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FOR AIRCRAFT

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SENCO

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GLOSSARY

TERMS AND UNITS

ATC	Air traffic control
Avgas	Aviation gasoline
Ceq	Carbon equivalent
CO_2	Carbon dioxide
GWE	Global Warming Effect
GWP	Global Warming Potential
JIT	Just In Time
Ma.km	Million aircraft-kilometres
MJ	Megajoule (10^6 Joules).
MJ/a.km	Megajoules per aircraft kilometre
MJ/s.km	Megajoules per seat kilometre
Mt	Million tonnes
MtC	Million tonnes of carbon
NO_x	Nitrogen Oxides
PJ	Petajoule (10^{15} Joules)
p.km	Passenger kilometre
t.km	Tonne-kilometres

TERMS

seat occupancy factor	proportion of seats occupied by passengers
load factor	proportion of aircraft carrying capacity used

ORGANISATIONS

CAEP	Committee on Aviation Environmental Protection (hosted by ICAO)
ETSU	Energy Technology Support Unit
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IPCC	Intergovenmental Panel on Climatic Change
WTO	World Tourism Organisation
WTTC	World Travel and Tourism Council
WTTERC	World Travel and Tourism Environment Research Centre
WWF	WorldWide Fund for Nature

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1. SUMMARY

1.1.1 Outline of study

The aim of this report is to stimulate the development of policies to protect the global environment from the impacts of aviation. The report discusses many complex areas relating to aviation and the environment: topics touched on include environmental objectives and impacts, transport demand, aviation technology and operations, economics, regulation, and alternative transport modes. A broad canvas is needed because many aspects of the issue are synergistic and cannot be considered in isolation; but in consequence the analysis on any particular topic is limited in depth.

1.1.2 Environmental impact

Aircraft presently release some 2 or 3% of global emissions of carbon dioxide and nitrogen oxides from fossil fuels and this fraction will grow rapidly with unchanged policies. Aircraft also emit a mixture of other pollutants including soot, carbon monoxide and hydrocarbons. About half of these emissions is injected into the atmosphere at an altitude of 8 to 12 km. At this height pollutants can have more serious and enduring effects than at ground level - even water may have adverse impacts. There are especial concerns about the possible contributions of nitrogen oxides and water emission to global warming and ozone depletion. Scientific uncertainty about the impacts is great, and will persist.

1.1.3 Futures

The **demand** for air transport is forecast to grow at 5% per year and so double in less than fifteen years, and the long term growth potential is vast because of the low current per capita demand in poor populous countries. Pollution emission will grow less rapidly than demand because of technological improvements, but with unchanged policies pollution from aircraft will double in two decades or so. A series of new or augmented policy measures is needed to moderate this increase.

There is scope for extending **technological** improvement. This might include the introduction of slower more fuel efficient aircraft optimised for passenger transport. **Operational** changes, especially increasing the load factor of aircraft, could reduce pollution substantially and rapidly by about 30%. However, even if these two categories of measures are applied to a maximum, fuel use and pollution still double in three decades or so.

In consequence, if aviation is to stabilise or reduce its current emissions of greenhouse gases and other pollutants, **demand management** will be required. Most air freight is not inherently urgent and much of it could be carried by less polluting surface modes. Business travel could be limited by the increased use of telecommunication. Leisure travellers could be encouraged to visit nearer locations and use less damaging modes where possible. Reducing the demand growth rate by over a half in these ways would, in conjunction with the technological and operational measures, stabilise emissions over for the next four decades after which emissions would once again increase.

All of these measures would be difficult to implement, especially a high degree of demand management. They will however all be required in order to stabilise emissions; to reduce emissions significantly and permanently, heavier constraints on demand or radical technological innovations will be necessary. In a situation of scientific uncertainty, deciding on appropriate policies and timing their implementation, is problematic.

1.1.4 Policy implementation

Aviation is an internationally integrated industry, and the political, regulatory and economic means for implementing emission control policies have to reflect this. First, targets for aircraft emissions need to be negotiated within the context of current scientific understanding and wider international accords aimed at protecting the global environment. The regulatory framework for aviation is complex and reaches from the management of international routes and competition, to emission limits for aeroengines. Regulation can have a powerful and fairly predictable effect on emission reduction, but further liberalisation or deregulation of the industry may aggravate environmental problems. Additional taxes on aviation fuel and general operations would probably not significantly diminish total demand, but they would encourage better fuel efficiency and emission control.

1. INTRODUCTION

A previous report[1] reviewed the problems and solutions to the environmental impact of aircraft. This report updates and extends this previous work. Although there is some duplication, certain issues are covered in more detail in the first report than in this, and vice versa. They should therefore be taken together. This report expands on the regulatory aspects raised by the first report and introduces some of the actions that will be necessary to control aircraft pollution. There is discussion of some of the existing and possible regulatory frameworks that might be used.

Globally in terms of gross quantity, aircraft give rise to a small, but not insignificant, proportion of atmospheric pollution. However a large part of aircraft pollutants is injected into the atmosphere at high altitudes. There the effects of pollutants can be different, and in many cases more serious, than at ground level. The carbon dioxide (CO_2) emissions from aircraft constitute about 2.7% (Barrett, 1991) of the total global emission of carbon dioxide from fossil fuels - this is about the same as that arising from fossil fuel combustion in the UK. The global warming potential of ozone formed as a result of nitrogen oxides (NO_x) emission from aircraft engines could also be very significant. Even the water vapour emitted by aircraft may bring about global warming. Given likely trends, the emission of CO_2 from aviation will almost certainly be responsible for at least 2% of global warming, and very probably more since aviation is growing faster than most sectors. The warming effect of NO_x and water from aircraft may be as large as their CO_2 emission, but scientific uncertainty about this is presently great.

The prospect for growth in air transport is that this sector will increase relative to most other sources of pollution. Urgent action is therefore needed at both national and international levels to quantify and control aircraft pollution and its deleterious effects.

Aircraft are of special interest because they seem to be the only environmentally significant technology currently subject to international regulation at a global scale. The regulatory framework developed for limiting the environmental impact of aircraft

[1]Aircraft Pollution: Environmental Impacts and Future Solutions by Mark Barrett for WWF International (August, 1991).

may therefore serve as a model for the future regulation of other technologies such as cars.

At present the understanding of the amounts and effects of aircraft pollution is limited. So also is the interplay between such factors as market and environmental regulation, the level of demand for air transport, technological change, and aircraft operation. This report does not treat these issues exhaustively; it raises them for discussion in order that serious work may start on reducing aircraft pollution through regulation and other means. A substantial proportion of this report is devoted to delineating topics that need research urgently.

The specific objectives of this report are:

(i) To briefly review the current understanding of the environmental impacts of aircraft in terms of ozone creation and destruction, global warming and other possible effects;

(iii) To look at the efficacy of policy measures in terms of controlling impacts; and to suggest specific and general policies that would better control the impact of aircraft.

This report does not investigate the possible impact of military and private aircraft in any detail. These may have a qualitatively different impact because of their operational patterns are generally different from those of commercial aircraft. More information on the operation, emissions and impact is urgently needed. The impact of large fleets of new supersonic civil aircraft flying at high altitude is also not discussed here.

2. THE ENVIRONMENTAL IMPACT OF AIRCRAFT

A review of recent scientific research indicates that the concerns expressed by other researchers and Barrett about the impacts of aircraft remain. These may be summarised as follows:

(i) The emission of CO_2 constitutes a small but fast growing contribution to global warming;

(ii) The emission of NO_x probably leads to ozone increase near the tropopause and this in turn may be a significant cause of global warming;

(iii) Water emission may lead to increases in high altitude clouds, and these may contribute to global warming;

(iv) The emission of water and NO_x may exacerbate stratospheric ozone loss;

(v) Other pollutants, such as soot and trace chemicals may also have effects either synergistically or separately.

Some of the concerns are summarised as follows:

> *"Engine emissions from subsonic and supersonic aircraft include oxides of nitrogen (NO_x), water vapour, unburned hydrocarbons, carbon monoxide, carbon dioxide, and sulfur dioxide. Addition of (NO_x) to the atmosphere is expected to decrease ozone in the stratosphere and increase ozone in the troposphere. Resulting changes in ozone, water vapour, and aerosol loading in the altitudes around the tropopause may have a climatic impact since the response of radiative forcing to changes in concentration is most sensitive here." (World Meteorological Organisation; 1991)*

Perhaps the first questions are: how much pollution is emitted by aircraft, and where is it emitted in the atmosphere? The global amounts of pollutants from aircraft are usually eventually calculated by applying emission coefficients (in grammes of pollutant per kilogramme of fuel) to the amount of fuel burnt. The global fuel burn of aircraft is only approximately known, and the proportion used in civil aircraft is to a degree uncertain. The coefficients for some pollutants (e.g. carbon dioxide and water) are known with accuracy and do not vary significantly with engine type and aircraft operation. The coefficients for others (e.g. NO_x and CO) are not precisely known, and do vary with type and operation. For example, the estimated total NO_x emitted by civil aircraft may not be accurate to better than 50% because of uncertainties in fuel burn and multipliers. [Taking for example, 10% uncertainty in total fuel burn; 10% uncertainty in the fraction due to civil operations; and 30% uncertainty in the NO_x emission coefficient.] The effects of pollutants can vary according to where, in terms of altitude, longitude and latitude, they are released in the atmosphere. Research is progressing into all these aspects (see for example: NASA, 1992; McInnes & Walker, 1992).

The second question is: what is the effect of these pollutants? A brief review of more recent scientific work has been undertaken. This shows continuing and burgeoning concerns about most aircraft pollutants.

2.1. Ozone generation and depletion

Certain anthropogenic pollutants generate or destroy ozone in the atmosphere. Unfortunately the NO_x from aircraft probably generates ozone where it is not wanted, at low altitudes; and removes where it is wanted, at high altitudes. At low altitudes (less than 15 km or so), extra ozone increases global warming. Its warming impact is thought to be greatest at about 12 km, large commercial jet aircraft typically cruise at about this altitude. Ozone at much greater altitudes decreases global warming.

"The increase of NO_x is large in comparison with background concentrations and may cause considerable increase in tropospheric ozone." (Schumann et al; 1992)

"At present, it appears that the emissions of nitrogen oxides have changed the background concentration in the upper troposphere in between 40°N and 60°N by 100% causing an increase in ozone by about 20%."   (Schumann; 1993)

"CO and HC emissions were included in the modelling work.... The indirect effect of these gases through ozone generation are accounted for in the model although they are thought to be much less important than NO_x."   (Martin, Michaelis; 1992)

"The major problem arises from the emissions of nitrogen oxides which have the potential to destroy significant quantities of ozone in the stratosphere......The PSCs (polar stratospheric clouds) could be enhanced by the HSCT (High Speed Commercial Transport), and lead to ozone decrease in the northern hemisphere". (XueXie et al; 1992) [This relates mainly to high altitude supersonic aircraft, but note that about 30% of subsonic aircraft emissions are near or in the stratosphere.]

2.2. Water vapour

Water vapour has two potential effects. First, through augmenting the formation of high altitude clouds, it can act as a potent global warming agent. Second, extra water vapour at high latitudes may increase the formation of polar stratospheric clouds that are implicated in ozone loss and the formation of the ozone hole.

"While aircraft flying at an altitude of 12 km and a temperature of -70°C produce a 150 m high and 1 km wide corridor whose relative humidity is increased by 40 percent; this value is reduced by more than a factor of 5 (down to 7.5 percent) at an altitude of 10.5 km where temperature rises to -60°C." (Held, 1990)

"..the aircraft will inevitably form condensation trails which will also persist for a longer period of time. The low temperatures needed for this process to occur are quite common near the tropopause. Higher geographical altitudes are particularly susceptible to such phenomena in winter because of the very low temperatures prevailing there even in the lower stratosphere which extends down to lower altitudes in this part of the globe than elsewhere. This is due to the fact that, unlike the stratosphere in mid-latitudes, water vapour is often close to saturation in these regions, even without outside interference. This is also demonstrated by the so-called stratospheric polar clouds." (Held, 1990)

"The global increase of water vapour concentration is small. However, satellite data and Lidar observations of contrails show that such contrails trigger

additional cirrus clouds which may have climatological effects, at least regionally." (Schumann et al, 1992)

"Regionally the observed annual mean change in cloudiness is of order 0.4%. The resultant greenhouse effect of changes in ozone and thin cirrus cloud cover causes a climatic surface temperature change of the order 0.01 to 0.1K." (Schumann; 1993)

"Contrails from aircraft flying in the upper stratosphere are thought to contribute to longer term cloud formation. This is confirmed by both ground level and satellite observations. Radiation/convection models of the atmosphere indicate that this increase in cloud cover may contribute to global warming, and that the contribution may be comparable with other aircraft impacts." (Martin, Michaelis, 1992).

2.3. Other concerns

Aircraft emit a number of other pollutants. This includes carbon monoxide, sulphur dioxide, metals, soot and lubricating oils. Although many of these are emitted in minute quantities which makes insignificant changes to pollution concentrations near ground level, at a high altitude the additions may be significant.

"Recent research indicates that the emissions at cruise altitudes may increase the amount of stratospheric aerosols and polar stratospheric clouds and thereby may have an impact on the atmospheric environment, to an as yet unknown degree." (Schumann; 1993)

"Even small amounts of soot are of interest because of its light absorption capability, hence its potential effect on the earth's radiation balance; it also is potentially significant for heterogeneous chemistry due to its large active surface." (Pueschel et al, 1992).

"... air traffic at this altitude is likely to increase atmospheric SO2 concentrations by 86 to 340 pptv (parts per trillion = 10^{-12} , by volume). SO2 released at an altitude of 10 km, like NO_x, has a much longer lifetime than surface clouds of SO2 which is sulphated, incorporated into clouds and thus eliminated from the atmosphere in a matter of a few days....It is also conceivable that the sulphate particles might act as additional condensation nuclei and thereby favour cloud formation." (Held, 1990)

It has to be emphasised that considerable uncertainties remain. These relate first to the amounts and spatial distribution of pollutants from aircraft; and second, to the precise functioning of many atmospheric processes and the impact of pollutants.

Many pollutants act synergistically. Their marginal impact depends on the concentrations of other pollutants, and indeed of the pre-existing level of the pollutant being considered. It is therefore not generally possible to assign a particular unique value for the impact of any pollutant. Such is the uncertainty in some of the processes that, for example, some pollutants at certain altitudes are now thought to decrease global warming, rather than increase it.

On top of this, there is the problem of the time frame of effects. For the shorter lived trace gases, such as NO_x, it is very important to specify the profile of emission over future years. This problem has been discussed at greater length by the author (Barrett, 1991).

2.4. Contribution to global warming

Apart from carbon dioxide, the contribution of aircraft emissions to global warming is highly uncertain at the moment. Therefore this is discussed outside the main text in the Appendix. A range of effects is discussed, as are the possible implications for aircraft operation. The possible global warming due to non carbon emissions is included in parts of the main text in order to highlight its potential importance in influencing aviation and environment policy.

3. PATTERNS IN CIVIL AVIATION

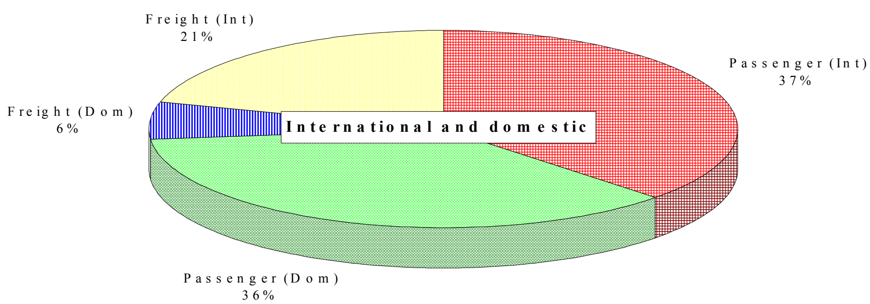
Air transport demand can be disaggregated in a number of ways. First it is emphasised that we are here concerned with commercial transport for civil purposes. Both military and private aviation are excluded. Together these may constitute approximately 15% to 20% of aviation fuel use and pollution.

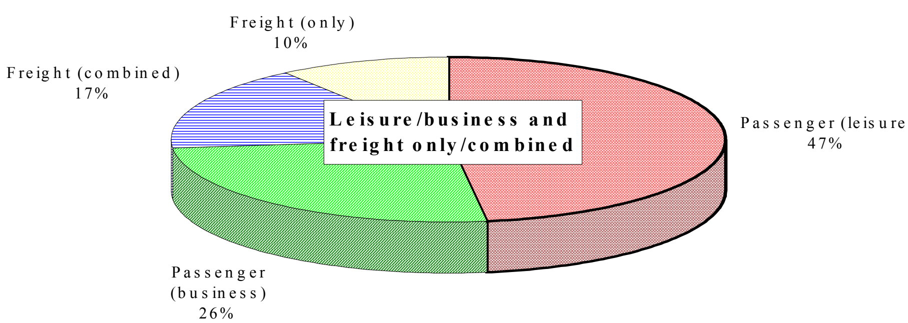
Civil commercial aviation may be subdivided by function (passenger or freight or both); by duty (domestic or international); and by service (scheduled or non-scheduled). In order to facilitate some comparison of passenger and freight transport, it is conventional to make 1 passenger.km equivalent to 0.09 tonne.kilometres. Figure 1 shows the composition of air transport demand in 1991 based on ICAO statistics supplemented by other information. Note that the ICAO statistics do not allow precise disaggregation in some respects.

The division of passenger transport into leisure and business travel is particularly problematic. There are no good publicly available statistics that allow an accurate disaggregation of passenger air travel into business and leisure. Boeing (1993) gives a breakdown by purpose that shows a large variation from over 45% business for US domestic travel, to less than 30% for US outbound travel, to less than 15% for Japan outbound travel. A world average of about 15% is estimated. Boeing predicts that the business proportion on international flights will gradually decrease to 14% in 2010.

In principle it would be possible to use total passenger travel data from ICAO, and international tourist travel information from the World Tourism Organisation (WTO) to improve current estimates. However the WTO travel data do not comprehensively include domestic tourist travel: domestic travel accounts for about half of total air passenger travel. There is a further problem that some trips combine leisure and business, although generally the prime purpose of such trips is business. This deeper analysis of passenger demand is outside the scope of this report. However, as argued below, this composition is important when considering measures such as subsituting telecommunications for business travel.

Figure 1 : Composition of Air Transport Demand (tonne.km): 1991



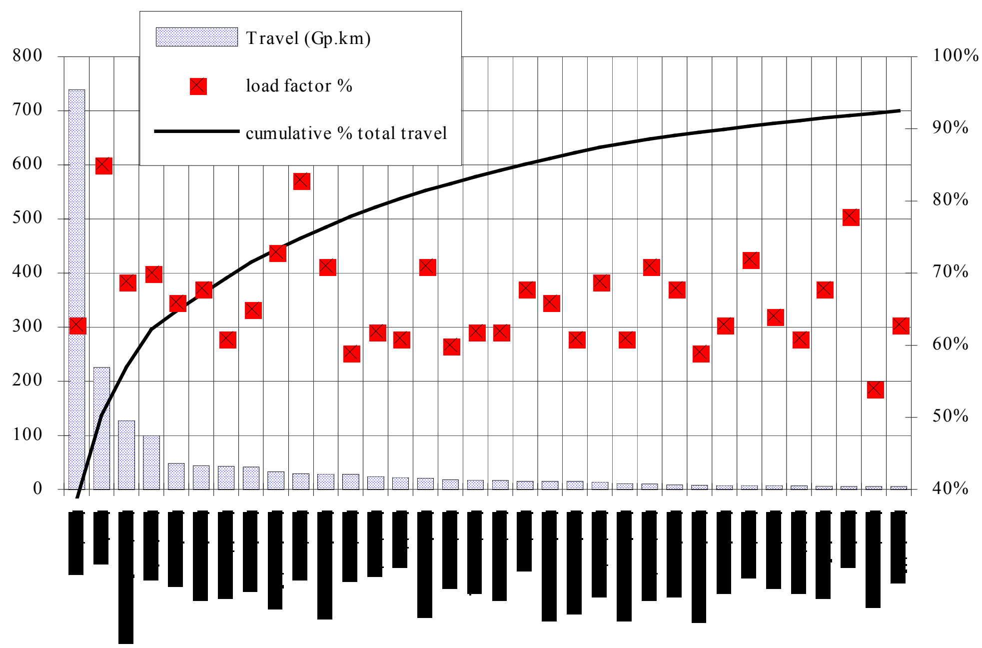


3.1. Passenger

Figure 2 shows the distribution of passenger air transport performed by the airlines of the major countries accounting for over 90% of air passenger transport. Note that this is not the same as the air travel done by citizens of those countries. Some countries, such as the UK and Singapore, have air industries that effectively export a large fraction of their services. We see that the USA accounts for some 38% of total air transport, and that the top ten countries account for over 75% of the total.

The Figure also shows how the passenger load factor of aircraft varies. The world's biggest user, the USA, achieves a load factor of only 63%. China and the CIS achieve 85%. The UK and Japan achiever higher load factors than average at 69% and 70% respectively. **Other things being equal** therefore, travellers on US airlines bring about 10% more pollution per kilometre than those from the UK and Japan, and 35% more than those in the CIS or China.

Figure 2 : Passenger Demand by Country Airlines



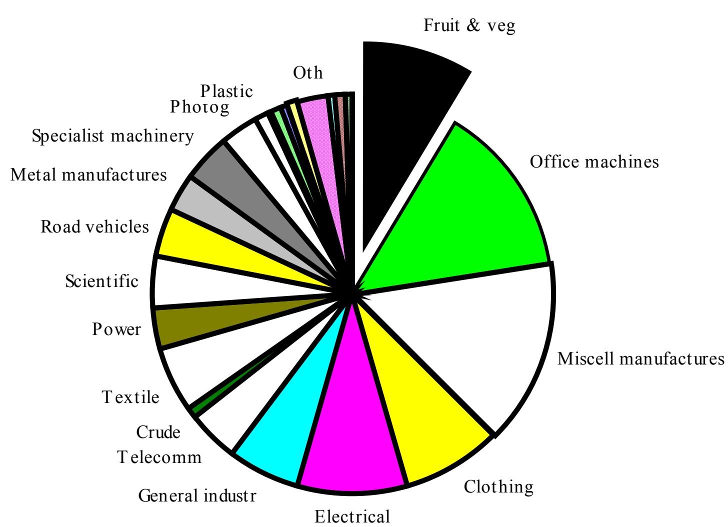
3.2. Freight

Air freight can be decomposed into various categories. First there is passengers' baggage which is not generally included as freight, and usually is carried with the passenger who owns the baggage. Secondly there is freight that is carried with passengers, but is not associated with them: this category is commonly divided into mail and other. Lastly there is freight that is carried in freight only aircraft. Most of these are purpose built freight versions of passenger aircraft; some are aircraft converted from passenger to freight duty.

A very wide range of types of freight is transported over a diversity of routes. The author does not currently have access to comprehensive data on the patterns of air freight globally. Information about air freight to and from the UK is however quite good.

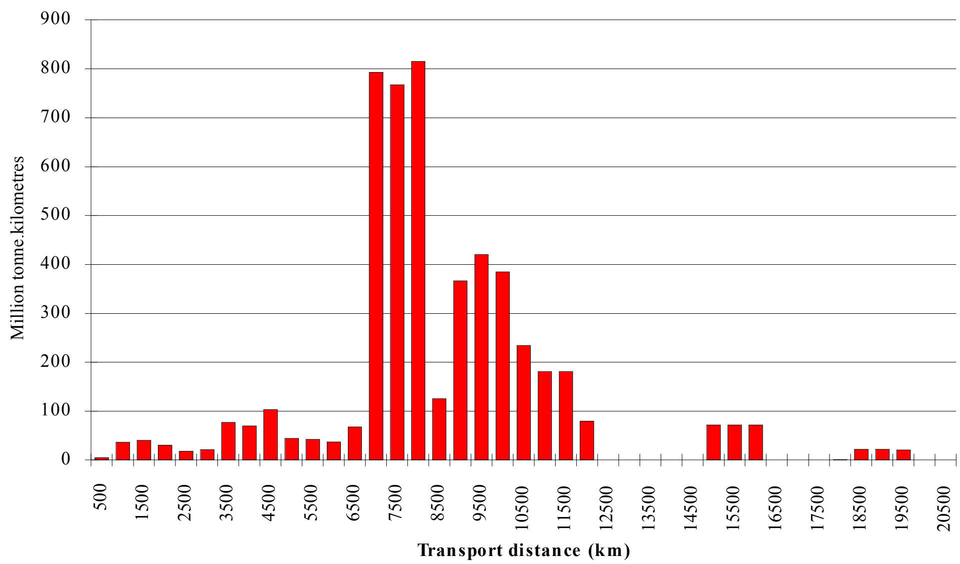
Figure 3 shows the composition of UK air freight by commodity type. There is quite an even mix of disparate commodities with no particular item being predominant. Certain categories of freight require rapid delivery: examples are goods that perish and can not be preserved with refrigeration (predominately food); some medicines; mail and urgent spare parts. The data available to the author suggest that the fraction of freight in terms of volume or weight taken up by these categories may be less than 10%.

Figure 3 : UK Air Freight by Commodity Type : Transport (Mt.km)



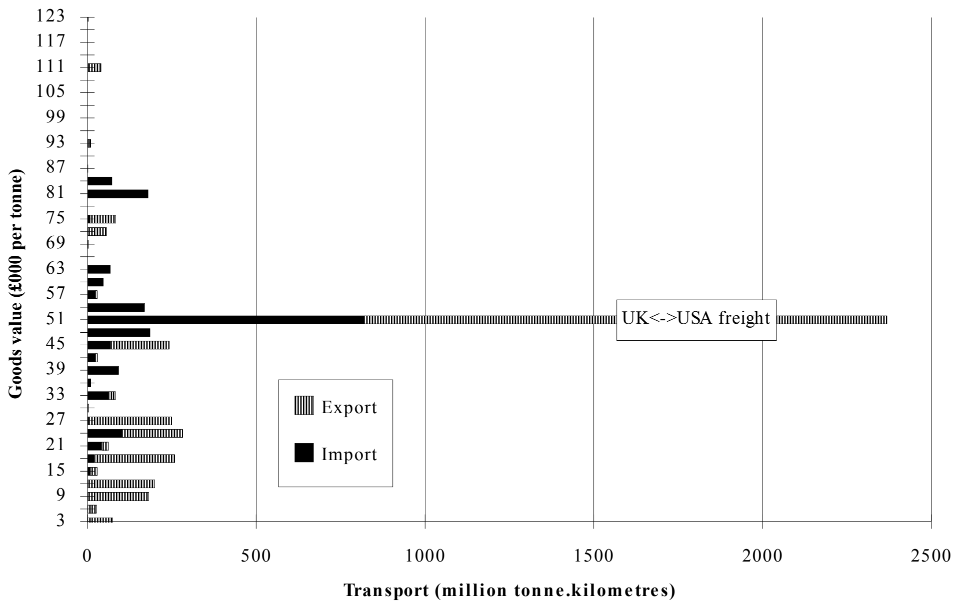
The distribution of air freight by distance transported us shown in Figure 4. In the particular case of the UK, trade with the USA is a dominant feature.

Figure 4 : UK Air Freight Distance Distribution



In 1990 the value of air freight in the UK varied enormously. The lowest value was an average £2400 per tonne for 11200 tonnes imported from Kenya; the highest value was £3.8 million per tonne for 40 tonnes imported from Brunei. The average value of air freight to and from the UK was £54000 per tonne. Air freight between the UK and the USA accounts for about a third in terms of the total value of freight transport. Figure 5 shows the distribution of trade by value and distance transported for all goods less than £123000 per tonne: this accounts for 98% of all UK air freight.

Figure 5 : UK Air freight: Transport by Value



3.3. Air transport trends

3.3.1. Historical

Over the period 1982 to 1991 the number of passengers carried increased by 47%, and because the average length of air journey increased by 10%, the total distance flown increased by 51%. During this same period freight transport (Gt.km) increased by 80%: within this mail increased by 31% and other freight by 86%.[2]

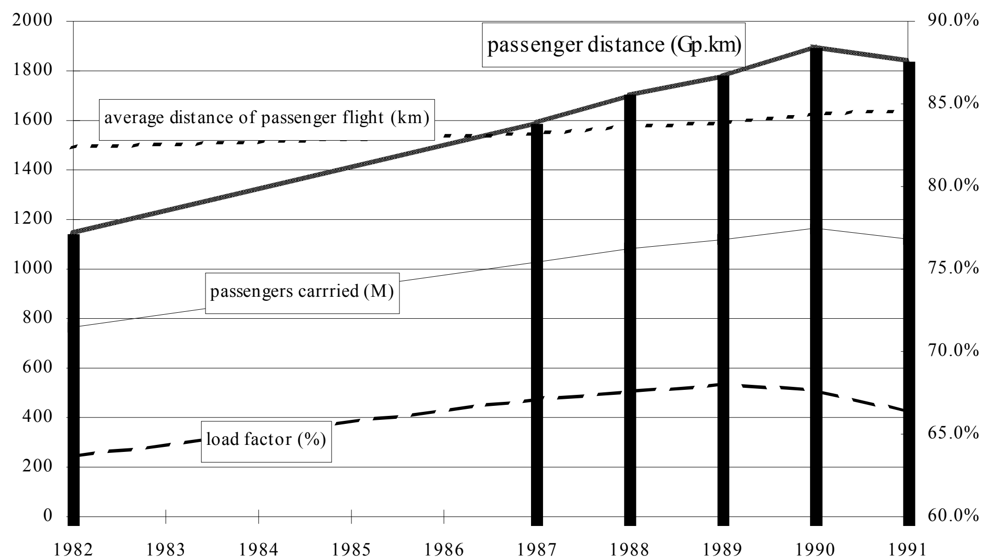
Figure 6 illustrates some of the trends in passenger transport by air on scheduled services over the period 1982 to 1991 (note that data for 1983 to 1986 are not depicted). Non-scheduled services are not included, but since they only account for about 10% of total passenger.km this Figure gives a good overview of trends. The main reason for the drop in passenger transport from 1990 to 1991 was the fall in

[2] Data quoted in this section is from ICAO (1992a) unless stated otherwise.

numbers of passengers carried, rather than the length of journey made. The average flight stage distance of passengers has grown at an average of 1.1% per annum over the past ten years. It is not known how much this is due to the total journey length (from origin to destination) of passengers is increasing, and how much is due to the gradually increasing range of aircraft.

The average number of passengers per aircraft was 111 in 1982, 117 in 1987 and 118 in 1991. This coupled with the levelling off of load factor implies that the average size of aircraft is no longer growing significantly. The average number of seats on aircraft operated by commercial air carriers on scheduled services was 174 in 1982, 174 in 1987 and 178 in 1991.

Figure 6 : Passenger Transport: Historical Trends



Tourism is an important and growing proportion of air travel. It has not been possible to analyse passenger travel patterns in detail for this report. In particular a good definition of leisure travel has not been made. Analysis done by the Department of Transport (DoT, 1990) indicates that in terms of **numbers** of international air travellers from the UK, business people account for 19% and other purposes 5%; a total of 24%. The residual 76% is made up of package holidays (38%), other holidays (25%) and visiting friends and relatives (13%). Assuming all holiday travel is called tourism, then tourists account for 63% of the total. This analysis relates to travellers from the UK. British Airways (BA, 1992) report that 60% of revenue passenger kilometres are derived from leisure travellers.

It seems reasonable to assume that about 60% of air travel in terms of passenger kilometres is for tourism. It is probable that, per kilometre, tourists generally have less environmental impact than business travellers. This is because the load factor of tourism is generally higher because of charter flying and more advanced booking, and because the seat spacing is less for tourist class than for business. It is not yet possible to quantify this, but assuming that 50% of fuel use and emissions for passenger air travel are due to tourism may be reasonable.

It is outside the scope of this report to analyse which tourist routes and destinations predominate in terms of distance travelled and/or fuel consumed and emissions. However, it is certain that tourist travel trends generally reflect those of air travel generally. More people are going further for their holidays.

Unfortunately data for freight if generally much less detailed than for passenger traffic. This lacuna must be remedied since freight traffic is currently growing about a third faster than passenger traffic and will therefore rapidly increase in relative importance.

Temporal variation in demand

As for any other service system, the capacity of the air transport system is determined by the peak demands imposed on it. The main seasonal variation in passenger transport demand is brought about by the variation in holiday travel. Thus, generally, demand is highest seasonally in the summer holidays of the northern hemisphere, and to a lesser degree by shorter holidays around Christmas and Easter. On a shorter time scale, demand tends to be higher at weekends since because of the effect of the working week on business and leisure travel patterns.

The total cost of travel is the sum of fixed and variable costs. During off peak times the total cost of travel tends to the variable cost only. Consequently off-peak travel is cheaper than on peak and operators will try to maximise the profits by increasing the utilisation of their capital assets in off peak times by selling tickets cheaply and increasing so called discretionary travel.

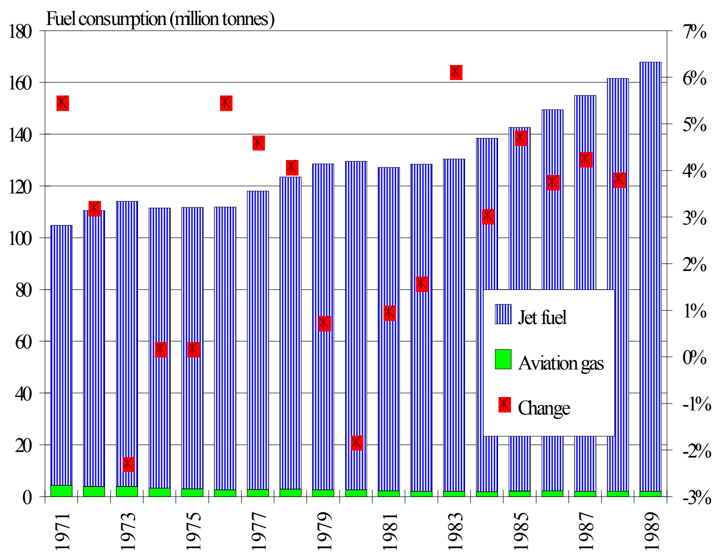
The temporal variation in demand strongly influences load factor. It may be that this variation on the global scale would make it possible to operate more efficiently by moving aircraft to routes in different parts of the world according to where peaks are occurring.

The evolution of the temporal pattern of demand is therefore an important element of forecasts.

3.4. Fuel use and emissions

The emission of most pollutants is directly related to fuel use, and CO_2 and water are particularly important examples. However, the emission of some pollutants, such as NO_x and CO are strongly dependent on engine design and operational regime. Nonetheless, given stability in operational patterns, the emissions of these pollutants can be fairly reliably projected taking into account technological developments.

Figure 7 : Historical Fuel Use



The IEA (IEA, 1989) publish data on global fuel use. This database includes figures for the consumption of jet fuel and aviation fuel for all aviation. The global total is 166.5 Mt for 1989. There are doubtless errors in this database, and it is not complete. It has not got data for China for example. Figure 7 shows the recent growth in the total consumption of aviation fuel given in the IEA database. It reflects the steady growth of the industry with only two years of the period exhibiting decreased consumption.

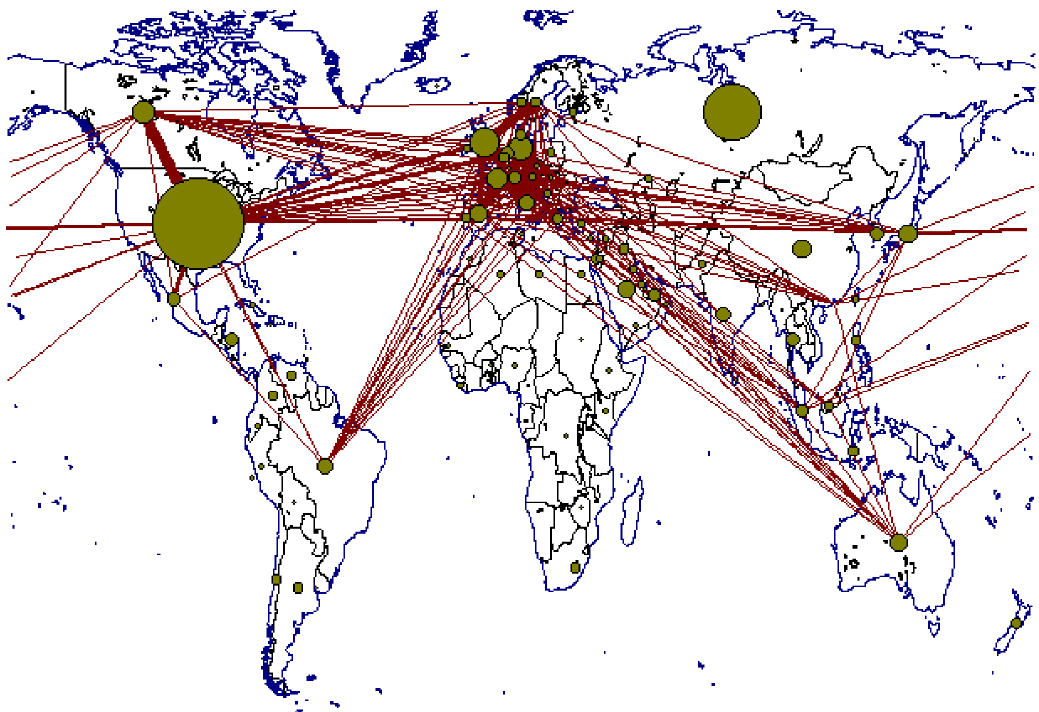
The IEA aviation fuel quantities are allocated to the country where the fuel was sold. Of greater interest here is how the actual consumption or burning of fuel may be allocated to countries, and to geographical regions. Fuel consumption could be allocated to countries according to the nationality of the airline. [Another possibility is to allocate by the nationality of the passengers using the aircraft. This has certain ethical advantages, but would be complex and difficult to implement.] It has not been possible here to allocate of fuel sales to countries by any of these methods. However, the author surmises that for most of the big aviation countries, that sales will correspond quite well with consumption. Certainly the geographical pattern of consumption will closely correspond with sales.

The IEA data may be used in conjunction with other information (UN, 1989) to give a reasonable picture of the global distribution of aviation fuel use. This is shown in

Figure 8. As outlined above, the pattern of emission will generally reflect the distribution of fuel burn. Also shown in Figure 8 are the major routes for **international** passenger travel for 1987. This is based on Travel & Leisures World Travel Overview 1988/1989. Route termini are taken as the centres of each country. All flights to south America have been allocated to Brazil. Other minor routes are not shown.

The USA sells about 41% of aviation fuel globally. The CIS (16%), Britain (4%), Germany (3%), Canada (2.5%) and France (2%) are the other countries selling more than 2% of global aviation fuel use. Given a good correlation between sales and consumption for such an aggregate, these countries, together with Japan, probably consume 70% of the world's aviation fuel: yet their combined populations constitute less than 15% of the world's people.

Figure 8 : Global Distribution of Aviation Fuel Use



ICAO has carried out a study of fuel use by airlines (Balashov, Smith; 1992). They estimate that the world's civil aviation industry consumed about 138 Mt of aviation fuel in 1990. Civil aviation thus consumes about 84% of total aviation fuel.

It would be interesting to improve these estimates of fuel, and to correlate fuel consumption with air transport service data such as aircraft, passenger and tonne kilometres, aircraft size and age, stage length and so on. This would facilitate some insights into the influence of such factors on emission. A preliminary statistical analysis has been carried out. This shows very little correlation of specific fuel burn per passenger.kilometre with average journey distance, aircraft size or load factor. The reasons for this need to be identified. It is possibly due to differences in aircraft technologies.

3.5. The future

To explore the possible future environmental impact of aviation it is necessary to make forecasts that produce, amongst other things, figures for fuel consumption and emissions. The first important stage is the forecast of the demand for passenger and freight services. Later stages involve predicting how these demands are met in terms of factors such as aircraft size and load factors - this results in aircraft movement in terms of landings and take-offs and aircraft.km. A later stage still is to take aircraft movement and apply technological factors to arrive at fuel burn and emissions.

Forecasts made by various bodies in the aviation industry generally use models in which the demand for air transport is fundamentally driven by GDP. Other factors are included: ICAO makes assumptions about aircraft size, load factor, yield and stage length; Boeing includes yield in their model. These projections do not apparently include the possible effects of environmental impacts on the policies and development path of the aviation industry. IATA's forecast is more or less an aggregate of the individual forecasts of their members. These may or may not be based on models and methodologies that incorporate the effect of environmental constraints.

3.5.1. Passenger demand

Annual passenger kilometres per person per year range from about 1700 for North America, through 480 for Europe, to 75 for Asia to 45 for Africa. Given the probable increases in population and some equalisation of air travel between regions, it is easily seen that the potential long term growth in demand is vast. If everyone today travelled as much as the average US citizen, then global air travel would increase to more than eight times today's level. If in a hundred years time, when the world population will be approximately double today's, average global per capita air travel reaches current US levels, then total travel will increase seventeen times.

The ICAO published forecasts of air transport demand for the period 1990 to 2001 (ICAO, 1992). The ICAO uses projections of world GDP increasing at an average 2.6% per annum in real terms. Passenger transport (in passenger km) is projected to increase at 6% for international flights, at 4% for domestic leading to an overall growth of 5% per annum. Freight transport is projected to increase at 6.5% per annum. The growth rates for passenger and freight transport are about twice GDP growth; and freight demand is projected to grow faster than passenger demand. Over the period 1990 to 2001, ICAO project increases in aircraft size (183 to 220) and load factor (66% to 68%).

IATA (1992) expects an annual growth rate of 5%/a for international scheduled passengers between 1990 and 1996. Within this average IATA reports a wide range of growth rates, with especially high figures found for less rich countries. For example, between 1992 and 1996 forecasts for average annual growth are 13.6 %/a for China, 14.8% for the CIS and 10.3 % for Indonesia. These countries constitute nearly 30% of the world's population.

3.5.2. Freight demand

Boeing (1992) has made a forecast of freight demand which projects that freight traffic will increase 2.5 times between 1990 and 2005; an average growth rate of 6.4%/a. This is in line with the ICAO forecast. The projected growth of mail is less than that of other cargo, but mail is a small proportion of the total. Boeing foresees the highest growth rates to come about in the Pacific Rim countries.

3.5.3. Some implications

The prospects are for rapid increases in traffic, and the indications are that traffic growth in the East and Pacific Rim will be faster than average with the global pattern depicted in Figure 8 changing accordingly. These forecasts lead to the conclusion that there will be big pressures to increase atmospheric pollution from aircraft. The changing geographical distribution may also be important. On the one hand, near the equator the tropopause is generally well above the cruising altitude and so the effects of pollution may be less: on the other, the impact of additional NO_x emission in the southern hemisphere is thought to be greater than in the north (Johnson et al, 1992).

4. CONTROL STRATEGIES

In this section some strategies for controlling the environmental impact of aircraft are described. The elements of strategies are largely approached in an exploratory manner. The reason for this is that the commercial aviation industry is exceedingly complex from many perspectives. First there is its size: some 1200 million people are transported worldwide on 42,000 aircraft. Second there are the tangled interactions between technical, social, economic and logistic factors. The industry itself does yet not have the data and analytic tools with which to assess many aspects of strategy described here. The elements of strategy proposed should therefore be taken as qualitative rather than quantitative descriptions of what might be possible. One aim is to stimulate further exploration of control strategies. This will entail the better availability of data, the development of analytic techniques, and, not least, the negotiations as to what the objectives of strategy should be.

Possible objectives and targets of strategy are first proposed. These are followed by an overview of the individual measures that might be applied and an exploration of some of the regulatory and fiscal means that might be used to bring the measures about. The possible effects of these control strategies are explored with an emission model of the civil aviation industry.

The civil aviation industry is becoming increasingly affected by environmental considerations. Every industry likes to consider itself special, and to argue that environmental limitations should be applied to others more than itself. There is no incontrovertible reason to place civil aviation in a special category and the prima facie position should perhaps be that it should bear the same pro rata emission limits as any other industry.

Some statements from bodies within the aviation industry and others outside give recognition to the importance of environmental concerns. The secretary general of ICAO, Dr Philippe Rochat concludes:

> *"ICAO's latest forecasts of world scheduled passenger and freight traffic ... imply an average growth rate of about 5 or 6 per cent during the 1990s ... and of about 5 per cent for the following decade. Inevitable, growth of this magnitude will bring with it increased environmental problems."*
>
> *"The results of a study within the ICAO secretariat indicate that in the last 20 years there have been substantial improvements in fuel efficiency and that further improvements can be expected, but unfortunately they will not be sufficient to offset aviation's high growth rates."*
>
> *"For many years we have been accustomed to growth in our industry. Now, we are faced with the prospect that environmental problems could restrain growth. ... The aviation community has an obligation to the world's population (many of whom have never been on an aircraft) ... and to future generations ... to act responsibly on environmental issues, particularly the global ones" (Rochat, 1993).*

World Travel and Tourism Council (WTTC, 1992) recommends that :

> *"Travel and tourism companies should seek to implement sound environment principles through self-regulation, recognising that national and international regulation may be inevitable and that preparation is vital."*

The WTTC gives a list of twelve specific items that travel and tourism companies should aim at, this includes:

They [travel and tourism companies] should aim to: ....
*4. **Practice** energy conservation*
*7 **Control and diminish** air emissions and pollutants."*
(World Travel and Tourism Environment Research Centre; 1992)

Any international accords setting global emission targets will generally be implemented by nation states. Thus if a particular country agrees a limit for a particular emission, such as carbon dioxide, then that country's government will decide how this limit is to be allocated to different sectors of the economy - industry, residential, transport and so on. It may be that the proportional allocation of such limits to aviation will vary widely from country to country.

The scope for the independent application of emission control options by countries is somewhat limited. This is because of international nature of the aviation industry, and because the body of international legislation constraining economic processes is continually growing. This may mean that some important options such as fuel or aircraft movement taxes, or ticket transfer, will have to be applied globally if at all. There are options that can be independently taken up: the improvement of the domestic environment to encourage holidays in the home country is one example. This of course would encourage travel by other modes such as the car, and attract more visitors from abroad.

4.1. Environmental objectives

One main objective of WWF is to preserve the environment such that biodiversity is maintained. In the context of pollution from aircraft, the global environment may be protected with the following three objectives.

(i) Control of global warming

(ii) Decrease risk of ozone loss

(iii) Reduce risks of other effects of upper atmosphere pollution

Note that the significant, but local impact of airports and their associated traffic is not considered in this report. This is because threats to biodiversity due to the land use and emissions of airports are generally smaller than those due to global or regional pollution problems. There are however, specific instances of airport developments affecting rare species.

4.1.1. Targets for the environment and emissions

The overarching objective of the policies under discussion here is that of achieving certain environmental targets. The limiting of climate change and the preservation of the ozone layer are two goals relevant to aircraft. These goals might be reached if the appropriate specific targets were set.

These latter could include the following:

(i) Maximum atmospheric concentrations of pollutants specified possibly by altitude and latitude.

(ii) Ceilings to global emissions of specific pollutants.

There are great difficulties in quantifying environmental and emission targets for global warming or other environmental impacts.

4.1.1.1. Global warming

The impact of climate change on biodiversity is extremely difficult to quantify for many reasons. Many species of flora and fauna have yet to be discovered, let alone described in biological terms. The interactions between species in ecosystems are understood well only for a few ecosystems. The response of individual organisms, of species and of ecosystems to environmental changes is largely unknown. It is difficult to enough to speculate on changes given some new environmental equilibrium; it is even more difficult to understand how biological systems will respond to a dynamically changing environment. How far and how fast will existing living systems adapt? It is therefore not yet possible to precisely quantify the biological effects of climatic change either during a period of rapid change, or once in an equilibrium state. Nonetheless, efforts have been made to estimate targets for the <u>rate</u> and <u>ultimate change</u> in average global temperatures that would allow many of the present systems to adapt. A consensus of views proposed in a number of reports (e.g. Rijsberman, Swart; 1990: Krause et al 1990) and by a number of bodies including the FRG Inquete-Kommission suggests a rate limit of 0.1 ^{o}C per decade; and absolute targets of 1 ^{o}C (lower risk) or 2 ^{o}C (high risk) increase over pre-industrial global mean temperatures.

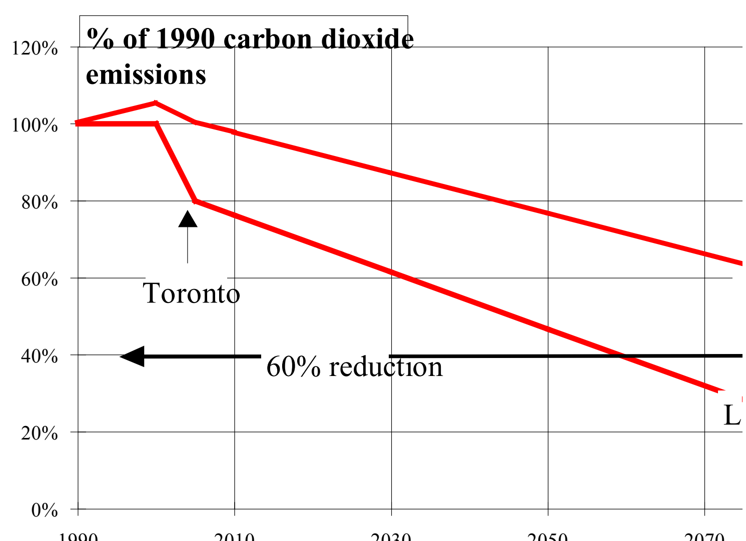
How do the emission of trace gases have to be constrained in order to attain these environmental targets? There is no simple answer, both because of the uncertainty of the effects of the gases, and because of the dynamics of climate change. The earth warms up slowly because of its thermal capacity. Consequently, even if trace gas concentrations were kept constant, the earth will continue to heat up to a new equilibrium temperature. Furthermore CO_2 remains in the atmosphere for 100-200 years on average, and so its concentration would fall very slowly even if emissions were to instantly cease. Even if emissions were kept at current levels from now on the global temperature would rise at some 0.2 ^{o}C per decade for several decades. The profile of emissions year by year is important, as is the total emission over a period of say a century. Krause et al (1990) explore the issue of emission profiles and climate change. The long residence time of CO_2 means that, in terms of time scales less than 100 to 200 years, a rapid small reduction in emission is as effective in meeting targets for climate change as a slower but larger reduction. Many important greenhouse gases such as ozone have much shorter residence times than CO_2.

The IPCC scientific assessment of estimates that a reduction in carbon emissions of some 60% is required to stabilise the concentration of carbon dioxide in the atmosphere at current levels (IPCC, 1990). To meet targets for climate change similar to those used above, Krause et al (1990) use a global emission target of 300 Gt for the period 1985-2100; because of the inertia in the socioeconomic and energy systems, the global emission scenario consistent with this limit show a rise in emission in the short term, followed by an eventual reduction in 2000 of total emission at 20% of 1985 levels - an 80% reduction. These reductions are long term targets. Other targets deal with the shorter term. The Toronto agreement is an example of an internationally discussed medium term target. This sets a 20% reduction on 1985 emissions by 2005.

The scientific uncertainties will gradually be narrowed, but it is unlikely that they will be entirely eliminated. Politicians are actively seeking to set emission limits in international fora. One result of this has been commitments to suppressing the emission of carbon dioxide in the short and medium term (i.e. less than twenty years). So far these commitments do not have the weight of strong international treaties or international law - but the movement is in that direction.

These analyses, proposals and negotiations suggest that the general envelope of greenhouse gas emission limits may be as illustrated as in Figure 9. This is not to say that actual future emissions will

Figure 9 : Greenhouse Gas Emission Targets



be contained by this envelope.

Of all the trace gases, the global warming effect of CO_2 is best quantified. The problem for aircraft is that the emission of other pollutants such as NO_x and water may lead to global warming of comparable magnitude to their CO_2 emissions. Given that many gases contribute to global warming, and that, in the case of aircraft, the control of NO_x is ultimately inimical to the control of CO_2 emission for technical reasons, it is important to include all the gases.

Two approaches can be suggested:

(i) Aggregate global warming pollutants emitted by aircraft (possibly including CO_2, NO_x, and water) in a standard way to give an overall warming index. This aggregation could employ different weightings for each gas. The could be measures in terms of CO_2 equivalent. However this approach is basically that of the GWP, and the IPCC expresses doubt about using such concepts for gases such as NO_x. Also, the weighting for NO_x and water should take into account the spatial distribution of emission (altitude and latitude).

(ii) Subject each greenhouse gas separately to proportional emission reduction limits.

As far as aircraft are concerned, these two approaches may not make such a difference because all emissions are generally related to fuel use. Setting a limit on CO_2 effectively limits fuel use (if fossil) and thereby limits water and NO_x emission - and vice versa. However there is an important compromise between carbon dioxide and NO_x emission control in jet engine design. Therefore, within limits, decreasing NO_x could increase CO_2.

There are reasons for arguing that greenhouse gas emissions from aircraft should be separately limited. First there is the advice from the IPCC not to use GWPs for NO_x. Second the global warming effects of NO_x and water vapour are very dependent on the altitude of emission - and possibly latitude.

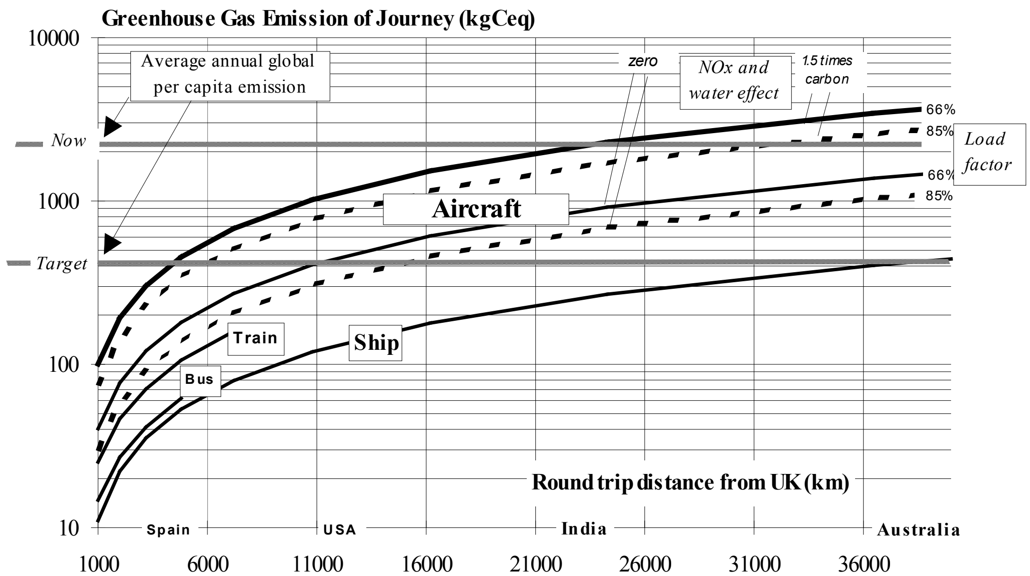
Another perspective is advanced for illustrative purposes. This is to look at the global warming impacts of individual journeys and to compare these with per capita emission targets.

Figure 10 depicts the approximate global warming of a single round trip travelling by different modes of transport[3]. Please note the logarithmic scale on the y axis: each y scale division represents a doubling of emission. Greenhouse gas emission is expressed in tonnes of carbon equivalent (tCeq). The warming due to aircraft is estimated for CO_2 only, and for the case where warming due to NO_x and water is 1.5 times that of the CO_2. This illustrates the sort of range to be expected. The global warming due to a single journey is compared with the global annual average emission of greenhouse gases. These global averages are given for 1990 and for a target reduction of 60% in total global emission. The 1990 average is about 2.3 tCeq per person per year. Given a global population increase of perhaps 100% over the next century, this average emission needs to be reduced to about 0.4 tCeq per person.

We see that a return flight to Australia from the UK brings about more than half the average per capita global warming effect even if it is assumed NO_x and water have no effect: if an effect 1.5 times that of the carbon emission is assumed, then a return flight to India has the same impact. Taking a 60% target reduction, a return flight to the USA uses up the per capita allocation assuming no NO_x effect: with the NO_x effect a return flight to Spain would exceed the per capita quota. The average flight length is currently about 1600 km, and the average return flight may therefore be about 3200 km. Such a flight would bring about 5% (no NO_x effect) to 15% (NO_x effect) of the current per average per capita global warming: with a 60% reduction in global per capita emission these proportions rise to 25% and 70% respectively.

[3] Some aspects of intermodal comparison are discussed below.

Figure 10 : Greenhouse Gas Emission of Journeys



Now this analysis uses assumptions about targets, population growth, fuel consumptions, NO_x effect and so forth. These may all be questioned, but these assumptions have to be radically adjusted if the implications of the analysis are to change. The main conclusion is that if there is any future convergence on interpersonal equity in terms of environmental impact allowance, then flying will quickly use up ones' personal allowance. A trip from the UK to New York would mean cycling the rest of the year and no heating in winter!

4.1.1.2. Other pollutants

Setting targets for other pollutants is even more problematic. Many have multiple and synergistic impacts. Scientific understanding about their impacts is changing rapidly. These observations especially apply to aircraft pollutants emitted at high altitude. It is therefore not yet possible to enter into quantified speculation. It can be suggested that any chemicals added to the atmosphere by aircraft will change atmospheric conditions away from those to which life is adapted. By this argument any alteration of natural background levels is deleterious. Unfortunately this argument is not of much practical use when trying to balance the known benefits of aviation against possible environmental damage.

4.1.2. Limits for aircraft

It may be that future scientific work will radically change the perception of the required reduction in greenhouse gas emissions with the consequence that tolerable limits will be higher than those enveloped in Figure 9 - or of course lower. A prima facie argument can be put that global emission limits for aircraft will follow those shown in Figure 9 on a pro rata basis. There is the possibility that the limits for aircraft might be less, or more stringent than those in the Figure.

How important is air transport to social, political and economic systems as compared to other sectors such as residential services, manufacturing industry, private motoring or electricity? It is a globally important industry, but it is not as vital as, for example, the provision of energy for cooking food, heating and lighting homes, or manufacturing essential commodities, or travelling to work. After all, about half of air transport is for people going on holiday. Furthermore only a small fraction of the world's population uses air travel at all. This leads the author to conclude that it is difficult to argue that aviation should be especially protected and should escape pro rate emission limits.

What is the technical scope and cost of limiting emissions from aircraft as compared to other sectors? Although most sectors and technologies have reduced energy use and emission per output over past years, it seems to the author that the scope for further cost-effective reduction in many non-aviation sectors is probably greater in proportionate terms than for aviation. This is not to say that the potential for reduction in aviation impacts is small.

National emission limits will be set in a context of internationally negotiated global targets. The allocation of national emission allowances to sectors will be made by national governments. These allocations will doubtless vary significantly from country to country according the particular characteristics of climate, development, economic structure and so on. However until such political negotiations have taken place, the presumption must be that globally aviation on average faces the same order of reductions in emissions as other sectors of the economy.

4.2. Control options

Relating to global air pollution from aircraft, there are two basic non exclusive control options:

- The total emissions of pollutants can be limited;

- Emission may be reduced in sensitive zones such that the impacts of pollutants are diminished.

To reduce the environmental impact of aircraft three categories of action are required:

(i) Research and monitoring are needed to establish the actual extent of emissions and their effects.

(ii) Policy options that mitigate environmental impacts need to be devised.

(iii) Mitigating policies have to be implemented through appropriate legislative and institutional frameworks.

Control options can be put into three categories: **demand management; operational change; and technological change**. Measures in each of these three categories can be implemented severally. Implementation methods can be divided into intelligence and information, incentive and disincentive, regulation and investment. Table 1 sketches out a matrix of basic options and means of implementation with examples of particular measures.

The complex interactions that occur in the aviation industry make it generally difficult to discuss and assess particular control options in isolation from others. Some examples of these interactions and potential dilemmas follow.

- Putting more taxes on fuel and aircraft movements might increase load factors, and make air travel more expensive thereby suppressing demand. Increasing load factors will decrease the capital cost element of flight thereby decreasing total flight costs and stimulating demand.

- Managing air freight demand can not be best accomplished without at the same time managing passenger demand. Presently two thirds of air freight is carried with passengers. This is at a relatively low marginal economic and environmental cost because of the design of aircraft for mixed passenger and freight transport.

- Large aircraft are generally more efficient per seat than smaller ones and therefore produce less gaseous emission. However it is difficult for large aircraft to meet noise limits, even though the larger the aircraft the fewer the aircraft movements.

Table 1 : Some emission control options

Options	Intelligence	Incentive	Regulation	Investment
Operations	flight planning models	fuel and emission taxes	bubble emission limits	global booking system
higher load factor	advanced booking; integrated flight planning	aircraft movement tax	ticket transfer permit	less seat spacing
shorter route	ATC			
lower altitude	optimum height		zone emission limits	
slower cruise		fuel and emission taxes		
less congestion	better ATC	aircraft movement tax		better ATC
Technology				
engine emission	information to operators and consumers	emission taxes	emission limits per unit thrust	more efficient, low emission engines
aircraft emission	information to operators and consumers	emission taxes	emission limits per seat.km	large aircraft optimised for passenger transport
Demand management	advertising and labelling			
passenger	advertising and labelling	passenger movement or distance tax		better local environment and holiday facilities
				telecommunicatio ns
				alternative modes
freight	economic information	freight tax		alternative modes
	advertising and labelling			localised production

The discussions of control options presented below centre on what seem, to the author, to emerge as some obvious foci for strategy. There is no particular ordering of the options, except that thorough monitoring and detailed information about the industry is a prerequisite of assessing strategies, and is therefore placed first.

It is again emphasised that a main aim of this report is to stimulate further exploration of the needs, objectives and means of emission control.

4.3. Monitoring and information

Clearly, firm information about the aviation industry is necessary for policy formulation. This means that extensions and additions to the present monitoring and reporting schemes are needed. Particularly important is better knowledge of the demand for air transport, the use of aircraft, and their emissions. At present the emissions from aircraft are not comprehensively monitored or calculated. In particular, little is publicly known about aircraft emissions at high altitude. The energy efficiency and emission characteristics of all aircraft and aeroengines under all operating conditions should be monitored and the results made public.

Comprehensive data for the aviation industry (including military aviation) should be made available and should therefore include:

(i) The energy efficiency and emission characteristics of all aircraft and aeroengines under all operating conditions including those pertaining whilst cruising at altitude, should be measured or accurately estimated, and the results made public.

(ii) Accurate estimates of fuel use and pollution emission incurred during actual operation should be published. These emissions should be given for and by each airline or aircraft operator.

(iii) National governments should include all of the principal aircraft emissions in national pollution inventories. Aircraft emissions should be given for the different altitudes at which the pollutants are released.

(iv) An appropriate international body, such as ICAO, should collate national data in order to produce a global picture. The distribution of aircraft emissions should be given by altitude, longitude and latitude - and possibly by time of day and year also. This is important for modelling the atmospheric effects of the pollutants.

Rapid progress is being made on much of the above. Research and data collection by bodies such as NASA and ICAO are advancing quickly, and some of this information is available free or at low cost to outside bodies.

Information should be provided for other transport modes also.

4.4. Environmental regulation

4.4.1. Emission limits

The fundamental limits to emissions are determined by environmental goals such as minimising the loss of biodiversity. These fundamental limits are specified as bubble limits for the world or for regions. Some emission limits, such as for NOx, might additionally specified in terms of limits for segments of the atmosphere since effects vary greatly. Fundamental global or regional limits are usually allocated to individual countries responsible for implementing policies to achieve limits. Fundamental limits can be met by setting a variety of 'effecting' limits that may be defined in terms of emission per unit of a variety of human, technological or economic variables. The Table below illustrates this.

Table 2 : Types of gaseous emission limit

		Limit type
Fundamental		global (Mt/a) [by atmospheric segment in some cases?]
		regional (Mt/a)
		national (t/country) [e.g. EC SO_2 limits, proposed CO_2]
Effecting	**Human**	per person (t/person)
		per person kilometre (g/p.km)
	Technology	per seat kilometre (g/s.km)
		per aircraft kilometre (g/a.km)
	Technical	per unit engine thrust (g/kN) [ICAO standards]
		per mass of fuel burnt (g/kg)
		per volume of exhaust (g/m^3) [EC large combustion plant limits]
		per standard test (g/test) [EC vehicle standards]
	Economic	per value added (g/$US)

At present there is no comprehensive regulation of gaseous emissions from aircraft. Existing standards, such as those administered by ICAO, relate to the emissions of certain pollutants from engines operating under particular low altitude level conditions.

4.4.1.1. Bubble limits

Bubble limits set ceilings to total emissions from particular geographic regions or economic groupings. For example, bubble limits could be applied to the world, to individual countries, to the air industry, or to individual airlines. At present there is no agreement to a global limit. Instead commitements have been made by certain countries to limit their emissions to some proportion of their historic emission. Ultimately however, it is difficult to envisage an alternative path to one in which first an international agreement as to global limits is made, to be followed allocations of emissions quota to countries. The basis of allocation might be by population. Other bases and systems such as 'pollution trading' have been discussed and might be applied to aircraft.

One interesting consequence of the present ICAO ceiling of 1000m on emission standards for aeroengines for pollutants such as NO_x is that some countries exclude all emission above this ceiling from their inventories - including carbon dioxide. The UK is one such country. This issue is briefly discussed in the author's previous report. Obviously from an environmental perspective, all emissions should be accounted for.

To whom should fuel use and emissions be allocated? A number of approaches could be adopted. In general the polluter pays principle means that the fuel use and emissions of a particular technology are assigned to the user, or possibly owner, of that technology. It is not always obvious who the user is, and the user and owner may be different.

In the case of aviation, users might be those using air transport (passengers and freight users) or those operating aircraft. In the users' case, the emissions of the aircraft on a particular journey would be allocated to countries according to the proportions of each nationality represented. This is perhaps the 'ethically clearest' method. Computerised airlines booking systems could be used to allocate emission and record them.

In the operators' case emissions would be allocated to the country in which the airline or operator was registered or owned . This would involve less data than the first method but raises some awkward problems. Should it be by registration or ownership? Airlines might be owned multinationally - should emissions then be allocated by percentage ownership? Airlines might enter into complex interlining and other agreements which would make it difficult to make the allocation.

In both of these cases an extensive data processing system would have to be devised involving the estimation and collection of emissions, and their allocation to whatever country.

Another method is to allocate according to the country where fuel is loaded. This was initially appealing to the author since statistics on this are already available. But there are drawbacks to this notion: it does not follow the polluter pays principle; and some emissions are dependent on engine characteristics and operation as well as fuel use.

4.4.1.2. Technology standards

A schedule of tightening emission standards for all the important pollutants should be drawn up and applied to individual categories of engines and aircraft. This process happens, in the main, under the auspices of ICAO.

Engine emission standards

Setting limits to the emission of pollutants from engines is an important measure for control, but a shortcoming is that they do not apply to the aircraft as a whole. The Committee on Aviation Environmental Protection (CAEP) of ICAO studies the practical means for controlling the environmental impacts of aircraft. Engine emission standards are recommended by ICAO for certain pollutants and are taken up by most countries. Presently CAEP's considerations include the control of CO_2 emission but more from an overall policy perspective, rather than with a view to specific engine or aircraft standards. Although the existing type of engine standards is important, they are not necessarily sufficient for controlling total pollution from the whole aircraft stock. There are at present no proposed standards for fuel efficiency for engines, let alone whole aircraft.

Historically, the main environmental concern of ICAO has been noise and emissions at or near airports; and the main measure considered for controlling these impacts has been improvements to engines. Emission standards have been expressed in terms of pollution emitted per kilogram of thrust of engines. Currently engine emission standards only apply to the landing and take-off cycle (under 1000 m.); it has been agreed that this should be extended to the whole flight cycle including cruise.

A new standard setting NO_x emissions per unit thrust 20% less than the current was recommended by CAEP and agreed by the ICAO Council in March 1993. The setting of standards is heavily influenced by aeroengine manufacturers. Obviously their expertise is essential in the setting of achievable standards, but it may be that they shy away from lower standards because of worries about lengthy high cost engine development programmes. Some bodies have argued that a 60% reduction is feasible, but their business is not the successful marketing of safe aeroengines and so they may argue for unrealistically low emissions.

Aircraft standards

Ultimately the best aircraft is that which transports a passenger over a given route with least pollution. Therefore, a more useful measure than emission per unit engine thrust or pressure is emission <u>per seat kilometre</u>. There are difficulties with this concept such as how to make allowances for differences in aircraft size and duty.

4.5. Demand management

The management of demand is key. The level and growth in passenger kilometres and tonne kilometres are the basic driving force for increasing pollution, and certain policies may help to restrain growth in demand. The general historic decrease in the cost of air travel in real terms and relative to incomes has been a crucial factor in demand growth. The concept of demand management does challenge a widespread tenet that there should be freedom to consume. However, there are an increasing number of examples of where environmental considerations are limiting such freedoms, such as the increasing control of car use in town centres.

It has been beyond the scope of this paper to look in detail at the extent to which demand might be managed, or to look at the means of management.

4.5.1. Managing passenger demand

4.5.1.1. Journey planning

Advanced and long term journey planning can help to avoid the repetition of trips and to integrate trips efficiently.

4.5.1.2. Telecommunications

Telecommunications can substitute for a certain amount of air travel, particularly for business travel. Technologies with video included are being rapidly developed. Systems such as video telephones, video conferencing systems, and desk top computers with video facilities could possibly reduce the need to travel for business. It is probable that such systems will rapidly offer communication that is cheaper in direct and indirect costs than physically travelling. It is unlikely that telecommunications could have much impact on leisure travel.

4.5.1.3. Improvement of the local environment

Improvement of the local environment can reduce the desire for long distance travel for holidays.

4.5.2. Freight

The trend is for manufacturing and commodity storage systems to be increasingly dispersed geographically. This is typified by 'world cars', the components of which may be manufactured in several different countries, and the car assembled in yet another. This is done to reduce the total cost of manufacturing and distributing various commodities. The concept of 'Just In Time' (JIT) goods delivery has been developed and applied to dispersed manufacturing and retailing systems. In JIT systems the stocks of goods are reduced to a minimum by providing punctual and rapid transport between manufacturing nodes. The application of JIT has tended to favour road and air over rail and sea. In many cases the favoured modes cause more pollution per tonne.kilometre.

Minimising the costs of manufacturing and distribution entails achieving the optimum balance between the costs of production, transport and storage. Both the actual costs of providing facilities and services and the interest payments on goods in transit are important. As the value of goods increases, so the optimum balance shifts away from slower cheaper modes such as ship or rail towards air or road. For perishable freight, mainly food, speed is important although refrigeration and other preservation methods can still leave slower modes viable. Speed is also important for a small proportion of freight such as mail or medicines.

Plainly, pushing the cost of air freight upwards through taxation or some other means will alter the optimum balance towards non-air modes. However, in the present aircraft stock, about two thirds of freight is currently carried with passengers and engenders a small penalty in terms of extra fuel burn and pollution. Therefore the environmental penalty of this fraction of freight transport will be small unless the existing stock of mixed passenger/freight aircraft is replaced by aircraft designed to maximise the number of passengers carried plus their baggage.

The UK data allow one to argue that about 90% of freight currently shipped to or from the UK by air could go by slower modes. Exceptional categories include urgent items such as mail and medicines, but these are small in terms of mass and volume. In the following the author assumes that this fraction could apply to global air freight, but plainly analysis of other data is required to justify such an assumption.

The strategy for moving freight from air to less polluting modes has a medium and long term component. The medium term component is to transfer all non urgent freight carried in freight only aircraft to other modes. This might be accomplished over a period of ten years or so.

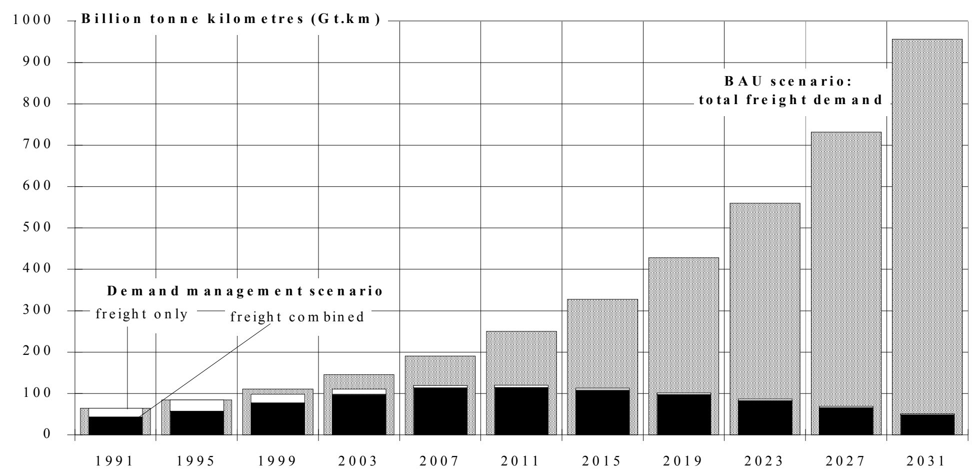
The longer term strategy is to transfer all freight that is not inherently urgent to slower and cleaner modes of transport. Eventually existing aircraft designed for mixed passenger and freight transport would be replaced by aircraft that are designed to carry the maximum number of passengers and their accompanying baggage. Then it would not be possible to carry large amounts of freight with passengers at a low marginal economic and environmental cost.

In the longer term alternative rapid surface freight transport systems would have to be developed. Rail and, if necessary, road transport could substitute for land routes. For sea routes conventional or new designs of ships could be used. There are well-developed proposals for relatively small and fast cargo ships such the 'FastShip' of Thorneycroft, Giles & Company [4]. Their ships would use gas turbine engines and could cross the Atlantic in 3.5 days. The overall cost per tonne.kilometre of transporting freight by these FastShips is estimated as one tenth of that incurred in a Boeing 747; the fuel consumption per tonne.kilometre is suggested to be about half that of the aircraft. As yet there is no firm experience to support these comparative figures.

As well as new rolling stock, vehicles and craft, there would be extensive infrastructure requirements such as more freight handling at ports and stations and more railway track.

Figure 11 illustrates the consequences of this strategy for air freight demand. It shows the phasing out of most freight only air transport over ten years and the effect of reducing the overall growth rate of air freight transport from 6.4%/a to 7%/a. Even though the strategy would bring about a large change from present trends, total air freight transport in 2025 is still greater than now.

Figure 11 : Freight demand management scenario



[4] 2550 M Street, NW, Suite 450, Washington DC 20037.

Freight transport can be as much as half of total revenues for certain airlines and route groups. Plainly the loss of most freight would affect these routes and airlines significantly. Passenger costs could rise in these areas and service flexibility decline. However the loss of freight business will be balanced at least partially by the increase in passenger traffic.

4.5.3. Modal change

One potential way of reducing pollution from aircraft is to switch transport to other modes. In general, a shift from air to other modes such as rail, sea or road will decrease the emission and impacts of pollutants. The main reason for this is that competing modes in many cases use less fuel per seat and passenger kilometre. However a principal reason for this is that the fuel use of vehicles per kilometre is strongly dependent on speed, and other modes are slower than air. Also there is limited scope for shifting from air to other modes because of the need for speed and the availability of alternative routes.

There are many factors that have to be included in intermodal comparisons; these include:

(i) Quantities and types of pollution. Different transport modes have different impacts in terms of gaseous pollution, visual impact, noise and so forth. These impacts are imposed on different parts of the environment: some occur near or in human settlements; others occur remotely at sea or high in the sky. The actual damage caused often depends on where pollutants are introduced to the atmosphere.

(ii) Cost, reliability, convenience, enjoyment. How does the consumer perceive the pros and cons of different modes? Cost differences can alter modal decisions, although much evidence suggests that cost differences have to be large to substantially influence passenger modes - this may not be so true for freight. The convenience of different modes in terms of frequency, total journey time, directness of route, luggage carriage and so on is important. Enjoyment of the journey is important, especially for long journeys: comfort, good views and facilities and so on can affect modal choice.

(iii) Future technological potential. For long distance surface transport technologies such as trains and ships, reducing weight and volume is not as important as in aircraft. This makes it easier to utilise propulsion technologies that reduce emissions. This can involve maximising the thermal efficiency of engines. It is also easier to employ 'end-of-pipe' pollution control measures such as catalytic converters for the control of NO_x.

(iv) Fuel types. The type of fossil fuel used significantly affects emissions of pollutants such as carbon and sulphur. Renewable electricity sources can greatly reduce the carbon emission from electrically propelled land based transport systems. Liquid fuels derived from renewable biomass can reduce carbon emissions. However, most renewable sources, if employed on a large scale, bring their own environmental impacts with them. It is difficult, for technical and economic reasons, to see electricity substituting a large proportion of fossil transport fuels in anything but the long term.

The total resources, pollution and time engendered in transporting a person or freight from door to door must be accounted for. This would include travel and time to and from the airport or station, time at the station, and so forth. For aircraft, the fuel consumption and emissions caused by taxiing, take off and landing, and stacking can be a large proportion for short journeys. For many long distance journeys the directness of route offered by aircraft as compared to surface modes will enhance air transport against other modes.

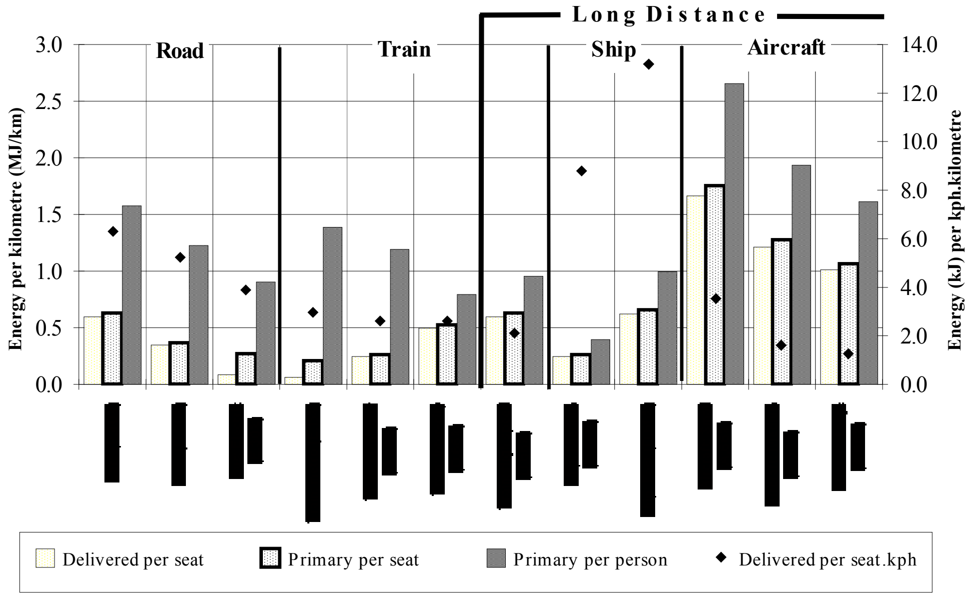
There are many technical and philosophical problems in comparing all these systematically. It is therefore difficult, if not impossible, to arrive at an entirely objective method for arriving at general conclusions of the form "This mode is better than that one". The likelihood therefore, is that although technical analysis will provide an input, modal decisions and priorities will ultimately result from political processes. It is certain that different modes and technologies will be considered most appropriate for different routes and duties.

Bearing all the above in mind, the author has assembled some illustrative data for the energy consumption of different modes and technology types of passenger transport: these are depicted in Figure 12. Most of the data for surface modes pertains to the UK. Delivered and primary energy per seat.kilometre is shown. Dividing these by a load factor gives primary energy per person kilometre. A single load factor has been assumed for all the long distance modes.

This shows that the energy consumption per seat or passenger kilometre is greater for aircraft than any other mode. Note however, that this is per kilometre travelled, and not per kilometre of shortest route between two points. This, for other than the shortest air journeys, distorts the comparison in favour of surface modes that have to circumnavigate natural obstacles and, in the case of land based transport, use man made roads or rails.

To a first approximation, global and regional environmental impacts more or less follow energy consumption, but the type of fuel is important. The primary energy per seat per kph cruising speed has also been estimated and illustrated. Cruising speed has some bearing on total journey time and therefore consumer preference. By this measure aircraft show advantages compared to other long distance modes. This shows, that according to the perspective taken, the choice of which mode is "best" may change.

Figure 12 : Intermodal Energy Comparisons



It may be that over reasonably long distances, large slow aircraft flying well below the tropopause could extend the competitive position in environmental and economic terms with surface modes offering the same journey time. Fuel and emission penalties incurred in take off and landing might be compensated by the lowered air resistance at altitude and the directness of route.

The author does not currently have the statistics required to assess the potential for modal change on a global basis. However Barrett (1991) estimated that for the UK probably less than 10% of air passenger transport (in passenger kilometres) could be transferred away from air given that current transport systems and consumer preferences would limit that switch to journeys less than 1000 km. From the global data in the author's possession (average trip length, international travel data etc.) it is judged that this maximum of 10% may be realistic globally. Of course changes such as the introduction of fast rail systems and cruise ships and longer holidays might increase this fraction.

4.6. Technological change

Technical improvements, especially in engine efficiency, are an essential companion to demand management for the control of pollution in the long term. The rate of introduction will be relatively slow and care must be taken that the dirtier aircraft are not displaced into operating in developing countries or as freight transporters. The resource implications and environmental impacts of manufacturing aircraft must be accounted for in a comprehensive analysis. However, it is probable that the impacts of operating aircraft are considerably greater than those entailed in building them.

The energy required to drive an aircraft through the air depends in a complex way on the design of the airframe and its size and weight; and on the speed and altitude at which it is flown. The fuel efficiency of aircraft engines also varies with speed and altitude, and with the type of engine. The variation of fuel consumption with operational and technical factors is discussed in the next section.

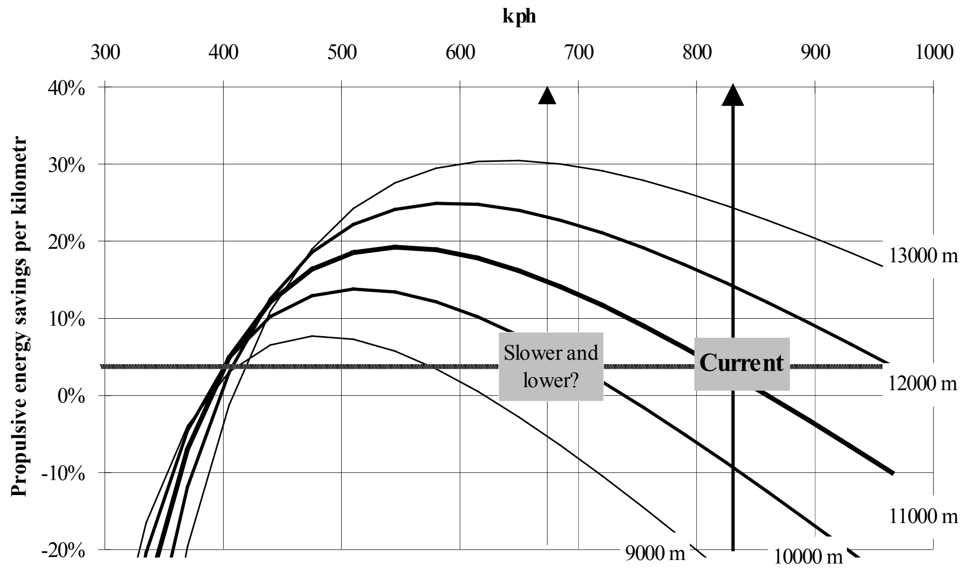
4.6.1. Energy, fuel and NO_x variation with speed, altitude and design

The idea here is to explore how the design and operation of existing and future aircraft might be altered to account for environmental considerations. It is not claimed that the analysis here produces very accurate figures for a particular civil aircraft the performance of which is optimised for a narrow range of cruise speeds and altitudes. The data input and results of the calculations do however broadly agree with estimates made by other authors. In much of the analysis it is assumed that 'typical' cruise conditions are a speed of 825 kph and an altitude of 11000 m. (In actual fact the cruise range is quite large with big long distance aircraft generally cruising faster and higher, and small short range aircraft vice versa.) The consequences of altering these conditions to a 'slower and lower' regime of 675 kph and 10000 m are explored.

4.6.1.1. Propulsive energy requirements

Figure 13 shows how the propulsive energy required, to drive the aircraft through the air and provide adequate lift, changes with altitude and speed. [Note it is energy, not fuel, since the engine efficiency is not accounted for.] The form of this relationship is derived from basic aerodynamic considerations as given by Anderson (Anderson, 1989). The author has assumed data that seem to be reasonably representative of today's commercial jetliners. The form of the relationship between energy consumption and speed and altitude will not change radically from one type of subsonic jet to another. Figure 13 illustrates how, as compared to current cruise conditions, the energy requirement increases with speed, and decreases with altitude. At low speeds energy requirement increases as the aircraft has to bring its nose up to avoid stalling and this increases drag. A reduction of 150 kph in cruise speed reduces energy requirement by 10% to 15%. A decrease in altitude of 1000 m increase energy requirements by 10% to 15%.

Figure 13 : Propulsive Energy Consumption Change with Speed and Altitude



4.6.1.2.   Engines

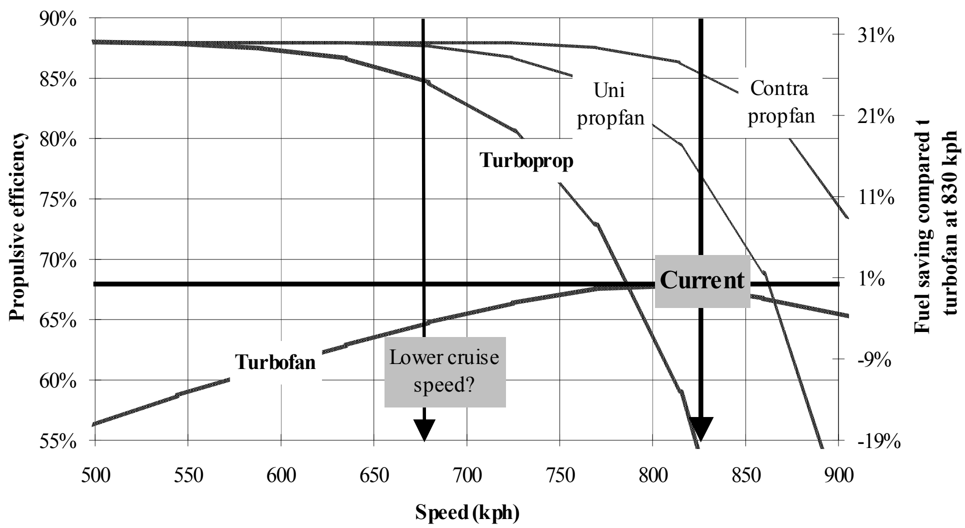
The majority of commercial aircraft capacity is propelled by turbofan engines. The efficiency of these has improved by about 40% since the first commercial jet engines through the use of large bypass fans and general improvements to combustion conditions. The scope for further improvements in the turbofan is smaller; perhaps a further improvement of 10% can be expected over the next decade or so.

Increased propulsive efficiency can be achieved by having a propeller driven by a jet engine. Turboprop engines are such a design and have been widely used since the 1950s. They are presently the most efficient engines for lower speed commercial aircraft, but their efficiency falls rapidly at speeds greater than 750 kph.   However, a reduction of about 20% in the cruising speed of jetliners from 825 kph to 675 kph would allow the turboprop to be used efficiently in place of the turbofan with fuel savings of up to 25% or more due to increased engine efficiency being possible. (There would be additional savings due to flying even slower, but at a cost of increased flying time.)

New designs of engines incorporating propellers, called propfans, have been developed. They have one (uni-rotation) or two (contra rotation) propellers with unconventional swept back blades, often mounted at the rear of the engine. They are estimated to offer savings of around 10% to 20% compared to turbofans without reducing cruise speed. Propfans are as yet undeveloped commercially and pose a number of design problems.

Figure 14 shows illustrative propulsive efficiencies for the common turboprop and turbofan engines, and for the new propfan engines. The right hand axis chart shows the fuel savings relative to a typical turbofan in aircraft cruising at 825 kph.

Figure 14 : Engine Propulsive Efficiency



Low NO_x engines

In general the fuel efficiency of an engine increases with the turbine exit temperature and compressor pressure ratio of the engine, unfortunately so also does the amount of NO_x formed. Incremental design change can reduce NO_x by perhaps 30% to 40% (Bahr, 1992) without degrading fuel efficiency. Even these incremental design changes take time to introduce into new engines - perhaps they will be available towards the end of the century. Then one has to allow for the time for these new engines to replace existing ones. The rate of introduction of new engines is determined by both environmental and economic factors. Should environmental concerns be paramount, then it would be possible to fit low-NO_x to existing as well as new airframes relatively rapidly. It may be that some of the very low NO_x engines will not easily fit existing aircraft. Constraining factors include production rates of the engine manufacturers and the availability of finance for the new engines.

Beyond a reduction of 30% or 40%, quite new designs of engines that achieve high fuel efficiency and very low NO_x emission are needed. However they incorporate quite different design elements from existing engines. It will therefore be expensive and time consuming to develop them, and the risks are high. There is therefore no short term prospect of radically reducing NO_x emission in this way.

There is the question of how much striving for low NO_x emission ultimately compromises fuel efficiency. At some point the altered combustion conditions and extra complexity and weight of consequent to low NO_x design will seriously limit fuel efficiency.   At that point it will be necessary to make some judgement as to which is the greater evil - more NO_x or more CO_2.

4.6.1.3. Specific fuel consumption

The amount of fuel required to drive the aircraft though the air may be found by dividing the energy required by the efficiency of the engine. Figure 15 shows how the specific fuel consumption (SFC) of a typical turbofan aircraft might vary with speed and altitude as compared to typical cruising conditions. Because turbofan engine efficiency increases up to cruising speed, the SFC is fairly flat around cruising speed the fuel saving in flying slower is probably at most 5% to 8%. There is thus relatively little gain in cruising existing aircraft with turbofan engines at lower speeds. For the author's hypothetical aircraft, reducing flight altitude from 11000 m to 10000 m increases fuel consumption by 10% to 15%. If consumption is to be kept nearly constant, then reducing the altitude by 1000m would require speed to be reduced to 650 kph.

Figure 15 : Turbofan Powered Aircraft SFC Variation with Speed and Altitude

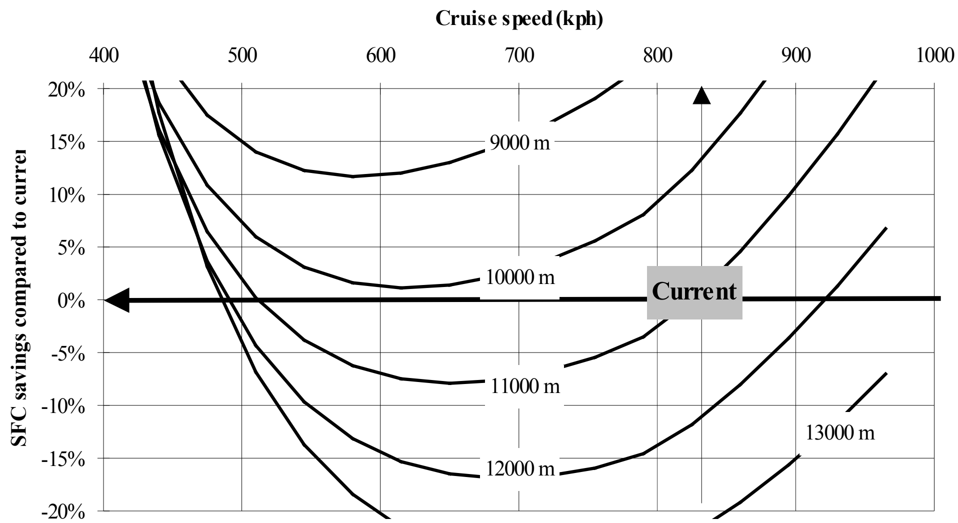
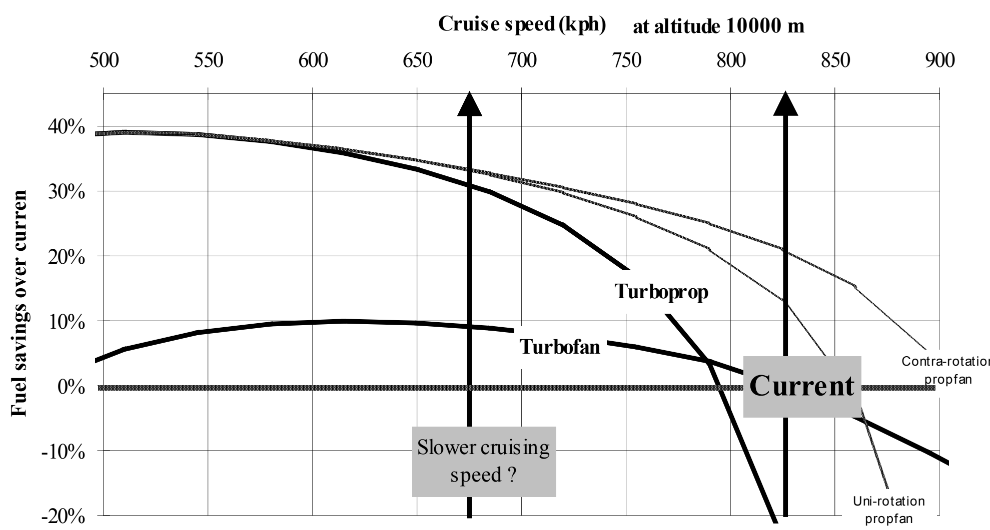


Figure 16 illustrates the decrease in SFC to be obtained by using innovative propfan engines at current cruising speeds; or by using turboprops or propfans at lower cruising speeds.

Figure 16 : Specific Fuel Consumption Variation with Speed and Engine Type



4.6.2. New aircraft design

These effects should therefore be taken into account both in the operation of existing and future aircraft, and in the design of new aircraft. The environmental advantages that could flow from designing new aircraft to fly slower and lower should be assessed. Aircraft that can fly efficiently at a wider range of speeds and altitudes would offer greater flexibility and thereby more potential reduction in environmental impact.

The first stage in aircraft design is to decide what duty the aircraft is to perform in terms of load (passenger or freight), range and speed. It is argued through this text that freight should generally be moved away from aircraft to surface transport modes. Therefore more consideration should be given to designing aircraft that are optimal for passenger transport. This would include maximising the number of passengers carried for a given aircraft size. Freight capacity should generally be limited to that necessary for carrying passengers' luggage although the exigencies of aircraft design will mean that there will be certain volumes of the aircraft not suitable for passengers. It is also argued that, from an environmental point of view, speed reduction is desirable because this generally leads to less pollution. The design of new aircraft should therefore be optimised for lower cruise speeds. What these lower cruise speeds should be is not a question that can be answered here, but at some point the environmental advantages of lower speed will be outweighed by economic and service quality degradation.

The general performance and emissions of aircraft are basically determined by its main components: the airframe (fuselage and wings) and the engines.

Airframe

There are a number of measures for improving the aerodynamics of an aircraft - some of these are discussed previously (Barrett, 1991). The fuel efficiency of an aircraft generally increases with the overall size because the carrying capacity to drag ratio improves. The marginal fuel efficiency benefits of scale do decrease with increasing size. The larger the aircraft the less the aircraft movement, and this in general leads to less congestion and fuel wastage. Boeing and Airbus are contemplating the introduction of aircraft capable of carrying as many as 1000 passengers on two decks. The development costs of such behemoths are enormous, and the development time long. Very large aircraft will necessitate changes at airports. It may be that some airports will not be able to accomodate the required changes, such as lengthened runways or larger parking bays.

Overall prospect

An aircraft optimised for a cruise speed of about 675 kph at an altitude 1000 m lower than a new modern aircraft might have a fuel consumption per tonne.kilometre 20% to 40% lower than today's new wide bodied jet using the best turbofan engines. The reduction in fuel use would decrease pollution emission by a similar proportion. The fuel savings would arise from a combination of lower cruising speed and more efficient engines and airframe. The aircraft would probably be powered by turboprop engines, although future propfan designs would provide efficient operation at higher speeds. On an average 1600 km flight, perhaps 20% of the time is spent flying at slower speeds when climbing, stacking and descending. The efficiency advantage of engines with propellers are greater at these lower speeds.

There would be drawbacks to such a design.

- On very long flights, flying time would increase by about 20% and thereby increase passengers' ennui and crew costs. The productivity of aircraft in terms of seat.km per year would fall meaning more aircraft and more investment, insofar as increased load factors do not counterbalance this.

- Slower cruising would mean more aircraft in the air at any time and so increase the congestion of airspace. But this would be counterbalanced by increases in load factor.

- Passenger comfort would be degraded because of more engine (propeller) noise. There is more turbulence at lower altitudes which leads to a bumpier ride.

- The use of conventional turboprops on large aircraft would bring problems. The power of turboprops is limited to about half of the turbofan because of engineering reasons. Consequently twice as many turboprops as turbofans are needed for equivalent power. This adds to maintenance costs, structural strength requirements and soundproofing. However less power is required for lower cruising speeds and this might, to a degree, reduce the requirements for extra engines.

More analysis of the fuel saving benefits and penalties of low energy aircraft designs should be carried out. It is probable that the balance of costs and benefits will alter according to the duty required of the aircraft - especially the range. The longer the range, the greater are the drawbacks of the slower, more efficient aircraft. However the time spent at speeds below cruise is considerable even on long journeys. The average stage distance per aircraft departure was 1000 km in 1991 and the average speed 613 kph (ICAO,1992a): for international flights these figures increase to 1840 km and 661 kph. Allowing 3 hours to/from/at airport, the total journey time for passengers for a 1500km journey would be increased (illustratively) from 5.5 to 6 hrs using the slower aircraft.

4.6.3. Alternatives

There are innovatory technologies and fuels that might decrease the emissions from air transport. These alternatives do not presently offer the means for replacing the services of conventional aircraft to any great extent. The alternatives can not be comprehensively reviewed here, but some examples may be given.

The Russians have developed an aircraft that, by flying very low (5 to 10 metres) using an aerodynamic phenomenon called the ground effect, can reduce drag and therefore fuel consumption. However the routes suitable for such an aircraft would be limited by the requirement of unobstructed areas such as is found over relatively calm seas and lakes.

Over shorter routes where surface modes are not effective, airships might substitute for aircraft. Their low speed efficiency is quite good. Their landing and take-off requirements allow them to be used nearer to population centres. However they are not fast and are strongly affected by wind conditions.

There are fossil fuels which contain less carbon per unit of energy delivered than conventional aviation fuels: for example natural gas (methane) produces 25% to 30% less carbon per energy content than kerosene. If such fuels could be carried and burnt safely and efficiently in aircraft then carbon emissions would be reduced. If aviation fuel were derived from some renewable energy resource such as biomass or wind generated electricity, then the net carbon dioxide emission of aircraft would be smaller (but not necessarily zero). Examples of such fuels are hydrogen and methanol. The costs of producing and using such fuels will be higher than conventional aviation fuels for some considerable time to come.

4.7. Operational improvements

Significant reductions in environmental impacts can result from the better use of aircraft. Some of the measures, such as increased load factor, could act in the short term. The operational measures which might be applied include:

(i) **Increase aircraft load factor** by using a greater proportion of load carrying capacities;

(ii) **Operate aircraft more cleanly** at a speed and altitude which minimises the amount and impact of pollutants - plainly the effect of doing this on costs would have to be considered;

(iii) **Improve the efficiency air traffic control** such that pollution due to delays, stacking, etc. are minimised.

4.7.1. Load factor

Increasing the load factor (the proportion of passenger or cargo capacity used) of aircraft potentially offers rapid reductions in the movement, fuel consumption and emissions of aircraft whilst delivering the same amount of passenger or freight transport in terms of passenger or tonne kilometres. To a first approximation, the amounts of fuel used and pollutants emitted are dependent on how a particular aircraft is operated, and these amounts do not significantly increase with the weight of passengers or freight on board. (In fact the fuel use of an aircraft does increase with weight, but the payload of passenger aircraft is not a large proportion of the total aircraft weight. Also a significant proportion of fuel use goes to overcoming drag and taxiing.)

The remainder of this section will focus on passenger transport. Figure 2 shows the large variation in seat load factor (the proportion of seats filled) from country to country. This Figure does not show the variation across types of service (e.g. scheduled and charter) or route. This is important. For example, load factors of 90% or so are not uncommon on charter flights.

To increase the load factor of aircraft there are measures that can be taken in both the short and long term. In the short term the existing seats can be more fully booked and the spacing of seats reduced.

Assume, for example, by more full booking the seat load factor (the proportion of seats filled) could be increased from the present average of about 66% (1991) to the level of 85% achieved by operators in the CIS and China. (These countries account for about 14% of world air passenger transport (See Figure 2)). Then, calculating from country specific data, aircraft distance flown would be reduced (other things being equal) by about 24%.

Just bringing the US load factor up to those in Japan or the UK would decrease global civil aircraft fuel use and emissions by about 3%, bringing it up to the CIS value would decrease global emissions by about 10%. Note that, valuable though such contributions would be, they are equivalent only to one and three years increase in emission respectively.

Another measure to increase the load factor of aircraft is to put more seats on board by lowering the seat spacing. On a Boeing 747 operating the route between London and New York for a certain airline the total number of seats is 240: 18 first class spaced at 62", 50 club class at 40", and 172 ordinary seats spaced at 31". If all seats were spaced at 31", the total number of seats would rise by 14% to 272. There are other factors that constrain the number of seats such as limited emergency access. It might be sufficiently cautious to assume that an increase of 7% in the number of seats might be achieved on average in today's stock.

If such improvements through more complete booking of available seats (24%) and smaller seat spacing (7%) were made, the total increase in load factor would be 33% since these factors are multiplicative.

Pollution emission would be reduced by about 33%. This reduction assumes passenger distance diminishes by the inverse of the ratio of increase in load factor. Fuel use and emissions would be reduced by at least this proportion: in practice emissions would, or could, almost certainly be further reduced because:

(i) Congestion and fuel wastage at and around airports on most routes would be decreased;

(ii) Fewer aircraft would be needed, and so the proportion of larger, more efficient, cleaner aircraft would be higher and thence reduce emission per passenger.kilometre;

(iii) The productivity of operators' aircraft (revenue per seat owned) would be higher, and the capital or fixed element of transport cost would be reduced. This would make the cost per passenger service provided of purchasing new aircraft lower. The rate of introduction of larger and cleaner aircraft would thereby be augmented. This would hasten emission reducing technical improvements in the long term.

Other advantages would accrue from increased load factor. Environmental impacts relating to aircraft movements and numbers, such as noise and the use of de-icing chemicals would lessen. Aircraft movements would probably be reduced by more than the ratio of increase in load factor (i.e. more than 33%). The pressure on airport capacity would be dramatically reduced.

The cost of travel per passenger.kilometre would fall. This is an advantage in some respects, but plainly it would encourage growth in demand for air transport and concomitant pollution.

As a policy option, increasing load factor offers several advantages. It can be implemented rapidly since it does not involve extra investment in major capital items such as aircraft or extra airport capacity - indeed it would generally reduce capital investment requirements.

There are a number of technical, economic and other reasons that tend to inhibit raising load factors - these include:

(a) Aggravated logistical problems in getting aircraft to the right place at the right time;

(b) Increasing seat load factor reduces flight frequency and thence flexibility in meeting passenger demand - this ultimately reaches the point where demand is not being met;

(c) Decreasing seat spacing would reduce the profits accruing from higher class passengers such as business people;

(d) In regions with developing countries, such as Latin America, the Middle East and Africa it may be more difficult to achieve high load factors. Air transport can provide essential transport services to places where alternative transport is not available. In such places income is generally low and so there is little discretionary travel to fill empty seats.

4.7.1.1. Implementation

Most trips, particularly for leisure purposes, are planned weeks or months in advance and so the potential for fuller booking and higher load factors is large. There a number of ways in which this potential might be realised.

(i) Long term and limited route franchising. The franchised access to routes could be made competitive by, for example, some sort of auction. If the franchises were long term and limited the number of operators, then airlines would probably achieve higher load factors.

(ii) Interlining. If passengers were allowed to buy tickets using more than one airline (interlining) then load factors could be increased, and better aircraft could be used.

(iii) No show problem. At present passengers can, with certain ticket classes and some airlines and routes, make multiple reservations for flights without incurring any financial penalty. Business people often do this so that if an earlier flight is missed they can take a later one. This makes it very difficult for airlines to maximise seat load factors since the number of passengers who show up is not predictable with certainty. In consequence, airlines sometimes reserve more seats than there are in the expectation there will be a certain number of 'no shows'. This problem generally leads to lower load factors, although occasionally a high proportion of people show up and there are insufficient seats in which case customer dissatisfaction soars.

(iv) Taxes and charges. The cost of aircraft movement could be increased through higher charges on landing, take off, fuel or emissions. This would encourage higher load factors.

The problem with (i) and (ii) is squaring this with any objectives concerning increasing competition between airlines.

Plainly increasing load factor offers great potential as a pollution control measure in terms of emission reduction and rapidity of implementation. Detailed research into this issue is most urgently required.

A case study of the USA might constitute a revealing case study. Why is the load factor in the USA low relative to the global average, and one third less than that in the CIS or China, and 10% less than that of the UK or Japan? Is it because of other factors such as different land use patterns or population density? Is it because the US system is deregulated and fragmented? Is it because air travel and wealth per capita in the US are high? Is the fact that aviation fuel is cheaper in North America than anywhere else in the world important; or that landing charges are among the lowest?

The preceding discussion has concentrated on passenger transport. It seems that there is also scope for increasing the load factor of freight transport (currently around 60%) which would offer the same types of benefit. Currently, most freight is carried with passengers and therefore has less importance: increasing the passenger load factor would require the freight load factor to be increased. There are important differences between freight and passengers. Most freight transport does not have strong temporal variations as strong as passenger transport: it varies less through the year, week and day. Also, most freight makes a one way journey, whereas the majority of passengers make return journeys.

4.7.2. Flight path

Altering the flight path of aircraft in terms of altitude, speed or route could reduce impacts by reducing total emissions or reducing emissions in sensitive zones of the atmosphere. This might be called environmental flight planning.

Minimising the flying **distance** of the route will, ceteris paribus, reduce emissions. This means the distance flown through the air which is not generally the same as the distance flown over land. This minimisation may be achieved by a flying as near to a great circle (the shortest distance between two points on a sphere) as possible; and by taking account of wind speed and direction. At the 1993 IATA conference Air Transport and the Environment (Washington, March 1993) Airbus reported research showing that on some routes the savings achieved by distance minimisation could be substantial.

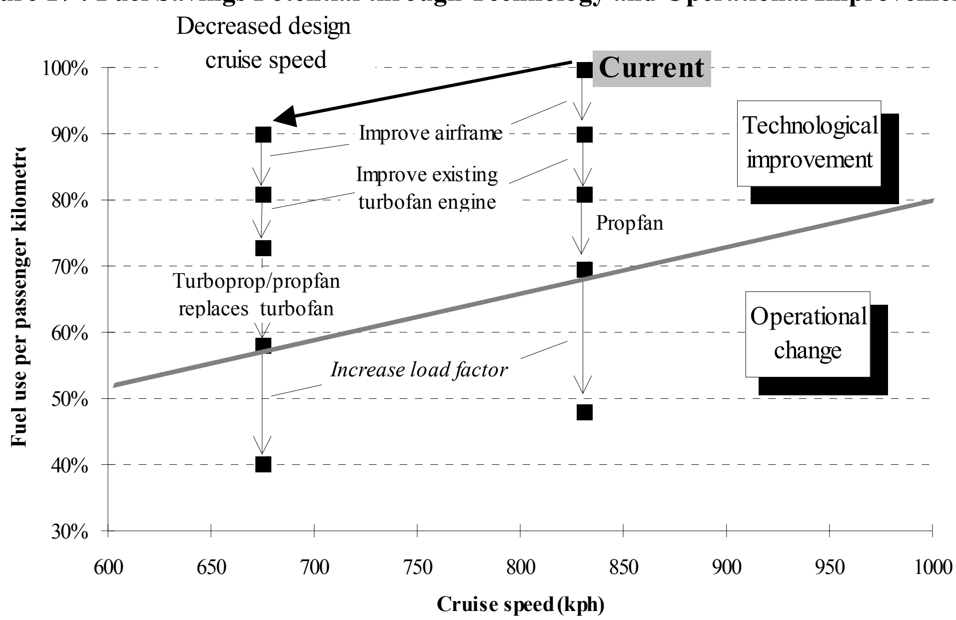
The possible importance of altitude and speed is discussed in the Appendix.

4.7.3. Summary of technology and operational savings

The preceding text has discussed some technological and operational measures that would reduce the fuel consumption per passenger.km; these are summarised in Figure

17. The technological improvements are ones that would be available in the next twenty years or so. The reduction in fuel use is compared to a 'typical' modern large jetliner. The savings over the whole stock of aircraft will be greater than shown since there is a large number of old aircraft with relatively low fuel efficiency to replace. Certain measures are not accounted for here such as improved air traffic control and flight distance minimisation. The savings from these are probably relatively small compared to the ones discussed.

Figure 17 : Fuel Savings Potential through Technology and Operational Improvements



4.8. General policies

The preceding sections have listed some specific measures. The following points are suggestions for more general policies that could be used to encourage or enforce these measures.

4.9. Market and environmental regulation

A thorough appraisal of the means and effects of the regulation of the air transport market is required. To date the author has found no such appraisals of historical deregulation such as occurred in the USA, or of forthcoming liberalisation and fragmentation as is occurring in the EC and CIS regions. Market regulation seems to be mainly done by governments on a bilateral (or sometimes multilateral) ad hoc basis. For example the US and UK negotiated deals on sales of Pan Am and TWA selling Heathrow routes to United Airlines and American Airlines. And the UK have won more landing rights in US, and can fly there from other European countries. However it seems likely that such negotiations will increasingly be conducted multilaterally, or even between larger political groupings. For example, the EC may, under certain circumstances, represent European interests in negotiating the political framework regulating access by foreign airlines to international and national markets with the US. The acceleration of the integration of regions such as the CIS and east Asia into the global air transport system will hasten the need to consider market regulation at the global scale.

A number of questions urgently need answering. What will be the impact of liberalisation in the EC? Is it a bad idea from an environmental perspective? Will the fragmentation of the CIS civil aviation system lead to a decline in environmental standards, or an improvement? Answering such questions is, unfortunately, beyond the scope of this particular report. Instead some issues are raised along with some possible consequences of deregulation.

- The fragmentation of large airlines will bring about more competition. This will lower the costs of travel, at least in the short term, and stimulate demand and thence emissions.

- Small airlines operating in a competitive system are less likely to plan for the long term. One implication of this might be less investment in new 'clean' aircraft. On the other hand deregulation can in some cases stimulate investment.

- The more competing airlines there are, the more difficult it is to plan logistically. This is partly because of mutual competition, partly because of the numbers involved.

- Competition is likely to lead to more frequent flights. This will mean smaller aircraft, or lower load factors, or both. Is fierce competition why load factors in the USA are lower than in the UK or Japan, and indeed lower than the world average?

- Competition will make it more difficult to transfer passengers from one flight to another to fill planes more. The load factor will therefore be low.

That these factors and concerns are important is confirmed by these quotations from the ICAO traffic forecast (ICAO, 1992b).

> *When passenger demand increases, air carriers can respond by scheduling extra flights, by using larger aircraft, or by managing load factors. During the 1970s, air carriers accommodated most of the growth in demand by introducing larger aircraft. As a result of both increasing aircraft size and improving load factors,*

> *the growth in aircraft movements was quite small in the 1970s despite rapid growth in passenger traffic. From the early 1980s, the trend in average aircraft size has levelled out and the growth rate in aircraft movements has approached the growth rate for passenger traffic.* [p39, para 3]

Concerning the factors influencing how carriers meet demand, ICAO observes (with my emboldened emphasis):

> *The first of these factors is the trend towards liberalisation or deregulation in some important markets. Deregulation in the United States domestic airline markets began in 1978, and the evolution of competitive strategies and market structures occurred throughout the 1980s. Adequate frequency and convenient interline and on-line connections, as well as low price became important tools....**The consequent increased priority given to frequency and direct service has tended to increase the number of aircraft movements required to satisfy a given level of demand.*** **[**p 40, para 6)]

ICAO envisages such trends continuing on the global scale with some possibility of countervailing influences:

> *These regulatory and technological factors described above are likely to continue into the 1990s. However, the financial pressures from the current economic climate and the more liberal regulatory environment are forcing consolidation and alliances among airlines that might eventually reduce the pressure to increase flight frequency at the expense of aircraft size.* [p41, para 9].

In balance, these observations of a commercially disinterested body suggest to the author that deregulation and liberalisation can lead to smaller aircraft and lower load factors. Other things being equal, this means more pollution per passenger kilometre.

4.10. Labelling, advertising, education and information

The behaviour of all the actors in aviation can be influenced by information and exhortation. The efficacy of these is difficult to predict. The following measures might be included in information programmes.

(i) Pertinent and usable information about the environmental impact of air transport should be given to consumers.

(ii) There is increased 'green labelling' of consumer goods. It is suggested that the environmental impact of associated transport be included. For example fruit and vegetable freighted by air should have this indicated in some way.

(iii) The general environmental advantages of using surface modes of transport rather than air should be transmitted to users of passenger and freight transport.

(iv) There are steps passengers can take to reduce their impact whilst flying. These include more advanced booking, the use of charter flights with a high load factor, and the use of airlines utilising the 'cleanest' modern aircraft. The difficulty lies in assembling the appropriate information and transmitting it in digestible form to consumers.

(v) Information about alternatives to air freight should be gathered and given to users of air freighting.

4.11. Taxation

Extra taxes on aviation will restrain demand growth, and make other modes of transport more attractive economically. Certain taxes will encourage changes to operation and technology that will lead to less pollution. Taxation is in some ways a better lever to apply than regulation. It allows the aviation industry to find its own preferred responses and these may be more efficient in economic and technical terms. One major disadvantage of taxation is that its effects are not predictable with any accuracy in the short, and particularly the long term; another is that many governments may not subject themselves to international tax regimes.

Taxation could be applied to the quantities of pollution emitted; aviation fuel; passenger distance (i.e. p.km) or airport movements; or aircraft movements or distance. These are discussed briefly in turn below. At this point it is worth saying that one advantage of a carbon tax is that it could be applied evenly across all transport and other energy consuming sectors. In so doing it would at least from the point of view of reaching carbon emission goals by an optimal path, be better than, say, a tax on aircraft movements. It would be a 'level playing field'. For other pollutants such as NO_x it is not effective to apply a single tax rate universally since its effects depend on where and when in the atmosphere it is emitted unlike carbon dioxide.

There are a number of complex issues that arise when considering the application of taxes to industries whose activities are international. These, coupled to a desire to promote international trade, have lead to international resolutions of the ICAO Council that hinder or prohibit many of the taxes on fuel and movements outlined in this report.

The Council has resolved that *"the fuel, lubricant, and other consumable technical supplies"* on board an aircraft when it lands in a State other than that in which it is registered, or taken on board when it departs from a State other than that in which it is registered, are exempt from all customs and other duties (Section I, ICAO, 1966).

The Council also resolved that "Each Contracting Sate shall reduce to the fullest practicable extent and make plans to eliminate as soon as its economic conditions permit all forms of taxation on the sale or use of international transport by air, including taxes on gross receipts of operators and taxes levied directly on passengers or shippers;" (Section IV, ICAO, 1966). It is the case however that taxes or charges are directly or indirectly intended to finance the cost of aviation facilities would be considered acceptable and not falling within the scope of this Resolution.

Plainly these Resolutions would have to be substantially modified or eliminated to allow some of the forms of taxation discussed below. It is not clear whether these Resolutions and the general surrounding philosophy would allow taxes designed to facilitate environmental improvement. CAEP is presently studying this issue.

4.11.1. Emission taxes: carbon, NO_x

Plainly a tax on pollution would be most appropriate. Emissions would have to be regularly calculated for each aircraft operation. A tax on NO_x emission might be problematic to apply because there is presently no reliable and cheap way of estimating in service emissions. A tax on carbon emission would be directly comparable with one on fuel unless unconventional fuels were used.

4.11.2. Fuel tax

In general, to the author's knowledge, tax is not paid on aviation fuel. This is primarily because it is a fuel used internationally and countries do not want to put their domestic aviation industries at a disadvantage by taxing their inputs more than competitors.

Even so, fuel costs vary. ICAO (1992c) report a wide range of 1.6:1 in the prices of aviation fuel in 1989: the price varied from a high of 26.8 cents per litre in Africa to a low of 16.3 cents per litre in North America. The impact of a tax would therefore differ according to the base cost of the region.

Many countries tax fuels with special fuel or energy taxes, or through general taxation systems such as Value Added Tax. In the UK, for example, the duty on petrol was 20 pence per litre in 1989 (which at current exchange rates is approximately 30 cents per litre). The duty on aviation fuel was abolished in 1984. Furthermore, there is mounting pressure in Europe and elsewhere for carbon taxes. It would seem therefore that politically it may not be too difficult to apply a fuel tax. The recent application of VAT to fuels in the UK, and the probable imposition of fuel taxes in the USA substantiates this view, although it is noteworthy that aviation fuel will be still be exempt in the UK.

The question arises as to what the rate of tax should be, and whether it should be a proportional tax (e.g. % of cost per litre) or an absolute tax (cents per litre). An absolute tax would tend to reduce regional differences between fuel costs. A fuel tax would have to be substantial to have significant effect because fuel costs are not a very large proportion of total cost (see discussion below). In the assessment of the impact of fuel taxes on air transport costs below, a tax of 100% on average cost is explored. **This is not to suggest that this is the optimum level of taxation.**

A fuel tax should encourage fuel savings and thence reduce total emissions. However, it may encourage operators to cruise their aircraft higher where fuel efficiency is higher, and this may increase environmental impacts due to the emission of NO_x and water near the tropopause.

4.11.3. Movement taxes

Taxes aimed at air transport more generally could be applied; the movement of people, freight, and aircraft would be taxed. This would generally encourage a switch to alternatives and better operational patterns.

4.11.3.1. Aircraft movements

Extra tax on aircraft movements would be applied at airports. The effect of this would be to increase the ratio of passenger movement and distance to aircraft distance - i.e. airlines would try to move more passengers with fewer aircraft. The tax would thus encourage higher load factors and the use of larger aircraft. Both of these generally reduce pollution. In addition congestion of airports and air routes would be lowered because of tax. This would further reduce fuel use and pollution. In addition there would be less pressure for more airport capacity.

At present, according to the author's limited knowledge, charges for aircraft are largely based on a cost per tonne of take off weight. According to ICAO (1992c) these charges varied from $2.9 per departed tonne (maximum take off weight of aircraft) in the Central America/Caribbean region to $13.6 per tonne in Europe: the world average was $8.2 per tonne. On average these charges accounted for 4% of total costs for international passenger operations. Plainly a tax would have to be a very large proportion of current take off charges to make a significant difference. It might be better that a tax be applied to aircraft movements as well as, or rather than, weight. A movement tax would further encourage the use of large aircraft and high load factors.

4.11.3.2. Freight movement and distance

A tax on freight transport might be a possibility. For most freight there is no vital need for speed and alternative modes are widely available. For these reasons an effective tax on air freight transport might be politically acceptable and not have an undue economic or social penalty. Freight accounts for perhaps 10-20% of aircraft emissions. A tax on air freight could radically alter the competitive position of alternatives such as rail, road or ship.

4.11.3.3. Passenger movements or distance

Taxes on passenger movements or passenger distance directly suppress demand. It is slightly easier technically to apply a tax to passenger movements than to distance. It could be added to the cost of an air ticket. Applying a tax to passenger movement (rather than distance) would make modal switch more likely for shorter journeys.

4.12. Air transport costs

This section looks at the cost structure of air transport, and at how this might change with certain of the control options proposed above. It has not been possible in this paper to comprehensively examine the cost implications of the options.

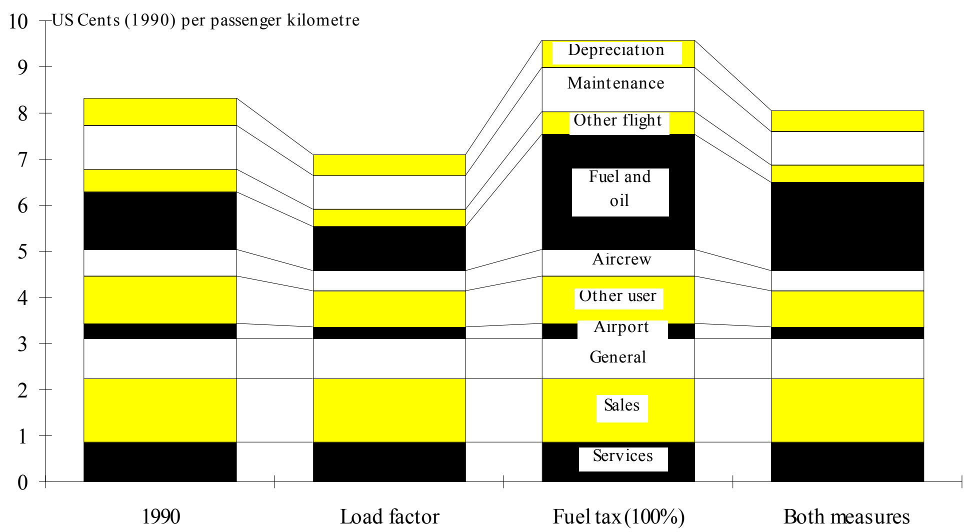
The compositions of passenger air transport costs are shown in Figure 18. These are based on data for 1990 from ICAO (1992b). Note that these data relate to scheduled services and include freight. The costs of air transport have been divided into those which are more or less dependent on aircraft movement, and hence are affected by load factor; and those which are independent of aircraft movement such as passenger service costs. The composition of costs can vary widely from region to region.

Depreciation, maintenance, and in flight costs are all assumed to be related to aircraft distance. General overheads and the costs of sales and customer service are assumed not to be reduced by increasing load factor: that is, they are related to passengers rather than aircraft movement. This analysis is thus quite simple and provides estimates for changes in average costs only. A more thorough analysis would look at the cost changes in more detail. Costs would be separately estimated for different classes of passenger over different routes and from different regions, and for freight only and combined operations.

The approximate effects of increasing the load factor and applying a tax on aviation fuel have been estimated and are also shown in Figure 18. It is assumed that the passenger load factor increases from its current 66% to 85%. The effect of increasing load factor is to lower the total cost of air transport per passenger.km by 15%.

The effect of a 100% fuel tax is to enlarge the fuel cost component from 15% to 26% of total, and to add 15% to the total cost of air transport . If the load factor and fuel tax options are assumed to be exercised together, then the total cost of air transport falls by 3%. The fuel tax, in this somewhat arbitrary instance, serves to prevent total transport costs from falling substantially, rather than increasing them.

Figure 18 : Composition of Average Air Travel Costs



Source of 1990 data: ICAO 1992b

It is necessary to consider changes in costs from at least two viewpoints. The first is that of the consumer of transport services, the second is that of the providers - the airline or aircraft operator.

To the consumer, the cost of flying is only part of the cost of a trip. As has been noted, one reason the total demand for passenger transport (p.km) has been growing has been the increase in the average air journey length. One reason for this is that the fixed costs of a trip to the air traveller in terms of money and time are quite large. Flying further afield does not increase the total cost markedly.

ICAO publishes a survey of fares including average economy class normal fares: the world average 1991 fares plus taxes and charges in US cents per passenger-kilometre from this survey are depicted in Figure 19. There are quite wide regional variations from the world average. The average cost per km declines markedly up to a total travel distance of 4000 km. Over 10000 km the average cost changes very little. An illustration of the trend in total travel time, including time at airports, is also shown.

Figure 19 : Cost of Air Travel for Different Distances

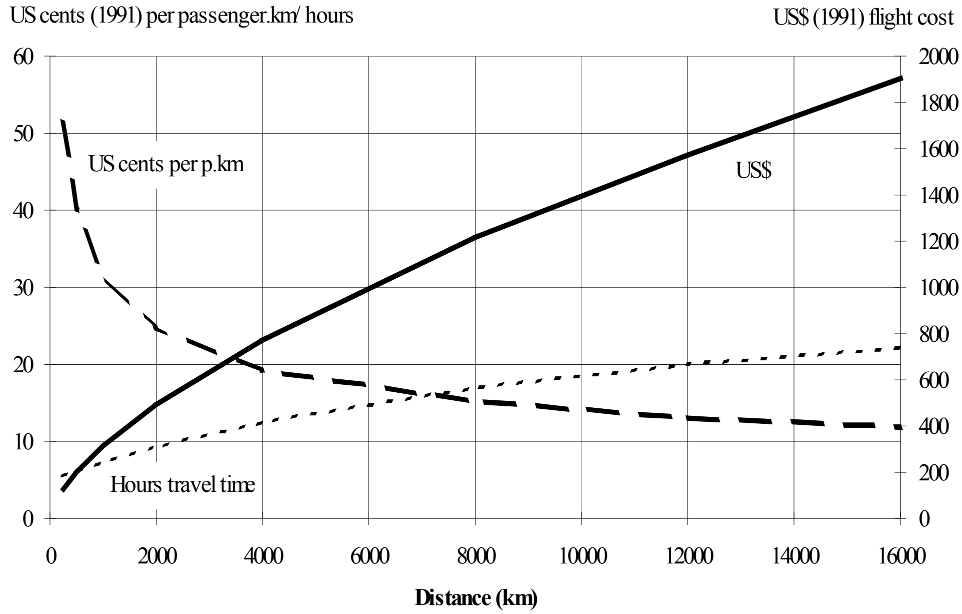
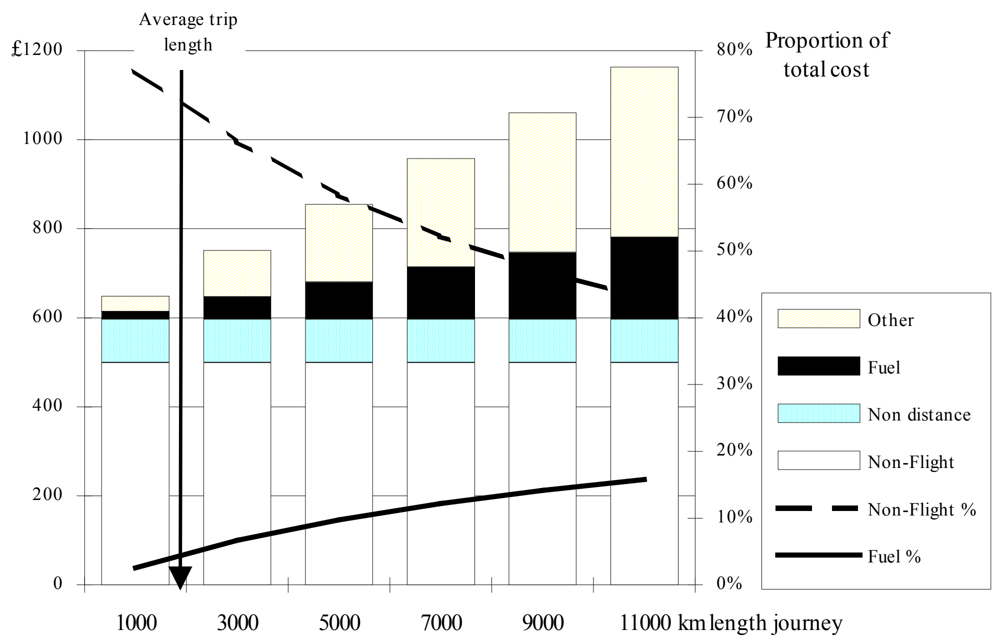


Figure 20 illustrates the importance of considering the **total** cost of a trip to a consumer: the cost elements of flight due to fuel, distance related and unrelated costs, and a nominal non-flight cost are depicted. Note that some elements of movement related costs are not linearly related to distance: for example there are fixed fuel costs (for taxiing and take off) and fixed staff costs because of time spent at the airport.

For illustrative purposes the non-flight cost of the trip (for accommodation, food etc.) has been taken as £500; this of course depends greatly on the nature and length of the trip, and the costs of living in the country of destination.

Figure 20 shows the relatively small proportionate increase in total cost with distance. Note that the journey length is the round trip distance. On the longest trips the cost of fuel reaches about 15% of total costs. There are probably great differences in cost structure. For example: the author made a week long business trip to Washington DC from the UK in March 1993. Hotel, subsistence, conference and non-flight travel together cost £1400; the flight cost £300 which is less than 20% of the total cost. The fuel cost element of the flight might have been about £50 - or less than 5% of the total trip cost.

Figure 20 : Total Trip Costs vs Journey Length



How would a changed load factor and fuel tax affect operators? This will depend on how competitive the market is generally. If it is very competitive then small differences in transport costs would give one operator and edge over another. A fuel tax would encourage higher load factors, slower cruise speeds and investment in more fuel efficient aircraft. It is not possible, in the scope of this report, to judge the effect of marginal operating cost differences on the competitive position of airlines.

At present the civil aviation industry is undergoing an extreme crisis of unprofitability. The large losses being incurred mean that investment in new and cleaner aircraft is relatively low. It must be accepted that the financial position of the industry must be robust so that the 'cleanest' equipment and systems can be acquired. To the author's view, the financial strength of the industry is more dependent on the regulation of commercial activity than on the sorts of taxes discussed above. The taxes should be evenly applied across the industry so as not to give advantage to one segment over another. The basis for this view is that most of the competition in the industry is between airlines and between manufacturers. There is relatively little competition with other modes of transport except on shorter routes for passengers, and more generally for freight.

The possibility that the further deregulation, liberalisation and fragmentation of aviation might exacerbate environmental problems is discussed elsewhere in this report. It may also be that these processes will undermine the stability and profitability of airlines and aircraft manufacturers, and thereby worsen the industry's environmental performance.

4.13. Institutions, law, treaties

There has not been space in this report to assess the potential roles of the bodies, legislation and treaties pertinent to aviation. There are the manufacturers and operators within the industry, and regulatory and a miscellany of other bodies outside the industry. They operate at many levels, from local to global. Plainly the actions of these bodies will have a great bearing on the development of the industry over the coming decades, and on its environmental impact. Table 3 gives an outline of some of the bodies operating at different levels in different sectors. There are agreements, codes of practice, regulations and so on associated with most cells in this Table. A few notes on the industry itself are given in the next section.

Table 3 : Outline of Aviation Bodies

	Government	**Private**	**Other**
Global	UN (ICAO, IPCC) GATT	Tourism and travel (WTTC, WTO,...)	Environment groups (WWF, FoE, Greenpeace..)
International	Trading/political groups (EC,..) Air traffic control	Trade associations (IATA, ICAA)	Airports (AACI,..)
National	Aviation administrations (FAA, CAA..) Environment departments Airlines	Airlines Manufacturers Fuel and other suppliers	Environment groups (AEF, EDF, WWF, FoE, Greenpeace...)
Local	Airport authorities (JACOLA,..)	Airport authorities (Heathrow...)	Airport groups Environment groups (AEF, EDF, WWF, FoE, Greenpeace...)

4.13.1. The response of the aviation industry

In the past the response of air transport providers to environmental concerns has been quite defensive, for understandable reasons. There has been particular resistance to any ideas of managing the demand for air transport and there are many arguments as to why the industry is a special case: this is exemplified by IATA's publication **Air Transport and the Environment**. However, it is in the providers' interest, and in all our interests, for the providers to take a more proactive stance. Efforts directed towards understanding the environmental problems now, and searching for solutions, will better serve everyone. The industry itself possesses, in many areas of concern in this report, better information and analytic methods than other bodies. Planning in advance will make the solutions cheaper and less potentially injurious to consumers and the aviation industry.

Fortunately, a more positive response is gradually being manifested by the industry as a whole. This is illustrated by the organising of the first large international conference on aviation and the environment by IATA. The explicit incorporation of environmental objectives into the operations of an increasing number of airlines is taking place. For example British Airways (BA, 1992) includes in its suggestions:

* *Put your own house in order - take a good look at your operation, including what goes on in your offices as well as your destinations.*

* *Accept that you are indirectly and partly responsible for some of the more direct impacts, for example noise and emissions, of those that carry your customers, i.e. the airlines.*

* *Consider introducing new, more "environmentally friendly" tour products or adapt your existing ones.*

* *Ask the "What if" question that is, "what if we do not consider the environment"?*

Studies of what the problems are, and how to solve them are being carried out by many players in the industry. It is likely that operators who develop positive policies will gain commercial advantages in the future as environmental concerns and constraints grow.

Inevitably, if the environmental impact of air transport is as serious as currently conjectured, political pressure for limiting the growth in air transport will increase. Furthermore, if significant <u>reductions</u> in impact are to be realised, then, barring as yet unforeseen technological breakthroughs, it will be necessary to decrease or at least limit the use of air transportation. This is counter to the economic philosophy of most countries that has an implicit or explicit objective of unlimited growth.

It would be advantageous if airlines and other parts of the industry sought to diversify their operations. This would enhance the prospects for rapid environmental improvement and the long term profitability and stability of the aviation industry. It is probable that those elements of the industry that do take environmental considerations into their planning will put themselves at a competitive advantage. This is occurring in other industries that have already been subjected to environmental pressures and regulation such as the motor vehicle manufacturers and the electricity supply industry.

An obvious diversification is into long range surface transport. The booking systems and passenger services of airlines can readily be applied to long distance transport by rail, sea or road. Perhaps the most obvious entry point is for medium distance journeys where the time disadvantage of non air modes is not large. Such services could be integrated with air transport. The development of hub and spoke systems offer the potential of such integration: transport between distant hubs by air, transport on spokes by surface. Aircraft manufacturers could also diversify. Many elements of airframe manufacture could be applied to high speed rail or sea transport. For example aviation turbine technology can be applied to trains or high speed ships.

5. SCENARIOS

This section develops scenarios for the possible evolution of civil commercial aviation and its environmental impact, The scenarios extend over a rather long period from 1991 to 2041. This time scale is chosen because global warming, one of the main environmental concerns, is a long term problem. Also, it is important to demonstrate the limits of measures that can only be implemented over decades.

First of all a business-as-usual (BAU) scenario is explored. This is loosely based on industry projections of demand, technology and operation. These projections have had to be 'heroically' extrapolated since most industry projections do not extend beyond 2000 or 2010. Second, the effect of the various impact control measures outlined in the text above is explored.

A model has been developed which calculates the values for key aviation variables using a given set of exogenous assumptions. The model is relatively simple and is designed to assess the approximate potential of **technical** measures for impact control, whether they are brought about by regulation, tax or the pursuit of profits. The model does not address most of the complex technical issues such as logistical planning: it does not explicitly incorporate any economic factors such as demand elasticities; and it does not calculate the capital or running costs of aviation as a whole or of the measures in particular. The need for such a model that does address these all these aspects comprehensively was discussed in the author's previous paper (Barrett, 1991). Certain components of such a model already exist.

The input for the model comprises assumptions in the three basic categories of control measure discussed above: **demand, operation and technology**. Outputs include aircraft kilometres, fuel use, and the emission of pollutants. **It is important to note that the emission reductions due to modal change do not yet include any estimates of the increase in emissions from the alternative surface modes used.**

Table 4 sets out the assumptions for changes in the key variables assumed. Changes are calculated by interpolating the variables between the initial and final values over the period between the first year of the scenario and the stop year. Linear and logistic forms of interpolation were used to emulate the varying rates of introduction of various measures.

Table 4 : Scenario Assumptions

Category	Determinant	Unit	Scenario	Initial value	Final value	Stop
Demand	tourists moved	%	BAU	4.3%/a	3.9%/a	2015
			low	4.3%/a	2.0%/a	2030
	tourist average trip length	km	BAU	1630	2200	2030
			low	1630	2200	2030
	business people moved	%	BAU	4.3%/a	3.9%/a	2015
			low	4.3%/a	-4.0%/a	2030
	business average trip length	km	BAU	1630	2200	2030
			low	1630	2200	2030
	tonnes moved	%	BAU	6.4%/a	5.5%/a	2030
			low	5.0%/a	-7.5%/a	2030
	tonnes average trip length	km	BAU	1630	2000	2030
			low	1630	2000	2030
	freight only tonnes	%	BAU	33%	33%	2030
			low	33%	5%	2005
Operational	seat occupancy factor	%	BAU	66%	75%	2020
			high	66%	90%	2005
	seat density index	%	BAU	90%	90%	2020
			high	90%	95%	2005
	freight combined load factor	%	BAU	68%	77%	2020
			high	68%	80%	2030
	freight only load factor	%	BAU	60%	70%	2020
			high	60%	90%	2030
Technology	passenger aircraft size	seats	BAU	178	250	2030
			big	178	300	2025

	freight aircraft capacity	tonnes	BAU	30	45	2030
			big	30	60	2030
	airframe efficiency	index	BAU	100%	77%	2030
			high	100%	72%	2030
	engine efficiency	index	BAU	100%	77%	2030
			high	100%	63%	2030
	NOx index	index	BAU	100%	70%	2030
			low	100%	60%	2030

Notes to Table:
[1] Airframe and engine indices multiplied together to obtain overall change in fuel efficiency.
[2] NO_x index based on emissions per kg of fuel, and must therefore be multiplied by fuel efficiency index to obtain overall change per aircraft km.
[5] Technology indices refer to the values for new stock.

5.1. Business as usual

The BAU determinant assumptions shown in Table 2 were input to the model. The emission of greenhouse trace gases from aircraft is shown in Figure 21. The consumption of fuel and the concomitant emission of carbon dioxide and water increase to over 450% of 1991 levels. [Please note in the Figures and diagnosis, that changes in carbon emission exactly match changes in fuel consumption.] There is a 50% reduction in fuel use per passenger.km because of technological and operational improvements. The introduction of lower NO_x engines means that NO_x emissions increase less than fuel and carbon, but still grow substantially to 320% of 1991 levels.

Figure 21 : BAU Scenario : Greenhouse Gas Emission

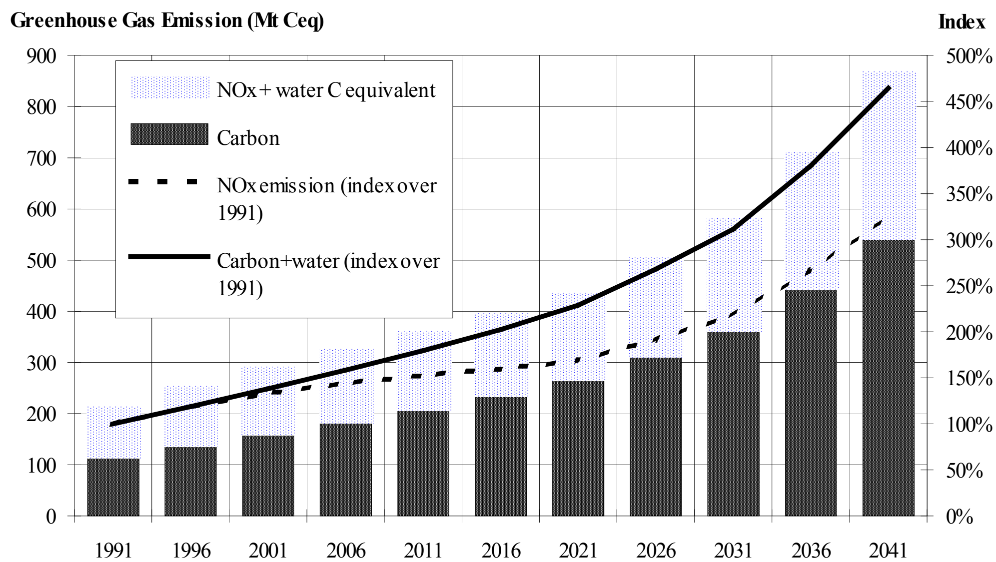
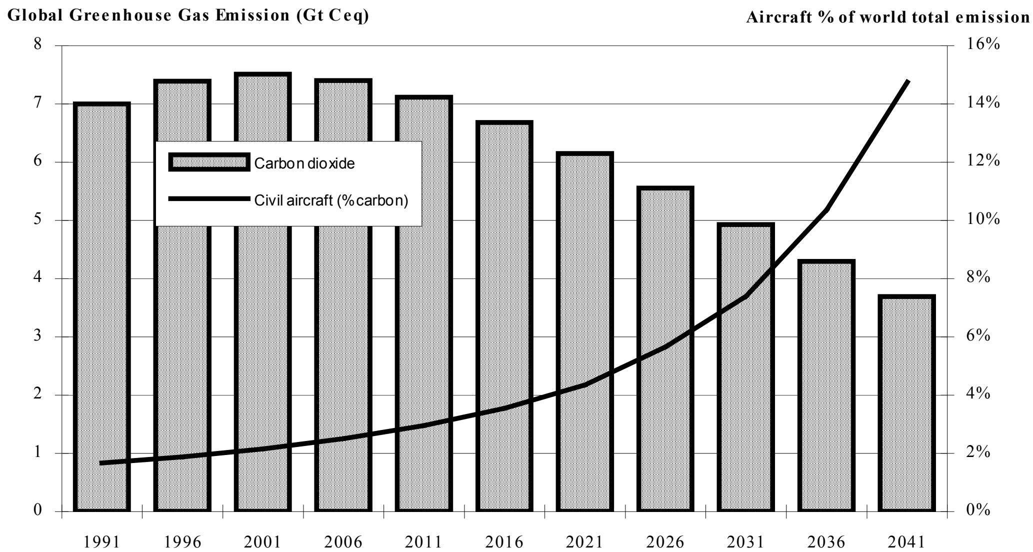


Figure 22 shows the global carbon dioxide emission and carbon emission of aircraft as a proportion of the total global emission. A schematic scenario is taken in which global carbon gas emission falls by about 40% from current levels by 2040. This lies below the middle of the range of global carbon emission target trajectories outlined above. Given this global emission scenario, BAU aircraft carbon emission rises to nearly 15% of the world total in 2040.

Figure 22 : Aircraft Contribution to Total Carbon Emission

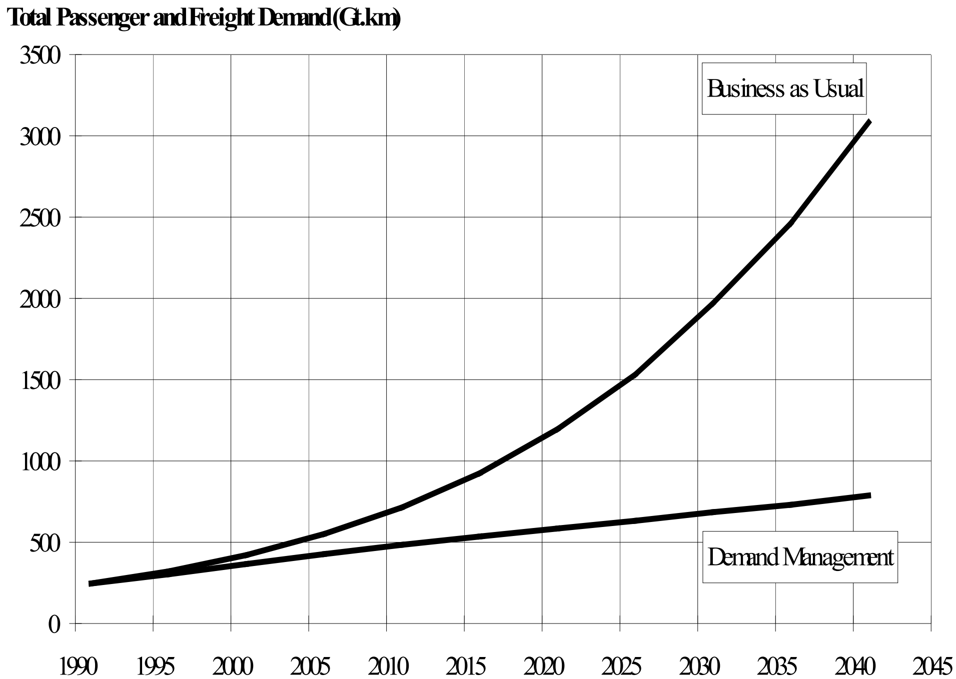


This demonstrates that the BAU scenario for aviation is quite inconsistent with any of the targets for the control of carbon emission and global warming that have been discussed. Even if the impacts of NO_x and water are essentially eliminated by cruising at low altitudes or because future scientific research shows their impacts to be negligible, then the 15% contribution to carbon emission remains. Even if it is assumed that global carbon emission is stabilised at the current level, the proportion due to aircraft quadruples to around 8% by 2040. The rapid increase in demand in the BAU scenario overwhelms technological and operational improvements.

5.2. Emission control scenarios

The aircraft emissions consequent from the BAU assumptions can not be accommodated in probable future global emission targets, assuming that no special and extreme allowance is given to aircraft. The efficacy of the various categories of control measures that will reduce emissions below BAU levels is accordingly explored in the scenarios below.

Figure 23 : High and Low Demand Scenarios



The first and most important measure it the management of demand. In the BAU scenario the total demand for air transport increases at an average 5.2%/a over the period such that total demand increases over twelve fold by 2040. A preceding section described how the bulk of air freight might gradually be eliminated. In addition it is assumed that much of business travel is eventually replaced by travel by other modes and telecommunications, and that tourist air travel grows more slowly. The consequence of these assumptions is that total demand increases at an average growth rate of 2.3%/a to reach a level in 2041 three times that of 1991. The two demands are depicted in Figure 23.

Figure 24 shows the emissions of carbon for the categories of measures applied independently, and in various combinations. The following observations may be made.

- Each of the categories of measures has a substantial effect, but demand management is most important in the medium and long term.

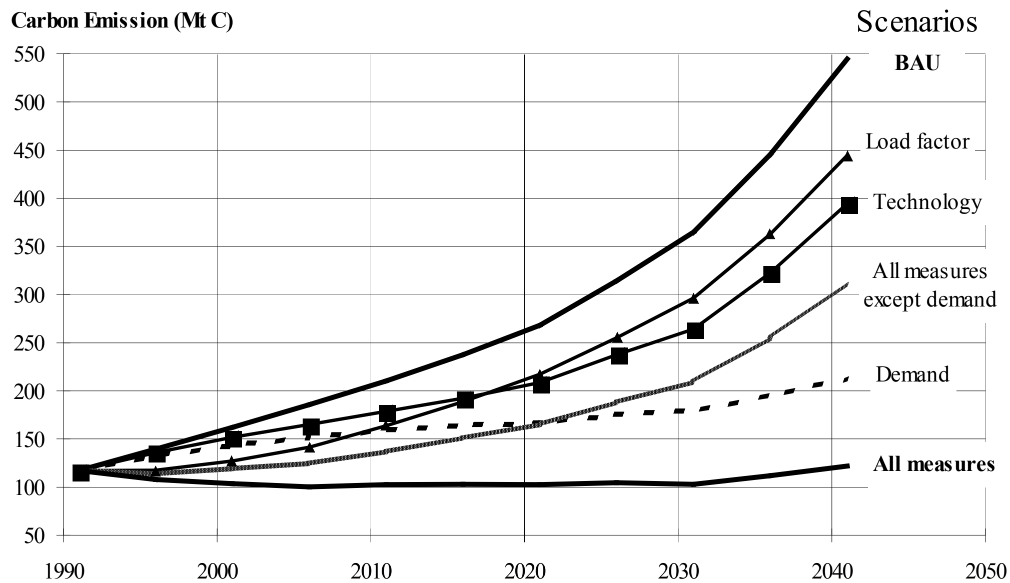
- In both the short and long term increasing the load factor is very effective.

- The impact of improved technologies is gradual because their rates of development and introduction to stock are moderate. Although they have a substantial and enduring effect, their potential is eventually exhausted.

- If all measures **except** for demand management are implemented, fuel use and emissions are comparatively stable up to 2005 after which demand growth is greater than improvements. By the end of the scenario fuel use has nearly tripled.

- If all control measures are applied, the emission of carbon dioxide remains fairly stable over the period, although a steady increase is apparent after 2030 as the potential of the measures is exhausted.

Figure 24 : Carbon Emission in Scenarios



The emission of pollutants other than carbon dioxide will generally follow the trends in carbon emission. An important exception is NO_x which will increase 30% to 40% less because of lower NO_x engines. The measure of lowering of cruise altitudes has not been explored here since the balance of effects of carbon, NO_x and water has yet to be quantified with any confidence (see Appendix for discussion of this issue).

The scenarios explored in this section show that pollution emission will rise steeply if aviation develops in terms of demand, operation and technology along the lines expected by the industry. It is difficult to see how such growth in emission can be accommodated in a world where burgeoning environmental concerns will increasingly constrain all activities with significant environmental impact.

It has been shown that a number of control measures might be effective in controlling aircraft emission and impact. Unfortunately it seems clear that even if high levels of each measure (such as load factor or engine efficiency) are adopted, that emission will increase in the short and long term unless demand management involving restriction is applied. Therefore, given that aviation emissions will have to meet targets similar to other sectors, there will be a choice between allowing demand to increase, and driving factors such as load factor or efficiency to ever higher levels.

The implications of the measures and scenarios in economic and logistical terms have not been evaluated beyond the qualitative discussions throughout this report. Also, it is important to remember that the environmental impacts of switching to other transport modes have not been assessed. This modal switching does not however account for a large proportion of emission reduction in any of the scenarios since, as argued earlier, it is difficult to envisage a very large modal switch away from air in the time frame considered.

6. AIR TRAVEL AND TOURISM

A particular concern of WWF is the integrated assessment of the impact of travel generally and of tourism in particular. The preceding sections have shown quite clearly that it is vital to add the impacts of travel into any appraisals of the environmental impacts of tourism. The emissions of gases harming the global environment from the air travel will often, or even usually, exceed those arising from activities at the holiday location. Of course the immediate local impact of holiday activities will often outweigh those due to aircraft. The impact of travel should be made explicit in the aims and guidelines of such bodies as the WTTC.

Limiting the environmental impact of tourists travelling can be accomplished with same general policies discussed elsewhere in this report. Some observations more specific to tourism rather than travel generally can be made however.

6.1. Demand management

Why are people travelling further and further for holidays? Addressing this question properly is difficult, and is certainly beyond the scope of this report. One can however speculate that the main reasons might include the enjoyment of better weather, different cultures, and different environments. It is obviously not generally possible to change these within a particular country and so to make holidays in ones' own country more attractive. It is however possible to preserve natural environments in any country and thereby make domestic holidays more appealing. Also important are such aspects as the provision of good recreational and child care facilities. The success in

Europe of holiday centres and villages has demonstrated that it is possible to attract people to take holidays in their own countries.

Mass tourism has eroded indigenous cultures and impacted on local environments. This has led to particular locales being despoiled and to people moving on to more pristine spots. These spots are generally further away and thus engender more travel. If this process continues eventually there will be no fresh places to visit. Therefore an important element in managing the impact of tourist travel is the preservation of local cultures and environments.

Some of these issues, and other relevant matters, are more extensively discussed elsewhere: see for example **Beyond the Green Horizon** (WWF, 1992).

6.2. Modal shift and load factor

The potential for modal shift for tourists may possibly be different than for the business traveller. Time spent travelling may be less constrained. For some tourists the journey itself might constitute an enjoyable part of the holiday (it is a rare person who actually enjoys sitting in airports and aircraft). The acceptability of long distance train, sea or bus travel could be improved. This might be done by increasing speed, improving comfort and facilities, and by explicitly making the journey part of the holiday.

Many tourist flights are chartered and have high load factors. Since the vast majority of holidays are booked well in advance, there is the potential to push load factors to very high levels indeed.

6.3. Costs

As discussed in more detail elsewhere, the extra cost in money and time of taking a distant holiday rather than a near one is small. Indeed the total cost may be less if the tourist is travelling from a rich to a poor country. The savings in the living costs of food, accommodation and so on may often exceed the extra cost of the flight. These observations, coupled with the fact that the cost of the flight may typically be a small proportion of the total holiday cost, means that the cost of flying would probably have to be increased massively to significantly suppress demand.

6.4. Summary

- Tourism probably accounts for about half of aircraft emissions due to passenger traffic, and this share is increasing.

- On an individual basis, it is difficult to see how frequent long distance flying can be made consistent with preservation of the global environment and interpersonal equity.

- The emissions and global impact of holiday flying probably generally exceed the those incurred at the holiday location and so these should be included in the environmental impact analysis of tourism.

- A number of measures to control impact can be taken. These include demand management, load factor and modal shift.

7. CONCLUSIONS AND RECOMMENDATIONS

This section summarises some of the main findings of the report. Recommendations arising from the analysis is presented. Neither of these is exhaustive. First a brief mention is made of topics which need more analysis.

7.1. Areas requiring further work

Several areas of importance have not been touched on or dealt with at length. For example the roles and responsibilities of institutions and groups such as the UN (ICAO), the IPCC or the EC have not been explored. The effects of international treaties and laws such as the GATT and EC law may important in some areas such as those relating to taxation and competition.

All of the issues raised in this report need further detailed work. These include:

(i) The general scientific understanding of the impact of aircraft emission on the atmosphere.

(ii) The scope for operational changes to reduce environmental impact.

(iii) The impact reducing potential of technological changes to air transport.

(iv) A thorough comparison of air transport with and alternative long distance modes.

(v) The possibility for demand management.

(vi) The effect of altered air transport patterns, technologies, taxes etc on air transport economics.

(vii) The effect of liberalisation and deregulation.

(viii) The logistics of the global air transport system.

7.2. Conclusions

(i) Currently the environmental impact of aircraft is currently small in many respects, but will probably increase rapidly because of its growth rate. The current contribution of civil aviation to the emission of global warming gases is almost certainly at least 2%, but may be much higher due to the emission of nitrogen oxides and water.

(ii) There are serious concerns about the specific impacts of aircraft at high altitude especially with respect to their effect on ozone, but the scientific uncertainties remain very great.

(iii) Emission limits should be applied to aircraft emissions of greenhouse gases generally. But there are problems suggesting limits for particular gases singly and in combination.

(iv) Tourism is the single most important demand for air transport and brings about some 50% of emissions from air passenger transport.

(v) The USA accounts for about 40% of aircraft pollution and is therefore a key country when considering control policies.

(vi) The prospect is for large long term increases in emissions from aircraft if current policies and strategies are unchanged.

(vii) The application of firm emission control policies would be effective in reducing emissions substantially below levels projected in business as usual conditions. If all the control measures suggested in this report were implemented then carbon dioxide emissions would not increase vastly over the current level in the medium term. However, reducing demand growth is the single most important element in such a strategy.

(viii) The aviation industry probably can not meet likely global greenhouse emission reductions currently suggested with the measures explored in this report. The industry will therefore either have to make a dramatic response to the challenge, or establish that emissions from aircraft do not have to be reduced pro rata as much as those from other sectors of the global economy.

(ix) There may a conflict between the pursuit of environmental goals and increased competition.

7.3. Recommendations

7.3.1. International accords

(i) A method and convention for calculating and allocating all aircraft emissions to individual countries needs to be developed.

(ii) The prejudice should be for limits to aircraft emissions to be allocated pro rata to other limits of a similar kind (e.g. carbon emission). It may be that special derogations might be allotted to aviation in particular regions.

(iii) Aircraft emissions above critical altitudes should be subject to separate international negotiations for their control and limitation in light of their special effects at altitude.

7.3.2. Policy

Policies to limit the environmental impact of aircraft should be implemented by the aviation industry as far as possible. However the policy framework within which specific aviation policies must reside is set by governments. Also, governments would bear partial or sole responsibility for some areas of policy: the management of demand and development and coordination of transport modes are two such areas.

The more important policy issues and measures include:

(i) The aviation industry should urgently develop policies aimed at reducing emissions. This development should be carried out by operators as well as manufacturers.

(ii) Air transport policy should be to transfer as much freight as possible to surface transport modes having a lower impact. In the medium term this should mean the virtual elimination of freight only air transport.

(iii) The load factor of aircraft should be sharply increased.

(iv) The possibility of reducing fuel use by lowering speeds should be investigated, as should the avoidance of cruising near the tropopause and in the lower stratosphere.

(v) Taxation should be applied if it efficiently encourages reductions in fuel use and emissions.

(vi) The development of aircraft and engine designs aimed at reducing emission should be promoted.

(vii) Demand management measures should be explored and implemented where feasible.

There are reasons to believe that many of the policy elements advanced in this report should be acceptable to the aviation industry. First, with the exception of short distance passenger journeys and most freight, there are no widely applicable alternatives to aircraft as means of transport. Second, the cost of the flight generally will not dominate the total cost of a holiday or business trip. This means that, insofar as there are extra costs involved in pollution control, they can generally be passed on to the passenger without causing a significant drop in demand whilst long distance travel is required.

The increase in load factors recommended, and many of the means of implementation it, would be welcome to many airlines. The demand for their services would be more predictable and business planning would be correspondingly easier. Improved financial stability would be one probable result. Improved load factors will generally decrease unit service costs. This reduction can be used to finance improvements such as the purchase of better aircraft, or taken as some combination of increased profit and reduced fares.

As far as the aircraft and aeroengine manufacturing industries go, the recommendations for the rapid introduction of cleaner and more efficient aircraft should be good news because it means more sales.

As for many other economic sectors, the control of pollution can change the cost structure and characteristics of the services provided. However many of the control measures proposed in this paper would not have such an enormous impact unless applied to the extreme.

APPENDIX : Global warming and aircraft operations

This Appendix discusses the implications for global warming due to three trace gases. First, the amounts and distributions of emission are discussed. Second, schema for the global warming potential of certain pollutants are presented. Third, the possible implications for aircraft operation are explored. Finally, the overall contribution of aircraft to global warming is revisited.

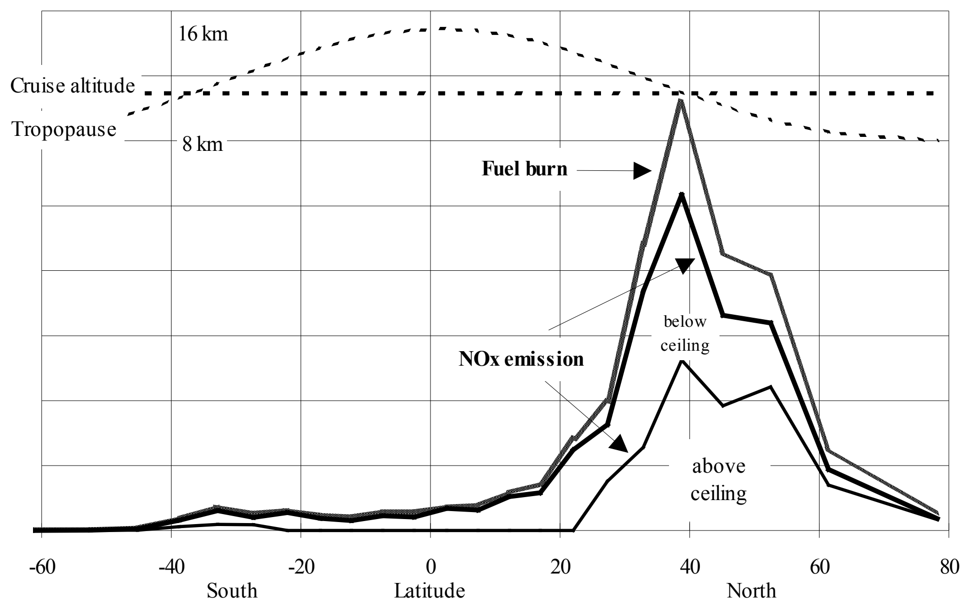
The Appendix is intended to highlight what some of the important issues might be and to suggest some methodologies that might be used to help inform the construction of aviation policy aimed at environmental protection.

Global distribution of aircraft fuel use and emission

McInnes and Walker (1992) estimated the amounts and distributions of fuel burn and emission for scheduled civil passenger aircraft. Their calculations only accounted for about half of the estimated global aviation fuel burn. The difference is in part due to the omission of military, cargo, non-scheduled and private operations.

Figure 25 shows the global distribution of fuel burn and total NO_x emission based on data produced by McInnes and Walker. They estimate that 44-47% of total NO_x emissions occur at an altitude between 10 and 12 km. The author has used their fuel and NO_x emission data to estimate the proportions emitted above a ceiling 80% of the tropopause altitude appropriate for the particular latitude. The author estimates that about 52% of total fuel consumption (and therefore water emission) and 43% of total NO_x emission is above this ceiling. Figure 25 serves as a reminder of the great imbalance in north and south hemisphere emission, and that the proportion of emission near the tropopause may change significantly with air traffic patterns.

Figure 25 : Global Distribution of Aircraft Fuel Burn and NOx Emission



Global warming potentials of trace gases

The Intergovernmental Panel on Climatic Change (IPCC) report of 1992 (IPCC, 1992) reviews some of the scientific understanding on the radiative forcing effect of different trace gases put forward in its first report (IPCC, 1990). The IPCC's general perspective remains unchanged, but there have been some alterations to its scientific view. The estimates of the global warming effect (GWE) of most of the trace pollutants are changed little. However, the IPCC is now more wary of using the concept of Global Warming Potential (GWP) for trace gases that are highly synergistic. In particular the IPCC cautions against the use of the GWP concept for NO_x.

The problem is that if GWPs are not used, how can trace gases with highly uncertain effects (due to synergism or other reasons) be accounted for in risk analysis and policy formulation? There is the danger that things which can not be quantified with some degree of certainty will be left out of the reckoning. This is particularly so for aircraft and their NO_x and water emissions.

Therefore the following adopts illustrative GWPs for NO_x and water, but with the IPCC warning to the fore. The analysis presented tries to account for uncertainty by using high and low figures and by making conclusions based on predicted effects with and without the effects of greenhouse pollutants other than CO_2.

The high estimate of GWP of high altitude NO_x previously used by Barrett was based on work by Johnson and Henshaw in 1990 (Johnson, Henshaw; 1990). More recent work by these researchers (Johnson, Henshaw; 1992), and by others, suggest that the GWP is perhaps five times less than first thought. The GWP would then be approximately half way between the low and high values previously used by this author.

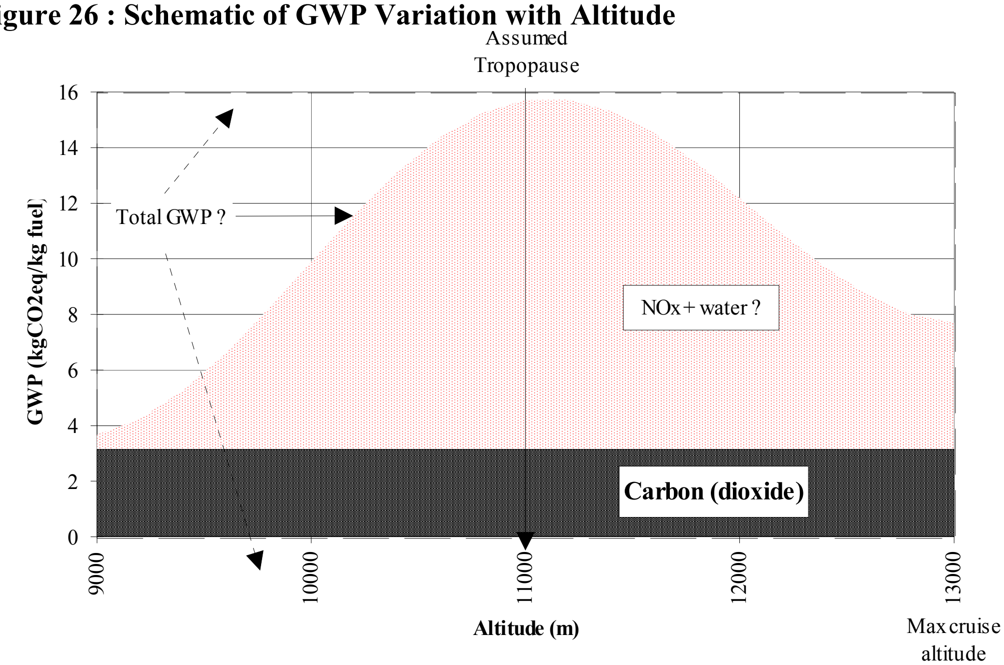
Figure 26 illustrates schematically how the GWPs of aircraft pollutants (expressed per kg of fuel) might vary with altitude. The actual variation with altitude will depend on many factors including season, latitude, tropospheric cloud cover and so on. Note that the height of the tropopause typically varies from around 16 km at the equator to 8 km at the poles and so the effects will vary with latitude. Furthermore the altitude of the tropopause varies seasonally. Certain conditions additional water vapour might lead to the formation of extra cloud of a type that reflect insolation and thereby act as a global **cooling** agent. It is again emphasised that the scientific uncertainty is enormous and that Figure 26 is for illustrative purposes only**.**

Taking mid range values for the NO_x and water GWPs in Figure 26 results in the average high altitude GW due to NO_x and water being 170% that of carbon emission per mass of fuel consumed between altitudes of 9000m and 13000m.

A GWP of 230 kg of carbon dioxide equivalent per kg of NO_x emitted is obtained; this is at the low end of the range according to current scientific views. These GWPs have been assumed in order to try and establish a range of global warming such that some context is provided for formulating policy responses. The assumptions also serve to promote discussions about, for example, the altitude at which aircraft should cruise. These GWPs are probably, but not necessarily, quite distant from values that may be stabilised by future scientific research: they may be lower or higher.

When near the tropopause, aircraft emission fractions of 43% for NO_x and 52% for water (from Figure 25) are taken, the GW due to these emissions is 60% of that due to carbon.

Figure 26 : Schematic of GWP Variation with Altitude



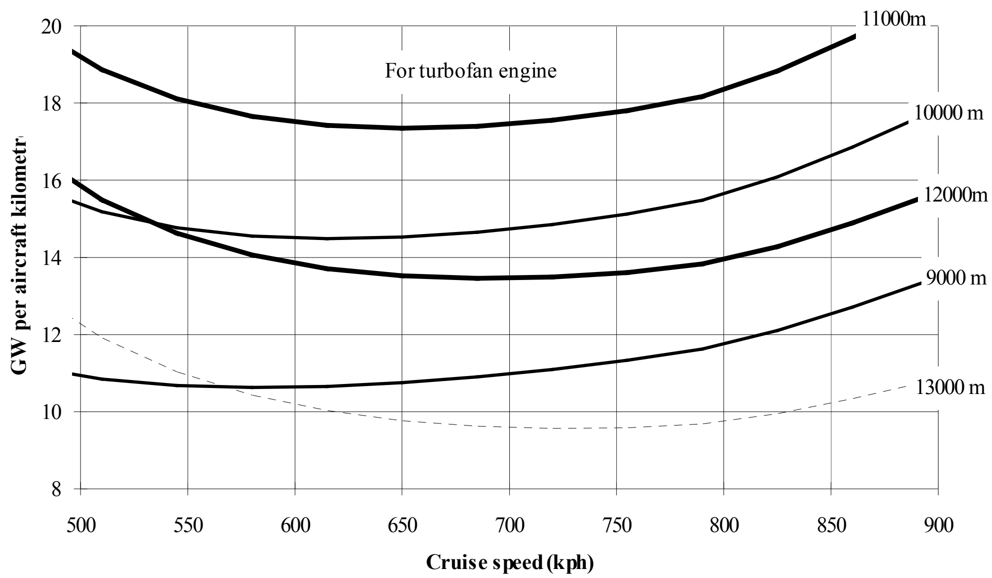
The reader is reminded that the relative values of GWPs changes radically according to the time scale being considered. In particular, NO_x has a short lifetime as compared to CO_2, and therefore its GWP compared to CO_2 over 100 years is much less than over 20 years. This problem gives rise to another layer of technical and philosophical difficulties when formulating policy responses.

Effects of altitude and speed on global warming

The global warming due to CO_2 is directly related to fuel consumption, and is relatively independent of the altitude of emission. This is not so for other important pollutants such as NO_x and water. We may use the notional GWPs shown in Figure 26 and apply them to illustrative SFC curves as given in Figure 15 in order estimate the variation in the total global warming effect of the three pollutants with altitude and speed. [Note that it has been assumed that the emission of NO_x per kg of fuel is constant with speed. In reality it may be expected that the specific emission of NO_x will marginally increase with speed since more thrust is required.] The result of this calculation is shown in Figure 27. Units have been deliberately omitted.

We see that for a given speed, a cruise altitude of 9000 m causes less global warming than altitudes of 10000m or higher because the reduction in global warming due to the diminished effect of NO_x and water outweighs the increased effect due to more carbon emission. Figure 27 also shows that cruising at 13000m would bring about less global warming given the notional variation of GWPs assumed above. However the possibility of ozone depletion and the general sensitivity of the atmosphere to pollution above the tropopause generally increase the environmental concerns associated with higher altitude cruising.

Figure 27 : Greenhouse Gas Emission Variation with Speed and Altitude



This discussion has focused on global warming. Other impacts, such as the destruction of ozone by NO_x at very high altitudes also vary with altitude.

Altering speed and altitude impacts on the economics, logistics and other dimensions of air transport. Fuel costs will increase if speed is maintained at a lower altitude. Conversely if speed is reduced, fuel costs will fall but other items such as the unit cost of aircraft capital and flight staff costs will increase. Lower speeds will also mean lower customer acceptability because journeys will take longer. However note that the total door-to-door journey time would typically not be greatly increased by reducing speed by, say, 15%.

The preceding discussion has shown how environmental flight planning might diminish environmental impact. Hypothetical variations in GWP with altitude were employed, and a hypothetical aircraft was assumed, although both of these sets of assumptions are based on scientific and technological information. No claim for accuracy is made, but clearly there is a prima facie argument that the operational regime of aircraft in terms of speed and altitude is an important determinant of environmental impact. It seems clear that designing aircraft for slower cruise speeds will reduce fuel consumption and reduce pollution emission. It is possible that reducing the cruise altitude will diminish environmental impacts including global warming and the risks associated with the emission in the low stratosphere of NO_x and water.

It is beyond the scope of this paper to discuss the possible implications of environmental flight planning for the industry as a whole. Such planning would have to cover a number dimensions: from sophisticated models of environmental impact to calculations of fuel use and emissions; from political negotiations for airspace allowances to maintenance of safety with aircraft following variable routes at variable speed.

The overall contribution of aircraft to global warming

There are still concerns about water (see section 2), and the possible contribution of NO_x to global warming. For example:

> *"About 1.5 - 2% of the Earth warming could be attributable to NO_x emissions from aircraft in the upper atmosphere, but this estimation has to be verified. At this stage it is not possible to quantify the global greenhouse effect due to troposheric ozone modifications in relation with aircraft emissions." (Carpentier; 1993)*

Barrett previously estimated the possible range of global warming due to aviation using the GWPs of two pollutants: carbon dioxide and NO_x (Barrett, 1991). He used high and low estimates of the GWP of NO_x, and time scales extending from 20 to 500 years. This resulted in a wide range of estimated contribution of aircraft to the total global warming due to anthropogenic trace gases: between 2.5% and 10% over 100 years; and between 5% and 28% over 20 years.

Barrett's estimate is founded on a number of assumptions about the quantities and spatial dispositions of pollutants emitted by aircraft; and the effects of these pollutants. Since 1990 there have been some changes in the understanding of the pollutants which possibly lead to global warming.

The assumptions he made for the total quantities of NO_x emitted still seem reasonable in that the emission coefficient he used (12 g/kg) is near the middle of other reported estimates (see for example McInnes & Walker, 1992; Olivier, 1991). Barrett assumed that the proportion of global trace gas emission due to aircraft does not increase in the future. This latter assumption probably underestimates the future global warming of aircraft because air transport is increasing faster than most other economic sectors. On the other hand Barrett assumed all NO_x and water to be emitted at an altitude leading to substantial ozone formation and global warming, whereas the proportion having these effects is probably less than 50%.

Barrett's estimate of global warming did not include pollutants other than CO_2 and NO_x. Most discussions of the possible effects by scientists indicate that if other pollutants not included in this estimate, particularly water, are added in, then the GWE of aircraft would be increased. There are few quantitative estimates of global warming due to any pollutants except carbon dioxide.

The atmospheric residence times NO_x and water are much less than CO_2. This has two important consequences in effects and policy terms. First, the warming effect of NO_x and water will be highest where their near tropopause emissions are greatest, in heavy air traffic corridors such as the north Atlantic route and the northern USA. Thus these pollutants may rather be seen as regional rather than global warming agents. Their contributions to warming in such regions would be higher than the globally averaged figures would suggest.   Secondly, policy changes will rapidly influence the effect of NO_x and water, unlike CO_2.

REFERENCES

Anderson J: 1989: Introduction to Flight: McGraw Hill International Editions, ISBN 0 07 100496 3.

Bahr D: 1992: Turbine Engine Developers Explore Ways to Lower NOx Emission Levels: ICAO Journal August 1992 : 1000 Sherbrooke Street West, Suite 400, Montreal, Quebec, Canada H3A 2R2.

Balashov B, Smith A (ICAO): 1992: ICAO Analyses Trends in Fuel Consumption by World's Airlines: ICAO Journal August 1992 : 1000 Sherbrooke Street West, Suite 400, Montreal, Quebec, Canada H3A 2R2.

Barrett M: 1991: Aircraft Pollution : Environmental Impacts and Future Solutions: Earth Resources Research, for Worldwide Fund for Nature International.

Boeing Commercial Airplane Group: 1991: World Air Cargo Forecast.

British Airways (BA): 1992: Airlines, Tourism and Environment.

Carpentier J: 1993: The Impact of Aircraft Emissions on the Atmosphere : in proceedings of IATA seminar on Air Transport and the Environment, Washington, March 1993.

Department of Transport (DTp): 1991: Transport Statistics Great Britain 1991: Department of Transport, HMSO, ISBN 0-11-551078-8.

Department of Transport: 1989: United Kingdom Airfreight 1977-1987: HMSO, ISBN 0 11 550907.

Department of Transport: 1990 : International Passenger Transport : Department of Transport: HMSO: ISBN 0 11 550953 4

Held (Ed) M: 1990: Ecological Impacts of Aircraft Emissions: Protestant Academy of Tutzing, Postbox 227, D-8132 Tutzing.

International Air Transport Association: ??: Air Transport and the Environment.

International Air Transport Association (IATA) : 1992: International Traffic Forecast: 1992-1996 - Scheduled Passengers.

International Civil Aviation Organisation: 1966: ICAO's Policies on Taxation in the Field of International Transport : Doc 8632-C/968: 1000 Sherbrooke Street West, Suite 400, Montreal, Quebec, Canada H3A 2R2.

International Civil Aviation Organisation: 1992a: Civil Aviation Statistics of the World: 1991: 1000 Sherbrooke Street West, Suite 400, Montreal, Quebec, Canada H3A 2R2.

International Civil Aviation Organisation: 1992b: Outlook for Air transport to the Year 2001: 1000 Sherbrooke Street West, Suite 400, Montreal, Quebec, Canada H3A 2R2.

International Civil Aviation Organisation: 1992c: Regional Differences in Fares, Rates and Costs for International Air Transport 1989: 1000 Sherbrooke Street West, Suite 400, Montreal, Quebec, Canada H3A 2R2.

International Civil Aviation Organisation: 1993: Survey of International Air Transport Fares and Rates : 1000 Sherbrooke Street West, Suite 400, Montreal, Quebec, Canada H3A 2R2.

International Energy Agency (IEA): 1992: Country Energy Balances: International Energy Agency, OECD, 2, rue Andre-Pascal, 75775 PARIS CEDEX 16, France..

IPCC (Intergovernmental Panel on Climate Change): 1990: Scientific Assessment of Climate Change, WMO/UNEP.

IPCC (Intergovernmental Panel on Climate Change): 1992: Climate Change 1992: WMO/UNEP.

Johnson C, Henshaw J: 1991: The Impact of NOx Emissions from Tropospheric Aircraft : AEA-EE-0127: Modelling and Assessments Department; AEA Environment and Energy, Harwell Laboratory, Harwell Laboratory, Oxfordshire OX11 0RA, UK.

Johnson C, Henshaw J, McInnes G: 1992: The Impact of NO_X Emissions on the Tropospheric Ozone and Global Warming: Nature Vol 355 January 1992.

Krause F, Bach W, Koomey J: 1990: Energy Policy in the Greenhouse: Earthscan Publications Limited, ISBN 1-85383-080-X.

Martin D, Shock R: 1989: Energy Use and Energy Efficiency in UK Transport up to the Year 2010: Department of Energy, ISBN 0 11 412956 8.

Martin D, Michaelis L: 1992: Research and Technology Strategy to Help Overcome the Environmental Problems in Relation to Transport: Science Research and Development, Commission of the European Communities.

McInnes G, Walker C: 1992: The Global Emission of Aircraft Air Pollutant Emissions: Warren Spring Laboratory, Gunnels Wood Road, Stevenage, Hertfordshire SG1 2BX.

NASA: 1992: Atmospheric Effects of Stratospheric Aircraft Flight (special annual meeting reports issue): National Aeronautics and Space Administration, HSRP/AESA Flyer Editor, Code SE-44, Headquarters NASA, Washington, DC 20546.

NASA (Stolarski, Wesoky eds): 1993: Atmospheric Effects of Stratospheric Aircraft: A Second Program Report : National Aeronautics and Space Administration.

Olivier J: 1991: Inventory of Aircraft Emission: A Review of Recent Literature: National Institute of Public Health and Environmental Protection, Bilthoven, Netherlands.

Prather M, Wesoky H, Miake-Lye R, Douglass AR, Turco RP, Wuebbles DJ, Ko MKW, Schmeltekopf AL): 1992: The Atmospheric Effects of Stratospheric Aircraft: A First Program Report: NASA (National Aeronautics and Space Administration.

Pueschel R, Snetsinger K, Hansen A: 1992: Stratospheric Soot : Abundance, Type, Single Scatter Albedo: NASA Ames Research Centre/Lawrence Berkeley Laboratory.

Rijsberman F, Swart R (eds): 1990: Targets and Indicators of Climatic Change: Stockholm Environment Institute.

Rochat P (ICAO); 1993: Civil Aviation and the Environment - the Key Issues : in proceedings of IATA seminar on Air Transport and the Environment, Washington, March 1993.

Schumann U, Arnold F, Hermann D, Reinhardt ME, Suasen R, Schlager H: 1992: On the Effect of High-Flying Air-Traffic on the Atmosphere: DLR, Institut fur Physik der Atmosphare.

Schumann U: 1993: On the Effect of Emissions from Aircraft Engines on the State of the Atmosphere: Institut fur Physik der Atmosphare Deutsche Forschungsanstalt fur Luft und Raumfart e.V. (DLR): W-8031 Oberpfaffenhofen, Germany. In proceedings of AGARD, 81 st Symposium on "Fuels and Combustion Technology for Advanced Aircraft Engines" in Colleferro near Rome, Italy 10-14 May 1993.

Tourism Concern: 1992: Beyond the Green Horizon: Panda House, Weyside Park, Godalming, Surrey GU7 1XR, UK, WWF UK, ISBN 0 947613.

Travel & Leisure: 1989: Worldwide Travel Markets.

United Nations: 1989: Energy Statistics yearbook 1987.

World Meterological Organisation : 1991 Scientific Assessment of Ozone Depletion: 1991Global Ozone Research and Monitoring Project - Report No 25.
National Aeronautics and Space Administration/National Oceanic and Atmospheric Adminstration/United Kingdom Department of the Environment/United Nations Environment Program/World Meterological Organisation.

World Travel and Tourism Environment Research Centre (WTTERC): 1992: Travel and Tourism: Environment and development: WTTERC/ World Travel and Tourism Council, OCTALS, Oxford Polytechnic, Headington, Oxford OX3 OBP.

Worldwide Fund for Nature UK/Tourism Concern: 1992: Beyond the Green Horizon: Worldwide Fund for Nature UK/Tourism Concern, 1992, Panda house, Weyside Park, Godalming, Surrey, UK, ISBN 0 947613 87 0.

XueXi T, Brasseur G, Cranier C, Rasch P: 1992: The Impact of High Altitude Aircraft on the Ozone Layer in the Stratosphere : in NASA (1992) : National Center for Atmospheric Research, PO Box 3000, Boulder, CO 8037.