6.3.3 Environmental Tax Sensitivity

For the sake of illustration, an environmental tax sensitivity case was modelled, based on the RASCO scenario and Composite (B) valuation profile. It was assumed that the expected value of the weighted average damage would be the basis of an environmental charge to be introduced over the period 2005-2010. The PED assumptions were as per the Gillen *et al* figures quoted by Wit *et al* (see Table 13). Whilst these possibly have a North American bias (as evidenced by a "long-haul domestic" journey category), they were used in place of the -1.0 PED assumed by DfT since ranges amenable to Monte Carlo analysis were quoted. In common with DfT / Halcrow, full cost pass-through and zero supply side response were assumed. The results are shown in Table 14.

Table 13: Assumptions for environmental tax sensitivity

Journey category	**% increase fare based on journeys in Table 12:**		**PED (triangular PDF; based on Gillen *et al*)**		
	Fare	**Destination**	**Low**	**Central**	**High**
Short-haul business	High	Vienna	-0.783	-1.520	-1.268
Short-haul leisure	Average	Vienna	-1.743	-1.520	-1.268
Long-haul business (OECD)	High	Chicago	-0.475	-0.265	-0.198
Long-haul business (LDC)	High	Delhi			
Long-haul business (NIC)	High	Singapore			
Long-haul leisure (OECD)	Average	Chicago	-1.700	-1.040	-0.560
Long-haul leisure (LDC)	Average	Delhi			
Long-haul leisure (NIC)	Average	Singapore			
Misc. (interliners etc.)	Average of above		-1.000		
LCA leisure	Low	Vienna	-1.743	-1.520	-1.268
Domestic	½ (avg+high)	Newcastle	Average of short-haul above		
Freight	N/A	N/A	N/A	N/A	N/A

Notes: The illustrative destinations selected approximate to the weighted average distance modelled for each of the various categories of passenger. In the absence of data, the PED for the miscellaneous category simply reflects the PED assumed by DfT for all traffic. The journey categories are further described in footnote 28.

Table 14: Results of environmental tax sensitivity

Values quoted in £$_{2000}$. Traffic quoted for year 2030.	**No environmental tax**		**Environmental tax**	
Unconstrained demand (mppa)	500.8		EV: 444.5 P5: 433.5 P95: 454.9	
	High capacity	**Low capacity**	**High capacity**	**Low capacity**
Capacity (mppa)	471	260	471	260
Average CO_2 emissions 2000-2030 (mT/yr)	61.0	48.1	54.9	46.3
Wtd avg damage / PAX	£8.7	£8.5	£8.4	£8.3
NPV of damage	£110.5 bn	£76.8 bn	£100.2 bn	£74.7 bn
Damage prevented (NPV)	N/A	N/A	£10.3 bn	£2.6 bn
Net damage from capacity expansion (NPV)	EV: £33.7 bn P5: ≤£3.2 bn P95: ≤£98.0 bn		£25.5 bn P5: ≤£1.8 bn P95: ≤£76.9 bn	

The conclusions to be drawn from Table 14 are as follows:

- The environmental taxes would be expected to have a material impact on demand (a reduction of circa 12% by 2030), although the low capacity case (i.e. no expansion) would still fall far short of meeting demand;
- In the high capacity case, the taxes would result in a reduction in average CO_2 emissions of 10% and a reduction in damage (in NPV terms) of over £10 bn;
- The reductions in emissions and damage in the low capacity case would be much lower, simply because the low case is capacity-constrained anyway. Thus, with a

tax in place, the difference in damage associated with capacity expansion would be approximately £8 bn lower than it would otherwise be;

- The weighted average damage per passenger is shown to fall slightly. However, this likely reflects the somewhat artificial approach to prioritising capacity between different types of journey (see 4.3.1) and is not considered a meaningful result.

Given the use of PEDs which are potentially inappropriate to the UK (and inconsistent with the PEDs underlying the unconstrained passenger demand forecasts used in the model), and given the extremely small number of samples of airfares[90], the environmental tax sensitivity case should be seen merely as an illustration of the potential impact of a tax.

The above analysis focuses only on the impact of internalising environmental costs, in isolation to other fiscal considerations in the aviation sector. For a study examining (via the SPASM model) the impact of removing fiscal privileges afforded to the aviation sector, see Airportwatch (2003).

6.3.4 Structuring Issues

A key issue is of course how economic instruments should be structured. This relates not only to the relative merits of tradable permits *versus* taxes (and, if the latter, whether recycled to the industry or not) but also to the activity which is capped or taxed.

The most obvious way of taxing CO_2 emissions would be to impose a tax on aircraft fuel. Similarly, monitoring of fuel consumption would be a way of monitoring compliance under a CO_2 tradable permits scheme. However, the discussion of radiative forcing in section 5 creates potential problems for economic instruments.

The first problem is that of CO_2 equivalence, i.e. whether a tonne of CO_2 emitted at altitude should be considered as equivalent to 2.7 tonnes of CO_2 or to some other multiple. Clearly, if this number is set at the wrong level, then the socially optimal level of emissions would not, *ceteris paribus*, be reached. Also, in a context where the scientific understanding is advancing relatively rapidly, a structuring consideration is whether the "exchange rate" between terrestrial and celestial sources of CO_2 can be adjusted over time and whether it is equally politically palatable for such an adjustment

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[90] Note that, to conduct this analysis properly, it would be necessary not only to sample fares for a larger number of journeys but also to obtain data on the fares actually paid by passengers (rather than quoted online on one particular day for a given number of weeks in the future).

to be upwards or downwards. It may, for example, be appropriate to use a weighting factor (such as implied by the Thought Experiment sensitivity described in 5.6.5) for non-CO_2 effects until such time as greater scientific certainty is achieved.

The second problem, which has been noted in a number of studies (e.g. Wit *et al*, 2003), is that simply taxing non-CO_2 effects via CO_2 emissions (or aviation fuel, as a proxy) gives industry participants an incentive to reduce CO_2 emissions but does not incentivise them to reduce other climate impacts (e.g. by reducing NO_x emissions). Indeed, since there is a trade-off between NO_x emissions and fuel burn, it may even create perverse incentives, both for airlines and for aircraft manufacturers. Similarly, contrail formation can be reduced or eliminated by changing altitude or route. This reduces radiative forcing even though it involves higher fuel burn (and CO_2 emissions). An instrument aimed solely at CO_2 emissions would not encourage such behaviour.

Clearly, the ability to devise economic instruments which tackle such impacts depends on technology for monitoring emissions and/or their effects (e.g. contrails) as well as on structuring ingenuity. It has been argued that some effects might be better addressed via regulation than economic instruments. Of course, such an approach would not obviate the need for economic analysis, since standards would need to be set at the level at which trade-offs with CO_2 emissions were optimised.

6.3.5 Conclusions re: Economic Instruments

Valuation of damage is an important step, but not the only issue to be confronted, in devising economic instruments. In the case of taxes, estimates of marginal damages (ideally, the marginal damage at the optimum level of emissions) need to be made and the tax related as directly as possible to the end damage being targeted.

The quantum of taxes is a matter for political judgement, informed by economic analysis. Key issues where the policymaker's judgement is needed are the level of confidence desired in relation to the internalisation of costs and the valuation profile to be adopted (informed by the policymaker's world view of adaptation, etc.). Clearly, there will be trade-offs with other political objectives, given that relatively important equity considerations are raised by internalisation of costs (e.g. social implications of the larger impact on leisure travel than on business travel).

Policy towards economic instruments has feedback effects on decisions regarding capacity. At some level of taxation, for example, the need for new capacity will be eliminated[91]. Based on one illustrative scenario here, it is suggested that an environmental tax equal to the expected value of damage would have a material impact on demand but would by no means eliminate the need for new capacity.

The impact of a tax is not entirely predictable, or even necessarily discernible, given the uncertainties as to the PED for air travel and the absence of a single price for a given journey. Further, the impact on demand may be very small[92]. Whether or not this matters is a question of perspective: if the objective is to internalise costs for the sake of economic efficiency or compensation (i.e. an equity version of the "polluter pays principle" – see Wit *et al*, 2003) then this is not a problem. If, however, the objective is to achieve a particular level of emissions (e.g. to ensure that aviation "does its bit" towards the Government's 60% target for CO_2 emission reductions), then a tax may be a less appropriate instrument than, say, a tradable permits scheme[93].

6.4 Wider Issues

6.4.1 Economic Valuation Using Stochastic Methods

This thesis is an exercise in the use of stochastic methods for valuing environmental impacts. In an area which is inherently prone to uncertainty, Monte Carlo analysis offers an attractive approach to quantifying impacts under uncertainty. Specifically, in the context of this thesis, it was used to derive a "menu-driven" trade-off between certainty and valuation which could be used by policymakers (see Figure 11). It was also found that, because of uncertainties in the underlying valuation of CO_2 emissions, point estimates of the damage from aviation emissions systematically understate the expected value. The level of underestimation was found to be material albeit unlikely, in the context of specific policy choices explored here (i.e. capacity expansion), to be the "make-or-break" factor between one option and another.

However, stochastic analysis has its limitations. Whilst it can deal well with parametric uncertainty (i.e. uncertainty as to the precise level of assumptions to be input), and can potentially be used to handle modelling uncertainties[94], it evidently cannot handle the

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[91] Indeed, the thrust of the Airportwatch (2003) document is that removal of fiscal distortions would eliminate the need for new runway capacity to be built.

[92] Supply side responses are not considered here, however.

[93] There is, however, an argument that a tax on aviation's environmental impacts sends a moral signal to consumers, which has an additional effect to the price signal.

[94] For example, if there is uncertainty as to the nature of the relationship between two variables, then the nature of the relationship could itself be used as a random draw in the Monte Carlo analysis. Such an approach was not adopted in the model constructed for this thesis.

"unknown". One of the potential drawbacks of stochastic analysis, then, is that it may be misinterpreted in the policymaking arena and used to exaggerate the level of certainty in relation to a particular finding.

Also, Monte Carlo is arguably a poor tool for evaluating the impact of conceptual issues, which are better taken account of through sensitivities and selection of a preferred approach. An example is the choice of discount rates and equity weighting. Valuations of global warming are sensitive to these assumptions and a PDF constructed with them fully randomised would give a broad range of results (for an example, see Tol, 2003a). In fact, this is an area where Government appears to have made a clear and coherent policy choice in the Green Book, by specifying a discount rate and prescribing the use of equity weighting[95]. This serves to reduce the range of uncertainty somewhat.

Even with discount rates and equity weighting out of the equation, there is substantial uncertainty as to the value of global warming damage. To an extent, this can be captured within Monte Carlo analysis: if high impact / low probability events are captured within a PDF, then policymakers can base decisions on outcomes at different confidence levels. However, the extent to which such impacts are captured within models is debatable, with particular difficulty in valuing impacts such as reductions in biodiversity, contingent social events, etc. Again, there is a risk that, faced with a broad range of values within a PDF, policymakers misinterpret the extent to which such impacts are or are not included in stochastic valuations.

It follows from the above that stochastic valuation methods capture a "snapshot" of particular types of uncertainty at a particular point in time. However, decision-making is a dynamic process. A policymaker needs to consider how progress in scientific and economic research (e.g. impact of cirrus cloudiness, regional valuations of climate change) is likely to affect the results. Policy decisions may therefore differ between situations when policies can be altered (e.g. revising environmental taxes) and when they are fixed (e.g. the difficulty of "unbuilding" an airport). This calls for judgement on the part of the policymaker, supported perhaps by additional analytical tools (e.g. valuation of the "real option" created by deferring a decision on capacity expansion).

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[95] There is a gap in the Green Book, however, in that a method of valuing mortality is not recommended. The method used by DfT (and cited in the Green Book) is unlikely to be generally applicable, since it is intended to cover accidents rather than deaths brought forward.

6.4.2 Research Needs

The main research need identified in this thesis is for the potential gap between the scientific and economic interpretations of aviation's impacts to be plugged. The issue is not so much the gap in scientific understanding (there is a gap, and it is progressively being filled); rather it that the economics and/or policymaking community may have misinterpreted RFI as a concept. It may be that a new metric is required for equating CO_2 and non-CO_2 impacts. Alternatively, it may be found that any such metric is doomed to failure and that a bottom-up approach is required for valuing the damage, impact by impact, taking account (where relevant) of regional as well as global impacts.

A major source of uncertainty is of course the valuation of climate change damage. This is an area of ongoing research, which hardly needs to be prompted by this thesis. Nonetheless, in the context of aviation, this thesis has reinforced the need for research to be conducted at a regional level, rather than mere extrapolation from a particular region of the world (such as the US). For example, one of the main routes where persistent contrails form is across the northern Atlantic Ocean between Europe and North America. To the extent that some climate impacts are relatively concentrated in this area (and their transmission to the wider global climate is of course a scientific question beyond the scope of this paper), the question arises whether such impacts cause any damage which can be measured in economic terms.

As identified in section 1, global warming is just one of the environmental impacts of aviation. If a full CBA is to be conducted of capacity expansion, or if economic instruments are to be aimed at internalising aviation's full environmental cost, then valuation is required of other impacts. A body of literature exists in relation to the valuation of local air pollutants and noise (see, for example, Pearce and Pearce, 2000). However, less work has been performed in relation to other types of impacts presented in section 1. This is an area calling for further research. An issue to be considered is, if environmental damages cannot be reliably generalised from one location to another, then how to structure a framework for economic instruments (or airport charges) which allows such impacts to be tailored to specific local circumstances.

Finally, although not a study of political institutions, a number of institutional issues are potentially ripe for further research. These include:

- The tension between the Green Book and the NATA/GOMMMS methodology. DfT (2003c) suggests that the economic methodology of NATA/GOMMMS is, subject only to minor revisions such as updating discount rates, consistent with the Green Book. However, such a claim has been identified in section 3 to be flawed. Whilst academic debate between MCA and CBA will no doubt persist, the factors allowing apparently contradictory policies to co-exist could be researched;
- The conduct of DfT's analysis and consultation in relation to aviation policy. An interesting issue is the manner in which the analysis and consultation exercises were sequenced. "The Future of Aviation" (DfT, 2000a) launched a consultation exercise on high-level strategy, with a relatively thin underpinning of detailed analysis. Analysis was then split into two separate workstreams, one of which (RASCO) presented national policy frameworks but lacked the analytical tool (SPASM) to bring that analysis to its logical conclusion, and the other of which (SERAS) focused on micro-analysis of options for the south east without adequate regard to the national policy context. A question for institutional research is why the work was conducted in this manner and whether, in particular, the split between RASCO and SERAS was viewed as a successful approach.

6.5 Review of Approach

Preparation of this thesis entailed construction of a relatively detailed model permitting the global warming damage of UK aviation to be valued, using both deterministic and stochastic methods. The results were prepared on a basis which could be compared with certain of the economic benefits claimed for an expansion of airport capacity. In this sense, the project can be judged to have accomplished its objectives.

There are, however, aspects of the work which are not entirely satisfactory:

- First, despite having identified a potential weakness in the use of RFI as a metric for valuing non-CO_2 impacts, it was not possible within the time and resources available to do anything other than follow an RFI-based approach;
- Second, the uncertainties associated with RFI and valuation of climate change are large. It is arguable that, in view of these uncertainties, a spuriously detailed model for the calculation of emissions was constructed. Whilst this was not entirely foreseeable (the relative predictability of emissions is a finding rather than an assumption), it does mean that the trade-off between flexibility and detail in the modelling process may have been sub-optimal;

- Third, the time period selected for evaluation was not ideal. The analysis covers (in common with DfT's analysis) the period to 2060; however, numbers were frozen beyond 2030. With a 3% discount rate (and demand growth outstripping 3%), the contribution towards the total NPV of the years beyond 2030 is by no means negligible (circa 40%, for the CS/hi case). Furthermore, the period beyond 2030 is characterised by substantial uncertainty associated with technology (supersonic travel, hydrogen fuels, etc.), and thus stochastic methods could have been of more benefit if the period analysed had been extended.

If the project were to be repeated, then the following changes would be made to the approach used:

- A smaller number of aircraft types would be used. The use of 26 types added substantially to the data collection exercise and model size yet arguably added relatively little to the analysis[96];
- Greater attention would have been paid to gathering data regarding freight. Whilst freight is a smaller source of emissions than passenger traffic, it is growing more rapidly yet is to some extent ignored in the literature;
- Demand would be modelled endogenously. This would allow greater consistency in the modelling of environmental tax sensitivities;
- Assumptions would not be frozen beyond 2030;
- Other emissions besides CO_2 would be modelled, so as to allow trade-offs between global warming and other environmental impacts to be valued.

Arguably, however, the analysis is not worth repeating or updating until such time as a more satisfactory method of valuing the non-CO_2 emissions is identified.

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[96] By contrast, the small number of journey types handled in the model was manageable and arguably more useful than the "short-haul" versus "long-haul" approach used in some studies.

7. SUMMARY AND CONCLUSIONS

Box 6: Objective One: Quantifying the Net Benefits of Capacity Expansion

- DfT has not prepared an all-embracing CBA for the national policy scenarios identified for aviation. DfT's analysis has therefore not evaluated whether the benefits of the expansion scenarios under consideration exceed the costs.
- It is possible to adapt the CBA performed by DfT to obtain a broad estimate of the (narrowly defined) economic benefits of particular capacity expansion scenarios.
- By modelling CO_2 emissions over a comparable period to that of the CBA, and placing a value on the incremental emissions associated with capacity expansion, the principal environmental cost can be compared with the economic benefits.
- The economic benefits of a high capacity expansion programme (increase of ~215 mppa), were, compared to no expansion, found to be in the order of £58 bn. The comparable figure for a lower expansion programme (~155 mppa) is £32 bn, implying a higher net marginal return for a large increase than a small increase.
- Over the time period modelled, the incremental CO_2 emissions associated with such capacity increases are relatively predictable, since breakthrough technologies are unlikely to make a significant impact on the aircraft fleet. Annual CO_2 emissions were estimated to increase from ~33 mt in 2000 to ~83 mt in 2030 (high capacity) or ~74 mt (low capacity), a CAGR of 3.1% and 2.7% respectively. This compares with 50 mt in 2030 if no capacity expansion takes place (CAGR of 1.4%).
- The Government has proposed a valuation of CO_2 emissions of £70/tC for 2000, rising to £100/tC by 2030. It has also adopted an RFI of 2.7 as an "exchange rate" between CO_2 emissions at altitude and aviation's other climate impacts. Applying these values to the incremental emissions and discounting back to 2000 at 3.0% implies a global warming damage estimate of £33.2 bn for the high capacity case and £26.4 bn for the low capacity case.
- Allowing an illustrative estimate of £2 bn for the NPV of local air pollution and noise, the net result of deducting the environmental damage from the economic benefits is a NPV of ~£23 bn for the high capacity case and ~£4 bn for the low capacity case. In other words, the NPV of a large increase is strongly positive and the NPV of a smaller increase narrowly positive. On a simple comparison, therefore, the case for expansion is not undermined by the environmental costs.

Box 7: Objective Two: Assessment of Uncertainties of Global Warming Damage

- Whilst the uncertainties associated with emissions are relatively modest over the time period considered, the physical impacts and economic damage associated with those emissions are subject to very considerable uncertainty. Accordingly a single point estimate of damage of the type shown in Box 6 is potentially misleading.
- For each step in the calculations uncertainty was assessed and, to the extent possible, expressed as a PDF. Monte Carlo analysis was performed so as to derive a probability distribution for the damage estimates. A number of CO_2 valuations were used representing the range of opinion found in the literature, although this was narrowed by choices made with regard to discount rates and equity weighting.
- The range of results obtained was wide and gave rise to very different outcomes for the NPV of capacity expansion. Under the lowest valuation profile, based on relatively favourable adaptation to the impacts of global warming, damage was found to be small compared to the economic benefits of expansion at all realistic probability levels. Conversely, the high valuation profiles, giving more weight to the potential for major damage, eliminated the benefits of expansion at quite plausible probability levels (e.g. ~70% for the high capacity case).
- The benefits of capacity expansion therefore depend on the world view underpinning CO_2 valuations and the level of confidence required that damage has been fully valued. These are inherently political issues where quantitative methods serve to inform decision-makers rather than give answers.
- The quantitative methods used do not fully capture uncertainty. A key example of this was the use of the RFI metric which, although randomised, raises conceptual (and unresolved) issues for economic valuation methods.
- Faced with these uncertainties, decision-makers need to exercise judgement in a dynamic context. For example, an appropriate decision on capacity expansion might not be an immediate decision to build a specific level of capacity but perhaps a phased approach either to decision-making or to the construction works.
- The same uncertainties apply in designing an environmental tax, and again the trade-off between certainty and tax levels is a political decision. Additional uncertainties arise in relation to the market response to a tax, with the possibility that mere internalisation of external costs gives rise to a relatively modest reduction in demand (illustratively modelled as 12%). Whether this matters depends on whether the objective is internalisation alone or the attainment of specific targets.

Box 8: Wider Implications

For policymakers

- The current range of GHG valuations remain broad enough for global warming to have a major or minor impact on the net benefits of industries such as aviation. The results can be narrowed somewhat via clarity, on the part of policymakers, with regard to discount rates, equity weighting, the weighting placed on adaptation and catastrophe, and the confidence level required for the results being evaluated.
- Within Government, the MCA approach of DfT sits uncomfortably alongside the CBA approach of HMT. Both can be undertaken in parallel; however, the narrow economic analysis produced by DfT does not meet HMT guidance on CBA.

For stochastic methods in economic valuation

- Where valuations are characterised by asymmetric distributions, then the discrepancy between the results of deterministic and stochastic analyses may be material to the policy decision. Even when this is not the case, stochastic methods impart information significantly more useful to evidence-based policymaking.
- However, stochastic analysis does not necessarily capture the full range of uncertainty, particularly when the nature of the relationship between variables is uncertain. Policymakers need to be informed as to the nature of such uncertainties.

For further research

- The applicability of the RFI for economic valuation needs to be reviewed if reliance is to be placed upon valuations of aviation damage dependent upon that metric.
- Progress in understanding the regional nature of aviation's climate impacts and in valuing climate impacts on a regionally disaggregated basis are needed.
- The wider economic benefits associated with marginal changes in the level of airport capacity need to be quantified.
- Valuation of the site-specific impacts of airport development, and a method for aggregating such impacts into national policy scenarios and a framework for economic instruments, would benefit from research.
- Institutional research into the structuring of the airport studies, including the separation of, and different emphases in, the SERAS and RASCO studies.
- Generally, a greater focus on valuing the impacts of air freight, which is under-researched compared to passenger travel yet a rapidly growing component of the aviation market.

Section 7: Summary and Conclusions

APPENDIX I: REFERENCES

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Appendix I: References

APPENDIX II: GLOSSARY OF ABBREVIATIONS

APPENDIX II: GLOSSARY

λ:	A constant relating changes in radiative forcing to changes in global mean surface temperature (see Box 5).
AMT:	Aircraft mile travelled.
APD:	Air Passenger Duty.
APU:	Auxiliary power unit.
AST:	Appraisal summary table.
ATM:	Air transport movement.
BA:	British Airways plc.
BCR:	Benefit/Cost Ratio, i.e. NPV divided by the present value of investment costs.
Bellyhold:	Air freight which is transported within the hold of passenger aircraft (rather than dedicated freighter aircraft).
CAGR:	Compound annual growth rate.
CBA:	Cost benefit analysis.
CEE:	Central and Eastern Europe.
CfIT:	Commission for Integrated Transport.
CH_4:	Methane.
CNS/ATM:	Communications, navigation and surveillance/air traffic management systems.
CO:	Carbon monoxide.
CO2:	Carbon dioxide.
CS:	Calibration Scenario (see 4.3).
CV:	Coefficient of variation, the standard deviation expressed as a fraction of the mean.
dB Leq:	Decibels (equivalent continuous noise).
DETR:	Department of Environment, Transport and the Regions.
DfT:	Department for Transport and (as the context requires) its predecessors, namely DoT, DETR and DTLR.

DoT:	Department of Transport.
DTLR:	Department for Transport, Local Government and the Regions.
EV:	Expected value, i.e. the arithmetic mean of the Monte Carlo simulation results.
FSU:	Former Soviet Union.
FTM:	Freight tonne-mile.
g/PMT:	Grams of CO_2 per passenger-mile travelled.
GHGs:	Greenhouse gases – principally CO_2, CH_4, NO_x and H_20.
GOMMMS:	Guidance on Multi-Modal Methodological Studies (as described in DfT, 2000f).
GWP:	Global warming potential, as described in Box 5.
H_20:	Water.
Hi:	A high capacity case.
HMT:	HM Treasury.
ICAO:	International Civil Aviation Organisation.
IPCC:	Intergovernmental Panel on Climate Change.
IFR:	Instrumental flight rules.
LCA:	Low cost airline.
LDC:	Less developed country.
Lo:	A low capacity case.
LTO:	Landing and take-off.
MCA:	Multi-criteria analysis.
MPB:	Marginal private benefit.
MPC:	Marginal private cost.
Mppa:	Million passengers per annum.
MSB:	Marginal social benefit.
MSC:	Marginal social cost.

Appendix II: Glossary

MtC:	Million tonnes of carbon (equivalent, in carbon content, to 3.67 million tonnes of CO_2).
N_20:	Nitrous oxide.
NATA:	New Approach to Appraisal (as described in DfT, 1998 b-c).
n/d:	Not disclosed.
NIC:	Newly industrialised country.
NO_x:	Oxides of nitrogen.
NPV:	Net Present Value of the future costs and benefits of a project, programme or policy.
O_3:	Ozone.
OEF:	Oxford Economic Forecasting.
PAX:	Passengers.
PDF:	Probability density function.
PED:	Price elasticity of demand.
PLF:	Passenger load factor, i.e. the percentage of passenger seats utilised on an ATM.
PM_{10}:	Particulate matter with a diameter of 10 microns and below.
PMT:	Passenger mile(s) travelled.
PRTP:	Pure rate of time preference (see 5.6.3).
RASCO:	Regional Air Services Co-ordination Study.
RCS:	Revised Calibration Scenario (see 4.3).
RF:	Radiative forcing, as described in Box 5.
RFI:	Radiative forcing index, as described in Box 5.
RRC:	RASCO Reference Case (see Table 3).).
RS:	RASCO Scenario (see 4.3).
SERAS:	South East and East of England Regional Air Service Study.
SIMTOOLS:	An add-in for Excel which can be used to generate probability functions not otherwise available within Excel. .

SMT:	Seat mile(s) travelled.
SO_2:	Sulphur dioxide.
SRTP:	Social rate of time preference (see 5.6.3).
/tc	Per tonne carbon.
TF:	Turbofan.
Thought Experiment Sensitivity:	A sensitivity test in which the non-CO_2 climate impacts of aviation are weighted
TP:	Turboprop.
TS:	Technology Scenario (see footnote 51).
UKC:	UK Constrained case (see Table 3).
VAT:	Value added tax.
VLYL:	Value of life years lost.
VSL:	Value of a statistical life.
VOCs:	Volatile organic compounds.
W/m^2:	Watts per square metre.
White Paper:	The Air Transport White Paper, due to be published in late 2003.

APPENDIX III: SUPPLEMENT TO SECTION 3

APPENDIX III: SUPPLEMENT TO SECTION 3

Calculation of Capacity Scenario NPVs (see 3.4.3)

High Capacity Scenario

The NPV of the high capacity scenario (relative to the very low capacity scenario) is calculated from the following three elements:

- The NPV of Package 18 (versus Package 1), as shown in Table 4 on page 27;
- An adjustment to the above figure, reflecting the fact that Package 1 assumes no capacity constraints in the regions and is therefore based on a higher level of traffic in the south east than the UKC (*circa* 175 mppa *versus* 144 mppa);
- An estimate of the NPV of the regional demand liberated by regional capacity expansion projects.

The adjustment to the Package 18 NPV can be approximated simply by applying the NPV per additional unit of capacity quoted in Table 4 (£116 and £325, the equivalent figure for a 3.5% discount rate) to the difference in the levels of south east traffic assumed in SERAS Package 1 and RASCO UKC (i.e. 31 mppa). This gives an additional NPV of £3.6 billion (6% discount rate) or £10.1 billion (3.5%).

Clearly, in the absence of a CBA for the regional projects excluded from Table 5, it is impossible to accurately estimate the net economic impact of the regional expansion projects implicit in the RASCO policy scenarios. However, since the three major projects shown in Table 5 account for approximately 60% of the difference in regional demand (in 2030) between the UKC and the RRC, a very broad estimate can be made by grossing up the NPVs shown. This would suggest an NPV of circa £3.1 billion for the regions as a whole (RRC *versus* UKC, 6% discount rate) or circa £10.2 billion (3.5% discount rate). If the view is taken that smaller, incremental investments are likely to have a higher economic return than the three major projects identified above, then an upper limit can perhaps be identified from the NPV per additional capacity for the equivalent SERAS case (i.e. £116 or £325 per passenger, the figures used in the first adjustment). This would set an upper bound for the regions as a whole of £5.7 billion (6%) or £17 billion (3.5%). For purposes of this thesis, a mid-range figure of £4.4 billion (6%) or £13.6 billion (3.5%) is adopted.

The resulting NPVs are shown in Table 15 below.

Table 15: NPV of high capacity scenario

	NPV @ 6.0%	**NPV @ 3.5%**
NPV from Table 4	£18.3 bn	£51.4 bn
Adjustment	£3.6 bn	£10.1 bn
Regional expansion	£4.4 bn	£13.6 bn
TOTAL	**£26.3 bn**	**£75.1 bn**

Low Capacity Scenario

A similar approach can be used to estimate the NPV of the low capacity scenario, the only differences being that:

- The NPV of Package 2 (versus Package 1) is used, as shown in Table 4 on page 27, in place of the NPV of Package 18;
- The value attributed to regional expansion is calculated as a proportion (representing incremental regional demand in the low capacity case, divided by incremental regional demand in the high capacity case) of the value attributed to regional expansion in the high capacity case.

The resulting NPVs are shown in Table 16 below.

Table 16: NPV of low capacity scenario

	NPV @ 6.0%	**NPV @ 3.5%**
NPV from Table 4	£5.0 bn	£14.7 bn
Adjustment	£3.6 bn	£10.1 bn
Regional expansion	£5.2 bn	£16.0 bn
TOTAL	**£13.8 bn**	**£40.8 bn**

Note that the NPV of regional expansion is higher than shown for the high capacity case. The reason for this is that, because of the strength of demand in the south east and the relative severity of capacity constraints in the south east, regional traffic forecasts are actually higher in the low capacity case than in the high capacity case, as a result of diversion of suppressed traffic from the south east.

APPENDIX IV: SUPPLEMENT TO SECTION 4

APPENDIX IV: SUPPLEMENT TO SECTION 4

International and Domestic Passenger Traffic (see 4.2.1 and 4.3.1)

The counting and allocation of passenger numbers is subject to a number of complicating factors. The first is that some types of passengers are counted more than once, because they pass through a UK airport more than one time for a single journey. Second, specific types of passenger are allocated differently by DfT's unconstrained forecasts and the SPASM model. This calls for a number of adjustments to be made to data, as described in the following paragraphs.

Domestic passengers travelling between UK mainland airports are counted at each end of their journey in the DfT and SPASM figures. In principle, it is necessary to divide domestic travellers by two in order to obtain the number of domestic passenger flights. However, a correction also needs to be made for travellers to/from the Channel Islands (who are only counted once) and, as described below, for "domestic interliners" (i.e. passengers making a domestic flight to connect to an international flight), who are counted three times.

Domestic interliners are treated differently in the DfT unconstrained demand figures and the SPASM model. It is understood that, in the DfT model, they are counted as domestic passengers but not as international passengers. In the SPASM model, they are counted as international passengers. For purposes of calculating passenger flights, it is necessary to consider both flights. Accordingly:

- The number of domestic interliners was estimated for the years 2000 and 2030. For 2000, this was done simply by interpolating DfT estimates of domestic passengers between 1998 and 2005 to obtain an estimate of total domestic passengers, and then subtracting the number of domestic passengers given by SPASM. This resulted in end-to-end domestic passengers of 27.2 m and domestic interliners of 8.6 m in 2000.
- For 2030, since the SPASM high capacity case traffic is very close to unconstrained demand levels, unconstrained interliner demand was estimated by grossing up the SPASM figures to the DfT unconstrained figures, and deducting the grossed-up SPASM domestic passengers from the DfT unconstrained domestic passengers.

This resulted in end-to-end domestic passengers of 55.2 m and domestic interliners of 29.9 m for 2030[97].

- The next step was therefore to re-allocate one third of the interliner passenger numbers (reflecting the airport passenger numbers associated with the international leg of the journey) from domestic to international journeys to obtain a revised allocation of unconstrained demand between international and domestic travel;
- For all of the constrained scenarios, domestic end-to-end passengers were estimated either from SPASM figures quoted in HMT / DfT, 2003a or from the propensity to fly calculations presented in Annex B of DfT, 2002a. The simplifying assumption was made that, since domestic interlining is essentially a derived demand for international journeys, domestic interlining would be a constant proportion of total international journeys under all constrained cases. It was thereby possible, by adding the estimates of domestic interlining and end-to-end domestic travel, to obtain the proportion of total journeys to be allocated to domestic travel, for the year 2030, under each of the constrained cases.

In fact, even with the above adjustments, a number of questions remain as to the derivation of flight passenger numbers from airport passenger numbers. In particular, it has been assumed in this study that the passenger numbers associated with international-to-international interliners (i.e. travellers between foreign countries who merely make a connecting flight in the UK) are the same as the number of flights made by such passengers. (In fact, such passengers are more important, in terms of absolute numbers, than domestic interliners.)

A slight inaccuracy, for which no adjustment has been made, arises from the fact that all passengers on LCAs have been allocated in DfT's forecasts to international demand, even though there are some LCAs operating domestic flights. Since it is assumed in the model that all LCA journeys are short-haul, the overall impact on fuel consumption and emissions is believed to be minor.

Allocation of Aircraft to Passenger Journeys (see 4.5.1)

As described in Section 4, allocation of aircraft to passenger journeys was an iterative process, aimed at satisfying multiple criteria simultaneously, namely that: the results (in

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[97] The resulting CAGR of unconstrained domestic interliner passenger demand is 4.2% p.a. Since this figure is between that of domestic demand growth (ex-interliner) and international passenger growth from the regions, it is considered reasonable.

terms of number of ATMs) should be comparable to those of Halcrow; the implied passenger fleet should be plausible compared to future fleet forecasts; and aircraft should serve plausible distances (as measured by average miles per journey). The model provides for a two-stage framework for (manually) seeking the optimum combination: first, the allocation of aircraft "bands" to journeys; and second, the composition of aircraft in that band.

Unsurprisingly, trade-offs were required between the above objectives. The following process was therefore employed:

- Within the Revised Calibration Scenario, a mix of (up to three) aircraft bands was assigned, using personal judgement, to each journey category, for the years 1998 and 2030[98] (separately, in the case of 2030, for the high case and low case). The proportions were varied until the implied aircraft fleet mix broadly corresponded (in terms of proportion of the total fleet within each band) to third party forecasts (a compromise between Airbus 2002, Boeing 2003b and Rolls Royce 2001). For most journey categories, relatively larger proportions of the higher aircraft bands were assumed for 2030 than for 1998 (reflecting industry forecasts of increasing average aircraft size); likewise for the low case relative to the high case (see footnote 46 on page 42).
- The mix of aircraft within each band broadly corresponded with the mix assumed by Halcrow (as set out in HMT / DfT, 2003a, page 28), subject to some differences in aircraft types assumed and the introduction of new aircraft types in each band (see 4.5). In the case of Band 1, where substantially different aircraft types were assumed compared to Halcrow's analysis, Rolls Royce's forecast (Rolls Royce, 2001) was used as a guide.
- In general, a somewhat lower rate of penetration of new aircraft types was assumed in the low capacity case than in the high capacity case, reflecting the assumption that less rapid fleet expansion would lead to less rapid penetration of new aircraft types. However, in the low capacity case, the penetration of Band 6 aircraft was slightly accelerated under the low case, reflecting the assumption that larger aircraft would be procured as a matter of priority if runway capacity were scarce.
- Average distances per aircraft type were compared with current data, as a check on reasonableness. In one particular case, the model was adjusted to avoid Boeing 757 serving alongside other Band 3 aircraft on journeys in the 2,001-5,000 miles

category. However, the average distance criterion was a relatively imprecise check, not least because the model does not cater for refuelling stops (which keep the average stage distance of very long-haul flights lower than implied by an analysis based on eventual destinations).

- The model incorporates a method for shifting the overall mix of aircraft bands allocated to journeys. For example, in the RASCO Scenario low case, it was assumed that, for all journey categories, the proportion of journeys served by the smallest applicable aircraft band would be reduced by 3% and that of the largest applicable aircraft band increased by 3%. This mechanism, although crude, avoids the need to fine-tune the aircraft fleet for each scenario separately (and is also used in the Monte Carlo simulation).
- For purposes of the Calibration Scenario, the above mechanism was used to settle on an aircraft allocation profile which generates (for the years 2000 and 2030) a number of ATMs which is close to the aggregate number of ATMs produced by Halcrow's model. It was found that, compared to the Revised Calibration Scenario, a higher proportion of the lower seat bands was needed for 1998 and 2030 (low case) but a lower proportion for 2030 (high case). See footnote 46 on page 42 for a comparison of the approaches taken by Halcrow and this study towards aircraft allocation in the low and high cases.

New Aircraft Technology (see 4.7.2)

The impact of new technology on the fuel consumption of new aircraft types is based on a report by Arthur D. Little (2000). In the case of the Technology Scenario, the only adjustment made to Arthur D. Little's forecast was to use multiplication to derive the total impact of individual fuel reduction measures rather than addition[99]. In the other scenarios, only specific technologies which are given medium or high take-up potential by Arthur D. Little are included.

The cumulative reductions in fuel burn (relative to comparator aircraft types included in the model) resulting from the above approach are tabulated below[100].

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[98] The model automatically interpolates aircraft allocation for the years between 1998 and 2030.

[99] The potential over-optimism of the latter approach is acknowledged by Arthur D. Little.

[100] Note that, unlike other assumptions within the Technology Scenario, the range quoted here for the Technology Scenario is not entirely subsumed within the range quoted for RCS. In other words, whereas other assumptions in the Technology Scenario reflect a particular point on the PDF assigned to the RCS (approximately the 100th percentile), and are not subjected to further randomisation, the PDF assigned to fuel burn of new aircraft types is distinct from the PDF applicable to the assumptions used in the RCS and is subjected to randomisation within the Monte Carlo analysis.

Table 17: Fuel Reductions – Technology Scenario

	2015	2030
Engine	15 – 20%	20 – 30%
Airframe	10 – 20%	30 – 40%
Total	**24 – 36%**	**44 – 58%**
Modelled as	**30% (±6%, uniform)**	**51%(±7%, uniform)**

Table 18: Fuel Reductions –Other Scenarios

	2015	2030
Staged combustor[101]	-0.3%	-0.6%
Airframe	10 - 20%	15 – 30%
Electricity generation	0 – 5%	5 – 10%
Materials	0 – 5%	5 – 10%
Gearing	0 – 5%	5 – 15%
Total	**10 – 31%**	**27 – 52%**
Modelled as	**20% (±10%, uniform)**	**40% (±12%, uniform)**

The reductions in fuel consumption are applied, for new aircraft types, to comparator aircraft types (as tabulated below) in the relevant band. It is assumed that the reductions are calculated per seat-mile. For example, the new Band 3 aircraft type is assumed to have 225 seats, whereas its comparator (Boeing 757-200) only has 200 seats. The fuel consumption of the new Band 3 aircraft is therefore not only multiplied by one minus the calculated level of technology efficiency saving, but also by 225/200.

Table 19: Comparator aircraft types

Aircraft Band	Comparator type
Band 1 – Turboprop	ATR-72
Band 1 – Turbofan	CRJ-700
Band 2	Airbus A320
Band 3	Boeing 757-200
Band 4	Airbus A340
Band 5	Boeing 747-400
Band 6	Airbus A380

Allocation of Fuel between Passengers and Bellyhold Freight (see 4.7.4)

Since the CORINAIR databank does not provide data regarding the increment in fuel consumption associated with alternative payloads, an alternative data source was required in order to calculate the allocation of fuel consumption between passengers and bellyhold freight.

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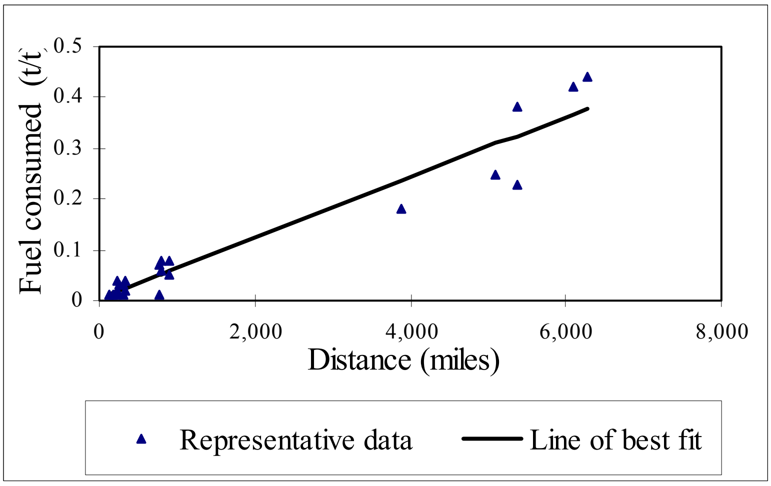
[101] Staged combustors are aimed at reducing NO_x emissions but have a detrimental impact on fuel consumption.

Luftfartsverket (2003) provides fuel burn data for a variety of aircraft journeys (by route and by aircraft type), with alternative passenger load factors of 65% and 90%. By making the assumption (per Dings *et al*, Annex V) that the extra payload associated with a single passenger is 100 kgs, it was possible to derive the marginal fuel burn associated with a marginal tonne of freight on a variety of journey and aircraft types. 26 representative journeys, spanning a range of distances and aircraft types, were selected from the Luftfartsverket sample, and regression analysis was performed to derive an average fuel burn per tonne-mile of 59.6 grams ($R^2 = 0.93$) (see Figure 13 below). This figure was then used for purposes of allocating a proportion of modelled total fuel burn to bellyhold freight[102].

Figure 13: Fuel burn per tonne of bellyhold freight versus distance



Surface Transport Emissions (see 4.8)

Assumptions for surface transport emissions were input into the model, expressed in kilograms of CO_2 per passenger and per tonne of freight. These were derived from HMT / DfT, 2003a (in turn based upon Halcrow, 2002d). However, except for the Calibration Scenario, adjustments were made in order to:

- Compensate for the fact that Halcrow may underestimate the proportion of surface transport journeys (for passengers) which are made by public transport;
- Include emissions from those surface transport journeys which are not made by private vehicle;
- Take account of emission levels likely to apply to the relevant mode of transport during the period considered (and not just 2030).

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[102] In principle, this method could be used to adjust overall aircraft fuel consumption with respect to PLF (see 4.7.1). However, since a number of apparent anomalies were noted in the Luftfartsverket databank, this approach was not considered sufficiently reliable.

A simplified methodology was used, reflecting the relatively minor contribution of surface transport to overall CO_2 emission levels. In particular, the fact that not all passenger journeys generate exactly one surface transport trip (for the reasons described earlier in this Appendix) was ignored. The method adopted was as follows:-

- Based upon Halcrow's forecast of passenger numbers in 2000 and 2030 and its assumptions regarding the proportion of trips made by car (90%) and the number of passenger occupants per vehicle (1.1), the numbers of vehicle trips assumed by Halcrow in respect of passenger traffic for the years 2000 and 2030 (high case and low case) were estimated;
- Based upon the estimate, for the Calibration Scenario, of the number of tonnes of airfreight and the assumption that the average surface transport load of airfreight is 100 kilograms per vehicle[103], the numbers of vehicle trips assumed by Halcrow in respect of airfreight (again, for the years 2000 and 2030) were estimated;
- Based upon Halcrow's stated assumption as to vehicle CO_2 emissions (147 g/km) and the total surface transport emissions quoted, the number of vehicle kilometres calculated by Halcrow was derived. By assuming that the average distance driven by passenger vehicles and freight vehicles is the same, it was possible to estimate the average distance of surface transport trips. As stated in 4.8, this was higher for the 2030 low case (47 kms) than for the high case (44 kms), although both cases were lower than for the year 2000 (50 kms). These distances were used for all scenarios (interpolated for intervening years), except that in the RASCO Scenario low case (the lowest capacity of all scenarios), it was assumed that the average distance remains as per the year 2000;
- It was assumed that, for the year 2000, the proportion of passengers travelling to/from the airport was 72% (based upon CfIT, 2001). It was assumed that vehicle CO_2 emissions in 2000 were 176.5 g/km (in common with CfIT), declining gradually to the 2030 level of 147 g/km assumed by Halcrow[104]. Thus, surface transport emissions per passenger were calculated for each year. Emissions for freight were calculated in the same way (assuming that 100% of freight is

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[103] The assumption of 100 kilograms per vehicle was chosen arbitrarily (although Halcrow is explicit that the majority of airfreight is transported by light goods vehicle); however, this will only have a distorting influence on the overall figure to the extent that the relative proportions of freight assumed by Halcrow and this study are significantly out of alignment.

[104] There is a case for assuming a higher level of vehicle fuel consumption reductions in the Technology Scenario than in the other scenarios, on the basis that this is intended to reflect a scenario of rapid technological progress. However, this approach was not adopted.

transported to/from the airport by light goods vehicle, and again using the assumption of 100 kgs of freight per vehicle);

- It was assumed (based upon CfIT, 2001) that rail and bus journeys accounted for 17% and 11% of surface transport journeys in 2000, rising to 20% and 15% respectively by 2030 (personal judgement[105]). It was assumed that these journeys would be of the same distance as passenger vehicle journeys, but that (for rail journeys only) a 15 km drive to the railway station is required. CO_2 emission factors for trains and buses were derived from CfIT's analysis; however, it was assumed that, over the period to 2030, fuel consumption reductions would be achieved *pro rata* to the reduction assumed for cars. CO_2 emissions per passengers travelling by rail and bus were calculated accordingly;
- The emissions of CO_2 per airport passenger were then calculated, as the weighted average of passengers travelling by private vehicle, train and bus.

The above approach entails a number of *ad hoc* assumptions, and the estimates must therefore be considered relatively uncertain. For purposes of Monte Carlo simulation, it was assumed that the estimates would be subject to a triangular distribution, with the low and high estimates equal to 50% and 150% of the central estimate.

In common with Halcrow's approach, 100% of CO_2 emissions from surface transport are allocated to the UK, whether in respect of international or domestic journeys. (Of course, no allowance is made for surface transport emissions at the other end of the journey, for international passengers, so this allocation is considered appropriate.)

Comparison of Model with DfT/Halcrow Results (see 4.9.1)

Table 20 below compares results produced by the Calibration Scenario with results published by DfT/Halcrow.

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[105] There is a case for assuming a higher proportion of public transport in the RASCO Scenario low case, on the basis that this implicitly reflects an aggressively pro-environmental policy arena. However, this approach was not adopted.

Table 20: Calibration Scenario *versus* DfT / Halcrow results

			1998			2000			2030	
		(A)	(B)		(A)	(B)		(A)	(B)	
	Units	**DfT**	**Model**	**(B)/(A)**	**DfT**	**Model**	**(B)/(A)**	**DfT**	**Model**	**(B)/(A)**
High capacity case:										
Passengers	mppa		159		179.3	176	98.0%	480.9	480.9	100.0%
Passenger ATMs	PATMs		1.58E+06		1757000	1.72E+06	97.8%	3630000	3.67E+06	101.0%
Bellyhold freight carried	kT	1,455	1,390	95.5%		1,600		4,221	4,378	103.7%
Freighter freight carried	kT	622	655	105.3%		857		7,572	7,492	98.9%
Freighter ATMs	FATMs	97,738	24,819	25.4%	118,454	32,447	27.4%	314,091	292,153	93.0%
Int'l passenger aircraft CO_2	tonnes		2.13E+07		2.33E+07	2.37E+07	101.6%	6.78E+07	6.74E+07	99.4%
Dom passenger aircraft CO_2	tonnes		1.05E+06		1.38E+06	1.12E+06	80.8%	1.98E+06	2.35E+06	118.7%
Int'l freighter aircraft CO_2	tonnes		1.18E+06		1.34E+06	1.55E+06	115.4%	6.40E+06	1.30E+07	202.8%
Dom freighter aircraft CO_2	tonnes		9.06E+03		8.00E+04	1.17E+04	14.6%	3.53E+05	9.97E+04	28.3%
Surface traffic CO_2	tonnes				1.26E+06	1.24E+06	98.0%	3.27E+06	3.32E+06	101.5%
Low capacity case:										
Passengers	mppa		159		179.3	176	98.0%	414.8	414.8	100.0%
Passenger ATMs	PATMs		1.58E+06		1757000	1.73E+06	98.5%	3557000	3.48E+06	97.7%
Bellyhold freight carried	kT	1,455	1,390	95.5%		1,597		3,491	3,480	99.7%
Freighter freight carried	kT	653	655	100.2%		858		7,911	7,646	96.6%
Freighter ATMs	FATMs	107,721	24,819	23.0%	118,454	32,408	27.4%	270,588	270,000	99.8%
Int'l passenger aircraft CO_2	tonnes		2.13E+07		23300000	2.37E+07	101.6%	5.85E+07	5.90E+07	100.9%
Dom passenger aircraft CO_2	tonnes		1.05E+06		1380000	1.11E+06	80.7%	1.65E+06	2.07E+06	126.0%
Int'l freighter aircraft CO_2	tonnes		1.18E+06		1340000	1.55E+06	115.5%	6.54E+06	1.34E+07	205.7%
Dom freighter aircraft CO_2	tonnes		9.06E+03		80000	1.17E+04	14.6%	3.52E+05	8.86E+04	25.2%
Surface traffic CO_2	tonnes				1.26E+06	1.24E+06	98.0%	3.17E+06	3.14E+06	98.9%

The following points should be noted in connection with the figures presented in the above table:

- The DfT/Halcrow figures are drawn from a number of sources and, in certain cases, may not be fully consistent with each other;
- The DfT/Halcrow figures shown for 2015 involve approximation, based on incomplete figures available from DfT data;
- DfT/Halcrow bellyhold demand for 2030 (high case) is based on unconstrained bellyhold demand (per Halcrow 2002f), adjusted for the imposition of passenger traffic constraints. Likewise freight carried aboard freighter aircraft.

The two principal differences between the two sets of results relate to domestic passenger aircraft emissions and freighter aircraft figures (number of ATMs in 1998 and 2000; emissions per ATM throughout).

The discrepancy for domestic passenger emissions is not fully understood. It may reflect a number of factors, such as differences in the methodology for allocating domestic interliners (see further above), differences in domestic journey distances[106], differences in aircraft bands assigned to short-haul journeys and/or the discrepancy

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[106] Halcrow's model is understood to impose a minimum domestic journey distance of 200 nautical miles, whereas the model used in this study makes no such assumption but applies an uplift to Great Circle distances, as explained in 4.6.2.

between Halcrow's fuel burn data and the data used in this thesis (which is more marked for short-haul journeys than for long-haul journeys). It should be noted that, since domestic passenger emissions are very low in comparison with international passenger emissions, the overall significance of the discrepancy is minor.

The reasons for the discrepancies in freighter figures are not clear. The adjustments to be made to the assumptions in order to bring the two sets of results into alignment (e.g. freighter load factors, freighter fleet composition, allocation of freight between journey distances) would be very large and, given the uncertainties inherent in Halcrow's own methodology towards freight traffic[107], not necessarily justified. One possible explanation for the discrepancy is that the journey origins/destinations on which this study is based are the country of origin/destination of the import/export in question. It is possible, either because of trans-shipment of UK freight at European airports or because of *en route* stops (which could perhaps be more prevalent for freight traffic than for passenger traffic because it is predominantly long-haul and, perhaps, less time-sensitive) that air freight is recorded in Halcrow's data as making shorter (first stage) trips aboard smaller aircraft than is assumed in the model. This would lead to a higher number of ATMs (as per 1998 and 2000) and lower CO_2 emissions per ATM than shown by the model.

If the above explanation were correct, then it would not necessarily be appropriate to revise the model. Arguably, the CO_2 emissions associated with the journey to/from the origin/destination of the import/export in question are a more legitimate measure of the environmental burden of UK air freight than emissions associated with an intermediate location. Also, it is in any case likely that the average distance travelled by freight in the future will increase (reflecting the relatively rapid economic growth of NICs and other long-haul locations) and that, as the air freight market matures, more direct flights will be undertaken. For these reasons, the results of the Calibration Scenario were allowed to stand, without further variation of the underlying assumptions in order to bring them into alignment with Halcrow figures.

Other explanations for the discrepancy cannot be ruled out, however. For example, if take-off weights are significantly lower for freight aircraft than for passenger aircraft

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[107] According to Halcrow (2002d, page 107), DfT's freight forecasting model does not provide the origin and destination of freight movements. Halcrow's approach was therefore to base the future pattern of freighter ATMs on ATMs from specific airports. It is possible that freight from these airports is not representative of UK air freight as a whole.

(reflecting relatively low load factors), then this would make a material difference to fuel consumption in a model which differentiates fuel consumption according to payload (as per Halcrow's model – see 4.7.1).

Whilst the discrepancy between CO_2 emissions from domestic air freight is large in percentage terms, the absolute amounts involved are very small and make little difference to the overall analysis.

Sensitivity Analysis (see 4.9.2)

Table 21 and Table 22 below present analysis of sensitivities performed on key assumptions (for the RCS high and low cases only). The assumptions used in the sensitivities represent the 10th and 90th percentiles from the PDF assigned to the underlying assumption. The approach of using a common percentile across the sensitivities relates the magnitude of the impact of the sensitivity to the level of uncertainty of the assumption in question and can potentially be used as a tool for prioritising further research (see 2.7).

A small number of the sensitivities are only meaningful when varied in combination with other assumptions and, in such cases, an appropriate combination has been selected (with the 10th and 90th percentile of each individual assumption utilised[108]). Otherwise, combination cases are not shown, since this is more appropriately explored via Monte Carlo analysis. Where assumptions are stated for particular years, intermediate year assumptions are derived in the model via interpolation and/or extrapolation. Note that the 10th and 90th percentiles are based on the numbers input into the model; neither percentile denotes that the sensitivity in question automatically represents an "upside" or a "downside".

The results are presented in terms of CO_2 emissions in the years 2015 and 2030. The general conclusions of 4.9.2 are confirmed by the sensitivities, i.e. that the major influence on emissions is demand growth (to the extent accommodated within available capacity).

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[108] It is recognised that utilising the 10th and 90th percentiles across more than one variable means that the overall probability is somewhat closer to the extreme end of either range than implied by the percentiles.

Table 21: Sensitivity analysis: RCS high case

	Assumptions			Results (mt CO_2)			
Assumption (as input to the model)	**10th %'ile**	**Base Case**	**90th %'ile**	**10th %'ile – 2015**	**90th %'ile – 2015**	**10th %'ile – 2030**	**90th %'ile – 2030**
Base Case	**-**	**-**	**-**	**63.7**	**63.7**	**83.0**	**83.0**
Demand & capacity							
Unconstrained passenger demand (Δ by 2020 relative to Base Case)	x0.90	x1.00	x1.10	59.2	68.0	74.3	91.9
Passenger capacity (mppa)	461	481	500	63.7	63.7	81.8	84.3
Passenger demand & capacity	A above	As above	As above	59.2	68.0	74.3	92.0
Unconstrained freight demand (Δ by 2020 relative to Base Case)	x0.90	x1.00	x1.10	63.1	64.2	81.4	85.1
Freighter capacity (ATMs)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Freight demand & freighter capacity	N/A	N/A	N/A	63.1	64.2	81.4	85.1
Load factors							
Passenger aircraft occupancy and Δ spare seats 2030 vs. 1998	x0.99 -14.6%	x1.00 -15.0%	x1.01 -15.4%	64.4	63.0	83.9	82.2
Bellyhold freight utilisation (1998 & 2030, relative to Base Case)	x0.97 x0.94	x1.0 x1.0	x1.03 x1.05	63.7	63.6	83.2	83.0
Freighter aircraft occupancy and Δ spare capacity 2030 vs. 1998	x0.97 -18.9%	x1.0 -20%	x1.03 -21.2%	63.8	63.5	83.3	82.8
Allocation of aircraft							
Share of smaller aircraft bands in journeys (1998 & 2030)	-2.7% -5.4%	+0.0% +0.0%	+2.8% +5.4%	63.7	63.7	82.8	83.2
Retirement of old aircraft types (years)	-4	0	+4	63.7	63.7	83.0	83.0
Introduction of new aircraft types (years)	-4	0	+4	63.1	63.7	82.5	84.2
Rate of uptake of new aircraft types	x0.87	x1.0	x1.14	63.7	63.7	84.0	82.0
Fuel burn & technology							
Aircraft fuel burn (LTO and cruise)	x0.97	x1.00	x1.03	61.8	65.7	80.5	85.6
Fuel consumption of new A/C types relative to 2000 (2015 & 2030)	-12% -31%	-20% -40%	-28% -50%	63.7	63.7	84.7	81.4
Operations & technology							
Size of uplift for great circle extension & dom/int'l distance	x0.87	x1.0	x1.13	63.0	64.1	82.6	83.4

Appendix IV: Supplement to Section 4

	Assumptions			Results (mt CO$_2$)			
Assumption (as input to the model)	**10th %’ile**	**Base Case**	**90th %’ile**	**10th %’ile – 2015**	**90th %’ile – 2015**	**10th %’ile – 2030**	**90th %’ile – 2030**
Base Case	**-**	**-**	**-**	**63.7**	**63.7**	**83.0**	**83.0**
CNS/ATM reduction in Gt. circle extension	40%	50%	61%	63.8	63.6	83.5	82.5
Other changes in fuel burn via operations	-3.4%	-5.0%	-6.6%	63.9	63.5	84.4	81.7
Timing of CNS & operational changes	2011-21	2013-25	2015-29	62.4	64.5	83.0	83.0
Surface transport							
Surface transport emissions	x0.71	x1.00	x1.27	62.9	64.4	82.1	83.9

Table 22: Sensitivity analysis: RCS low case

	Assumptions			Results (mt CO$_2$)			
Assumption (as input to the model)	**10th %’ile**	**Base Case**	**90th %’ile**	**10th %’ile - 2015**	**90th %’ile – 2015**	**10th %’ile – 2030**	**90th %’ile – 2030**
Base Case	**-**	**-**	**-**	**63.3**	**63.3**	**74.1**	**74.1**
Demand & capacity							
Unconstrained passenger demand (Δ by 2020 relative to Base Case)	x0.90	x1.00	x1.10	58.9	67.6	73.0	74.1
Passenger capacity (mppa)	398	415	431	63.3	63.3	71.7	76.5
Passenger demand & capacity	A above	As above	As above	58.9	67.6	71.7	76.5
Unconstrained freight demand (Δ by 2020 relative to Base Case)	x0.90	x1.00	x1.10	62.8	63.8	72.4	76.2
Freighter capacity (ATMs)	0.259m	0.270m	0.281m	63.3	63.3	74.1	74.1
Freight demand & freighter capacity	N/A	N/A	N/A	62.8	63.8	72.4	76.2
Load factors							
Passenger aircraft occupancy and Δ spare seats 2030 vs. 1998	x0.99 -17.0%	x1.0 -17.5%	x1.01 -18.0%	64.0	62.6	74.9	73.5
Bellyhold freight utilisation (1998 & 2030)	0.97 0.94	x1.0 x1.0	x1.03 x1.02	63.3	63.3	74.4	74.1
Freighter aircraft occupancy and Δ spare capacity 2030 vs. 1998	x0.97 -18.7%	x1.0 -20.0%	x1.03 -20.5%	63.5	63.2	74.4	73.9
Allocation of aircraft							
Share of smaller aircraft bands in journeys (1998 & 2030)	-2.7% -6.0%	+0.0% +0.0%	+2.8% +2.3%	63.3	63.4	73.8	74.3
Retirement of old aircraft types (years)	-4	0	+4	63.3	63.3	74.1	74.1

	Assumptions			**Results (mt CO_2)**			
Assumption (as input to the model)	**10th %'ile**	**Base Case**	**90th %'ile**	**10th %'ile - 2015**	**90th %'ile – 2015**	**10th %'ile – 2030**	**90th %'ile – 2030**
Base Case	**-**	**-**	**-**	**63.3**	**63.3**	**74.1**	**74.1**
Introduction of new aircraft types (years)	-4	0	+4	62.8	63.3	73.7	75.1
Rate of uptake of new aircraft types	x0.87	x1.0	x1.14	63.4	63.3	75.0	73.2
Fuel burn & technology							
Aircraft fuel burn (LTO and cruise)	x0.97	x1.00	x1.03	61.4	65.3	71.9	76.5
Fuel consumption of new A/C types relative to 2000 (2015 & 2030)	-12% -31%	-20% -40%	-28% -50%	63.3	63.3	75.4	72.9
Size of uplift for great circle extension & dom/int'l distance	x0.87	x1.0	x1.13	62.6	63.7	73.8	74.5
CNS/ATM reduction in Gt. circle extension	40%	50%	61%	63.4	63.3	74.6	73.7
Other changes in fuel burn via operations	-3.0%	-4.5%	-5.9%	63.5	63.2	75.2	73.1
Timing of CNS & operational changes	2011-21	2013-25	2015-29	62.1	64.1	74.1	74.1
Surface transport							
Surface transport emissions	x0.71	x1.00	x1.27	62.5	64.0	73.2	75.0

Graphical Presentation of Scenarios/Cases (see 4.9.2)

Figure 14 and Figure 15 below present graphs analogous to Figure 6 (and based on Box 3) for the TS/hi and RS/lo cases. The conclusion to be drawn from these graphs is that, even in a high technology scenario, the savings in fuel consumption via technology do not compensate the increase in traffic. The introduction of capacity constraints (in this case, the relatively severe constraints associated with the RS) has a larger overall impact on emissions, with a gradual reduction in total emissions (albeit not back to their original level) once capacity constraints are reached.

Figure 14: Components of passenger emissions (TS/hi)

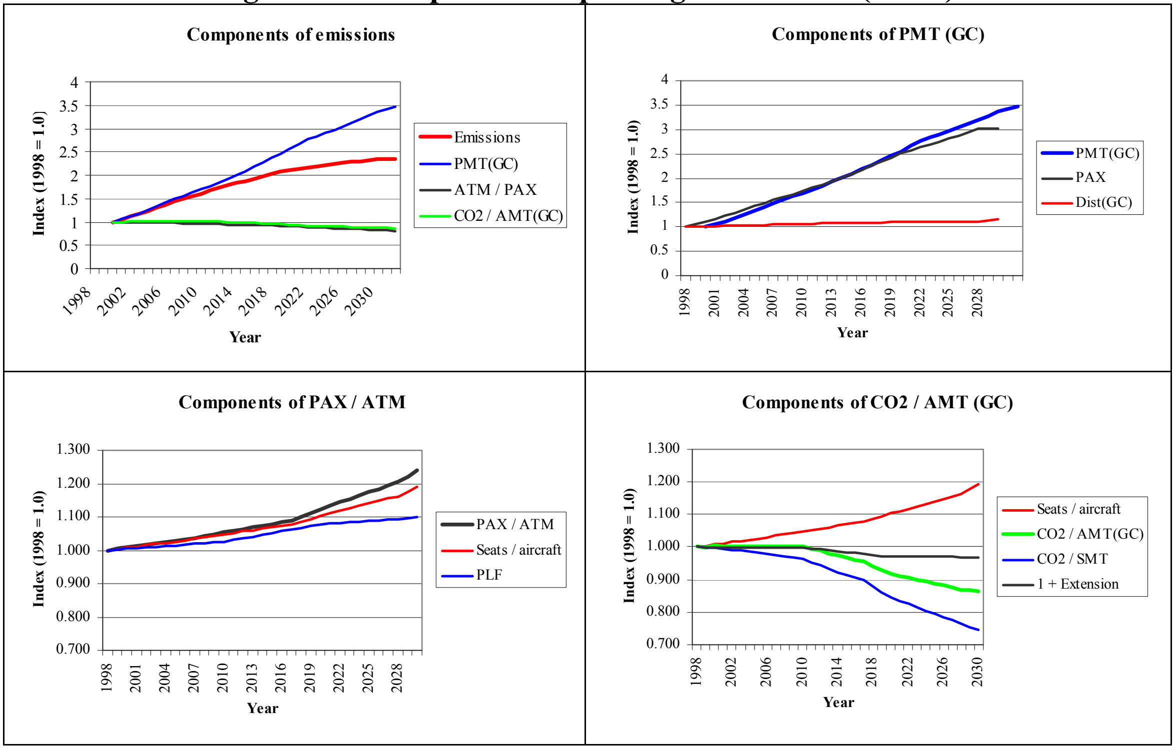
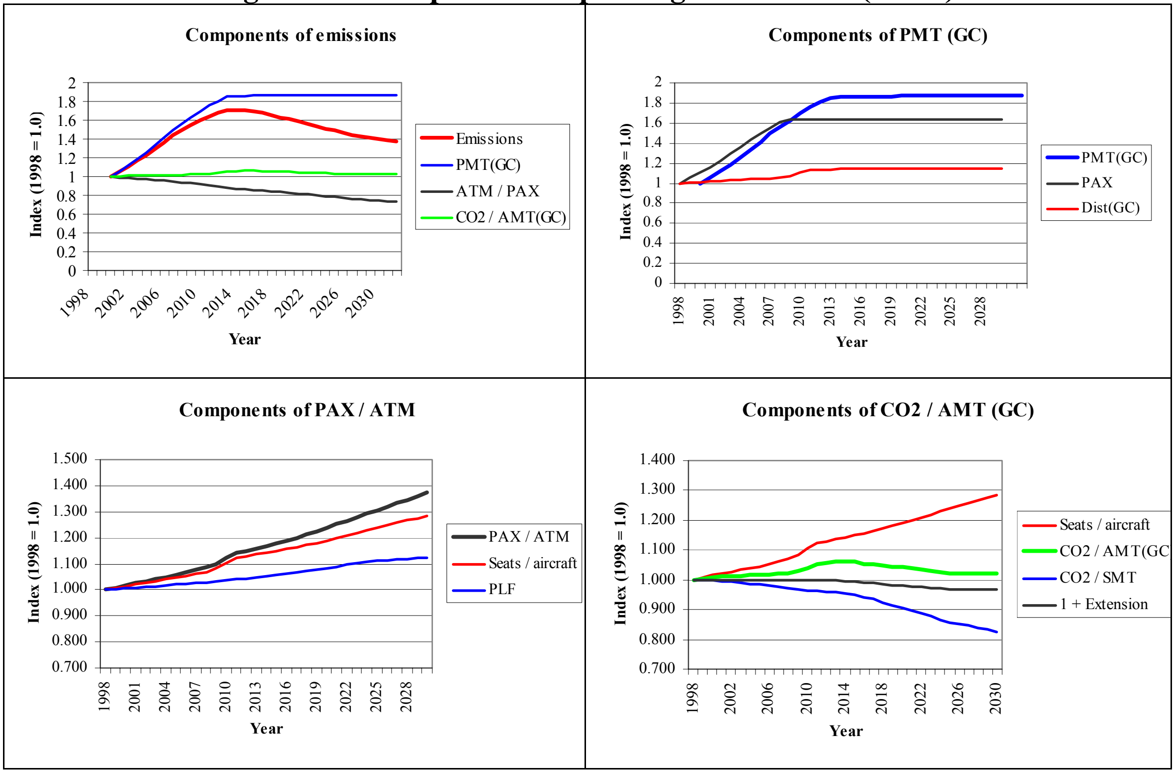


Figure 15: Components of passenger emissions (RS/lo)



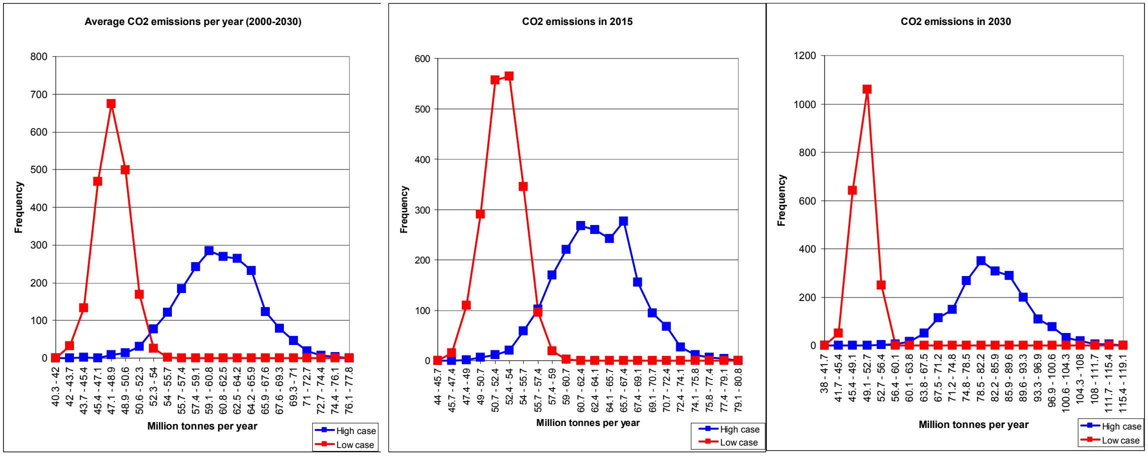
Monte Carlo Results (see 4.9.3)

The graphs and tables below present equivalent information in relation to the estimates of emissions for the RASCO Scenario and Technology Scenario as is presented in respect of the Revised Calibration Scenario in 4.9.3.

For the Technology Scenario, the randomisation of a number of the technology-related assumptions was “switched off”. This is because, for most of these assumptions, the Technology Scenario represents a world in which a particular point on the probability spectrum (circa the 100th percentile of the PDFs assigned to the underlying technology-related assumptions) is realised. An exception is made for technological progress in relation to fuel burn, since the range assigned to the Technology Scenario is not entirely subsumed within the range applied to other scenarios (see Table 17 and Table 18 above). Randomisation is therefore used for these assumptions.

Figure 16: Histogram of emissions for RASCO Scenario

Emissions per year Average for 2000-2030 **Emissions per year 2015** **Emissions per year 2030**



Emissions per PMT Average for 2000-2030 **Emissions per PMT 2015** **Emissions per PMT 2030**

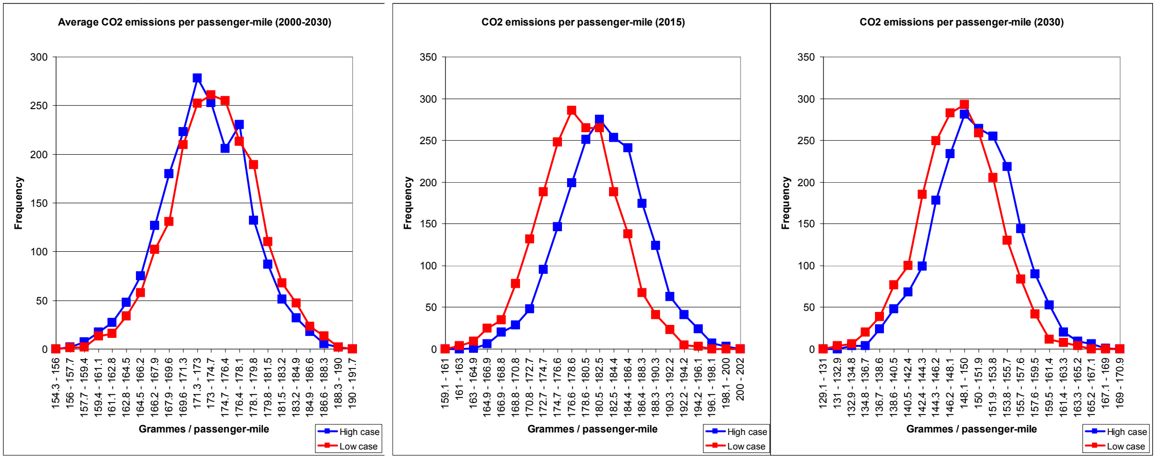


Table 23: Estimates of uncertainty of emissions for RASCO Scenario

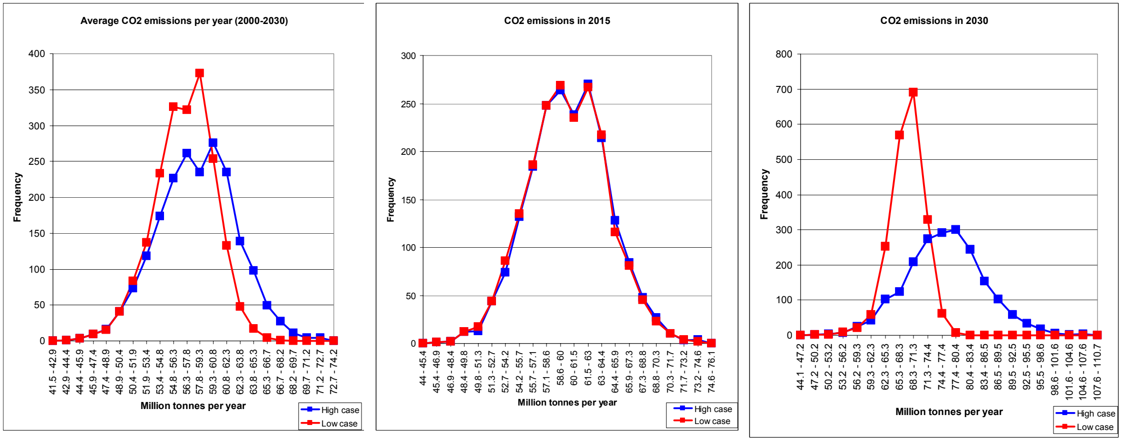
Scenario / indicator	High case			Low case		
	Result	SD/mean	95th/5th %’ile	Result	SD/mean	95th/5th %’ile
Average emissions 2000-2030	61.0 mt	7.6%	1.29	48.1 mt	4.0%	1.14
Total emissions 2015	63.3 mt	7.3%	1.27	52.4 mt	4.1%	1.15
Total emissions 2030	83.0 mt	10.9%	1.44	50.0 mt	4.7%	1.16
Average emissions / PMT 2000-2030	173 g/PMT	3.0%	1.11	174 g/PMT	3.0%	1.10
Total emissions / PMT 2015	182 g/PMT	3.1%	1.10	179 g/PMT	3.0%	1.10
Total emissions / PMT 2030	150 g/PMT	3.6%	1.13	148 g/PMT	3.5%	1.12

Figure 17: Histogram of emissions for Technology Scenario

Emissions per year
Average for 2000-2030

Emissions per year
2015

Emissions per year
2030



Emissions per PMT
Average for 2000-2030

Emissions per PMT
2015

Emissions per PMT
2030

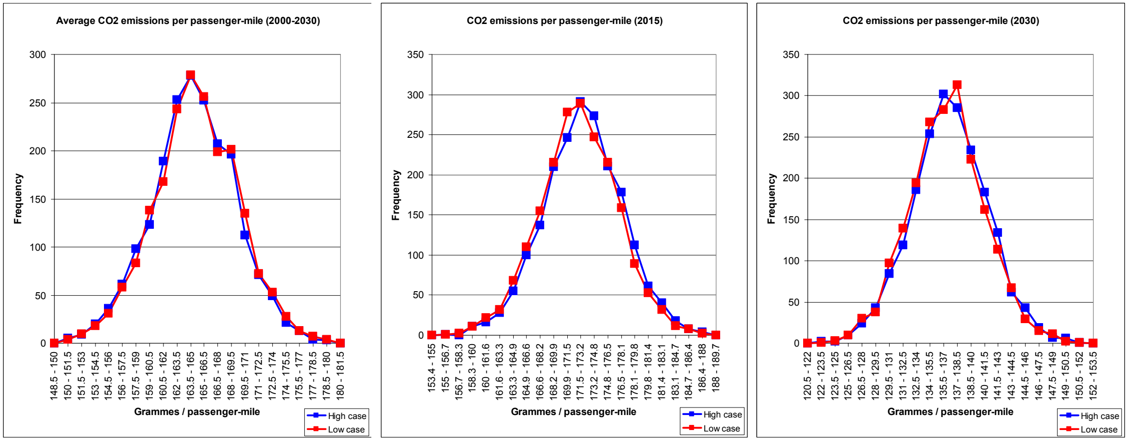


Table 24: Estimates of uncertainty of emissions for Technology Scenario

Scenario / indicator	High case			Low case		
	Result	SD/mean	95th/5th %'ile	Result	SD/mean	95th/5th %'ile
Average emissions 2000-2030	58.2 mt	7.4%	1.28	56.8 mt	5.8%	1.21
Total emissions 2015	60.2 mt	7.0%	1.26	60.1 mt	7.0%	1.26
Total emissions 2030	76.6 mt	10.7%	1.44	68.4 mt	5.2%	1.18
Average emissions / PMT 2000-2030	165 g/PMT	2.8%	1.10	165 g/PMT	2.8%	1.10
Total emissions / PMT 2015	173 g/PMT	2.8%	1.10	172 g/PMT	2.8%	1.10
Total emissions / PMT 2030	137 g/PMT	3.1%	1.11	137 g/PMT	3.0%	1.10

APPENDIX V: SUPPLEMENT TO SECTION 5

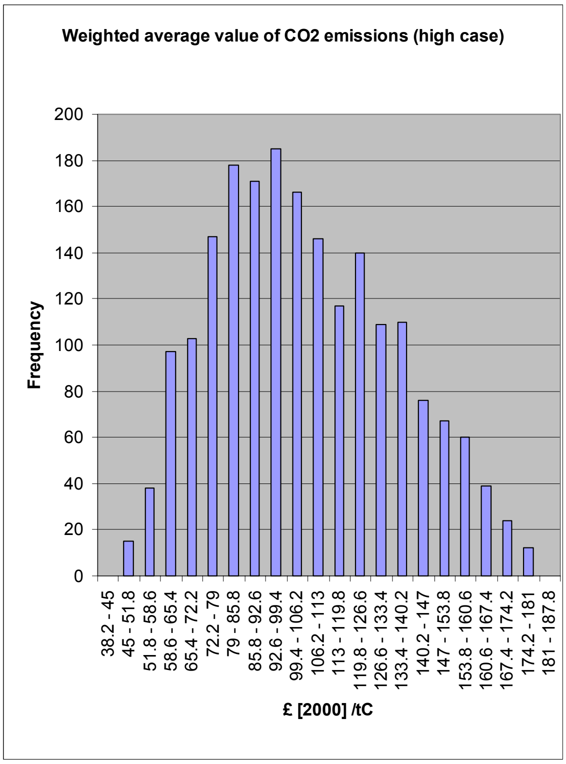
APPENDIX V: SUPPLEMENT TO SECTION 5

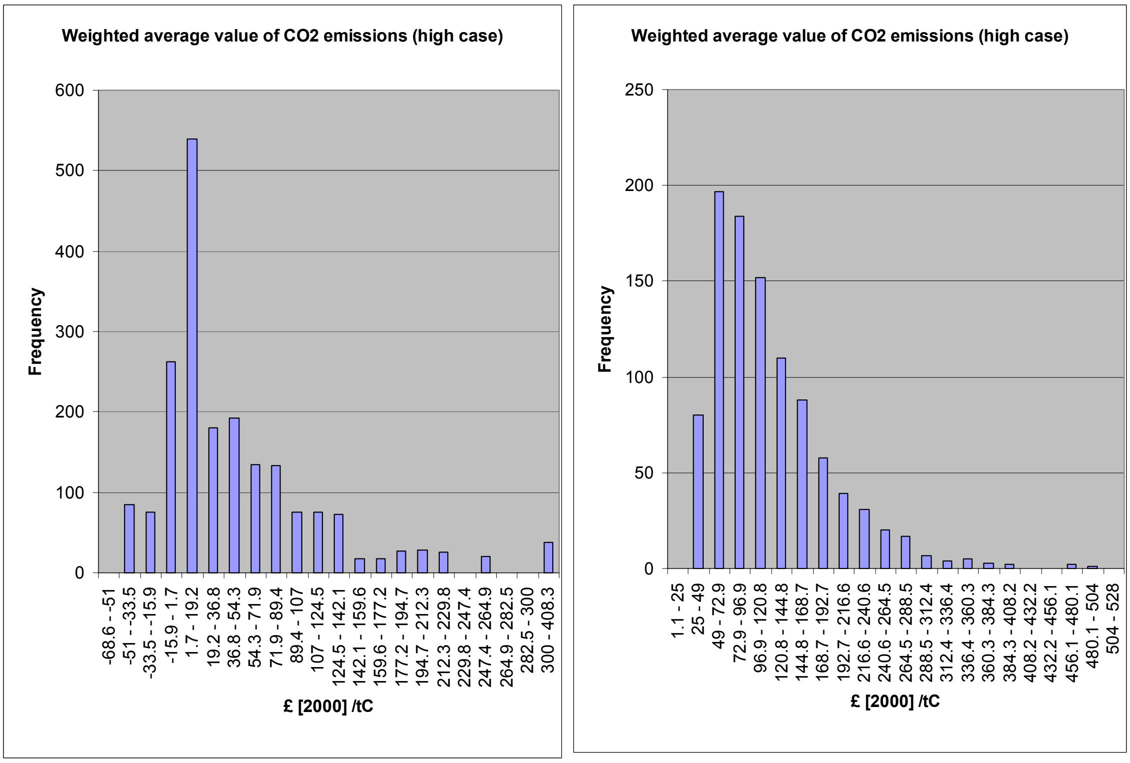
Histograms of Valuation Profiles (see 5.6.4)

The following graphs shows histograms of the weighted average total damage from aviation divided by the number of tonnes of CO2 produced. This takes account of the RFI assumptions and also the mix of emissions at altitude *versus* emissions on or near the surface. The weighted average is calculated using a discount rate of 3%.

Figure 18: Histograms of valuation profiles

(1) Clarkson and Deyes





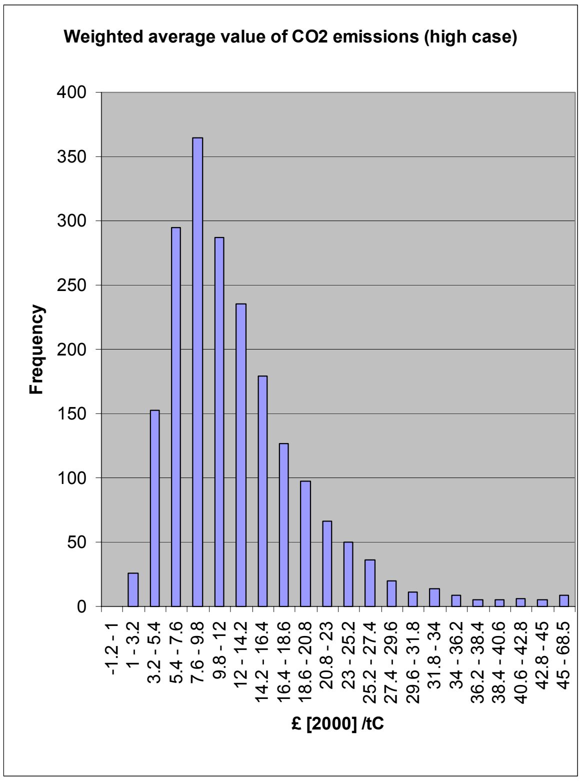
(2) Literature Survey

(3) FUND 1.6

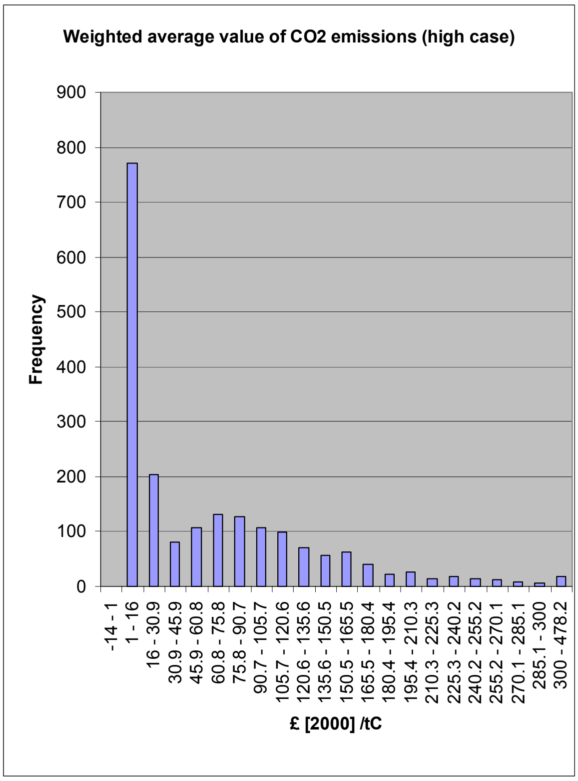
Continued overleaf…

Figure 18: Histograms of valuation profiles (contd.)

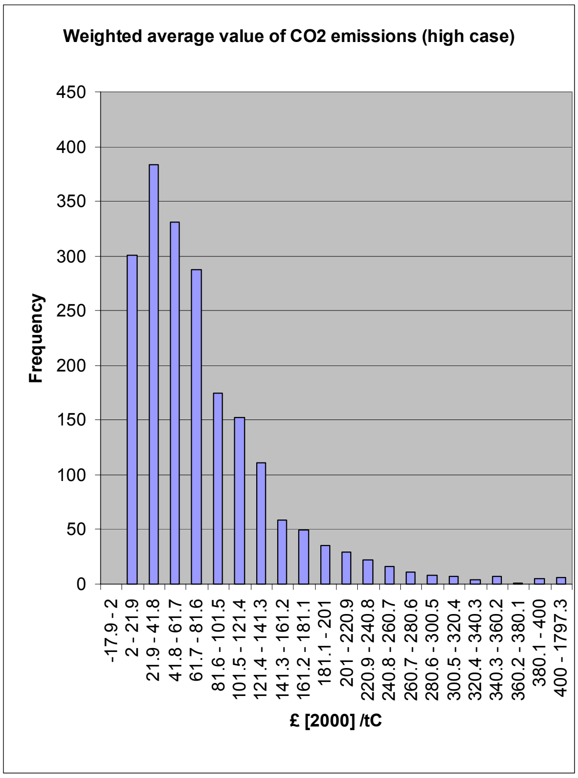
(4) FUND 2.0



(5) Composite (A)



(6) Composite (B)



Deterministic Results (see 5.7.1)

In Table 25 below, the numbering is as follows:

- Scenario (1): Calibration Scenario;
- Scenario (2): Revised Calibration Scenario;
- Scenario (3): RASCO Scenario;
- Scenario (4): Technology Scenario;
- Profile (1): Clarkson and Deyes;
- Profile (2): Literature Survey
- Profile (3): FUND 1.6
- Profile (4): FUND 2.0

Table 25: Results of Deterministic Analysis

Scenario no. / profile no.		**1 / 1**	**1 / 2**	**1 / 3**	**1 / 4**	**2 / 1**	**2 / 2**	**2 / 3**	**2 / 4**	**3 / 1**	**3 / 2**	**3 / 3**	**3 / 4**	**4 / 1**	**4 / 2**	**4 / 3**	**4 / 4**
High case																	
NPV CO2	£ [2000] bn	42.6	23.4	42.7	4.9	44.2	24.1	44.3	5.1	44.0	24.0	44.1	5.1	41.6	22.7	41.8	4.8
NPV GHGs	£ [2000] bn	106.4	58.5	106.7	12.3	122.2	66.8	122.6	14.1	121.8	66.6	122.2	14.0	115.0	62.7	115.3	13.2
Weighted avg value /tC	£ [2000] /tC	91.3	50.2	91.6	10.6	90.5	49.5	90.8	10.4	90.5	49.4	90.7	10.4	90.2	49.2	90.4	10.4
Damage / PMT 2000	£ [2000] /PMT	0.8	0.4	0.8	0.1	1.1	0.5	1.1	0.1	1.1	0.5	1.1	0.1	1.1	0.5	1.1	0.1
Damage / PMT 2030	£ [2000] /PMT	1.1	0.6	1.1	0.1	1.2	0.7	1.2	0.1	1.2	0.7	1.2	0.1	1.1	0.6	1.1	0.1
Weighted avg damage / PMT	£ [2000] /PMT	0.9	0.5	0.9	0.1	1.2	0.6	1.2	0.1	1.2	0.6	1.2	0.1	1.1	0.6	1.1	0.1
Damage / PAX 2000	£ [2000] /PAX	6.8	3.2	6.9	0.7	9.1	4.2	9.1	0.9	9.1	4.2	9.1	0.9	9.1	4.2	9.1	0.9
Damage / PAX 2030	£ [2000] /PAX	10.0	5.9	10.1	1.2	11.1	6.5	11.1	1.4	11.2	6.6	11.2	1.4	10.0	5.9	10.1	1.2
Weighted avg damage / PAX	£ [2000] /PAX	8.4	4.4	8.4	0.9	10.4	5.4	10.4	1.1	10.4	5.4	10.5	1.1	9.9	5.1	10.0	1.1
Damage / FTM 2000	£ [2000] /FTM	2.5	1.1	2.5	0.2	2.7	1.3	2.7	0.3	2.7	1.3	2.7	0.3	2.7	1.3	2.7	0.3
Damage / FTM 2030	£ [2000] /FTM	5.0	2.9	5.0	0.6	4.1	2.4	4.2	0.5	4.1	2.4	4.2	0.5	4.0	2.4	4.1	0.5
Weighted avg damage / FTM	£ [2000] /FTM	3.8	2.0	3.8	0.4	3.7	1.9	3.7	0.4	3.7	1.9	3.7	0.4	3.6	1.9	3.6	0.4
Damage / tonne 2000	£ [2000] /tonne	84.8	39.2	85.2	8.3	97.0	44.8	97.3	9.4	97.0	44.8	97.3	9.4	97.0	44.8	97.3	9.4
Damage / tonne 2030	£ [2000] /tonne	173.1	101.4	173.6	21.4	145.9	85.5	146.3	18.0	146.2	85.6	146.6	18.0	141.7	83.0	142.0	17.5
Weighted avg damage / tonne	£ [2000] /tonne	132.3	70.1	132.7	14.8	129.9	68.4	130.2	14.4	129.9	68.4	130.3	14.4	126.1	66.4	126.5	14.0
Low case																	
NPV CO2	£ [2000] bn	40.4	22.1	40.5	4.7	41.8	22.7	41.9	4.8	32.1	17.3	32.2	3.6	39.6	21.5	39.7	4.5
NPV GHGs	£ [2000] bn	100.9	55.3	101.2	11.7	115.4	62.8	115.7	13.2	88.7	47.7	88.9	10.0	109.1	59.3	109.4	12.5
Weighted avg value /tC	£ [2000] /tC	90.9	49.8	91.2	10.5	90.1	49.0	90.3	10.3	88.4	47.5	88.7	10.0	89.8	48.8	90.0	10.3
Damage / PMT 2000	£ [2000] /PMT	0.8	0.4	0.8	0.1	1.1	0.5	1.1	0.1	1.1	0.5	1.1	0.1	1.1	0.5	1.1	0.1
Damage / PMT 2030	£ [2000] /PMT	1.1	0.6	1.1	0.1	1.2	0.7	1.2	0.1	1.1	0.7	1.1	0.1	1.1	0.6	1.1	0.1
Weighted avg damage / PMT	£ [2000] /PMT	0.9	0.5	0.9	0.1	1.2	0.6	1.2	0.1	1.1	0.6	1.1	0.1	1.1	0.6	1.1	0.1
Damage / PAX 2000	£ [2000] /PAX	6.8	3.2	6.9	0.7	9.1	4.2	9.1	0.9	9.1	4.2	9.1	0.9	9.1	4.2	9.1	0.9
Damage / PAX 2030	£ [2000] /PAX	10.2	6.0	10.3	1.3	11.2	6.6	11.2	1.4	10.9	6.4	10.9	1.3	10.2	6.0	10.2	1.3
Weighted avg damage / PAX	£ [2000] /PAX	8.4	4.4	8.4	0.9	10.4	5.4	10.5	1.1	10.5	5.3	10.5	1.1	10.0	5.2	10.0	1.1
Damage / FTM 2000	£ [2000] /FTM	2.5	1.1	2.5	0.2	2.7	1.3	2.7	0.3	2.7	1.2	2.7	0.3	2.7	1.3	2.7	0.3
Damage / FTM 2030	£ [2000] /FTM	5.2	3.1	5.3	0.6	4.1	2.4	4.2	0.5	4.6	2.7	4.6	0.6	4.1	2.4	4.1	0.5
Weighted avg damage / FTM	£ [2000] /FTM	3.9	2.0	3.9	0.4	3.6	1.9	3.6	0.4	3.7	2.0	3.8	0.4	3.5	1.9	3.5	0.4
Damage / tonne 2000	£ [2000] /tonne	84.9	39.2	85.2	8.3	96.8	44.7	97.1	9.4	96.5	44.6	96.9	9.4	96.8	44.7	97.1	9.4
Damage / tonne 2030	£ [2000] /tonne	187.5	109.8	188.0	23.1	146.3	85.7	146.6	18.0	175.2	102.7	175.7	21.6	142.3	83.4	142.7	17.6
Weighted avg damage / tonne	£ [2000] /tonne	134.8	71.4	135.2	15.0	128.4	67.6	128.8	14.2	135.7	71.5	136.1	15.1	125.0	65.8	125.3	13.9

Note that damages expressed as a value per PMT, per FTM and per tonne are aggregate damages before apportioning only a proportion to the UK. Damages expressed in absolute terms and per PAX are the damages attributable to the UK.

Monte Carlo Results for RASCO Scenario (see 5.7.2)

In Table 26 and Table 27 below, the numbering of the valuation profiles is as follows:

- Profile (1): Clarkson and Deyes;
- Profile (2): Literature Survey
- Profile (3): FUND 1.6
- Profile (4): FUND 2.0
- Profile (5): Composite (A)
- Profile (6): Composite (B)
- Sens: Thought Experiment sensitivity

Table 26: Monte Carlo: RASCO Scenario (NPVs)

Valuation profile	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**Sens**
High capacity case							
Base case (deterministic)	121.8	66.6	122.2	14.0	N/A	N/A	N/A
Mean of Monte Carlo results *(CO2 only)*	144.6 *(52.5)*	81.5 *(23.8)*	166.7 *(60.8)*	17.2 *(6.2)*	91.4 *(33.1)*	110.5 *(40.0)*	90.0 *(40.0)*
Median	136.4	31.5	135	14.6	42.4	81.0	67.9
Standard deviation (SD)	58.7	127.9	116	11.2	109	117	99.0
SD / mean	41%	160%	69%	65%	120%	106%	110%
5th percentile	67.3	-26.7	48.7	5.8	6.8	14.5	13.3
95th percentile	256.4	336.7	401.8	37.6	313	309	243
Geometric mean	133.2	36.7	136	14.5	44.2	73.8	61.9
Geometric SD	1.51	5.43	1.89	1.80	3.58	2.55	2.44
Low capacity case							
Base case (deterministic)	88.7	47.7	88.9	10.0	N/A	N/A	N/A
Mean of Monte Carlo results *(CO2 only)*	103.6 *(37.5)*	59.2 *(17.4)*	117.8 *(42.9)*	12.3 *(4.5)*	64.8 *(23.4)*	76.8 *(27.8)*	62.8 *(27.8)*
Median	98.9	23.1	97	10.5	31.9	57.0	47.8
Standard deviation (SD)	37.9	92.8	76	7.9	74.2	78.9	67.4
SD / mean	37%	157%	64%	64%	115%	103%	107%
5th percentile	52.1	-18.4	39	4.1	5.0	11.2	10.2
95th percentile	175.6	251.3	265	27.3	215	212	167
Geometric mean	96.8	26.4	98.7	10.4	31.9	52.8	44.3
Geometric SD	1.45	5.49	1.81	1.79	3.57	2.45	2.35
Average of high and low							
NPV total damage / NPV CO_2 damage (mean high & low case) – 5th & 95th %'iles	2.0 3.6	2.0 3.6	2.0 3.6	2.0 3.6	2.0 3.6	2.0 3.6	1.6 3.2

Notes: All values are presented in $£_{2000}$ bn. 2,000 iterations were performed for all profiles, except for the FUND 1.6 profile (for which 1,000 were performed). Damages are the damages attributable to the UK.

Table 27: Monte Carlo: RASCO Scenario (weighted average damage / PMT)

Valuation profile	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**Sens**
High capacity case							
Base case (deterministic)	1.16	0.60	1.16	0.13	N/A	N/A	N/A
Mean of Monte Carlo results	1.35	0.73	1.53	0.16	0.84	0.96	0.79
Median	1.30	0.29	1.27	0.13	0.41	0.71	0.61
Standard deviation (SD)	0.46	1.14	0.96	0.10	0.96	0.97	0.83
SD / mean	34%	156%	63%	63%	114%	101%	106%
5th percentile	0.71	-0.24	0.52	0.05	0.06	0.15	0.13
95th percentile	2.22	3.13	3.43	0.34	2.75	2.63	2.05
Geometric mean	1.27	0.33	1.29	0.13	0.41	0.67	0.56
Geometric SD	1.41	5.41	1.79	1.78	3.60	2.41	2.31
Low capacity case							
Base case (deterministic)	1.14	0.59	1.15	0.12	N/A	N/A	N/A
Mean of Monte Carlo results	1.33	0.71	1.51	0.15	0.83	0.93	0.76
Median	1.28	0.28	1.25	0.13	0.40	0.69	0.59
Standard deviation (SD)	0.45	1.11	0.96	0.10	0.95	0.94	0.80
SD / mean	34%	156%	64%	63%	115%	101%	106%
5th percentile	0.70	-0.23	0.51	0.05	0.06	0.14	0.13
95th percentile	2.18	3.06	3.42	0.33	2.73	2.55	1.99
Geometric mean	1.25	0.32	1.27	0.13	0.40	0.65	0.54
Geometric SD	1.41	5.42	1.80	1.78	3.63	2.41	2.31

Notes: All values are expressed in pence$_{2000}$ per PMT. They represent the aggregate amount of damage before apportioning only a proportion to the UK.

APPENDIX VI: DETAILED MODEL ASSUMPTIONS

APPENDIX VI: DETAILED MODEL ASSUMPTIONS

Introduction

The detailed assumptions used in the model are presented in tabular format in this Appendix. In certain cases, where the information is voluminous, the reader is referred to the relevant worksheet within the CD-ROM included in Appendix VII.

Where only one figure is given, then this is used for all scenarios and cases. Where differentiated by scenario or case, the abbreviations shown in Table 28 apply:

Table 28: Scenarios and cases

CS:	Calibration Scenario – this is intended to replicate, to the extent practicable, results produced by Halcrow (see 4.3).
RCS:	Revised Calibration Scenario (see 4.3) – this mirrors the capacity assumptions made in the CS but in other areas introduces revised assumptions selected for this thesis.
RS:	RASCO Scenario (see 4.3) – this introduces alternative levels of capacity to the levels assumed in the CS and RCS, so as to provide cases which can be compared with the economic analysis described in Section 3, but otherwise (except where appropriate as a result of changes in capacity assumptions) reflects the assumptions of the RCS.
TS:	Technology Scenario (see footnote 51 on page 45). Except where explicitly stated, all assumptions for this scenario are as per the RCS. Differences relate to the introduction of more aggressive assumptions relating to technological innovation.
/Hi:	Used, for each of the above scenarios, to describe a high capacity case (see 4.3).
/Lo:	Used, for each of the above scenarios, to describe a low capacity case (see 4.3).

Table 29: Passenger Demand, Capacity and Traffic

Assumption	Assumption used	Comment
Unconstrained passenger demand:	See rows 1-200 of Dem_ass worksheet in the model. For purposes of Monte Carlo analysis, it is assumed that the PDF is normally distributed and that the DfT low and high sensitivity cases (15% below and above the mean by 2020) are assumed to represent the 95% confidence interval.	See 4.2.1 for derivation.

Assumption	Assumption used	Comment
Break-down of destination by distances, and distance bands (in statute miles):	**W. Europe**: 0-500 miles – 41.8% (333); 501-1,000 miles – 14.3% (745); 1,001-2,000 miles – 43.9% (1,250). **OECD**: 501-1,000 miles – 6.8% (853); 2,001-5,000 miles – 81.8% (4,124); >5,000 miles – 11.4% (7,614). **NICs**: >5,000 miles – 100% (6,261). **LDCs**: 1,001-2,000 miles – 17.0% (1,610); 2,001-5,000 miles – 67.4% (3,699); >5,000 miles – 15.6% (5,760). **Domestic**: 0-500 miles – 100% (273).	See 4.4 for derivation.
Domestic share of passenger traffic:	Until full capacity is reached, as per unconstrained demand. Thereafter, steadily increases or decreases to 2030 level, namely: CS/Hi: 15.0% CS/Lo: 15.7% RCS/Hi: 15.0% RCS/Lo: 15.7% RS/Hi: 15.1% RS/Lo: 17.9%	See 4.3.1 and Appendix IV.
Maximum capacity:	CS/Hi: 480.9 mppa CS/Lo: 414.8 mppa RCS/Hi: 480.9 mppa RCS/Lo:414.8 mppa RS/Hi: 471 mppa RS/Lo: 260 mppa For purposes of Monte Carlo simulation, it is assumed that the PDF is uniform, across a range 95-105% of the central estimate.	See 4.3.1 for derivation.
Passenger aircraft occupancy:	**CS**: Occupancy of aircraft progressively rises from 70% in 2000 to 74% in 2030. **RCS**: Occupancy, by aircraft band, in 1998: Band 1- 56%; Band 2 – 66%; Band 3 – 71%; Bands 4-6 – 77%. Steady reduction in spare seats per aircraft band, to give an overall PLF of ~74% in 2030. **RS**: Occupancy in 1998 as per RCS. Steady reduction in spare seats per aircraft band, to give an overall PLF of ~74% (RS/Hi) or ~76% (RS/Lo) in 2030. A triangulated distribution is assumed around the resulting load factors, utilising the multiples 0.975, 1.0 and 1.025 (lowest, best estimate, highest) for 1998; 0.95, 1.0 and 1.05 for 2030.	Data from a variety of sources (CAA 20021, FAA circa 1997, Rolls Royce 2001) supports differentiated approach. The overall rise in occupancy assumed by Halcrow is supported by Rolls Royce 2001. The use of a higher eventual PLF in the RS/Lo scenario is premised on the judgement that scarcity of capacity will lead to more efficient utilisation of that capacity. The wider PDF for 2030 (compared with 1998) reflects the greater uncertainty associated with future load factors.

Assumption	Assumption used	Comment
Passenger traffic:	See rows 204-284 of the Dem_ass worksheet of the model.	

Table 30: Freight Demand, Capacity and Traffic

Assumption	Assumption used	Comment
Unconstrained demand, 1998:	Bellyhold: 1,455 kT Freighter: 622 kT	Source: Halcrow, 2002f.
Unconstrained demand growth:	Gradually declining growth rate. Growth rate in 1998: 8.9% (bellyhold) and 14.4% (freighter), declining by 3.2% and 4.6% p.a. respectively.	See 4.2.2.
Break-down of demand by distance band, and average distance (in statute miles):	**UK/international -** 72.5%, comprising: 0-500 miles: 9.2% (339) 501-1,000 miles: 4.5% (762) 1,001-2,000 miles: 7.2% (1,422) 2,001-5,000 miles: 49.3% (4,022) >5,000 miles: 29.8% (6,379) **Trans-shipment** – 25%, comprising: 0-1,000 miles: 50% >1,001 miles: 50% (Distances as above) **Domestic** - 2.5% (273)	See 4.4.

Assumption	Assumption used	Comment
Maximum capacity:	Bellyhold: N/A. Freighter: CS/Hi: 400,000 ATMs CS/Lo: 270,000 ATMs RCS/Hi: 400,000 ATMs RCS/Lo: 270,000 ATMs RS/Hi: 400,000 ATMs RS/Lo: 150,000 ATMs For purposes of Monte Carlo simulation, it is assumed that the PDF is uniform, across a range 95-105% of the central estimate.	Bellyhold: capacity is a function of assumed levels of maximum passenger aircraft hold utilisation (see below) Freighter: high case capacity is set at a level which, in effect, causes no constraint. See 4.3.2 re: derivation of constrained capacity.
Maximum bellyhold freight load factors:	For all scenarios and cases, the following basic utilisation factors are used: domestic, and international up to 2,000 miles - 20%; 2,001-5,000 miles – 40%; >5,000 miles – 40%. These percentages are then multiplied by an adjustment factor to reflect the specific scenario: CS: 1998 – 1.2; 2030/Hi – 0.7; 2030/Lo – 0.6. RCS: 1998 – 1.2; 2030/Hi – 1.0; 2030/Lo – 1.1. RS: 1998 – 1.2; 2030/Hi – 1.0; 2030/Lo – 1.2. A triangulated distribution is assumed around the resulting load factors, utilising the multiples 0.95, 1.0 and 1.05 (lowest, best estimate, highest) for 1998; 0.90, 1.0 and 1.10 for 2030/Hi and 0.90, 1.0 and 1.05 for 2030/Lo.	The more efficient utilisation of capacity on long-haul routes than on short-haul is well documented (see Halcrow, 2002f; FAA, circa 1997). The CS utilisation factors are designed to give broad equivalence to Halcrow's forecasts, and the 1.2 adjustment factor was used for all cases to reflect 1998 actual figures (approximately). The decline in utilisation implicit in Halcrow's figures was assumed to be an anomaly reflecting modelling discrepancies, and was not carried forward to the RCS and RS scenarios. The higher utilisation in RS/Lo reflects more efficient use of constrained capacity. The wider PDF for 2030 (compared with 1998) reflects the greater uncertainty associated with future load factors[109]. In the high case, the upper estimate is narrowed, since an increase is already taken into account in the central estimate.
Suppressed bellyhold demand:	50% diverted to freighter demand.	Based on Halcrow, 2002f, but with no differentiation between the south east and the regions.

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[109] The PDFs for bellyhold load factors are assumed to be broader than the equivalent PDFs for PLFs, reflecting the generally greater uncertainty associated with the freight market.

Appendix VI: Detailed Model Assumptions

Assumption	Assumption used	Comment
Freighter aircraft load factors:	CS: 50% load factor throughout. RCS and RS: Differentiated by aircraft and adjusted over time. 1998 occupancy levels: A320/B757 – 46.5%; B767 – 55.7%; DC10/MD11 – 60.4%; B747 – 65.0%. Spare capacity reduced by 2030 by 20% (RCS Hi/Lo and RS/Hi) or 25% (RS/Lo). A triangulated distribution is assumed around the resulting load factors, utilising the multiples 0.95, 1.0 and 1.05 (lowest, best estimate, highest) for 1998; 0.95, 1.0 and 1.05 for 2030; 0.9, 1.0 and 1.1 for 2030/Hi; and 0.90, 1.0 and 1.05 for 2030/Lo.	CS assumption is based on Halcrow, 2002d, page 97. Differentiation by aircraft type (RCS and RS) reflects operating experience in the U.S. (FAA, circa 1997). The initial level of occupancy and assumed reduction over time gives an overall load factor of 60% rising to 67%, in line with published forecasts (Rolls Royce, 2001). The higher level of occupancy assumed for RS/Lo (2030) reflects the assumption that scarcer capacity will be utilised more efficiently (70% load factor). The wider PDF for 2030 (compared with 1998) reflects the greater uncertainty associated with future load factors. In the low case, the upper estimate is narrowed, since an increase is already taken into account in the central estimate.
Freight traffic:	See rows 290-400 of Dem_ass worksheet of the model.	

Table 31: Passenger Aircraft Allocation and Characteristics

Assumption	Assumption used	Comment
Allocation of journeys to aircraft bands:	See rows 48-70 of the AC_ass worksheet of the model, reflecting the allocation of seat bands to journey categories, before and after adjustments reflecting scenario differentiation. For purposes of Monte Carlo analysis, it is assumed that a random percentage of passengers in each journey category are re-allocated from the highest to the lowest seat band serving that journey category (or *vice-versa* for a negative number). The randomisation uses a triangulated distribution of -5%, 0% and +5% (lowest, best estimate, highest) for 1998, -10%, 0% and +10% for 2030/Hi, and -10%, 0% and +5% for 2030/Lo.	See 4.5.1 and Appendix IV for a description of methodology. The PDFs used in the Monte Carlo simulation reflect the greater uncertainty associated with aircraft allocations in the future, as compared with the present; also, the skewed distribution for 2030/Lo reflects the fact that, in a constrained scenario, a re-allocation in favour of smaller aircraft is considered relatively unlikely.

Assumption	Assumption used	Comment
Allocation of aircraft within seat bands:	See rows 73-103 of the AC_ass worksheet of the model for assumptions pertaining to the relative shares of current aircraft in passenger allocation in 1998, the retirement profile of old aircraft, and the introduction of new aircraft. For the Monte Carlo simulation, the date by which old aircraft are retired is randomised (±5 years, uniform distribution). Similarly, the initial date for introduction of new aircraft types is varied (±5 years, uniform distribution applied separately to each new aircraft type), and the rate of penetration into the fleet is also varied (±25%, uniform distribution, applied equally to all new aircraft types).	
Aircraft characteristics:	See rows 14-42 of the AC_ass worksheet of the model for assumptions pertaining to characteristics of passenger aircraft (seat band, average stage distances, maximum range, seats, occupancy, annual miles flown, and bellyhold freight capacity).	
Fuel consumption – existing and planned aircraft types:	The fuel consumption assumptions are taken from EEA, 2002, subject to the following adjustments. A simplified approach is taken to interpolating between the quoted aircraft distances. The per mile fuel consumption is assumed to be equal to that for the quoted distance range immediately below that of the assumed journey category. In the case of the BAE146, A310, DC10, A330 and B747-200, per mile fuel consumption is extrapolated beyond the quoted distance range. Fuel consumption assumptions for the RJ145, CRJ-700 and A380 are adapted from press and manufacturer data (Flug Revue, 2003; Bombardier, 2003; Airbus, 2003). For the CS only, fuel burn is multiplied by 0.88. Fuel consumption is randomised according to a normal distribution with a standard deviation of 3%.	See 4.7.1. The adjustment made to the CS reflects the weighted average discrepancy between fuel burn figures given by Halcrow (HMT / DfT, 2003a, page 28) and those implied (for comparable journeys) by EEA, 2002 (as used in this thesis).

Assumption	Assumption used	Comment
Fuel consumption – new aircraft types:	Base case scenarios are a reduction in fuel consumption per seat-mile of 34.8% or 24.5% for aircraft introduced in 2018 (Technology Scenario and other scenarios respectively). No new aircraft types are assumed in the Calibration Scenario.	See 4.7.2 and also Table 17 to Table 19 on pages 122 to 122 for further details of the derivation of these figures.
Reductions in fuel consumption:	See Operational Assumptions below.	

Table 32: Freighter Aircraft Allocation and Characteristics

Assumption	Assumption used	Comment
Allocation of aircraft types to journeys:	See rows 128-138 of the AC_ass worksheet of the model.	
Aircraft characteristics:	See rows 109-122 of the AC_ass worksheet of the model.	
Fuel consumption – existing and planned aircraft types:	It is assumed that the fuel consumption of freighter aircraft is exactly equal to the fuel consumption of the equivalent passenger aircraft. In the case of the MD11 (which is not represented in the assumed passenger fleet), it is assumed that fuel consumption is 25% lower than that of the DC10 (which it replaces over time).	See 4.7.1. The assumption regarding the MD11 is based on information from Japan Airlines (Japan Airlines, 2003).
Fuel consumption – new aircraft types:	N/A	
Reductions in fuel consumption:	See Operational Assumptions below.	

Table 33: Operational Assumptions

Assumption	Assumption used	Comment
Load factors:	See “Passenger Demand, Capacity and Traffic” and “Freight Demand, Capacity and Traffic” further above.	

Assumption	Assumption used	Comment
Distance uplift – regional-international flights:	International flight distances are multiplied by the following factors to reflect the proportion of international flights originating outside the south east: Up to 500 miles: 10.2% 501-1,000 miles: 4.5% 1,001-2,000 miles: 2.6% 2,001-5,000 miles: 0.9% >5,000 miles: 0.5% For purposes of Monte Carlo simulation, these factors are subject to the same randomisation as the Great Circle uplift (see below).	See 4.4 and footnote 40.
Uplift to Great Circle distances (pre-CNS/ATM):	Except for the CS, flight distances are multiplied by the following factors to reflect flight extensions over Great Circle distances. Up to 500 miles: 8.9% 501-1,000 miles: 8.0% 1,001-2,000 miles: 7.0% 2,001-5,000 miles: 6.0% >5,000 miles: 5.0% This is subject to randomisation according to a lognormal distribution with a standard deviation of 0.1. No extension factors are assumed for the CS.	See 4.6.2.
Reductions to Great Circle distance uplift:	Reduction of 50% (TS: 70%) in Great Circle uplift, implemented over the period 2013-2025 (TS: 2010-2019). These reductions are multiplied by a random factor based on a triangular distribution (0.6, 1.0, 1.4).	See 4.6.2.

Assumption	Assumption used	Comment
Other reductions in fuel consumption:	CS: None assumed. RCS/Hi: 5.0% reduction, realised over the period 2013-2025. RCS/Lo: 4.5% reduction, 2013-2025. RS/Hi: 5.0% reduction, 2013-2025. RS/Lo: 4.0% reduction, 2013-2025. TS/Hi: 7.0% reduction, 2010-2019. TS/Lo: 6.3% reduction, 2010-2019. The reductions are randomised using a factor, uniformly distributed, of 0.6 to 1.4. The commencement and duration of the reduction programme are randomised, with a uniform distribution of ± 3 years.	See 4.7.1.

Table 34: Surface Transport Emissions

Assumption	Assumption used	Comment
Passenger surface transport CO_2 emissions (kgs per passenger):	**CS**: 6.0 (2000); 5.3 (2030/Hi); 5.7 (2030/Lo). **RCS**: 7.2 (2000); 5.2 (2030/Hi); 5.6 (2030/Lo). **RS**: 7.2 (2000); 5.2 (2030/Hi); 5.9 (2030/Lo). Triangular distribution: x0.5 (low); x1.0 (central estimate); x1.5 (upper).	See 4.8 for underlying rationale and assumptions.
Freight surface transport CO_2 emissions (kgs per tonne):	**CS**: 73.6 (2000); 65.0 (2030/Hi); 69.4 (2030/Lo). **RCS**: 88.3 (2000); 65.0 (2030/Hi); 69.4 (2030/Lo). **RS**: 88.3 (2000); 65.0 (2030/Hi); 73.5 (2030/Lo). Triangular distribution: x0.5 (low); x1.0 (central estimate); x1.5 (upper).	See 4.8 for underlying rationale and assumptions.

Table 35: Other Assumptions

Assumption	Assumption used	Comment
Radiative forcing:	Refer to rows 137-138 of the Drivers worksheet of the model.	See 5.6.2 and 5.6.5.
Valuation of GHGs:	Refer to rows 139-149 of the Drivers worksheet and rows 26-113 of the Other_ass worksheet of the model.	See 5.6.4.
Discount rate:	3% p.a.	See 5.6.3.

APPENDIX VII: COMPUTER MODEL

APPENDIX VII: COMPUTER MODEL

CD-ROM

A CD-ROM is attached as the final page of this Appendix. It includes the following:

- The spreadsheet (Davis_model_A.xls) used to generate the results quoted in this thesis;
- A copy of the SIMTOOLS software add-in (filenames simtools.xla and formlist.xla) used to generate certain of the PDFs used in the Monte Carlo analysis, together with a document (Myerson_circa2001.html) prepared by the authors of SIMTOOLS (Myerson, *circa* 2001) explaining how to install and use SIMTOOLS;
- An alternative version of the spreadsheet (Davis_model_B.xls), in which the PDFs reliant on the SIMTOOLS add-in have been converted to raw numbers, so as to avoid the need to install SIMTOOLS.

Users wishing to run Monte Carlo analysis on the model utilising a new set of random draws should install the SIMTOOLS add-in on their computers and use the Davis_model_A version of the model. Users not wishing to create new random draws should use the Davis_model_B version of the model and need not install SIMTOOLS. Other than creating new random draws, this retains all functionality of the model, including the ability to perform Monte Carlo analysis (utilising the model's existing random draws).

The user's attention is drawn to the Important Notice (governing conditions of use of the model) set out at the top of the "Drivers" worksheet.

Layout of the Model

Throughout the model, a colour-coding convention is used, as explained immediately below the Important Notice on the "Drivers" worksheet. For purposes of the User, the important colour codes are:

- Black text on white background. These cells represent the workings of the model (including results) and are not intended to be amended by the user;
- Blue text on yellow background. These are input cells, whose contents may be amended in order to generate revised calculations;
- Yellow text on red background. These are ranges where hard-coded numbers have been copied for purposes of preparing various graphs which are dependent upon

more than one scenario. These numbers, and the graphs based upon them, do not automatically update when the model is recalculated.

With very few exceptions, all input cells are located in the “Drivers” worksheet or in worksheets ending with the characters “_ass” (denoting that they are assumptions worksheets). These worksheets also contain intermediate calculations (e.g. interpolation, sensitisation, randomisation, etc.) in order to prepare the assumptions for input into the later calculation worksheets.

The model incorporates the following worksheets:

- “Drivers”. As well as incorporating the Important Notice and cell formatting conventions, this worksheet incorporates key assumptions which are varied between scenarios, as described further below. It also incorporates certain “flags” (enabling particular calculations to be switched on or off), conversion factors and error-checks;
- “MC_ass”. This worksheet incorporates the random draws used for purposes of Monte Carlo analysis, and various results emanating from those draws (which are used to generate histograms and other results in the “MC_res” worksheet);
- “Dem_ass”. This worksheet incorporates assumptions relating to demand and traffic, including passenger traffic, bellyhold freight and dedicated freighter freight;
- “AC_ass”. This worksheet incorporates assumptions relating to aircraft (both passenger and freight aircraft) and to certain operating factors (e.g. uplift over Great Circle distances);
- “Other_ass”. This worksheet incorporates other assumptions, for example relating to surface transport and valuation assumptions;
- “HPT” (high passenger traffic). This worksheet calculates ATMs, AMTs and aircraft fleet characteristics for the high traffic cases;
- “HCT” (high cargo traffic). This worksheet calculates corresponding information in respect of freight (both bellyhold and dedicated freighter freight) for the high traffic cases;
- “HFC_LTO” (high fuel consumption - LTO). This worksheet calculates LTO fuel consumption by passenger and freight aircraft for the high traffic cases;
- “HFC_cruise” (high fuel consumption – cruise). This worksheet calculates cruise fuel consumption by passenger and freight aircraft for the high traffic cases;

- "HFC" (high fuel consumption). This worksheet adds together information in the preceding two worksheets to give total fuel consumption figures for passenger and freight aircraft for the high cases and also, in the case of passenger aircraft, allocates that fuel consumption between passengers and bellyhold freight;
- "LPT", "LCT", "LFC_LTO", "LFC_cruise" and "LFC". These worksheets are the corresponding worksheets for the low capacity cases. They are identical in layout to the "HPT", "HCT", "HFC_LTO", "HFC_cruise" and "HFC" worksheets;
- "GW". This worksheet calculates CO_2 emissions from surface transport, converts fuel consumption figures from the "HFC" and "LFC" worksheets into GHG emission data and values those emissions;
- "Det_res". This worksheet presents results pertaining to the deterministic analysis;
- "MC_res". This worksheet presents results pertaining to the Monte Carlo analysis.

Guide to Using the Model

For most purposes, the key information used to generate scenarios, sensitivities and Monte Carlo simulation is presented in the "Scenarios and Sensitivities" section of the "Drivers" worksheet.

For purposes of running one of the main scenarios described in this thesis (and assuming, first of all, that Monte Carlo simulation is not to be performed), the following steps should be taken:

- The number of the scenario to be run (see the top row of the table in the "Scenarios and Sensitivities" section of the worksheet) should be entered into the cell labelled "Scen_choice". Note that it is not necessary to specify whether the relevant high or low capacity case is desired, since both cases are automatically generated in separate model worksheets;
- "N" should be entered in the cell labelled "MySwitch", denoting that Monte Carlo simulation is not be performed;
- No amendment need be made to the two cells immediately below "MySwitch", since these are only pertinent to Monte Carlo simulation;
- Those assumptions which differ as between the various scenarios are all shown in the table beneath the above inputs. In some cases (e.g. maximum capacity assumptions) these are the input assumptions which are directly carried forward to the assumptions worksheets. In other cases (e.g. sensitivity factor for passenger aircraft occupancy) they are numbers which are used to vary (whether by

multiplication or addition) assumptions used in the assumptions worksheets[110]. The assumptions can be changed for the scenario to be run, as desired. Alternatively, if a significant number of amendments are to be made, one of the unused scenario columns can be used to generate a new scenario altogether;

- Having selected the desired scenario and assumptions, {F9} should be pressed in order to recalculate the model. The "Error Trapping" table located beneath the "Scenarios and Sensitivities" section should be checked, to see whether any errors have arisen.
- In reviewing the results and calculations set out in the model, the user should note that histograms and results contained in the "MC_ass" worksheet will be retained from previous Monte Carlo simulations, and will not be applicable to any runs performed in deterministic mode.

In addition to the assumptions in the "Drivers" worksheet, assumptions throughout the assumptions worksheets (colour-coded as described above) can be varied. However, the model was not originally designed to be used by third parties, and not all of the assumptions are entirely self-explanatory. Users are encouraged to use a process of trial and error to satisfy themselves of the impact of varying any such assumptions.

If Monte Carlo analysis is to be performed on the desired scenario, then (assuming that the existing random draws are to be utilised):

- The desired scenario and sensitivity assumptions should be entered, as above;
- "Y" should be entered into the cell labelled "MySwitch";
- The number of iterations (up to 2,000)[111] should be entered into the cell labelled "MyIterations";
- If the user wishes to isolate any particular assumptions from the Monte Carlo simulation, then the input "Y" should be changed to "N" in the relevant row of the "Randomise?" column of the inputs table[112];
- The Monte Carlo calculation macro should be invoked by pressing {Ctrl} + {Shift} + {Z}. (When the model is initially opened in Excel, the user may be prompted to confirm that macros should be enabled, in order to allow the macro to run.)

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[110] In cases where the nature of the adjustment made by these input cells is not immediately obvious, the user is advised to find the cells which are dependent on the input cells (by using the Tools / Formula Auditing / Trace Dependents facility of Excel and checking the impact of varying the input assumption.

[111] Clearly, the more iterations, the longer the model takes to perform the Monte Carlo simulation.

[112] This should only be changed for cells with a yellow background. A number of assumptions within the table are not capable of being randomised, as denoted by "N" on a white background.

- A counter in the bottom-left corner of the screen will monitor progress as iterations are being performed. A message will appear once recalculation is complete.
- Throughout most of the worksheets, the calculations will reflect the random draws used in the final iteration. However, results are stored from each iteration in the "MC_ass" worksheet, and are automatically incorporated into the histograms and results presented in the "MC_res" worksheet.

The Monte Carlo process in the model applies random factors (generated in the "MC_ass" worksheet, based on the PDF selected for the random variable in question) to the input relevant to the scenario in question. In some cases (e.g. deferral or acceleration of introduction of new aircraft) this is a process of addition; in other cases (e.g. maximum capacity assumptions) it is by way of multiplication. An important feature of the model, therefore, is that it is possible to run a sensitivity in tandem with Monte Carlo simulation, i.e. a sensitised assumption can, if desired, be used and either randomised (randomisation column set to "Y") or isolated from the randomisation (randomisation column set to "N").

If desired, the random draws used in the "MC_ass" worksheet can be refreshed (in the Davis_model_A version of the spreadsheet). As this is not automated within the Monte Carlo macro, this involves using the Tools / Data Analysis / Random Number Generation feature of Excel to randomise all of the columns in the "MC_ass" worksheet denoted to be generated via "Toolpak". Guidance is given in the relevant column on the parameters used in generating the random numbers, although different randomisation parameters can be used. Note that, in many cases, random numbers have been generated using a uniform distribution between zero and one, and then adapted to the PDF required via a separate column incorporating a formula (whether from SIMTOOLS or conventional Excel formulae). These columns (denoted as "Formula") should not be overwritten via Tools / Data Analysis / Random Number Generation, although the parameters shown in the top rows of the column can be varied if desired. Having updated or amended the "MC_ass" worksheet as desired, the Monte Carlo simulation can be performed as described in preceding paragraphs.

AFFIX CD-ROM HERE