The Environmental Effects of Civil Aircraft in Flight
Special Report

Contents

The Environmental Effects of Civil Aircraft in Flight

Special Report

1 The cause for concern

1.1 For many years the Royal Commission on Environmental Pollution has been expressing concern about the environmental impact of air transport. Its First Report in 1971 pointed to both the local and the global problems associated with air transport, focussing on noise and the problems of supersonic flight, and concluding that 'a watch should be kept on the situation'.[1]

1.2 The Commission returned to air transport in 1994 in its Eighteenth Report, *Transport and the Environment*, which warned of the prospect of 'irreversible damage to the Earth's atmosphere from the growth of air transport, or at least serious damage of a long-term nature'.[2] The Report stated that there was a powerful case on environmental grounds for regulatory action and that 'the demand for air transport might not be growing at the present rate if airlines and their customers had to face the costs of the damage they are causing to the environment'.[3] In its Twenty-second Report, *Energy – The Changing Climate*, the Commission re-iterated the need for action to secure a tax on aviation fuel.[4]

1.3 In 2001, the Commission responded to the first round of consultation on 'The Future of Aviation', the forthcoming aviation White Paper, and concluded that 'aviation policy must not simply respond to current growth patterns. A primary aim of policy must be to seek to limit aviation's contribution to global warming. This will require significant constraints on the growth of air traffic'.[5]

1.4 The Commission's Twenty-third Report, *Environmental Planning*, discussed the government's intention to publish a national aviation strategy supplemented by seven regional consultation documents exploring capacity options.[6] For the first time in aviation history there seemed to be some prospect of a shift away from the 'predict and provide' approach, though the Commission commented that it remained to be seen whether this would happen in practice.

1.5 In 2002, a proposal that the Commission should study the environmental effects of aviation (for its Twenty-fifth Report) attracted support from a wide range of consultees. In the event the Commission concluded that a full-scale report would be too late to influence the anticipated White Paper setting out the government's policy on aviation for the next 30 years. It agreed, however, that the opportunity to inform the policy should not be missed, and decided to produce a Special Report on a specific, but crucial aspect of aviation.

1.6 In July 2002, the Department for Transport (DfT) published a national consultation paper on the future development of air transport in the regions.[7] The consultation paper refers to proposals by the Department for Environment, Food and Rural Affairs (Defra), that climate change assumptions should be built into national policymaking, and confirmed that this would apply to the air transport White Paper. However, the consultation paper offers little information on how that might be achieved and devotes more attention to addressing the economic factors associated with airport development. One of the primary concerns in the consultation paper, especially in respect of a hub airport in the South East of England, appears to be the maintenance of traffic through UK airports against perceived competition from other European airports.

1.7 The DfT does not accept that its policy amounts to a predict and provide approach. The Department has argued that this would only be the case if 'Ministers decided to meet unconstrained demand without regard to the consequences'.[8] However, recent ministerial comments, following publication of the consultation documents, have suggested that the government believes that current airport capacity must inevitably be increased to meet predicted demand.

1.8 The Commission, therefore, remains concerned that the environmental problems posed by aircraft in flight may not be given sufficient attention in the White Paper. Our specific contribution to the debate focuses on the environmental effects of aircraft in flight as, to date, environmental concern has concentrated more on ground-level pollution and quality of life in and around airports. In this Report we considered emissions to the atmosphere and whether technological improvements are likely to contain the effects of unconstrained growth in aviation. We reached some conclusions about the likely impacts of aviation in the future and considered ways in which they might be avoided or mitigated.

1.9 Section 2 of this Report sets out some of the trends in aviation which are at the root of our concerns. We consider the environmental impacts of aircraft in flight in Section 3, covering the changes in atmospheric ozone and associated surface ultraviolet (UV) changes, and the implications for climate forcing of the growth in air transport. In Section 4 we review the technological constraints on and scope for improvement in the environmental performance of aircraft, in terms of the air frames, engines and fuels used. We also consider the relative environmental impacts of flights of different distances and altitudes. Section 5 concerns possible policy measures to limit the damage that aviation might do to the environment over the first half of this century. Our conclusions and recommendations are summarised in Section 6.

2 Trends in air transport

Short and long-term trends

2.1 Commercial aviation has undergone enormous growth over its relatively short history as the globalisation of industry and commerce has increased and air travel's relative affordability has contributed both to a boom in international tourism and to a large rise in the volume of air freight. Air transport has become an integral part of many people's lifestyle and its continued growth is taken for granted by many.

2.2 Various forecasts of growth are available. One of the most widely accepted for the UK is from the Department for Transport, Local Government and the Regions (DTLR),[9] which gives a mid-range scenario prediction that air traffic at UK airports will grow at an average of 4.25% per annum. This is based on 'unconstrained forecasts of the underlying demand for air travel' up to 2030 and is intended to cover all market segments. The Department's highest and lowest growth scenarios are for growth at 4.9% and 3.6% respectively. Without the restriction of any limiting measures imposed at global, European or national level, these forecasts imply that British airports will be serving over one billion passengers a year by 2050.

2.3 'Passenger-kilometres' flown from UK airports increased from 125 billion in 1990 to 260 billion in 2000.[10] The most rapid growth has been seen in international travel, though domestic flights have also risen steadily. The huge expansion of the 'no-frills carriers' has contributed to this growth. In the last five years the passenger-kilometres carried by these operators have more than doubled, and now account for about 20% of the total passenger-kilometres flown from UK airports.[11] This is even more remarkable considering that these services operate only on domestic and short-haul routes.

2.4 Until 2001 the actual growth rate followed one of the higher growth scenarios although there was a drop below that trend in 2001 which was accentuated following the terrorist attacks in the USA on 11 September 2001. Many analysts believe this downturn to be temporary, and signs of recovery are already apparent. The DfT has stated that 'despite fluctuations arising from economic and other events, traffic growth will return to its long run trend'.[12]

2.5 Largely helped by the rise in express delivery services, which require airports with 24-hour operation, air freight has been growing even faster than passenger transport. The tonnage of freight carried by air, landing or taking off at UK airports, rose by an average of 8.7% per annum between 1992 and 1998 and this trend is expected to continue. In 2001, 18.7% of tonnage of freight landing at or taking off from UK airports was carried between the UK and the other European Union Member States; 2.7% was carried over domestic routes. The majority of air freight though is carried over longer distances.[13]

2.6 Originally air freight was used only as a way to fill excess storage space in passenger aircraft, but as wider bodied planes were developed, freight transport became an important activity in its own right. This eventually resulted in all-cargo aircraft. In 2001, a third of air freight landing or taking off from UK airports was carried in all-cargo aircraft.[14] The DfT's consultation on the future development of air transport in the regions includes proposals to establish airports supplying 'substantial, dedicated air freight provision', including the suggestion to develop Alconbury, Cambridgeshire as an 'express parcel hub'.[15]

2.7 Although we have limited our attention to commercial aircraft, we note that a significant, if falling, proportion of the world's aircraft is military. In 1992, 18% of the world's fleet were military aircraft and by

2015 they are estimated to amount to 7%.[16] In the early 1990s, military aircraft consumed approximately one third of the fuel used by the commercial fleet.[17] The performance requirements of military aircraft suggest that, compared to civil aircraft, they are likely to produce proportionately more emissions of some climate-changing pollutants, oxides of nitrogen in particular.

Service lives of aircraft

2.8 Some of the environmental impacts of flight can be addressed through new technology. However, there is a considerable delay between the development of conceptual new technologies and such developments becoming available for use.

2.9 Evidence to us indicated that a new design for aircraft might take ten years in development and another ten in construction.[18] The aircraft would then be expected to be in service for three decades. Consequently, new technologies will take at least twenty years to come into use and following that there will be a period during which a proportion of older, more polluting stock will remain in service. This ‘overlap’ problem is compounded by the growth of small carriers and of airline industries in developing countries. Large airlines in developed countries sell on their out-of-date stock to these younger airlines, meaning that such craft can remain in service even longer.

2.10 Even so, the gradual replacement of the old aircraft fleet with newer designs ought to have a positive environmental impact. But this must be considered against the fact that new aircraft are not designed primarily for their environmental features, as is apparent in some aircraft designs currently under discussion.

Benefits of the air transport industry

2.11 The aviation industry has brought many benefits to society in both economic and social terms. The relative affordability and speed of air transport today have made international travel accessible to many people who would never previously have had the time or financial means to enable them to travel overseas.

2.12 This broadening of the collective horizon is likely to benefit society generally, even though the proportion of the global population who are able to travel in this way remains small. The wide availability of air transport is still limited to the affluent developed world and to the elite few in the developing countries. However, the environmental costs of aviation can be global: climate change will affect every person and its consequences may be most damaging for those in the developing world.

2.13 One study estimates that the aviation industry directly provides jobs for over 180,000 people in the UK, and contributes some £10.2 billion to the gross domestic product.[19] In addition the Department for Trade and Industry (DTI) draws attention to the trade in goods, industrial developments and economic services that air transport facilitates.[20] This trade creates wealth, which, the DTI believes, could be used for global as well as national development. The extent to which these benefits, in practice, improve global conditions is difficult to ascertain. How much they would be compromised if the growth in aviation were curtailed would depend on the ways in which this was done and the quality of the alternative transport and communication methods available. In any case the resources displaced by restrictions on air transport would find other uses in due course, probably with similar or only slightly lower market value and much less damaging environmentally.

Organisation of the industry

2.14 Many different industries are involved in the aviation sector. Separate companies construct engines and airframes; airlines and air freight companies are independent organisations, as are the airports from which they fly; and many other companies supply a range of goods and services. All these organisations are distinct, yet have to co-operate and work closely together.

2.15 The industry is subject to air traffic control systems and regulation from bodies such as the Civil Aviation Authority (CAA) in the UK and, at an international level, the International Civil Aviation Organisation (ICAO). ICAO was set up in 1947 and is the permanent body charged with the administration of the principles set out in the 1944 Convention on International Civil Aviation (Chicago Convention) and is a specialised agency of the United Nations (UN). ICAO has 188 contracting states.

2.16 ICAO includes in its aims: 'to achieve maximum compatibility between the safe and orderly development of civil aviation and the quality of the environment'.[21] Its current environmental activities are largely undertaken through the Committee on Aviation Environmental Protection (CAEP), which has eighteen members.[i] CAEP comprises five working groups; two focussing on aircraft noise issues, two on emissions and one dealing with market-based measures. It sets out its recommendations every three years for consideration and possible adoption by the ICAO Assembly.

2.17 ICAO has no powers of enforcement and sets only recommended standards and guidelines. Its members are bound morally rather than legally to act in accordance with the ICAO resolutions. It is up to individual countries to transfer the standards into national law, and in some cases member states deviate from the recommendations, or do not implement them at all.

Direction of airframe development

2.18 Currently, the development of airframes is split between serving two market views, 'fragmentation' and 'consolidation'. The fragmentation view is that a larger number of direct flights will occur between 'local' airports so creating a requirement for a large number of smaller, higher speed aircraft. The consolidation view sees further development in 'hub airports', flights between which would be provided by larger high capacity aircraft. Such hubs would be nodes in an integrated transport system, possibly including flights to and from smaller regional 'feeder' airports, a role which might be played by an improved rail or multi-modal network (as developed for Schiphol in The Netherlands).

2.19 Over a set distance, smaller aircraft often have lower emissions per flight than larger aircraft, but their emissions per passenger kilometre are greater. The higher altitude at which the newer designs of aircraft might fly could also increase their impact on the climate (see paragraph 3.43).

2.20 The increasing development of hub airports in the consolidation model also raises problems. It is possible that as aircraft become larger aircraft emissions affecting air quality within the airport boundary might increase at a rate greater than aircraft movements. There may come a point when local air quality issues become the main limiting factor on the growth in the use of these hubs by aircraft.

---

i The members of CAEP are Australia, Brazil, Canada, Egypt, France, Germany, Italy, Japan, The Netherlands, Poland, Russian Federation, Singapore, South Africa, Spain, Sweden, Switzerland, Tunisia, United Kingdom and USA.

2.21 Over the past 40 years, fuel burn and emissions of carbon dioxide and oxides of nitrogen have reduced dramatically for new aircraft, owing to increased efficiency of airframe and engine design. Improvement is complicated by the competition between developing quieter engines and reducing emissions.

Passenger density

2.22 The number of passenger movements is currently increasing faster than the number of aircraft movements because of the development of bigger aircraft with a higher passenger capacity. However, overall, passenger densities are decreasing at present. This is caused by the increase in business and first class travel, which use the increase in space available per passenger as a selling point.

2.23 Furthermore, most flights do not fly at full capacity. On average only 78% of seats on international flights, and 65% on domestic flights, are filled. This causes difficulty in interpreting figures for emissions per passenger-kilometre, which are often calculated on the basis of a full aircraft. Measures to increase passenger density might reduce emissions per passenger-kilometre and result in fewer aircraft movements for a given number of passengers. Such measures may simply result in increasing the numbers of passenger movements as airlines would be tempted to maximise profits by not reducing the number of aircraft movements but by filling those flights.

Regulation and taxation

2.24 Unlike fuel for motor vehicles or trains, under an interpretation of Article 24 of the 1944 Chicago Convention, there is no tax levied on fuel for aviation, either as fuel duty or VAT. This interpretation has been implemented through some 4,000 bilateral agreements between nations, making any renegotiation difficult. Exemption from taxation amounts to a subsidy for the aviation industry, compared with most other modes of transport. Shipping is also tax-exempt as no duty is levied on maritime fuel.

2.25 Arguments against placing taxes on aircraft fuel rest on the difficulty of securing united global action, while unilateral action would simply result in 'tankering' - fuel being purchased in countries where it was not taxed, and transported to where it was needed - thus aggravating the problem. We are not convinced by such arguments, at least as applying to any EU level initiative, as proposed below. There is a strong case for some form of charging, not least to reflect the 'polluter pays principle'.

2.26 The Kyoto Protocol was signed in 1997, committing signatories to cutting emissions of 'greenhouse gases' by 5.2% of 1990 levels by 2012. However, international aviation and maritime emissions were excluded from the Kyoto Protocol under Article 2.2. Responsibility for regulating emissions from international aviation has been left to ICAO, which has no powers of enforcement. Domestic aviation *is* covered under the Kyoto Protocol and currently accounts for about 0.5% of the UK's carbon dioxide emissions; but the Kyoto Protocol places limits only on carbon dioxide emissions, not the emissions of oxides of nitrogen and water vapour. These gases, when emitted at high altitudes, cause more damage than they do at ground level, resulting in greater 'radiative forcing' (see paragraph 3.21) from aviation than might be expected from its carbon dioxide emissions alone.

3 The environmental impacts of aircraft in flight

Introduction

3.1 The main environmental concerns associated with aircraft are:

- climate change
- stratospheric ozone reduction, leading to increased surface UV radiation
- regional pollution - changes in tropospheric chemistry for tens to hundreds of kilometres downwind of the airport. In particular, emissions of oxides of nitrogen in air increase ozone
- local pollution - both noise and decreased air quality caused by aircraft and also by the associated ground transportation.

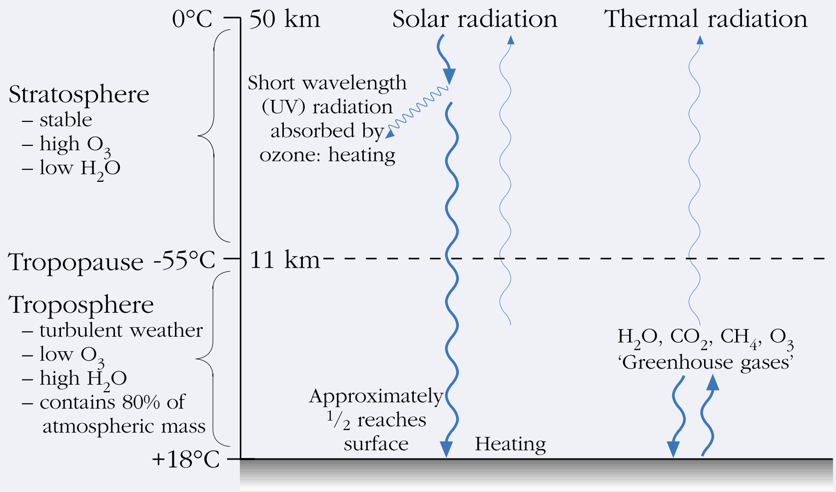
3.2 There is no doubt that both local pollution and regional pollution are very serious issues. It is thought that European Directives on permitted levels of oxides of nitrogen may limit the expansion of some airports.[22] Concern has been expressed to us that the techniques for assessment of the impact of aircraft emissions on both local and regional air quality are poorly developed and that the available modelling tools are in general inadequate.[23] This issue needs addressing urgently, especially in the light of the recent consultation documents on regional airport development. However, the focus here is on the possible larger-scale impacts of aviation, on surface UV radiation through changes in atmospheric ozone and on climate.

Aircraft emissions

3.3 During flight, aircraft engines emit carbon dioxide, oxides of nitrogen, oxides of sulphur, water vapour, hydrocarbons and particles - the particles consist mainly of sulphate from sulphur oxides, and soot. These emissions alter the chemical composition of the atmosphere in a variety of ways, both directly and indirectly. On the larger-scale, sulphur oxides in aircraft emissions are important only as a source of particles.

3.4 The unique feature of these emissions is that the majority of them occur far above the Earth's surface. Subsonic aircraft generally cruise in an altitude range of 9 - 13 km, close to the tropopause, the sharp transition between the troposphere and the stratosphere (see box 3A). The troposphere is the region in which the turbulent motions and precipitation related to weather occur. In contrast the stratosphere is relatively stable and the vertical motions in it are generally sufficiently small compared with the horizontal motions that the air travels almost horizontally.

Box 3A The structure of the atmosphere below 50 km



Ultra-violet (UV) solar radiation is absorbed by ozone (O_3) as it passes through the atmosphere, heating the upper portion of this region and causing a temperature maximum near 50 km. Below this, some of the solar radiation is reflected, mainly by clouds, and some is absorbed but about half gets through to the surface. This heats the near surface region and results in a second temperature maximum, this time at the surface. The tropopause marks the sharp boundary between the troposphere, in which the temperature drops markedly with height, and the stratosphere, where it generally increases with height.

Various atmospheric constituents allow most of the short-wave solar radiation through but absorb and then re-emit the long-wave thermal radiation. This warms the near surface region, the so-called greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4) and ozone (O_3) are examples of important 'greenhouse gases'. A convenient measure of the greenhouse effect of a change in a constituent is provided by the imbalance between solar and thermal radiation at the tropopause when the change in the constituent is suddenly imposed. This is known as radiative forcing.

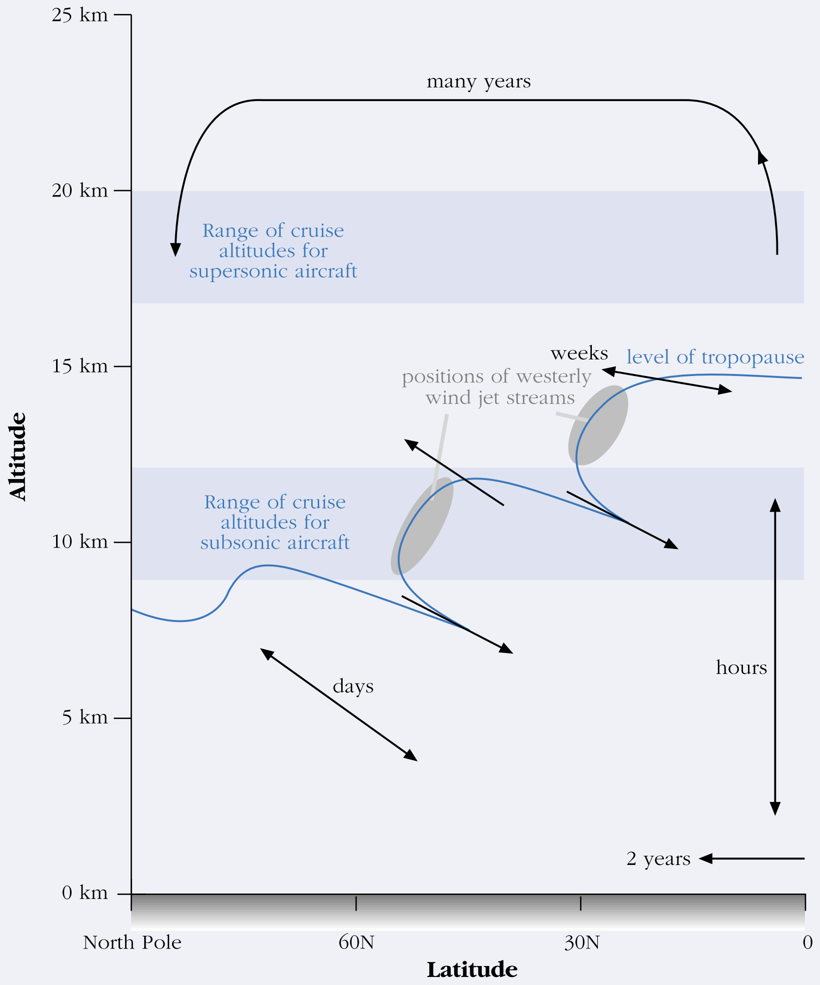
3.5 At the top of the atmosphere, the solar energy absorbed by the Earth/atmosphere is balanced by the emission of longer wavelength thermal radiation (heat). However, the thermal radiation emitted from the near surface region is absorbed by greenhouse gases (see box 3A), which then re-emit back towards the surface, keeping it warm. The heat lost to space is from levels typically near 5 km where the air is colder than at the surface.

3.6 The impact of aircraft emissions can be very different depending whether they are in the upper troposphere or the lower stratosphere. Both the abundance of trace gases and the dominant chemical composition and associated chemical reaction are very different in the two regions. In particular water vapour content is relatively high in the troposphere and low in the stratosphere whereas ozone levels are much higher in the stratosphere. Stratospheric ozone absorbs radiation from the sun. This leads to a heating profile in the stratosphere that determines its character, and also protects life at the surface from the harmful effects of the UV radiation.

3.7 The height of the troposphere varies with latitude. In the tropics the tropopause is higher than the normal range of subsonic cruise altitudes but in polar regions it is usually at the lower end of this range. Whether an aircraft cruises in the upper troposphere or the lowermost stratosphere depends on its location, the weather and the time of year (see box 3B). Supersonic aircraft typically cruise at levels in the range 17 - 20 km, which is always in the stratosphere.

3.8 Jet streams are typically located at the tropopause in regions where there are abrupt transitions in the horizontal between the troposphere and the stratosphere. Since eastward-flying aircraft are often routed in the strong westerly winds in jet stream regions to save fuel and time, they often fly close to this almost vertical tropopause.

Box 3B Transport times in the Northern Hemisphere



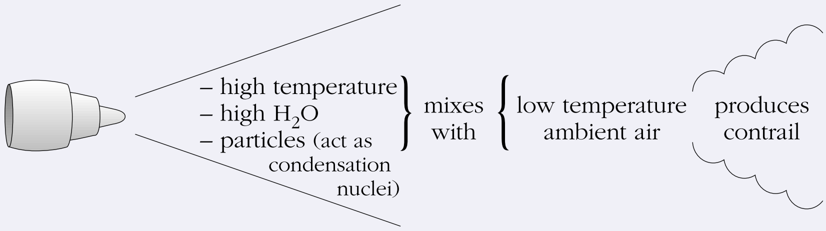
A schematic showing a latitudinal profile of the tropopause in the Northern Hemisphere and giving transport time-scales. The tropopause is typically near 9 km in altitude in polar latitudes and 16 km in equatorial regions. On any particular day at any particular longitude its position could be as shown, with a structure determined by the weather systems. The likely position of 'jet streams', westerly wind maxima, is indicated. The range of cruise heights for subsonic and supersonic aircraft are shown. Arrows indicate typical directions for transport of gases and time-scales for these transports are given.

3.9 The dominant physical and chemical processes differ between the troposphere and stratosphere, as do the time-scales for transporting air between regions. Water vapour added by any human activity in the troposphere is soon lost through mixing and precipitation processes, whereas at 20 km it persists and moves slowly towards the pole.

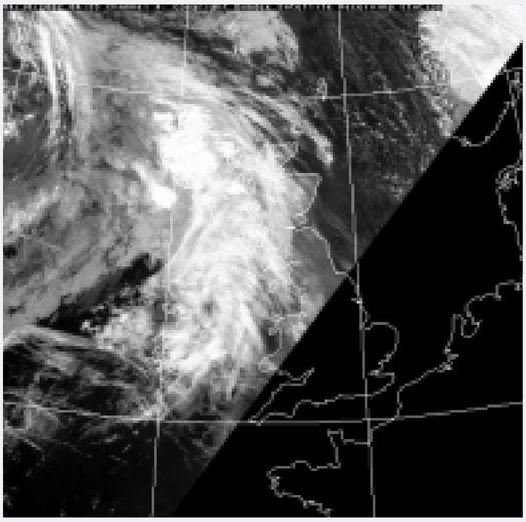
3.10 A 'conservative gas' is one that becomes well mixed throughout the atmosphere so that the point of emission is irrelevant for its impact on climate. The carbon dioxide produced by the combustion of kerosene in aircraft engines behaves as a conservative gas and so becomes well mixed. However, oxides of nitrogen, produced by high temperature burning in the engine, are rapidly involved in chemical reactions that lead to changes in both ozone and ambient methane. These reactions are complex and sensitive. Ozone is generally produced by oxides of nitrogen in the troposphere and destroyed by it in the lower stratosphere. Since the lifetime of ozone is relatively short, its aircraft-induced increase or decrease is restricted in both the vertical and the horizontal. The lifetime of methane, however, is sufficiently long that the reduction in it produced by the emitted oxides of nitrogen becomes distributed throughout the atmosphere.

3.11 In the troposphere the amount of water vapour emitted in aircraft exhaust is negligible compared with the pre-existing concentrations in the atmosphere. However, along with the particles emitted, the water vapour can lead to condensation trails (contrails - see box 3C), some of which can persist for hours and perhaps trigger the development of cirrus clouds. Subsequent cirrus cloud may also be further influenced by particles emitted by aircraft.[24]

Box 3C Contrails



Contrail persists if ambient air is supersaturated (~ 10 – 15% at 10 km)
Contrail can spread to form extensive cirrus cloud



When the moist, high temperature air from a jet engine mixes with the ambient cold air, saturation can occur and the moisture can condense onto particles in the atmosphere, and in particular those present in the exhaust. The result is a condensation trail, or contrail.

On about 10 - 15% of occasions in the upper troposphere in middle latitudes, the ambient air is already supersaturated with respect to ice. In supersaturated conditions contrails will persist and tend to spread. Sometimes they can spread to form or initiate a cirrus cloud, though the amount of such cirrus cloud formed by aviation is currently unknown. The extent of the contrail and cirrus cloud can be striking, those shown in the lower left corner of the plate to the left persist out over the Atlantic.

Contrails and cirrus clouds reflect some solar radiation and therefore act to cool the surface. They also absorb some upwelling thermal radiation, re-emitting it both downwards, which acts to warm the surface, and upwards. On average the latter warming effect is thought to dominate.

Changes in atmospheric ozone and associated surface UV changes

3.13 The total ozone in an atmospheric column above the surface is one determinant of the UV radiation there. Aircraft emissions of oxides of nitrogen in the troposphere will act to increase ozone levels and therefore decrease surface UV radiation, whereas emissions in the stratosphere near 20 km, act in the opposite way.

3.14 In its 1999 report *Aviation and the Global Atmosphere*, the Intergovernmental Panel on Climate Change (IPCC) estimated that in 1992, due to the overwhelming dominance of subsonic transport, the net oxides of nitrogen-induced change in ozone was an increase of about 6% at cruise altitudes in the Northern Hemisphere. They calculated that this ozone increase would rise to 13% by 2050 under their basic reference scenario. The associated increase from 1970 levels in the total ozone in a column of air was calculated to be 0.4% and 1.2% by 1992 and 2050, respectively.[25]

3.15 Increased atmospheric ozone concentrations result in a decrease in the UV reaching the Earth's surface. For 1992, the consequent reduction in erythemal dose rate (surface solar UV radiation weighted according to its sunburn impact) due to aviation was estimated to be about 0.5% in July at 45N. In fact, due to other human activities the column ozone was observed to *decrease* and the dose rate consequently *increased* by 4% in the period from 1970 until 1992. For 2050, the projected decrease in the Northern Hemisphere July erythemal dose rate due to aviation alone was 1.3%. The Southern Hemisphere changes were predicted to be some four times smaller.

3.16 Since, at the stratospheric flight levels of supersonic aircraft, the oxides of nitrogen emissions act to decrease ozone there are competing effects on the column ozone and the surface UV when such aircraft are included in the fleet. In the reference scenario for 2050 with 11% substitution of subsonic by supersonic aircraft, IPCC found that the small number of stratospheric-flying aircraft would dominate to give a projected increase of 0.3% in the Northern Hemisphere July erythemal dose rate.[26]

3.17 The projected changes in damaging UV radiation are very small. Unless there is a major change in the number of supersonic aircraft cruising in the stratosphere, present knowledge suggests that there does not appear to be a significant problem from ozone-related change in surface UV associated with aircraft.

Climate change

3.18 Many of the emissions from aircraft change the absorption of solar radiation and the absorption and emission of thermal radiation. They may, therefore, affect climate. Important aspects of such climate change could be a local change in average precipitation or the frequency and intensity of heat waves. Here, as in other assessments of the potential impact of human activities on climate, discussion of the effects of air transport will largely be restricted to consideration of possible changes in globally averaged surface temperature. However, it should be noted that such a measure of climate change is limited in its scope. Further, the importance of regional and local changes in climate forcing is likely to be particularly underestimated by this global measure.

3.19 Carbon dioxide is a greenhouse gas and emissions of it from aircraft become well mixed (see paragraph 3.10) and act to warm the surface of the Earth globally. The aircraft-induced reduction in the greenhouse gas methane is also well mixed and therefore acts to give a global cooling effect.

3.20 Ozone is also a greenhouse gas and its impact is normally considered in terms of a global warming effect. However, aviation-induced increases remain quite local and impacts on climate from such increases are therefore likely to be more subtle than suggested by its impact on globally averaged temperature. Contrails and cirrus clouds, though even more local, have also usually been considered in terms of a global warming effect.

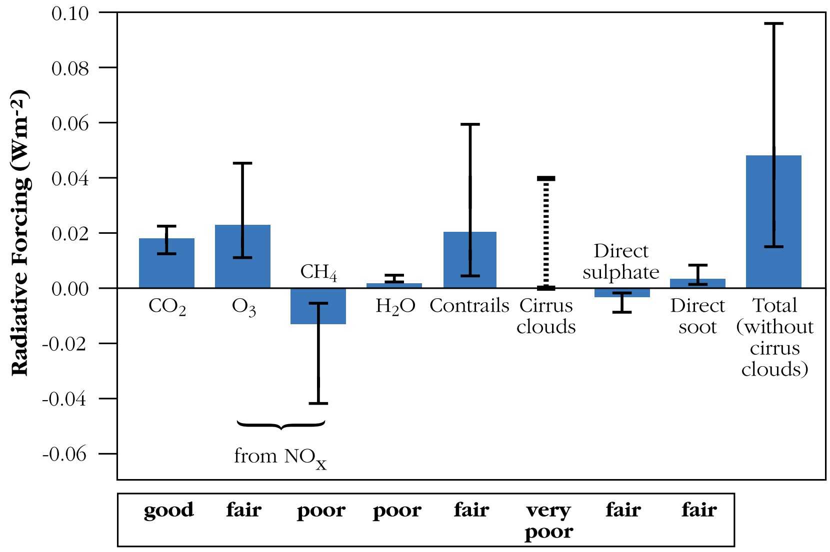
3.21 To estimate the relative and absolute importance of various activities and emissions on climate, IPCC[ii] has used a globally averaged measure, known as ‘radiative forcing’, of the imbalance in solar and thermal radiation caused by the sudden addition of the activity or emission (see box 3A). This is a useful concept because models show that the change in globally averaged surface temperature is usually approximately proportional to radiative forcing.

---

ii In its reports including IPCC (1999). *Aviation and the Global Atmosphere.*

3.22 According to IPCC, in 1992 aviation was responsible for 2% of carbon dioxide emissions due to the total burning of fossil fuel and 13% of that associated with transport. However, the total greenhouse impact was more important than this would suggest (see figure 3-I). Since the vast majority of the flights were subsonic and therefore in the 9 - 13 km height range, the emissions of oxides of nitrogen led, on average, to an increase in ozone as well as a decrease in methane. Relative to carbon dioxide, the radiative forcing factors were estimated to be +1.3 for ozone and -0.8 for methane. The factor +1.1 was given for contrails. The impacts of water vapour, and sulphate and soot particles were given as small and positive. The total radiative forcing was calculated to be about 2.7 times that of the carbon dioxide alone, a factor that compares with numbers generally in the range 1 - 1.5 for most other activities. Consequently, aircraft were seen as being responsible for 3.5% of the total radiative forcing in 1992.

Figure 3-I Radiative forcing from aviation effects in 1992



IPCC's estimates of the radiative forcing in Watts per square meter from subsonic aircraft emissions in 1992. The bars indicate the best estimates of the forcings related to the different aircraft induced effects and their total (apart from cirrus clouds) while the line indicates a range of uncertainty. The evaluations of the relative levels of scientific understanding are indicated below the graph.

3.23 The IPCC indicated for each component the level of scientific understanding and the uncertainty range for its radiative forcing. The range for the total radiative forcing is given by IPCC to be about +1 to +5 times the best estimate for the effect of the carbon dioxide alone. The radiative forcing estimate for carbon dioxide was considered to be fairly robust but for the other emissions and effects there were considerable uncertainties.

3.24 The radiative forcing factor relative to carbon dioxide for ozone was given the range +0.6 to +1.8, and that for methane –0.3 to –2.2. More recent estimates[27] have supported IPCC's best estimate for the positive impact of ozone but suggested that the negative impact of the methane loss should have been at the small end of the range given.

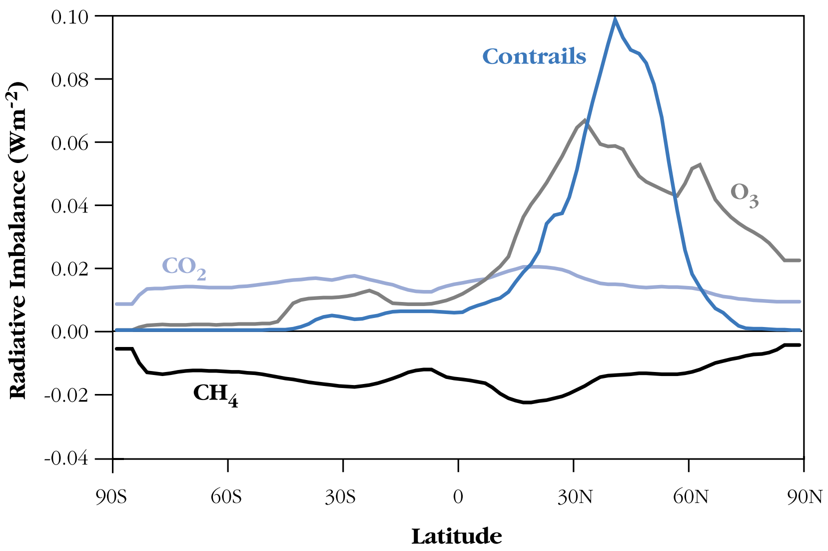
3.25 The uncertainty range given by IPCC for the radiative forcing due to contrails was extremely large, from +0.3 to +3.2 times the impact of the carbon dioxide.[28] For cirrus cloud stimulated by aircraft emissions and the associated contrails, the uncertainty felt by IPCC was such that they did not even give a best estimate, and they did not include it in their total radiative forcing figure for aviation. However, they gave a range of 0 to +2.1 for the factor relative to the carbon dioxide.

3.26 One very recent study has suggested a much smaller best estimate for the contrail impact than IPCC,[29] and other methodologies produce a wide range of answers. Since IPCC's report in 1999, it is apparent that the uncertainties over contrail impacts have increased rather than decreased.[30] However, evidence provided to us in connection with this study suggests that the relationship between air traffic and cirrus cloud is becoming more certain.[31]

3.27 It should be noted that a recent comparison of the three-day period following 11 September 2001, when all commercial aircraft in the United States were grounded, has shown some evidence of a 1°C to 2°C increase in the day-night difference in temperature over the USA.[32] This is consistent with the theoretical proposition that aircraft contrails and related cirrus cloud act to lower day-time temperatures by reducing solar radiation and raising night-time temperatures by reducing heat loss. If the result turns out to be robust it will be the first empirical evidence that aircraft contrails and related cirrus cloud are indeed significant in the Earth's radiation balance.

3.28 The use of the global radiative forcing concept and the opposite signs of the two oxides of nitrogen-related impacts associated with changes in ozone and methane should not be taken to imply that the combined effect is unimportant. An indication of this is given by figure 3-II which shows the radiative imbalance as a function of latitude. The well-mixed gases lead to effects which are almost uniform with latitude and the methane reduction tends to compensate the carbon dioxide increase in the Southern Hemisphere. The radiative imbalance is concentrated in the middle latitudes of the Northern Hemisphere. The contrast between the two hemispheres could have global climate importance and the region with the stronger radiative forcing would be expected to experience larger local climate change.[33]

Figure 3-II Radiative imbalance at the tropopause as a function of latitude

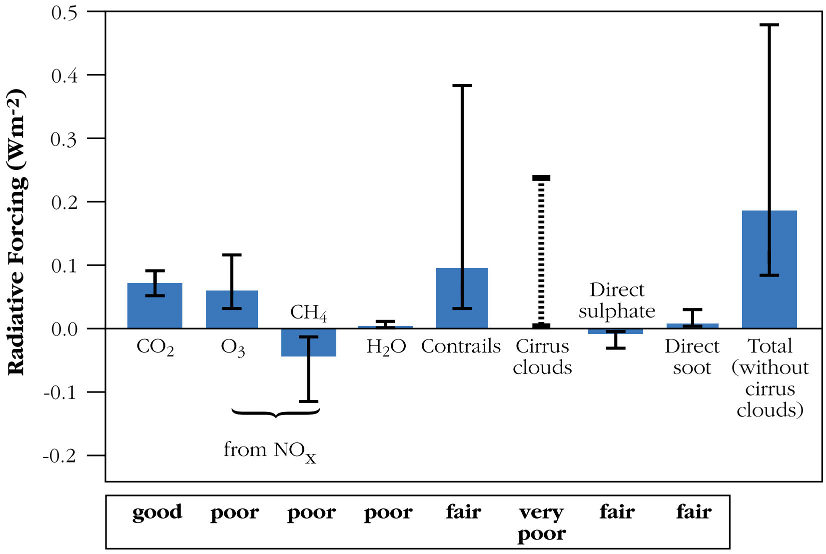


IPCC calculation of the aviation induced 1992 radiative imbalance at the tropopause in Watts per square meter as a function of latitude.

3.29 For the period 1990 to 2050, IPCC introduced various scenarios for traffic growth and two technical scenarios for fuel burn and oxides of nitrogen production, which are discussed further in Section 4. These scenarios gave an increase in carbon dioxide emissions by a factor ranging between 0.5 and 9. The reference scenario used by IPCC and referred to above had a traffic growth of 3.1% per annum (less than that seen in the last decade) and a fuel burn rate growth of 1.7%. Thus by 2050, the traffic would be a factor of 6.4 larger and the fuel burn 2.7 times larger, the difference being because of the large improvements in aircraft efficiency assumed.

3.30 At any time, the radiative forcing associated with a long-lived gas such as carbon dioxide depends on the emissions over the previous period and not just the instantaneous emissions. For its reference scenario IPCC estimated that the radiative forcing by carbon dioxide was about a factor of 4 larger than in 1992 (figure 3-III). Relative to this 2050 carbon dioxide impact, the best estimates for the radiative forcing factors associated with oxides of nitrogen were +0.8 associated with increased ozone and –0.6 associated with decreased methane. The best estimate for contrails was a factor 1.2. The total radiative forcing, not including cirrus cloud, was about 2.6 times that of the carbon dioxide alone and a factor 3.8 larger than its 1992 value.

Figure 3-III Predicted radiative forcing from aviation effects in 2050



IPCC estimates of the radiative forcing in Watts per square meter from subsonic aircraft emissions in 2050 for its reference scenario.

3.31 IPCC considered six aviation emission scenarios constructed from different transport and aircraft construction scenarios. The reference scenario discussed here was at the lower end of the range of radiative forcings, the lowest of which was a factor of 1.5 times smaller and the highest a factor of 3 times larger than the reference scenario. The range of radiative forcings is 2.6 - 11 times that for 1992.

3.32 For a supersonic aircraft flying in the 17 - 20 km range, IPCC suggests that the oxides of nitrogen-induced decrease in ozone gives a radiative forcing that is comparable with that for the carbon dioxide but of the opposite sign. Methane changes are not significant, and contrails and cirrus cloud are not produced. In this case the radiative forcing is totally dominated by the impact of the water vapour emitted: its forcing is positive and 10 times larger than that of the carbon dioxide. This issue is discussed further in Section 4.

3.33 IPCC considered one alteration from their reference scenario, in which 11% of the fleet was replaced by supersonic transports. The radiative forcing of the supersonic aircraft was calculated to be about a factor of 5 larger than that for the subsonic aircraft displaced. Consequently, the total 2050 radiative forcing due to aviation then rose by more than 40% to a figure some 5.4 times its 1992 value.

Implications

3.34 The major, large-scale environmental problem associated with the continuing expansion of aviation is the forcing of climate change. One aspect of climate change is global warming and a convenient, but approximate, measure of the tendency to produce global warming is the concept of radiative forcing. The IPCC's estimates of radiative forcing due to aircraft emissions appear to remain valid, though the uncertainties are still at least as large. The magnitude of the positive impact of increased cirrus cloud remains the major unknown.

3.35 The total radiative forcing due to aviation is probably some 3 times that due to the carbon dioxide emissions alone. This contrasts with factors generally in the range 1 - 1.5 for most other human activities.

3.36 The IPCC reference scenario assumes less aviation growth than seen in the period up to 11 September 2001 and large technology advances. For 2050 the radiative forcing estimate, without a cirrus cloud estimate, is about 3.8 times larger than in 1992 and would correspond to about 14% of the total radiative forcing for 1992. The range of scenarios give 2050 radiative forcings that are 2.6 - 11 times larger than in 1992 and from 10% - 40% of the 1992 total.

3.37 IPCC compared their estimates of aviation radiative forcings with those from a benchmark scenario of future emissions due to all anthropogenic activities as used by them in their *Second Assessment Report - Climate Change 1995*.[34] However, for their *Third Assessment Report - Climate Change 2001*, IPCC developed a new set of emission scenarios up to 2100.[35] We used some of these in our Twenty-second Report as a basis for longer-term scenarios. One scenario (B1 in IPCC 2001 terminology) gives an approach to stabilisation of climate with carbon dioxide capped at about twice the pre-industrial level, consistent with the target recommended by us in our Twenty-second Report. Here we use the 2050 radiative forcings from this scenario as a benchmark for the aviation scenarios. However, we note that this scenario would have all emissions peaked or starting to fall by 2050 whereas the aviation emissions on each scenario would be on a continuing upward trend.

3.38 Compared with this benchmark stabilisation scenario, in 2050 the contribution of aviation to the total radiative forcing would be in the range 4% - 17%, with the reference aviation scenario contribution being 6%.

3.39 Since IPCC's 1999 report, *Aviation and the Global Atmosphere*, research has broadly supported the projections made there, but also suggested a number of adjustments. Some later research has suggested that IPCC may have over-estimated the possible climatic effect of contrails. However, as explained in paragraph 3.25, there is conflicting evidence and huge uncertainty. In any case, three other results from recent research more than compensate any implication that the impact of aviation may be smaller than IPCC suggested. Firstly, there is an increasing indication that aviation-induced cirrus cloud will indeed be a significant contributor to warming. Secondly, recent research suggests that the cooling effect of the aviation-induced methane reduction had previously been over-estimated.

3.40 Finally, recent estimates for the growth of aviation in the period 1992 - 2000 have shown that it is continuing to be larger than the IPCC reference value.[36] The distance travelled in the period was estimated to have risen by 43% and the fuel usage by 33%.[37] These correspond to annual percentage growths of about 5% and 4%, respectively, and follow IPCC's higher growth scenario rather than the more central reference value. As discussed in Section 2, the decrease in passenger transport since 11 September 2001 is widely expected to be only a temporary dip.

3.41 In summary, we consider that the IPCC reference value for the climate impact of aviation is more likely to be an under-estimate rather than over-estimate. We conclude that, unless there is some reduction in the growth in the sector, or technology improves considerably more than was assumed by IPCC, by 2050 aviation will be contributing at least 6% of the total radiative forcing consistent with the necessary stabilisation of climate. A safer working hypothesis is that it will be in the range 6% - 10%. If significant fleets of sonic or supersonic aircraft are flown then the aviation contribution would be higher than this.

3.42 It is likely that the amount of time that subsonic aircraft spend in the stratosphere has been rather underestimated by calculations made using climatological tropopause heights.[38] The current knowledge of the chemistry in this region is such that it is difficult to determine the importance of this. Contrail and cirrus cloud effects would be absent but the radiative forcing due to water vapour emissions would be expected to be significantly more important.

3.43 It is possible that a decrease in cruise level would, because of the higher ambient temperatures, lead to less contrail and cirrus cloud impact. It is also likely that it would lead to less radiative impact from ozone production. Some recent calculations[39] suggest that for radiative forcing these benefits may out-weigh the increased carbon dioxide emissions associated with higher fuel usage. However there is still great scientific uncertainty in this area.

3.44 Modern weather forecasting capabilities are increasingly such that the regions of likely supersaturation in the upper troposphere and the height of the tropopause in any region may be usefully predicted some days in advance. When there is more scientific understanding of the various elements involved in the climatic impact due to aviation, it should be possible to route individual aircraft so that, for example, they spend less time in regions where persistent contrails and enhanced cirrus cloud could be formed, or so that they almost always remained in the troposphere where the water vapour effects are negligible.

3.45 Supersonic aircraft flying at 17 - 20 km have a radiative forcing some 5 times greater than the 9 - 13 km subsonic equivalent. They also contribute to ozone depletion. A subsonic aircraft at 14 - 15 km would be expected to have a radiative forcing between the two values, though again a confident prediction at this time is impossible. Significant fleets of any such higher-flying aircraft would be expected to have very important global environmental impacts.

3.46 Liquid hydrogen as a fuel would clearly remove the carbon dioxide effect at the point of emission. The effects of oxides of nitrogen would still be present, depending on the burn temperature, and because 2.6 times as much water vapour would be produced, other impacts are likely. More water could mean more contrails. However, recent work has suggested that the decrease in emitted particles that act as condensation nuclei might mean that the drop size increases sufficiently to compensate for this effect.[40] If, as appears likely, hydrogen fuelled aircraft were to cruise at higher levels, then the increased water emitted into the stratosphere would suggest larger radiative forcing.

3.47 Since a hydrogen fuelled aircraft produces 2.6 times as much water as a kerosene fuelled aircraft, and since the water vapour produced by the latter cruising at 17 - 20 km gives a radiative forcing some 5 times that of a lower flying subsonic aircraft, a hydrogen fuelled supersonic aircraft flying at stratospheric levels would be expected to have a radiative forcing some 13 times larger than for a standard kerosene fuelled subsonic aircraft. This is discussed further in Section 4.

3.48 Local and regional pollution issues, though not the focus of this report, are also very important. There can be conflict between measures to tackle them and the larger-scale flight-related environmental issues. In particular, both technological and flight routing measures to tackle noise from take-offs and landings, and technological measures to decrease emissions of oxides of nitrogen during these and on the ground can lead to larger radiative forcing associated with carbon dioxide emissions through the entire flight and emissions of oxides of nitrogen at the cruising altitude. This too is discussed further in Section 4.

4 Technical possibilities

4.1 In this section, we investigate the extent to which technological improvements might off-set the environmental impacts of air transport. We examine three possible areas for development:

- airframes, that is for conventional aircraft, the fuselage, wings and tail
- engines and fuels
- operation, including air traffic management and routeing.

4.2 The environmental impacts of aircraft and engine manufacture are not considered since they are negligible compared to effects from aircraft in use. Recent studies by Airbus have shown that energy use in service represents more than 99% of total energy consumption over the aircraft life cycle.[41] In 1992, the Energy Technology Support Unit (ETSU) estimated that energy use and emissions during manufacture of an Airbus A-320 correspond to about one week of service.[42]

4.3 The composition and quantity of the fuel used in an aircraft determine its emissions of carbon dioxide and water vapour. Airframe and engine design both determine fuel use and hence these emissions, and are also the principal determinants of aircraft noise. Other emissions, in particular oxides of nitrogen and particulates, depend on engine design and operating conditions. Operation determines the fuel use over a flight and also affects the environmental consequences (see Section 3).

4.4 Developments in both airframe and engine design have progressively improved fuel efficiency and reduced noise and other emissions,[43] while maintaining a safety record that is better than any other mode of transport when compared on a passenger-kilometre basis.[44] The speed of these changes has been helped by the inherent benefits to the airlines in minimising fuel use. However, as discussed in Section 2, older and less efficient aircraft remain in service after more efficient designs are introduced and therefore changes to the overall emissions profile of the sector have a significant time delay.

4.5 The performance of an aircraft differs between the different phases of a flight. For assessment of engine emissions, ICAO concentrates on landing and take-off by recognising four operating modes: approach (below 914m or 3,000 ft), taxi/ground idle, take-off, and climb-out (to 3,000 ft).[45] However, these modes refer to relatively localised emissions around airports whereas the emissions discussed in Section 3 arise primarily from flight above 3,000 ft. 'Climb-out' as defined by ICAO usually lasts no more than a few minutes[46] whereas an aircraft typically takes 17 - 30 minutes to climb to its cruising altitude, the higher values corresponding to long-haul flights.[47]

4.6 ICAO has published standards for engine performance based on a take-off and landing cycle comprising 0.7 minutes take-off, 2.2 minutes climb-out, 4 minutes approach and 26 minutes idle. The standards have been applied since 1986 to all major newly manufactured turbojet and turbofan engines. CAEP (see paragraph 2.16) is responsible for ongoing revision of the regulatory emission levels and is now pursuing new certification methodologies that will also take account of the flight mode. For oxides of nitrogen, the CAEP/2 standard became effective for new aircraft types in 1996 and for all newly manufactured aircraft in 2000.[48] The 1998 CAEP/4 set new standards which will come into force on 1 January 2004 for new aircraft types, with a possible production cut-off in 2008 whereby all aircraft delivered after 2008 may have to meet the CAEP/4 standards. The CAEP/6 meeting planned for January 2004 is expected to define further new levels of stringency for oxides of nitrogen, but these will not come into force for new aircraft types for several years.[49]

4.7 Some aviation industry bodies and companies have announced targets for further improvements in efficiency and environmental performance. In Europe, these are co-ordinated by the Advisory Council for Aeronautical Research in Europe (ACARE). ACARE has set targets for improving the environmental performance of the whole industry, covering engines, airframes and operations (see table 4.1). Much of the technology development is being carried out within the EU-funded EEFAE programme. This includes two programmes, ANTLE and CLEAN, with research targets for a demonstration engine. As leader of the EEFAE programme, Rolls Royce plc. has declared intermediate targets for the performance of its own new engines, in combination with airframes for the noise target. The differences between the targets arise from the different timescales and from the recognition that the performance of a production engine falls below that of the demonstration engine. The apparently more ambitious ACARE targets for fuel and carbon dioxide demonstrate the possible scope for improving operations in addition to improving engine and airframe design.

Table 4.1 Industry targets for emission reduction

Programme	Industry: ACARE	Engines			Engines and Airframes: ICCAIA/IPCC	
		ANTLE	CLEAN	Rolls Royce	Scenario a	Scenario b
Target Year	2020	2008	2015	2010	2050	
Fuel burn and CO_2 formation (per passenger-kilometre)	50%	12%	20%	10%	40-50%	30-40%
NO_x (relative to CAEP/2 standards)	80%	60%	80%	50%	10-30%	50-70%
Noise	50%			50%	50%	

Key:
ACARE - Advisory Council for Aeronautical Research in Europe
ANTLE - Affordable Near-Term Low Emissions
CLEAN - Component vaLidator for Environmentally friendly Aero eNgines
EEFAE - Efficient and Environmentally FriendlyAero Engines
ICCAIA - International Coordinating Council of Aerospace Industries Associations
Rolls Royce - as lead party in EEFAE.

4.8 The prospects for technological improvement were also reviewed by IPCC[50] over a longer time horizon. These targets are also summarised in table 4.1; they refer to engines and airframes. The IPCC's assessments were based on 1997 projections by the International Coordinating Council of Aerospace Industries

Associations (ICCAIA), which ran up to 2050. The ICCAIA figures are also shown in table 4.1 for two scenarios:

a. continued development to reduce both fuel use and formation of oxides of nitrogen

b. concentration on reducing oxides of nitrogen with less emphasis on fuel efficiency.

Airframes, fuel use and flight distances

4.9 The thrust force required from an aircraft engine depends on the design of the airframe and the weight of the aircraft and its contents (see box 4A). The thrust force required also varies between the different phases of a flight. The amount of fuel needed to achieve the requisite thrust depends on the engine efficiency. Therefore, improvements in both airframe design and engine design reduce fuel use and hence emissions of carbon dioxide and water vapour.

Box 4A Altitude, drag and fuel use

The forces on an aircraft in steady flight can be simply resolved into lift and drag:

Lift - the force, mainly on the wings, that supports the weight of the aircraft and its contents

Drag - the force that resists motion, and which therefore has to be balanced by the thrust of the engines.

The rate of fuel burn in steady flight is proportional to the drag. An aircraft has an optimum condition, fixed by the airframe design, at which the drag is lowest for a given weight, so that the ratio of lift to drag is roughly constant.

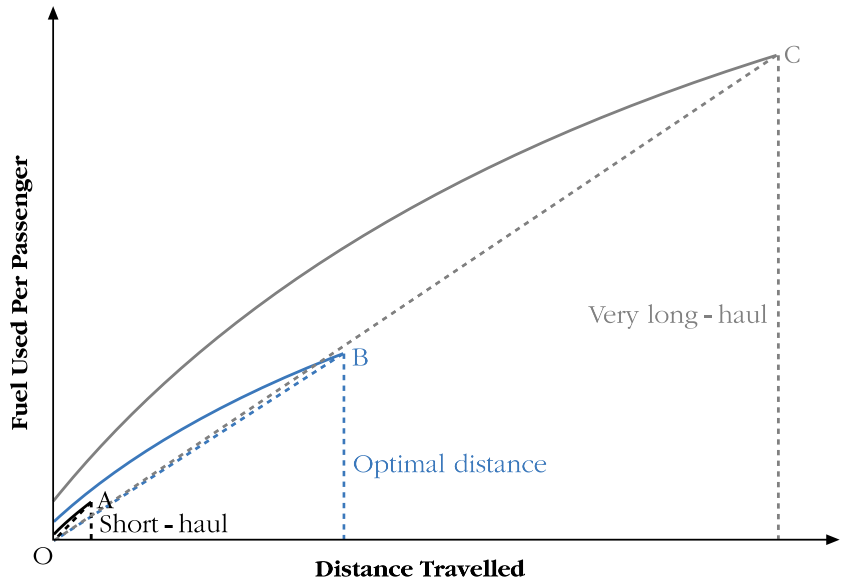
Both lift and drag are proportional to the density of the surrounding air. When an aircraft with a fixed cruising speed is heavily laden, it must fly at relatively low altitudes where the air is relatively dense. As fuel is used and the aircraft becomes lighter, it can move to higher altitudes where the air is less dense. This reduces the drag, so that the rate of fuel use decreases. In addition to the fuel used to overcome drag, further fuel is used in take-off to get the aircraft to its cruising altitude and speed. Some additional fuel may also be used in landing, especially if the aircraft is 'stacked' before being able to land.

For a long-range aircraft the majority of its load at take-off is its fuel; the fuel might be five times the weight of the payload. Thus, for the same number of passengers, a very long-range aircraft must be bigger and heavier to accommodate this fuel. To get the heavy aircraft up to the final cruise altitude and to overcome the extra drag requires more thrust and more fuel to be burned. Typically, such an aircraft begins its cruise at about 9,500 m (31,000 ft) and climbs progressively to about 12,500m (41,000 ft) as the flight proceeds and fuel use decreases its weight.

4.10 The rate of fuel burn varies widely between the different phases of a flight.[51] Take-off may use the full engine thrust, but airport runways are normally sufficiently long for the engines to be derated; this reduces noise and prolongs engine life. The rate of fuel use declines during climb-out and in the climb to cruising altitude; during the cruise phase it is typically less than half the rate for maximum thrust, falling to 25% or less during approach.

4.11 The high rate of fuel burn during take-off and initial climb represents a disproportionate fuel usage for short flights. This is shown schematically in figure 4-I. Curve A represents a typical flight between Stansted and Edinburgh: around 500 km (310 miles or 270 nautical miles) at a cruising speed of just over 1,000 km/hr (620 mph). Some 20% of the total fuel use arises from getting airborne and landing, with the remaining 80% corresponding to the 'en-route' part of the flight that contributes distance (including the climb to cruising altitude). The average fuel use per passenger-kilometre over the whole flight is then up to 25% higher than the use en-route. The proportion of fuel used during take-off and landing and the overall average fuel use per passenger-kilometre increases even further for shorter flights, such as between London and Amsterdam or Paris at around 350 km (220 miles or 190 nautical miles), or London and Manchester at a distance of only 260 km (160 miles or 140 nautical miles). Improvements in technology might reduce overall fuel use per passenger-kilometre but cannot eliminate the increase in average fuel use for short-haul flights.

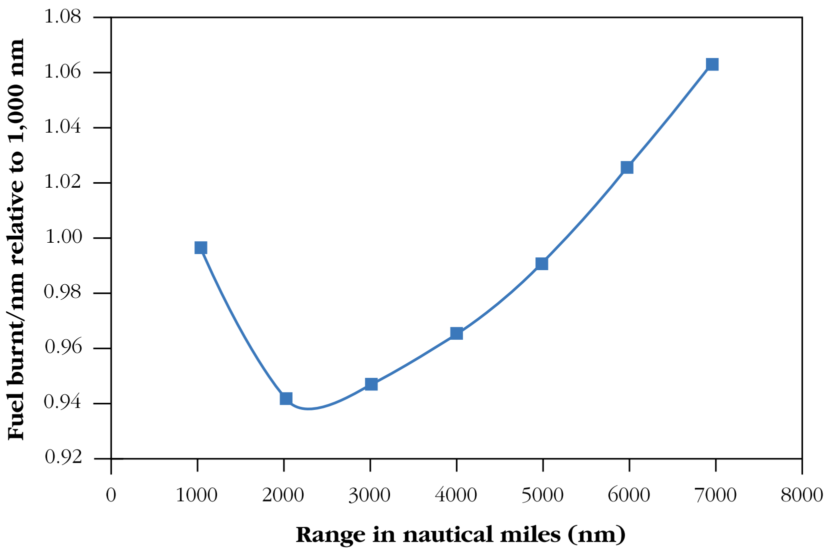
Figure 4-I Fuel used per passenger on short and longer-haul flights



4.12 The disproportionately large fuel use for very short flights, including all UK domestic flights and many flights within Europe, can be further compounded by delays in landing, for example, if an aircraft is put into a holding pattern because of air traffic constraints on landing slots. The higher fuel use by short-haul flights is often further exacerbated because many of the aircraft in this kind of service are of older, less efficient design. Confirming the significance of relatively short-haul flights, the Air Travel - Greener by Design Steering Group (see paragraph 4.14) estimated 'that more than two thirds of jet fuel is used over sectors shorter than 5,000 km and more than half over sectors shorter than 2,800 km (1,700 miles or 1,500 nautical miles)'.[52] When considered alongside the local impacts of take-off and landing, the conclusion must be that short-haul air traffic has disproportionate environmental impacts.

4.13 Take-off and landing become less significant as the flight distance increases. However, fuel use per passenger-kilometre increases for very long-haul flights because of the large quantity of fuel that has to be carried during the early stages of the flight - this is explained in box 4A and illustrated by curve C in figure 4-I. There is an intermediate range of flight distances for which the average fuel use is least, illustrated by curve B in figure 4-I. The most fuel-efficient flight distance is around 2,300 nautical miles (4,300 km or 2,700 miles) corresponding, for example, to flights from Europe to the east coast of North America. Figure 4-II illustrates this optimal range, showing representative values for average fuel use per passenger-kilometre for longer flights, recognising that aircraft are optimised for their design range in terms of size and passenger capacity. Note that short-haul flights are not shown on figure 4-II but would show a very high fuel use per passenger-kilometre for the reasons explained in the preceding paragraphs.

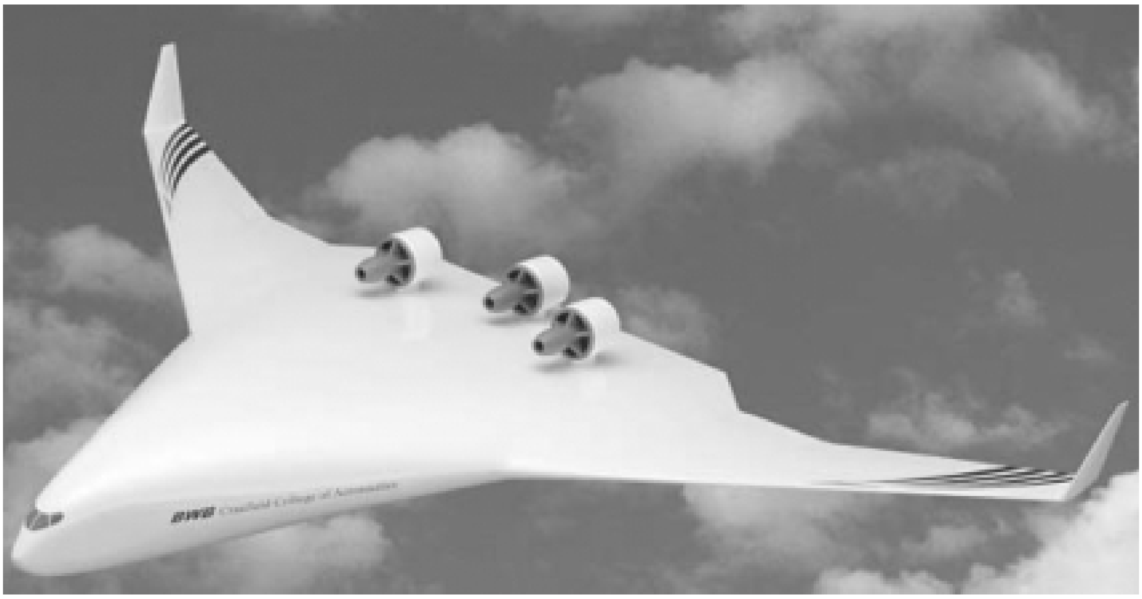
Figure 4-II Average fuel use per passenger-kilometre for flights of varying length



4.14 Partly in response to the challenge articulated by IPCC, the Royal Aeronautical Society, the Society of British Aerospace Companies, the British Air Transport Association, among others, formed the Air Travel - Greener by Design Steering Group and carried out a study, entitled *Greener by Design*, which included possible changes in airframe design.[53] The study noted the need for a systematic methodology for designing aircraft to minimise climate change impacts per unit of payload range.

4.15 Of particular interest was a new design concept, the blended wing-body (BWB, also known as the 'Flying Wing'). This design has the body partly or wholly contained within the wing, so that the interior of the wing in the central part of the aircraft becomes a wide passenger cabin (see plate 4.1). The design is innovative; we are convinced that it could, as its proponents claim, be significantly lighter and experience very much lower drag than the conventional swept wing-fuselage airframe design. Its fuel usage will therefore be reduced, perhaps by as much as 30%,[54] further reducing weight of the aircraft plus fuel at take-off. Because of the lower weight and drag, this type of aircraft would have lower cruise altitude and longer optimal range (see box 4A). We regard the BWB concept as a development to be pursued in place of supersonic or near-sonic aircraft.

Plate 4.1 Impression of the BWB Design Aircraft



4.16 However, the BWB remains at the conceptual stage. In particular, the stability and controllability of such an aircraft are unproven. Because it is at such an early stage in its development, any introduction into commercial service is, at the most optimistic forecast, at least a decade away. Given the long service lives of aircraft (see Section 2), it will therefore be many decades before BWB aircraft approach their maximum contribution to air travel. It is also clear that the BWB concept is only applicable to large aircraft, for the simple geometrical reason that the embedded passenger cabin must be tall enough to enable passengers to stand up. It could, therefore, contribute to long-haul transport and does not represent a solution to the impacts of relatively short-distance flights.

4.17 The Greener by Design report concludes:

> *'If we include 50 years of technological advance in the projection (based on BWB aircraft) coupled with an engine which reduce NO_x emission by a factor of three, we see a more than tenfold reduction on greenhouse effects relative to today's long range, high altitude aircraft.'*

We regard this statement as optimistic. It implies complete technological and commercial success of the new type of aircraft, maximum possible market share with any new design completely replacing rather than adding to existing aircraft, and reductions in oxides of nitrogen emissions at the top end of the range foreseen by ICCAIA (table 4.1). It is also to be noted that these improvements could only apply to long-haul flights.

4.18 More modest but nevertheless significant improvements can be achieved by incremental measures such as 'lightweighting' using new materials and composites. These improvements are taken into account in the IPCC projections. Other possible developments, such as Active Aeroelastic Wing technology to reduce drag, are altogether more speculative and therefore unlikely even to be introduced for decades.[55]

Fuels, emissions and engine design

4.19 Kerosene is currently used as aviation fuel. It is a mixture of hydrocarbons of chain length typically in the range C9 to C16. Kerosene has been used for aircraft because it provides the best combination of energy density, vapour pressure and combustion characteristics. Combustion of 1 kg of kerosene releases around 43 megaJoules of energy,[56] producing roughly 3 kg of carbon dioxide and 1.2 kg of water vapour.[57]

4.20 Emissions of pollutants differ between the different phases of engine operation. Oxides of nitrogen emissions are greatest when the engines are running at high power during take-off and climb-out. Particulate emissions per unit of fuel are greatest during taxiing and idling, but greatest in absolute quantity during take-off and climb-out. Carbon monoxide emissions are greatest during taxiing and idling. Whereas carbon dioxide and water vapour production are proportional to fuel use, production of oxides of nitrogen and particulates can be reduced by improved engine design.

4.21 The basic gas turbine design emerged in 1947. It has been the dominant form of aircraft engine for some 50 years and there is no serious suggestion that this will change in the foreseeable future. Developments in engine design have brought about impressive reductions in fuel consumption and emissions of oxides of nitrogen and particulates, and increase in maximum thrust. Improvements in the combination of engine and airframe have reduced aircraft noise.

4.22 However, the technology is now relatively mature. Further improvements in engine design, using approaches such as lean-burn and staged combustion,[58] require a trade-off to be made between fuel efficiency, oxides of nitrogen emissions and noise.[59] This is the reason for the two different sets of targets considered by ICCAIA (see paragraph 4.8). Overall, the targets in table 4.1 are challenging. A possible new engine design, the contra-rotating fan, could achieve further improvements but would need to be mounted above the wing. Therefore, it could form part of the BWB development (see paragraph 4.15). Mounting the engines on the top of the aircraft could lead to further noise reduction by providing some shielding between the engine and the ground, either reducing noise or easing the trade-off between noise, oxides of nitrogen and fuel efficiency.

4.23 Hydrogen has been proposed as an alternative fuel for aircraft.[iii] The Commission briefly reviewed the possible introduction of hydrogen, particularly as a transport fuel, in its Twenty-second Report.[60] We noted that hydrogen is not an energy source, but a carrier produced from hydrocarbons by chemical 'reforming' processes or by electrolysis from renewable energy sources. To achieve a major reduction in carbon dioxide emissions over the whole energy supply chain from hydrocarbon sources requires the carbon dioxide from the reforming process to be sequestered rather than emitted to the atmosphere.

4.24 For transport uses, switching from hydrocarbon fuels to hydrogen eliminates carbon dioxide emissions at the point of use, can lower nitrogen oxide emissions, and greatly diminishes emissions of particulate matter. It would also increase the amount of water vapour produced. These changes in emissions would apply to aircraft as well as to other forms of transport.

iii The CRYOPLANE project is, from its own literature, carrying out a 'system analysis covering all aspects relevant for assessing the technical feasibility, safety, environmental compatibility and economic viability of using liquid hydrogen as an aviation fuel'. It involves a consortium of 35 partners from 11 European countries and is supported under the European Commission Fifth Framework Program.

4.25 For ground transport, much of the benefit of hydrogen will result from its use to power fuel cells driving electric transmission for motive power. This leads to substantial increases in energy conversion efficiency by avoiding fundamental thermodynamic limitations on the efficiency of combustion engines.[61] For air transport, however, hydrogen would still have to be used as a fuel for combustion engines, so that its principal advantage for surface transport would be absent.

4.26 Compared to conventional hydrocarbon fuels, hydrogen requires a completely different system for distribution and storage. If used as an aircraft fuel, it would have to be loaded and carried as a liquid at cryogenic temperatures, and would need pressurised and insulated fuel tanks to maintain those temperatures.[iv] The on-board fuel system would be heavier than for kerosene.

4.27 The fuel itself would be lighter, at approximately one quarter of the mass of kerosene needed for equal calorific value. But it is much less dense. Overall the volume of fuel carried would be some 2.5 times that of the equivalent kerosene. The airframe would therefore need to be larger, and so would have a correspondingly larger drag.[62] The combination of larger drag and lower weight would require flight at higher altitudes (as described in box 4A). Therefore, if and when hydrogen does come into use as an aviation fuel, it will be used in large long-haul high-altitude aircraft. It is not seen as a way to reduce the impacts of very short flights. The requirement to carry a greater fuel volume may present an added difficulty for a hydrogen-fuelled BWB aircraft, a design otherwise well suited to long-haul flights (see paragraph 4.16).

4.28 We, therefore, conclude that, even if hydrogen should come into widespread use as a transport fuel, it will be used first for surface transport for which both storage and use will bring greater benefits with less difficulty than for air travel. It follows that hydrogen can be discounted as a way to reduce the climate change impacts of air travel, at least for many decades.

4.29 Furthermore, the environmental benefits of using hydrogen rather than kerosene for fuelling aircraft engines are uncertain. Switching from kerosene to hydrogen would replace carbon dioxide from aircraft with a three-fold increase in emissions of water vapour. For the reasons set out in Section 3 and by IPCC,[63] uncertainties over contrails and cirrus cloud formation, and the radiative impact of water vapour at higher altitudes, raise questions over whether hydrogen fuelling would actually reduce the contribution of air travel to radiative forcing.

4.30 Other possible fuels generally lack the operational benefits of kerosene, or even hydrogen. Of the renewable biofuels, ethanol has been suggested as a possible aviation fuel. However, it has lower energy density than kerosene, requiring aircraft to carry more fuel, and would increase water vapour emissions from aircraft in flight. Moreover it has less attractive combustion characteristics. In particular, under conditions prevailing in some phases of a flight, especially approach, it would be difficult to eliminate formation of formaldehyde as a pollutant in the exhaust gases.[64]

4.31 We therefore share the view that kerosene will remain the fuel for air travel for the foreseeable future.

iv The CRYOPLANE project suggests a design in which the fuel is stored in tanks above the fuselage of a swept wing conventional airframe, in a bulbous extension of the airframe along its top surface.

Operations

4.32 In the near-term, the greatest improvements can clearly come from better use of the existing stock of aircraft. If higher load factors can be achieved, reductions in environmental impact per passenger-kilometre would follow (see Section 2). Reductions in impacts of around 10% are generally regarded as feasible by reducing delays in landing and allowing aircraft to fly on more optimal routes.[65] These operational improvements are part of the ACARE targets for reduced fuel use and carbon dioxide emissions (see table 4.1).

4.33 However, to achieve this benefit will require some non-technical barriers to be overcome.[66] Particularly in Europe, the fracturing of air space between different national air traffic control systems and the use of different technologies are seen as a barrier. Europe-wide action is needed to optimise the use of European air space by harmonising air traffic control technologies and procedures.[67]

4.34 In the longer term, there is the possibility that aircraft on long-haul flights could be routed to minimise their environmental impacts rather than just their fuel consumption. However, as noted in Section 3, this requires better scientific understanding of the effect of altitude, particularly relative to the tropopause. For the same reason, any estimates of the possible improvements achievable by this means remain uncertain.

Comparisons with other transport modes

4.35 In summary, we have received no evidence suggesting that technological improvements are in prospect beyond those considered by IPCC in 1999. We therefore endorse the conclusion reached by IPCC that technological improvements will not offset the growth in air transport represented by any of IPCC's scenarios. We note that this is consistent with the findings of a study carried out for the Department for Environment, Transport and the Regions[68] which concluded that:

> *'even with deployment of the most promising future technologies, if demand is unconstrained by capacity then, in absolute terms, the net effect of the aviation industry on the environment is set to increase.'*

4.36 We further conclude that IPCC's estimates for likely improvements in the environmental impacts of air transport are if anything optimistic; projections should certainly not be any more so. Therefore, the figures discussed in Section 3 remain as our best estimates. By 2050, growth in air transport at the rate foreseen by IPCC would increase its carbon dioxide emissions by a factor of 2.7 and its contribution to radiative forcing by a factor of 3.8 relative to air transport in 1992. Neither of these estimates allows for the effect of cirrus clouds, so that these figures are possibly underestimates.

4.37 The Commission's Twenty-second Report foresaw a stabilised atmospheric composition of 550 parts per million (ppm) carbon dioxide as necessary to avoid risks of catastrophic changes in climate patterns.[69] This, together with the estimates in paragraph 4.36, means that air transport could contribute in the range of 6% - 10% of total radiative forcing. We question the desirability of allowing the environmental impacts of air transport to rise to such levels unchecked and unconsidered, and review the policy implications in Section 5. We consider here how air transport compares with other transport modes.

4.38 As an indicative comparison, the fuel use and carbon dioxide emissions per passenger-kilometre for a fully-loaded cruising airliner are comparable to a passenger car carrying three or four people. Allowing for the effects outlined in Section 3 leading to a factor of around 3 in the radiative forcing of carbon dioxide from aircraft compared to terrestrial transport, travelling by air is broadly equivalent to one or two people travelling in a passenger car.[v] The Commission has already pointed out in its Eighteenth and Twentieth Reports that passenger cars are more environmentally damaging than any other form of surface transport. The comparisons presented here show that air transport is in the same category, albeit with a much better safety record.

4.39 For rail travel, carbon dioxide emissions and fuel use per passenger-kilometre are typically at least an order of magnitude lower.[vi] We noted in paragraph 4.11 that, for relatively short journeys such as within the UK or to nearer parts of continental Europe, the environmental impacts of air travel are disproportionately high. These are precisely the journeys for which efficient rail travel should be available. Promoting air rather than rail for these journeys therefore amounts to a failure to provide a properly integrated transport system. We return to the policy implications of this conclusion in Section 5.

4.40 The comparisons are even sharper for freight. In round numbers, the carbon dioxide emissions for freight carried on long-haul flights are of the order of 1 kg of carbon dioxide per tonne-kilometre. Carbon dioxide emissions and fuel use for rail freight are a factor 20 - 100 lower. For marine freight, fuel use and carbon dioxide emissions per tonne-kilometre are a factor of two or more lower again.[vii] Aircraft are usually able, of course, to take more direct routes than rail or marine freight, but the higher tortuosity of rail or marine routes will not offset the factor of about 3 to be applied to carbon dioxide emissions in estimating the contribution of air freight to radiative forcing.

4.41 We conclude that air freight is so much more environmentally damaging than other transport modes that it must be regarded as a particular luxury reserved for very high value, and usually perishable, goods. Any proposal to expand air freight movements must be examined with particular care.

---

v Calculations based on data in Archer (1993), IPCC (1999) and evidence submitted by ATAG, allowing for tortuosity of road journeys. This broad comparison is consistent with data reported in Lee, J., Madden, P. and Beesley, C. (1999). *Fuel Emissions from Aircraft*. Paper presented at the 9th Annual Meeting of the Society of Environmental Toxicology and Chemistry - Europe, Leipzig, May 1999, which show air travel as roughly equivalent to 1.2 people in a passenger car. It is also consistent with an analysis carried out for ATAG by the Swiss consultancy Infras [Maibach, M. and Schneider, C. (2002). *External costs of corridors: a comparison between air, road and rail*, Infras, Bern]. Detailed comparison is not possible because Infras have aggregated all environmental impacts into single values for 'external costs'.

vi Precise estimates for fuel use and emissions for passenger rail travel vary according to the type of engine used; they are, of course, lowest for modern electric trains but then still depend on the energy mix used to generate the electric power. Figures also depend on how the environmental impacts associated with building and maintaining the rail infrastructure are allocated to passenger movements. For these reasons we have presented broad comparisons here rather than detailed numerical estimates. However, the comparisons are consistent with other sources, notably IPCC (1999) and Infras (for ATAG, 2002). All modes of transport can be expected to show technological improvement, so that comparisons are likely to be more durable than absolute values.

vii Figures estimated from data in Archer (1993), IPCC (1999) and evidence submitted by ATAG, and consistent with data in the SIMAPRO database for Life Cycle Assessment [Pré Consultants, 2000]. SIMAPRO was used as the data source for rail and marine freight. The difference between air and rail is greater for freight because of the higher rail payload density compared to passengers.

5 Policy and action

5.1 The Commission's Twenty-second Report emphasised the importance of reducing all climate changing emissions to a sustainable level - one at which long-term impacts on the Earth's atmosphere and climate could be contained within acceptable limits, so that irreversible environmental harm would be avoided.

5.2 The analysis in the preceding sections leaves us deeply concerned at the prospect of continuing rapid increases in air transport, particularly an increase in short-haul flights and air freight, and the serious and continuing impact this will have on the prospects for achieving the necessary overall reductions in greenhouse gas emissions, with their crucial implications for the atmosphere and climate. The government shows few signs of bringing forward policies that will address these issues, either in the short or the long-term. On the contrary, the policies set out in the consultation exercise on regional airports[70] are likely to exacerbate the problems.

5.3 The climate forcing emissions from the projected increase in domestic air transport are covered by the UN Framework Convention on Climate Change and the Kyoto Protocol. Increasing air transport will either reduce the UK's ability to meet its Kyoto obligations, or represent an additional reduction to be imposed on other industries to offset the increase. In all these respects, we see plans to facilitate the growth of air transport as inconsistent with many other policies of the UK government and with its stated commitment to *sustainable* development.

5.4 In this section we propose means by which the government could address the issue of sustainability for the aviation industry. These include:

- moderating demand through emissions charging
- optimising the use of existing airport capacity
- increasing consumer choice by providing less environmentally damaging alternatives for short-haul flights
- encouraging the development of technologies to limit the climate changing effects of flight
- incorporating the sector into an open emissions trading scheme.

If the adverse environmental impacts are to be averted, the government could and should take initial steps now, and must build upon them in the coming years and decades.

Moderating demand through the use of economic instruments

5.5 A conventional approach to demand management is to consider imposing taxes. But because of the international nature of the aviation industry and its regulation by governments, there are challenging obstacles to the imposition of an aviation fuel tax.

5.6 Under one interpretation of Article 24 of the Chicago Convention, aviation fuel used in international air transport is exempt from taxation. This has been enshrined in a large number of bilateral agreements between signatory states. The exemption has given aviation a significant competitive advantage over other modes of transport. Shipping is the only other transport industry whose fuel is exempt from tax. It is not acceptable that the aviation industry should continue to receive what is in effect a large subsidy at the expense of other modes of transport or sectors and the environment.

5.7 Tax exemption, in as much as it extends to domestic flight, represents a penalty on other industries emitting carbon dioxide in the UK, because emissions from domestic flights are included in the total domestic carbon dioxide inventory and so are covered by the Kyoto Protocol. It is now a matter of some urgency that this distortion of competition be corrected. In a wider context, any attempt to use economic instruments to reduce total emissions to a particular level while exempting one sector from taxation will have to commensurately increase the tax burden on other sectors.

5.8 Renegotiation of the Chicago Convention and the subordinate bilateral agreements would be an enormous task and would be unlikely to achieve a consensus on global action. Therefore, there is a risk that unilateral action by a body such as the UK or even the EU could easily be circumvented by the ready availability of cheaper, tax-free fuel outside the EU.

5.9 Instead of a fuel tax, therefore, a better way of addressing the market distortion would be a Europe-wide emissions charge, which airports would be required to levy on all aircraft, passenger or freight, taking-off from or landing at European airports. The charge would be differentiated between aircraft types and loads and the distance travelled over Europe, or over the ocean to the point mid-way to the nearest country in the direction of the flight, to reflect their estimated emissions.

5.10 Some at least of this emissions charge would be likely to be passed on by the airlines to passengers in the form of a rise in ticket prices. The availability of cheap air transport currently enjoyed by the public is a very recent phenomenon. It is not a traditional 'right' in any sense. An increase in ticket price would act to reduce demand below what it would otherwise be, especially for short-haul flights. Similarly the growth in air freight would be restrained.

5.11 Putting a credible financial value on the environmental problems associated with air transport has proved difficult. There have been many attempts to do so and estimates have ranged from a few pounds on the cost of a ticket to several hundred pounds. The government has suggested that environmental costs of around £3 per passenger on short-haul operations and £20 per passenger on long-haul aircraft[71] would be appropriate, although the estimates that formed the basis for these figures are illustrative and subject to high levels of uncertainty. A tax set at this level would have a negligible effect on the numbers who would actually travel, and would be easily outstripped by the projected growth in passenger numbers. This, though, does not justify inaction. If the same argument were applied to other sectors it would undermine carbon dioxide reduction efforts across the economy.

5.12 Calculations of the financial value of the environmental costs of air transport are in any case not sufficiently robust to act as the basis for deciding the level of the emissions charge to be set. It is likely that, to have a significant effect on demand, the level of the charge would need to be substantial, though this would depend to some extent on the transport substitutes that were available, especially for short-haul flights.

5.13 The Institute of Public Policy Research will suggest in a forthcoming report that a tax of £35 on a single ticket would go some way towards removing the discrepancy of treatment between aviation and motor fuel.[72] The emissions charge could be set at an initial rate to achieve this kind of increase in ticket price for European flights. Moreover, a charge that impinged appreciably on the ticket price, and was identified on the ticket as a climate protection charge, could be a valuable signal to the travelling public, heightening public awareness of the environmental damage caused by air transport and associated activities.

5.14 Over time the charge could be increased, along with taxation or charges on other sources of greenhouse gas emissions, in order to ensure that such emissions did in fact start to decline in line with the objective of climate stabilisation. The revenue generated by a charge on aircraft movements could be used to assist with funding the development and improvement of the more environmentally benign transport media.

5.15 Taking such measures to reduce the contribution to climate change from European-related air transport would provide a sound position for Europe in international negotiations in attempting to extend a similar approach to other countries, for example, through the OECD as we recommended in our Twenty-second Report. In time, and provided that international aviation emissions were by then incorporated in countries' controlled totals of emissions, the emissions charges could be replaced by the participation of the aviation sector in the greenhouse gas emissions trading system envisaged by the Kyoto Protocol. The potential for an emissions trading scheme for air transport is explored further in paragraphs 5.32 – 5.36.

Optimising the use of existing airport capacity

5.16 Environmental charges are not the only instrument available to governments; managing demand can encompass a broad range of options that the UK government should consider. The government has recently been reported as saying that 'doing nothing is not an option' regarding the expansion of airports across the country. This may be so, but it does not mean that the only option is airport expansion.

5.17 Constraining any increase in airport capacity would sharply and progressively increase competition for, and the implicit price of, slots at the major airports. This would increase the pressure on airlines to maximise their income from the slots available. It would intensify the pressure already being felt, for example, at London Heathrow, to move away from domestic and short-haul flights towards the long and medium-haul journeys which generate greater income.

5.18 Not expanding airport capacity should not, therefore, be synonymous with 'doing nothing'. Emphasis should shift towards providing reliable, efficient and more sustainable alternatives to flight. This should include improvements in communication technologies, such as telephone and video conferences, which could remove the need for some journeys. We have noted recent airline advertisements that appear to recognise business by e-mail as a real competitor. Alternative modes of transport must also be encouraged, and we discuss this in the following paragraphs.

Inducing and encouraging modal shift

5.19 Currently 18% of passengers are carried on domestic flights;[73] so encouraging a shift away from the use of air transport over such distances, and even those on shorter European flights, could reap considerable environmental benefits as well as relieving pressure on major airports. Rail transport is demonstrably more sustainable than air transport, as illustrated in paragraph 4.39. While it is not a viable alternative to long- or medium-haul air journeys, it ought to be a serious competitor to short-haul flights.

5.20 The fact that rail transport cannot compete at present, at least in the UK, is a consequence of several factors but these certainly include a failure to invest in rail infrastructure and a failure to reflect environmental externalities in the cost of air transport. Instead of encouraging airport expansion and proliferation, for internal UK travel and some intra-European journeys, it is essential that the government should divert resources into encouraging and facilitating a modal shift from air to high-speed rail.

5.21 In order to make rail travel over such distances attractive there must be better provision of affordable services across the country and into the major airports. The dedicated overhead passenger system linking Birmingham International Airport to the West Coast Mainline is one example of a step in the right direction, but the development needs to be more comprehensive across the UK. In the longer term, the development of a European network (which is already under way in some Member States) will allow rail to compete with air over a greater range of intra-European journeys.

5.22 This action would benefit rail companies and allow the aviation sector to maximise the return from its existing assets. Rail companies must come to play a far larger role than just shuttling passengers from the airport into the local city centre. Instead rail-air connections should be developed, as they have in The Netherlands, where there is an extensive rail network linking Schiphol airport to all areas of the country so that Schiphol has become a major transport hub, not just an airport.

5.23 We conclude that instead of encouraging the development of regional airports, the government should be injecting resources and encouraging private sector investment into developing established airports as land hubs, serviced by an efficient and convenient rail network.

Technological development

5.24 We have considered the various possibilities for improving the environmental performance of aircraft in flight, both in terms of technological advances already on the horizon and those which experts thought might come into sight before long. Significant opportunities for reducing emissions and other environmental impacts do exist, but their effect is likely to be outstripped by the projected increases in air transport. We advocate the encouragement of technical advance (properly funded by industry) in this area but recognise that technical improvements alone will not offer a solution to the problem. We are also concerned that some potential developments may make matters worse.

5.25 We note with interest the work towards developing BWB aircraft, which are likely to have a significantly better environmental performance than conventional designs. These aircraft, as discussed in Section 4, would be operated on long-haul routes and this is consistent with the role of air transport that we advocate in this Report. BWB aircraft are currently only in the concept stage so that, even if proved viable, they could not enter service for decades even on the most optimistic prognoses. They would not represent a significant proportion of aircraft movements for many decades, so they would make no significant difference to the total aviation impacts for at least the first half of this century. Two thirds of all the aircraft that will be flying in 2030 are already in use.

5.26 In Section 4, we also considered alternatives to kerosene as aviation fuel and concluded that none of the current options were viable for the foreseeable future. Hydrogen has been promoted as a future energy source for aircraft but would carry comparable climate change impacts to those from aircraft using kerosene and would not offer the efficiency benefits possible when using it to power fuel cells in surface transport vehicles. Hydrogen does not, therefore, offer an environmentally attractive alternative for fuelling aircraft.

5.27 We are also concerned about the development of supersonic or near-sonic aircraft. As explained in Section 3, these aircraft fly at greater altitudes than conventional subsonic aircraft, cruising well into the stratosphere where the effects of emissions are much longer lived. The evidence suggests that any development of a fleet of supersonic or near sonic craft could be extremely damaging to the global environment.

5.28 There is also some discussion by IPCC of the impacts of 'business jets', including supersonic business jets carrying typically eight to ten passengers.[74] The contribution to global climate change of this kind of aircraft would be so disproportionate that their development and promotion must be regarded as grossly irresponsible.

5.29 We recommend that research into options for technological improvement of the environmental performance of aircraft should be encouraged by the government and properly funded by the industry. An emissions, charge such as that recommended above, would give incentives for the industry to realise those environmentally beneficial technical changes that are available. It must be recognised, however, that these changes, while useful, are limited and the environmental problems of aviation cannot be satisfactorily addressed in this way alone.

5.30 There is also scope for technological development and research opportunities beyond aircraft design. As noted in Section 3, when aircraft fly through supersaturated areas of the upper troposphere, which are quite common in middle latitudes, the contrails formed tend to persist and spread. Information about current meteorological conditions and prediction of future conditions in this region should be used to direct aircraft away from these supersaturated areas, thus reducing contrails and their possible implications for climate change.

5.31 The aviation industry already undertakes research into how air transport can be made less environmentally damaging. It could do more. In particular, the installation of research instrumentation into aircraft would allow the collection of data on atmospheric processes relevant to climate change, thus helping to increase our understanding of such processes. A limited programme of this kind in Europe has already proved extremely useful.[75]

Emissions trading schemes

5.32 We were disappointed that international aviation emissions were left out of the Kyoto Protocol and find it extraordinary that their inclusion seems little closer now. This issue needs to be addressed with urgency. The Commission recognises and welcomes the discussions at an international level, working towards managing global emissions from the aviation sector. The credibility of these negotiations now depends on them achieving firm proposals in the near future for how the sector's emissions could be treated like those from the rest of the economy.

5.33 One logical step would be the inclusion of international aviation emissions in the emissions trading scheme that is envisaged as one of the Kyoto Protocol's implementing mechanisms. In our response to the consultation paper on the Future of Aviation in 2001,[76] we drew attention to some of the potential pitfalls of emissions trading schemes. In particular, there is a risk that if the industry supports either renewable energy, energy efficiency or carbon sequestration schemes to offset its own growth in emissions, the resulting emission savings could be double-counted as part of the host nation's commitments and no net emission reduction result. Thus, if the aviation sector is to participate in emissions trading, it must be on the basis of the inclusion of international aviation emissions in national emission totals.

5.34 Any inclusion of aviation emissions in an emissions trading scheme will also have to take into account the fact that the total radiative forcing of aviation is about three times that of the carbon dioxide emitted (the reason for this is explained in Section 3). Just as non-carbon dioxide greenhouse gases are accounted in terms of their global warming potential compared to carbon dioxide, so aviation emissions will need to be accounted to reflect their true contribution to climate change. This requires that the aviation industry should acquire three carbon emission permits for each unit of carbon that it actually emits.

5.35 The objection is sometimes raised that proposals to control the environmental effects of aviation through the use of economic instruments will make it so expensive that it will effectively limit air transport to the more wealthy sections of even relatively prosperous countries like the UK, and that this is not equitable. While in largely market economies, like that of the UK, the price mechanism is widely used to allocate goods and services, especially in respect of luxuries, it need not be the only mechanism employed. It is possible to envisage alternative mechanisms such as a system of tradable (air mile) permits allocated at the individual level. But we have already noted that air transport is at present limited to the wealthier sections of the world population (see paragraph 2.12), while its environmental impacts will have disproportionate negative effects on economically disadvantaged sections that do not fly. This is certainly not fair.

5.36 An emissions trading scheme in which the quantity of emissions permits was controlled and reduced over time in order to achieve the climate stabilisation target would provide a surer means of reaching that target than repeatedly adjusted emissions charges. Once such a scheme was established, and the aviation sector and its greenhouse gas emissions were included in it, these arrangements could substitute for emissions charges. In the interim, however, emissions charges have an important role to play in stimulating emission-reducing technical change, managing demand and providing an indication of the cost of greenhouse gas abatement in the sector. The government should work for the introduction of emissions charges in the EU as soon as possible.

6 Conclusions and recommendations

6.1 The Commission has expressed deep concerns about the environmental consequences of the growth in air transport on a number of occasions. In this Report we have examined the larger-scale impacts of aviation, both on surface UV radiation through changes in atmospheric ozone and on climate.

6.2 The Commission has particular concerns about the contribution that aircraft emissions will make to climate change if this growth goes unchecked. The total radiative forcing due to aviation is probably some three times that due to the carbon dioxide emissions alone. This contrasts with factors generally in the range 1 - 1.5 for most other human activities.

6.3 The ambitious targets for technological improvement in some industry announcements are clearly aspirations rather than projections; IPCC's projections are already optimistic. Despite the considerable opportunities for incremental improvements to the environmental performance of individual aircraft, these will not offset the effects of growth. Kerosene will continue to be the industry fuel for the foreseeable future. A non-incremental change could result from radically new airframe designs, with improved fuel efficiency and possibly lower noise and emissions, but this change will not affect the industry for decades and even then will only affect large long-haul aircraft.

6.4 Short-haul passenger flights, such as UK domestic and European journeys, make a disproportionately large contribution to the global environmental impacts of air transport. These impacts are very much larger than those from rail transport over the same point-to-point journey.

6.5 We are also concerned by the growth in air freight. Carbon dioxide emissions and fuel use per tonne-kilometre for rail freight are a factor of 20 - 100 lower than for air. For marine freight, fuel use and carbon dioxide emissions are a factor of 2 or more lower again. Air freight is so much more environmentally damaging than other transport modes that it must be reserved for very high value, and usually perishable, goods. Any proposal to expand air freight movements must be examined with particular care.

6.6 If the reductions in carbon dioxide emissions from ground-level activities recommended in the Commission's Twenty-second Report are achieved, and the growth in air transport projected by IPCC materialises, then air travel will become one of the major sources of anthropogenic climate change by 2050. The Commission fears that the government shows little sign of having recognised these problems, but regards further substantial growth in aviation as inevitable. We recognise that the problems of reducing the impact of air transport are more challenging than action in some other sectors contributing to climate change. But it is imperative that environmental priorities are not simply sidelined as being too difficult.

6.7 We have made recommendations in this Report which encompass a wide range of measures that the government ought to be taking to reduce demand for air travel and to moderate the damage caused by the future growth that does take place:

- impose climate protection charges for aircraft taking off and landing within the EU, and press for such charges to be adopted beyond Europe (paragraphs 5.5 to 5.14)
- restrict airport development to encourage greater competition for, and raise the implicit price of, the available take-off and landing slots, in order to optimise the use of those slots towards longer-haul flights and to increase the prospects for a modal shift to rail for domestic journeys (paragraphs 5.16 to 5.18)

- encourage a modal shift to more environmentally benign methods of transport for short-haul flights, including the development of major airports into land-air hubs integrated with an enhanced rail network (paragraphs 5.19 to 5.23)
- support technological development to lessen the damage done by air travel, continuing airframe improvements and optimising aircraft routeing (paragraphs 5.24 to 5.31)
- include international aviation in the emissions trading scheme that is envisaged as one of the Kyoto Protocol's implementing mechanisms (paragraphs 5.32 to 5.36).

6.8 We urge the government to seize the opportunity presented by its forthcoming White Paper to implement our recommendations at the domestic level, and to argue for their adoption by the EU, and globally, where necessary and appropriate. We believe that the arguments put forward in this Report are sufficient to show that if no limiting action is taken, the rapid growth in air transport will proceed in fundamental contradiction to the government's stated goal of sustainable development.

References

1 First Report, Chapters III and V.

2 Eighteenth Report, paragraph 5.33.

3 Eighteenth Report, paragraph 5.39.

4 Twenty-second Report, paragraph 6.131.

5 Royal Commission on Environmental Pollution (2001). *Consultation on the future of aviation: Response by the Royal Commission on Environmental Pollution*. (see www.rcep.org.uk/news/01-1c.html, paragraph 16).

6 Twenty-third Report, paragraph 8.53.

7 Department for Transport (DfT) (2002). *The Future Development of Air Transport in the United Kingdom: A National Consultation*.

8 Unpublished presentation on Air Traffic Forecasts by the Department for Transport. Cross Regional Key Issues Meeting on the Air Transport White Paper, London, 27 October 2002.

9 Department of the Environment, Transport and the Regions (DETR) (2000). *Air Traffic Forecast for the United Kingdom 2000*.

10 Civil Aviation Authority (CAA) (2001). *Summary of Activity at UK Airports 2001*.

11 Air Traffic Forecasts (see ref. 8).

12 Air Traffic Forecasts (see ref. 8).

13 CAA (2001). *International and Domestic Freight 2001*.

14 CAA (see ref. 13).

15 DfT (see ref. 7).

16 Intergovernmental Panel on Climate Change (IPCC) (1999). *Aviation and the Global Atmosphere*. Cambridge University Press, Cambridge.

17 Barrat, M. (1991). *Aircraft Pollution. Environmental Impacts and Future Solutions*. Research paper by World Wildlife Fund, Geneva.

18 Evidence from Rolls Royce plc., August 2002.

19 Oxford Economic Forecasting (1999). *The Contribution of the Aviation Industry to the UK Economy*.

20 Evidence from the Department for Trade and Industry, July 2002.

21 International Civil Aviation Organisation (ICAO) (2001). *ICAO Assembly Resolution A33-7: Consolidated statement of continuing ICAO policies and practices related to environmental protection*, Appendix A.

22 Evidence from J. Pyle, Cambridge University Chemical Laboratory, August 2002.

Evidence from D. Lee, QinetiQ, September 2002.

Evidence from the Department for Transport (DfT), September 2002.

23 Evidence from D. Lee (see ref. 22).

Rogers, H. L., Lee, D. S., Raper, D. W., de Forster, P. M., Wilson, C. W. and Newton, P. J. (2002). *The impacts of aviation on the atmosphere*; QinetiQ report number QINETIQ/FST/CAT/TR021654.

24 Evidence from U. Schumann, Deutschen Zentrum für Luft- und Raumfahrt (DLR) Institut für Physik der Atmosphäre, September 2002.

25 IPCC (see ref. 16).

26 IPCC (see ref. 16).

27 Evidence from the Department for Environment, Food and Rural Affairs, August 2002.

Evidence from U. Schumann (see ref. 24).

Evidence from D. Derwent, The Met Office, August 2002.

28 IPCC (see ref. 16).

29 Marquart, S. and Mayer, B. (2002). Towards a reliable GCM estimation of contrail radiative forcing, *Geophysical Research Letters*, **29**, No. 8.

Also quoted in evidence by U. Schumann (see ref. 24).

30 Evidence from D. Lee (see ref. 22).

Evidence from DfT (see ref. 22).

31 Evidence from D. Lee (see ref. 22).

Evidence from DfT (see ref. 22).

32 Travis, D., Carleton, A. and Lauritsen, R. (2002). Cited in Contrails Reduce Daily Temperature Range. *Nature*, **6898**, 601.

33 Rogers *et al.* (see ref. 23).

Stuber, N., Sausen, R. and Ponater, M. (2001). Stratosphere adjusted radiative forcing calculations in a comprehensive climate model. *Theoretical and Applied Climatology*, **68**, 125–135.

34 Intergovernmental Panel on Climate Change (1996). *Second Assessment Report – Climate Change 1995*. Cambridge University Press, Cambridge.

35 Intergovernmental Panel on Climate Change (2001). *Third Assessment Report – Climate Change 2001: Synthesis Report*. Cambridge University Press, Cambridge.

36 Sausen, R., Gierens, K., Ponater, M. and Schumann, U. (1998). A diagnostic study of the global distribution of contrails part I: Present day climate. *Theoretical and Applied Climatology*, **61**, 127–141.

37 Evidence from D. Lee (see ref. 22).

Evidence from DfT (see ref. 22).

38 Schumann, U. and Amanatidis, G. T. (2001). *Aviation, aerosols, contrails and cirrus clouds; A2C3,'* Proceedings of a European workshop, Seeheim (Frankfurt), Germany, 10 to 12 July 2000.

39 Evidence from U. Schumann (see ref. 24).

40 Evidence from U. Schumann (see ref. 24).

41 Evidence from Airbus, September 2002.

42 Energy Technology Support Unit (ETSU) (1992). *Research and Technology Strategy to Help Overcome Environmental Problems in Relation to Transport*. Final Report, Study Group 2. UK Atomic Energy Authority, Harwell Laboratory, UK.

43 IPCC (see ref. 16).

44 Air Transport Action Group (ATAG) (2002). *Industry as a partner for sustainable development: Aviation*. ATAG and the United Nations Environment Programme.

45 ICAO (1993). *International Standards and Recommended Practices, Environmental Protection – Annex 16 to the Convention on International Civil Aviation, Volume II: Aircraft Engine Emissions*.

46 Archer, L. (1993). *Aircraft Emissions and the Environment: CO_x, SO_x HO_x and NO_x*. PhD thesis, University of Oxford.

47 Evidence from Rolls Royce plc. (see ref. 18).

48 IPCC (see ref. 16).

49 Evidence from Rolls Royce plc. (see ref. 18).

50 IPCC (see ref. 16).

51 Archer, L. (see ref. 46).

52 Air Travel - Greener by Design (2002), *Greener by Design*. Society of British Aerospace Companies Ltd., London.

53 Air Travel - Greener by Design (see ref. 52).

54 Liebeck, R. H. (2002). *Design of the Blended Wing Body Subsonic Transport*, Wright Brothers Lecture, 15th January 2002.

55 Arthur D Little Ltd. (2000). *Study into the potential impact of changes in technology or the development of Air Transport in the UK*, DETR Report on Contract No. PPAD 9/91/14.

56 IPCC (see ref. 16).

57 Archer, L. (see ref. 46).

58 Air Travel - Greener by Design (see ref. 52).

59 Evidence from the European Association of Aerospace Industries, September 2002.

Evidence from British Airways, September 2002.

Lee, J., Madden, P. and Beesley, C. (1999). *Fuel emissions from Aircraft*, Paper presented at 9th Annual Meeting of the Society of Environmental Toxicology and Chemistry – Europe, Leipzig, May 1999.

60 Twenty-second Report, chapter 8.

61 Twenty-second Report, chapter 8.

62 Evidence from Rolls Royce plc. (see ref. 18).

63 IPCC (see ref. 16).

64 Evidence from Rolls Royce plc. (see ref. 18).

65 IPCC (see ref. 16).

Arthur D Little Ltd. (see ref. 55).

66 IPCC (see ref. 16).

67 Arthur D Little Ltd. (see ref. 55).

68 Arthur D Little Ltd. (see ref. 55).

69 Twenty-second Report, paragraph 10.10.

70 DfT (see ref. 7).

71 Department of the Environment Transport and the Regions (DETR) (2000). *Valuing the External Costs of Aviation*.

72 Institute of Public Policy Research (in preparation). *Sustainable Development in Aviation*.

73 DETR (see ref. 71).

74 IPCC (see ref. 16).

75 Marenco, A., Thouret, V., Nedelec, P., Smit, H., Helten, M., Kley, D., Karcher, F., Simon, P., Law, K., Pyle, J., Poschmann, G., Von Wrede, R., Hume, C. and Cook, T. (1998). Measurements of Ozone and Water Vapour by Airbus in-service aircraft: The MOZAIC airborne program, An overview, *Journal of Geophysical Research*, **103**, pages 25, 631 - 25, 642.

76 Royal Commission on Environmental Pollution (see ref. 5).

77 Archer, L. (see ref. 46).

Appendix A

Scope and limitations of the Special Report

A.1 The scope of this Report has been restricted to the environmental effects of aircraft in flight because, in common with many other forms of transport and manufactured products, the use-phase dominates the environmental impacts of an aircraft over its life cycle. To date, environmental concern has focused more on ground-level pollution in and around airports. Indeed, the majority of pollution inventories take account only of emissions from the standard landing and take-off cycle, which is defined as up to 915 metres.[77]

A.2 The Commission chose to adopt a global perspective because air transport itself operates globally and its impacts on the atmosphere, particularly those that could result in climate change, will have worldwide consequences. We investigated potential domestic actions that might lead to possible European policies. We also considered how the EU could establish a position for international negotiations.

A.3 We decided that both passenger and freight transport merited discussion as both sectors are growing exponentially, with commensurate increases in their environmental impacts. We have also considered possibilities for, and environmental impacts of, encouraging 'modal shift', the transfer of passengers or goods to other modes of transport, particularly rail.

A.4 Issues that are beyond the scope of this Report include those impacts of air transport not associated with aircraft in flight, such as the local effects of airports and their supporting infrastructure. The Commission has not considered the land-take issues associated with airports or the environmental impacts of increased ground traffic around the airport, though these are important issues and were addressed more generally in our Twenty-third Report. Nor does the Report consider noise or local air quality in detail, except where there are direct linkages with the issues we report on here.

A.5 Many of the issues relevant to air transport that fall outside the scope of this Report were addressed by the Commission in its Eighteenth Report. We are disappointed that the government has yet to make a formal response to the recommendations contained in the Eighteenth Report.

A.6 The Commission considered only the effects of the growth in international tourism in terms of its contribution to the rapid growth of passenger numbers. The environmental pressures caused by this growth may be substantial, but it was not possible to include them in the Report in the time available.

A.7 Nor could we examine local economic effects of the increase in air transport. For example, the economic and skills benefits to developing countries whence the airline industry sources some components have been excluded, as has the effect on the economies of some developing countries, where the availability of cheap air transport has encouraged the growing of luxury cash crops such as cut flowers for the developed world.

A.8 The Commission is also aware of, but has not addressed, the health problems that have been linked to flight, including the increased risk of deep vein thrombosis and the potential effects of the increased exposure to cosmic radiation experienced by passengers, and particularly crew.

A.9 Due to the nature of their use, it is difficult to assess accurately the environmental implications of the military fleet and consequently we have limited this Report to civil aviation. However, the environmental problems caused by military aircraft are likely to be significant and the Commission therefore recommends that the government takes this into account in developing its policies.

A.10 All of these issues are important. They were too diverse and complex for inclusion in this Report, but any new policy developments that encourage or facilitate growth in air transport ought to be supported by a full investigation of all the social, economic and particularly environmental impacts of air transport to determine the extent to which the projected growth in air transport is sustainable.

Appendix B

Conduct of the report

B.1 The Commission announced the Special Report in July 2002 and called for evidence from a wide range of organisations and individuals. The questions focussed on: the extent and understanding of the environmental impacts of air transport; the possibility for, and extent to which, technological developments could lessen these impacts; whether such developments would have other benefits or problems associated with them; what measures might be brought to bear at what level to reduce environmental damage caused by flying; and how consumer demand might be managed.

B.2 This invitation was also placed on the Commission's website with an open invitation to respond. Overall twenty-one organisations responded to the invitation. The report was drafted during September and October 2002.

B.3 The organisations and individuals who responded to our invitation to submit evidence or provided information on request or otherwise gave assistance are listed below.

Government Departments

Department for Environment, Food and Rural Affairs
Department for Trade and Industry
Department for Transport

Other organisations

Airbus
Air Transport Action Group
Aviation Environment Federation
Boeing International Corporation
British Air Transport Association
British Airways
Centre for Transport Studies, Imperial College
Civil Aviation Authority
Friends of the Earth
HACAN Clear Skies
Intergovernmental Panel on Climate Change
Rolls Royce Plc
Royal Academy of Engineering
Society of British Aerospace Companies

Individuals

Professor Richard Derwent, The Met Office
Dr Graham Earl, BAA plc
Ms Helen Hosmaston, Centre for Environmental Strategy, University of Surrey
Mr Tony Houseman, European Association of Aerospace Industries
Dr Arthur Lieuwen, EUROCONTROL

Ms Rattanawan Mungkung, Centre for Environmental Strategy, University of Surrey
Professor John Pyle, Cambridge University Chemical Laboratory
Dr Helen Rogers, Cambridge University Chemical Laboratory
Professor Ulrich Schumann, Deutchen Zentrum für Luft- und Raumfahrt (DLR) Institut für Physik der Atmosphäre
Mr Brendon Sewill, Gatwick Area Conservation Campaign
Professor Keith Shine, Department of Meteorology, University of Reading

Appendix C

Members of the Commission

Sir Tom Blundell (Chairman)
Sir William Dunn Professor and Head of Department of Biochemistry, University of Cambridge and Professorial Fellow of Sidney Sussex College

Professor Roland Clift
Professor of Environmental Technology and Director of the Centre for Environmental Strategy, University of Surrey

Professor Paul Ekins
Head of the Environment Group at the Policy Studies Institute

John Flemming
Warden of Wadham College, Oxford and Chairman of Management Committee, National Institute of Economic and Social Research

Sir Brian Follett
Professor, Department of Zoology, University of Oxford and Chairman, Arts and Humanities Research Board

Dr Ian Graham-Bryce
President, Scottish Association of Marine Science

Professor Stephen Holgate
Medical Research Council Clinical Professor of Immunopharmacology at the University of Southampton

Professor Brian Hoskins
Royal Society Research Professor and Professor of Meteorology, University of Reading

Professor Richard Macrory
Professor of Environmental Law at University College London, and Board Member of the Environment Agency

Mrs Cheryl Miller
Chief Executive of East Sussex County Council

Dr Susan Owens
Reader in Environment and Policy, University of Cambridge and Fellow of Newnham College

Professor Jane Plant
Chief Scientist, British Geological Survey (Natural Environment Research Council)

John Speirs
President of the National Society for Clean Air and Environmental Protection

Professor Janet Sprent
Emeritus Professor of Plant Biology at the University of Dundee and Board Member of Scottish Natural Heritage

Secretariat

Secretary
Peter Hinchcliffe

Assistant Secretaries
Georgina Burney
Howard Morrison

Policy Analysts
Anna Bradbury
Andy Deacon
Jonny Wentworth

Information Systems Manager
Cathy Garretty

Office Manager
Rosemary Ferguson

Administrative Officers
Janice Downes
Patrizia Bergonzi

Personal Secretary to Sir Tom Blundell and Dr Hinchcliffe
Dot Watson

Appendix D

Reports by the Royal Commission on Environmental Pollution

23rd report	Environmental Planning	Cm 5459, March 2001
22nd report	Energy - The Changing Climate	Cm 4749, June 2000
21st report	Setting Environmental Standards	Cm 4053, October 1998
20th report	Transport and the Environment - Developments since 1994	Cm 3752, September 1997
19th report	Sustainable Use of Soil	Cm 3165, February 1996
18th report	Transport and the Environment	Cm 2674, October 1994
17th report	Incineration of Waste	Cm 2181, May 1993
16th report	Freshwater Quality	Cm 1966, June 1992
15th report	Emissions from Heavy Duty Diesel Vehicles	Cm 1631, September 1991
14th report	GENHAZ A system for the critical appraisal of proposals to release genetically modified organisms into the environment	Cm 1557, June 1991
13th report	The Release of Genetically Engineered Organisms to the Environment	Cm 720, July 1989
12th report	Best Practicable Environmental Option	Cm 310, February 1988
11th report	Managing Waste: The Duty of Care	Cmnd 9675, December 1985
10th report	Tackling Pollution - Experience and Prospects	Cmnd 9149, February 1984
9th report	Lead in the Environment	Cmnd 8852, April 1983
8th report	Oil Pollution of the Sea	Cmnd 8358, October 1981
7th report	Agriculture and Pollution	Cmnd 7644, September 1979
6th report	Nuclear Power and the Environment	Cmnd 6618, September 1976
5th report	Air Pollution Control: An Integrated Approach	Cmnd 6371, January 1976
4th report	Pollution Control: Progress and Problems	Cmnd 5780, December 1974
3rd report	Pollution in Some British Estuaries and Coastal Waters	Cmnd 5054, September 1972
2nd report	Three Issues in Industrial Pollution	Cmnd 4894, March 1972
	First Report	Cmnd 4585, February 1971