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CIVIL AIRCRAFT DESIGN PRIORITIES: AIR QUALITY? CLIMATE CHANGE? NOISE?

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Abstract

A variety of related questions is posed. Are the right priorities for future aircraft design being set now? New civil aircraft types could be 'silent', ie make much less noise than current types. They could be 'green', ie safeguard the environment. Is silent as important as green? The crucial answer is that future aircraft design should focus on substantial reductions on climate change impact. The air quality targets proposed by the 'Sustainable Aviation' initiative appear very ambitious: they should be pursued only to the extent that they do not affect improved fuel efficiency and reduced climate-changing emissions. Good progress has already been made on the aircraft noise targets proposed by the Sustainable Aviation' initiative, but again they should be pursued only to the extent that they do not affect improved fuel efficiency and reduced climate-changing emissions. The financial case for designing to reduce aircraft noise in order to deliver novel financial benefits, eg increase airport flights at night and/or relocate airports, is weak.

1. INTRODUCTION

Research and development into new civil aircraft has always engaged the minds of some of the most talented people working in aviation. But what should they be focusing their efforts upon? If new civil aircraft types are 'silent', ie make much less noise than current types, will airlines immediately buy them? If they are 'green', ie safeguard the environment, will they then be introduced quickly through business decisions? Or will additional regulatory action be required by government (society?) to meet desirable or necessary environmental objectives? And if these new types are introduced, will that produce changes in the nature of airports and/or air traffic management (ATM)? So is silent as important as green?

From an airline business perspective, the important point today is that environmental concerns, in the widest use of the phrase, are more likely to affect aircraft purchasing decisions than in the past. Airline purchasing decisions have generally focused on markets, investment timing and operating costs.

Tomorrow's aircraft purchases require research and development to be done today – or rather over the coming decades – in order to create the kinds of aircraft that airlines will want – or should want – to buy. Are the right priorities for future aircraft design being set now?

These are big strategic questions. The timescale from new concept to operational reality is a lengthy one, and commercial aircraft have long lives. Major changes in the kinds of civil aircraft in use at major airports would be expected to take between 20 to 50 years, say to 2050. It is an act of hubris to attempt to look so far forward: the focus here is therefore on trying to contribute by identifying those key facts that are most likely to constrain the future. The analysis tries to review, clarify and question research and modelling results, whilst trying very hard to paint a fair picture.

The main stimulus for this analysis was the substantial and innovative piece of work by the SBAC 'Air Travel - Greener by Design' team [(1)] (see also Green [(2)]), and the subsequent 'Sustainable Aviation' initiative [(3)] [NB: coordinated by the SBAC, AOA, BATA and NATS]. Thus, the following is in part a critique of some of the recommendations of those documents and of the Silent Aircraft Initiative (Cambridge-MIT Institute [(4)], Morimoto and Hope [(5)]).

The effects on Heathrow airport operations will generally be used as a 'case study' to illustrate points. There is a value in examining the issues at a real airport rather than a hypothetical one. Heathrow is mainly chosen because of the size of its environmental problems compared with other UK airports, but also because so much relevant information about it is made available from the BAA and UK government. Aviation is of course a global industry: case studies of other airports might bring out different aspects.

The following text is organised into nine sections:

2. Airline Decision-Making and New Aircraft
3. Externalities
4. Risk of Aircraft Crash to Third Parties
5. Aircraft Noise Annoyance
6. Noise and Health
7. Weighting the Externalities
8. Silent Aircraft
9. Sustainable Aviation Initiative
10. Conclusions

2. AIRLINE DECISION-MAKING AND NEW AIRCRAFT

A well-known – and variously attributed – aviation quotation is "The airline business has all features of businesses – apart from profits." Traditional 'full service' airlines, many state-owned, have not consistently made profits over the years, and, over the last decade, established UK operators have faced competition from low-cost carriers. Doganis [6, 7] are very clear explanations of some of the financial complexities of the airline industry.

The airline industry is embedded in an aviation industry that generally does make money. This is illustrated by Figure 1, which is a simplified version of material in Button [8].

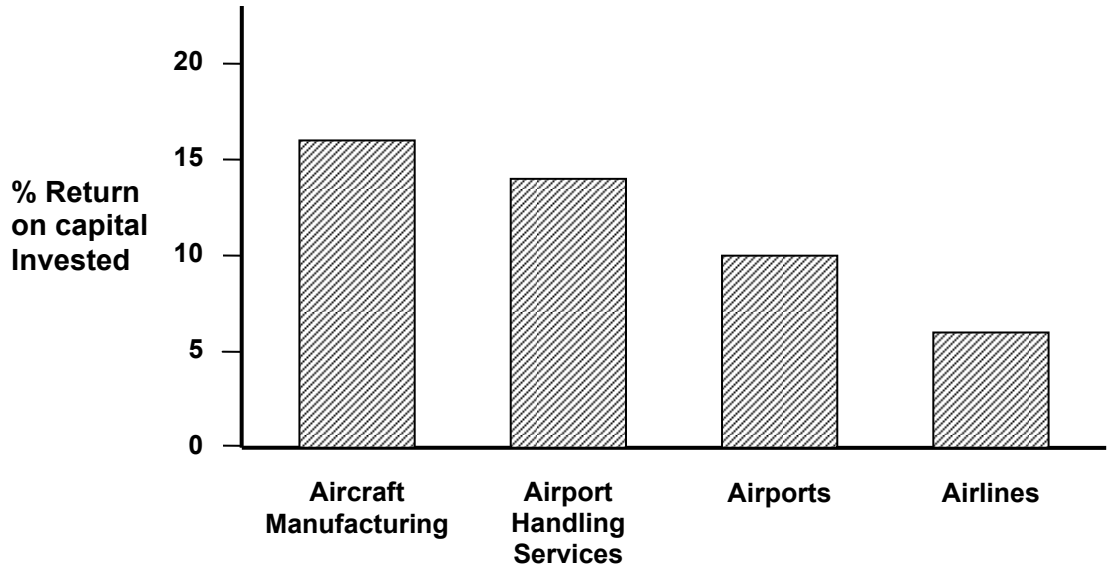


Figure 1. Rate of return on capital invested (1992-1996), adapted from Button [8]

The data in Figure 1 derive from a McKinsey study. This is some years old, but from a more stable period than (say) the last five years. Why these numbers are what they are raises large business, economic and regulatory policy issues: Button [8, 9] offers some explanations in terms of the microeconomic structure of the industry. The key point is that many of the airlines suppliers, in the widest sense of the word, eg airports, aircraft-makers and banks, are protected by oligopoly powers or regulatory constraints (Button's rent-seeking behaviour).

In contrast, Airlines operate in an extremely competitive world. Their customers compare price information, increasingly using the Internet. There are few barriers to entry for new airlines, so too much airline capacity tends to chase demand and profitable new routes (see Button [9] re the 'empty core problem'). Typically, about 80%-90% of an airline's costs are fixed and 10%-20% are variable, which means that it is worthwhile filling seats close to flight departure time at very low marginal costs – thus making only a small contribution to average costs.

Airline finance is a complex subject (eg see Morrell [10]). For example, airline finances are increasingly complicated by the growth of aircraft lessors (Economist, [11]). Firms such as General Electric Commercial Aviation Services and an AIG subsidiary own aircraft and lease them to airlines. This has, for example, tax advantages in the USA – which, at the time of writing (Summer 2005), has six major full-service, hub-and-spoke airlines operating with at best low margins (including US Airways and United Airlines in Chapter 11 bankruptcy protection).

The financial decision tools that are used by airlines when purchasing aircraft should in principle be the same tools that any industry would use to assess possible large-scale investments. Standard textbooks such as Morrell [10] and Clark [12] certainly describe standard tools (compare Pike and Dobbins [13]).

Timescales for recovering the cost of an aircraft are generally long, so that the 'time value of money' is a key factor. Assessment methods almost invariably use Net Present Value (NPV) techniques. Figure 2 sets out the standard NPV expression to discount money flows in the future. A discount rate of r % implies that £1 in n years time is worth £1 / $(1 + r)^n$ today.

Net Present Value – NPV

$$\mathbf{NPV = \sum (B_i - D_i - C_i) / (1 + r)^i}$$

B_i = Benefits in year i
D_i = Disbenefits in year i
C_i = Costs in year i
r = Discount rate
$\sum$ = Summation over years 1 to n

The best investment is the one with the highest positive value

Figure 2. NPV expression

The costs, benefits and disbenefits in Figure 2 are the cash flows that arise from the investment. A distinction is made between costs and disbenefits. A cost would be an actual expenditure of cash to secure the aircraft (eg on maintaining equipment) while a disbenefit would be an estimated operational cost arising out of the aircraft (eg increased fuel usage). If an aircraft has a residual value at year n, the value of C_n would need to be adjusted to correspond to net amounts. All cash flows here are in constant/current year prices, in order to avoid the problems of forecasting inflation for the different cost and revenue items.

The discount rate r % is intended to reflect alternative uses for investment capital. As the opportunity cost of capital, it should be at least as high as the interest rate available at the bank. Indeed, it needs to be an even greater figure than this, to reflect the fact that all investments into the future involve some, possibly considerable, risk. The Weighted Average Cost of Capital (WACC) estimates a more robust minimum discount rate. Clark [(12)] [NB: published 2001 – hence not current] gives some airline examples, with typical gearing ratios, to produce a commercial WACC of the order of 10%.

Future cash flows some years ahead are usually very sensitive to assumptions about demand and competition. An airline's key decisions from year to year are in fact whether or not to do 'something' versus carrying on with current operations and systems. The latter 'do nothing option' (actually often a very difficult decision to take) would generally involve retaining the present fleet of aircraft.

What lessons are there from this financial sketch? The following is a, rather blunt, business summary of what airlines want:

- cash – hard cash, real money not notional transfers
- relatively quick and assured financial payback for investment
- costs not to rise and new taxes not to be imposed – because this affects profits and higher prices tend to suppress demand
- no shocks, because the airline cannot absorb large new costs quickly – eg airlines have to impose surcharges on fares when there is a substantial increase in fuel prices.
- demand to keep rising – so load factors (and so potential profits) are high and there is not cut-throat competition for shrinking passenger numbers
- long lives for aircraft – to get back the return on investment
- retain any differential advantages, eg historically-based airport slots

These are rational and obvious for firms facing harsh competition, but they are sometimes concealed by rhetoric. Airlines may have to achieve these goals through lobbying of their governments and regulatory bodies. ICAO [(14)] serves to illustrate this, particularly the article by Jane Garvey, then the FAA Administrator:

> "The aircraft noise problem threatens the further development of international air transport, but there is a way forward. The best solution is to balance the various noise reduction measures so that environmental progress is achieved without diminishing the health of the industry.
>
> Given today's technology, a phase-out of Chapter 3 aircraft is hugely expensive, especially when compared with the actual benefit achieved."

3. EXTERNALITIES

Environmental concerns are usually classified by economists as 'externalities'. Externalities are things arising from the production or consumption of goods that affect third parties. Transport generates a variety of externalities [15]. In the case of aviation, the externalities that affect people would include:

- Risk of aircraft crash
- Aircraft noise
- Air quality deterioration
- Climate change

The first three of these examples are largely local to an airport, but the fourth is a contribution to a global effect.

The focus here will be mainly on risks and noise, which will be discussed in later sections. This section summarises some important features of the other externalities, with particular reference to Heathrow. The UK Parliamentary Office of Science and Technology report [16] is a good general reference.

Air quality deterioration

Emissions from aircraft produce a local deterioration in air quality at ground level and for several hundred metres above ground level. Airport-related emissions are produced by fuel combustion during take-off and landing, ground auxiliary vehicles, and surface access movements. There is a huge literature on the topic: a representative selection of recent publications is: Air Travel - Greener by Design [1], BAA [17], Bickel et al [15], DEFRA [18, 19], DETR [20], DfT [21, 22], Dings et al [23], Green [2], Hollander [24], ICAO [25], Lampert et al [26], and RCEP [27, 28].

The International Civil Aviation Organisation (ICAO) sets engine certification standards. These limit the emissions of unburned hydrocarbons, CO, NOx and smoke during the LTO cycle up to an altitude of 3,000 feet. LTO is the Landing and Takeoff operational cycle for engines: idle, taxi, takeoff, climb out, descent, and approach. In 1999, ICAO mandated a further NOx reduction of 16% on LTO for all aircraft jet engines certificated after December 2003 [26].

The main aviation emissions affecting air quality, ie which pose possible threats to people's health, are:

NOx	Nitrogen Oxides (mainly NO_2, Nitrogen Dioxide)
CO	Carbon Monoxide
VOCs	Volatile Organic Compounds (eg benzene)
SO_2	Sulphur Dioxide
O_3	Ozone (secondary pollutant – chemicals above react with sunlight)

PM_{10} particulate matter of size <10μm

Mandatory European Union (EU) limits will come into force for NO_2 and PM_{10} in 2010 and 2005/2010 respectively: these are usually seen as having the most significant health (eg respiratory illnesses) and environmental effects. The most recent EU policy statement on air pollution targets is the European Commission's Thematic Strategy [29], which *inter alia* emphasizes, to a much greater extent than before, the costs and benefits of potential different emissions reduction strategies. For example, this might mean that it would be judged more cost effective to move people away from areas exceeding air quality targets, rather than to act to reduce source emissions affecting those areas.

DfT [21] notes that the EU levels for NO_2 are likely to be exceeded at Heathrow in the next few years, but that this is less likely for PM_{10} concentrations. It must be stressed that the recorded levels of these pollutants include emissions from all sources, including road traffic in particular. Lampert et al [26], which is the most recent of 10+ years of monitoring, quotes a 1993 figure, for Heathrow perimeter sites, that aircraft sources contributed 21%-43% of annual NOx, and all airport sources contributed 28%-54%.

BAA [17] (consistent with DEFRA [18]) quotes 2001 data that, of UK emissions, civil aircraft contribute:

<0.3% of NOx

~0.1% of CO

<0.1% of VOCs

<0.1% of PM_{10}

These 'global' figures obviously conceal large variations locally. An example of the importance of road traffic to pollutant levels is shown by the comparisons made in BAA [18], simplified in Table 1.

	Pollutant (mean, max in brackets)		
Site	**NO_2 μg m^{-3}**	**CO mg m^{-3}**	**PM_{10} μg m^{-3}**
Heathrow LHR2 'Old Apron' just within airport perimeter	59 (191)	0.5 (3.3)	24 (208)
London Hillingdon suburban residential area ~30 metres from M4 motorway	54 (199)	0.5 (9.3)	23 (116)
London North Kensington within the grounds of a school, surrounding area mainly residential	44 (195)	0.5 (3.4)	22 (145)

Table 1. Comparison of measurements at Heathrow LHR2 with other UK National Monitoring Sites 1st January to 31st December 2003 (with typo corrected)

There are several UK publications covering air pollution's effects on health (which take full note of international research). A good starting point is the UK Department of Health's Air Pollution Website [30], which provides references to source material. Several of its reports originate from with the Committee on the Medical Effects of Air Pollutants (COMEAP), an Advisory Committee of independent experts. Current COMEAP advice [31] includes:

- The main sources of outdoor air pollution are road traffic, manufacturing industry and non-nuclear power generation in the UK.
- Air pollution can worsen the condition of those with heart or lung disease.
- Air pollution can aggravate, but does not appear to cause, asthma.
- In the longer term, air pollution probably has additional effects on individuals, including some reduction in average life expectancy, though the extent of this is not fully understood at present.
- As a result of international agreements, Government regulations and action by local authorities, the Environment Agencies and industry, air pollution levels in the UK are generally reducing, though still a cause for concern at specific times.

It is worth noting that this advice does not explicitly mention airport-generated pollution – nor indeed does the Parliamentary Office of Science and Technology (POST [32]) briefing paper on the topic.

Useful statistics on air pollution trends are produced by DEFRA [33], which states that: "In general there has been a long term decline in the number of air pollution days, largely because of a reduction in particles and sulphur dioxide, but fluctuations from one year to the next can occur because of differences in weather conditions." Ozone is a particular problem for high summer temperatures, such as 2003. [NB: an 'air pollution day' is one with moderate or higher air pollution, the 'moderate' pollution band corresponding to when "mild effects, unlikely to require action, may start to be noticed amongst sensitive individuals". Note the caveats here]

Recent studies examining valuing health effects and general progress on air pollution improvements are Brunekreef and Holgate [34], Chilton et al [35], AEA Technology Environment [36], and WHO [37]. This aspect will be returned to in Section 7.

Climate change

Thousands of research papers and policy documents have been published about climate change. A relevant set for present purposes, from which the following summary is drawn, is: Air Travel - Greener by Design [1], DfT [22, 23, 38], ICAO [15], IPCC [39, 40], RCEP [27, 28], and Williams et al [41]. DfT [42] appears to be the most recent UK Government technical statement specifically concerned with aviation and global warming.

Climate change comes about because of the 'greenhouse' effect' (although the physical mechanism is not actually the same as in a normal greenhouse). The sequence – worth setting out simply so the factual/logic flow can be seen – is:

1. The earth receives radiant energy – including light – from the sun.
2. Over the millennia, the energy flows 'in and out' have produced an energy balance, with the earth at about its present temperature.
3. A variety of lower atmosphere 'greenhouse' gases, including water vapour, carbon dioxide (CO_2), and methane (CH_4), absorb infrared radiation and thus trap heat near to the Earth's surface.
4. If the amounts of these greenhouse gases increase then there will be tendency for the surface to heat up.
5. Greenhouse gases, most usually CO_2, are produced by burning fossil fuels, including aviation fuel: the progressive industrialisation of the last 100 years – particularly the last 25 years – has led to global warming.
6. Continued expansion of industry through the use of fossil fuels will lead to further global warming.
7. In the long term, global warming will on average over the Earth produce bad results, although some countries might benefit by having (eg) a longer growing season.

Not every scientist, nor every politician, in the world currently believes all the steps in this sequence or the policy implications that should be drawn (eg see Ceronsky et al [43]). It must be stressed that the argument is based on atmospheric physics as well as extrapolations of climate records and correlations with greenhouse gas generation (eg Jones and Palutikof [44]). For present purposes, the picture as painted in the RCEP and DfT references above will be taken as authoritative.

The impact of aviation on climate change is increased over that of CO_2 alone by the range of secondary emissions released and their specific effects at altitude, plus other indirect effects. The other emissions include ozone and methane, which are generated by nitrogen oxides. The other effects include contrail formation (although the impact might be reduced by changed operational procedures, eg Williams et al [41], but see also Mannstein et al [45]) and cirrus clouds [28, 46].

Because of these additional effects, it was argued by the RCEP [28] that the total impact of aviation emissions on climate change should be taken as 2.7 or 3 times the impact of its CO_2 emissions alone, and that any environmental charge on aviation should reflect this. The multiplier 2.7 is in fact the estimate in IPCC [39] of the value in 1992 of the 'radiative forcing index' (RFI). RFI is the ratio of the total heating effect to that from CO_2 emissions alone, and so is a measure of the importance of aircraft induced climate change. Aviation has a high RFI compared with other sources.

The best current (published August 2005) estimates of the aviation RFI are by Sausen et al [46]. These suggest (see its Tables 1 and 2) that the radiative forcing from non-CO_2 sources and from contrails are somewhat less than the earlier IPCC estimates, but that aviation-induced cirrus is a large effect – indeed greater than CO_2 itself. Making these kinds of estimates of effects is incredibly difficult: for example, it has been questioned whether the RPI might over-estimate the effects of ozone emitted at aircraft cruise level (~upper troposphere/lower stratosphere) [47].

DfT [21] states that:

> "For 2000, estimates show that UK civil passenger aviation produced 30 million tonnes of CO_2, which corresponds to 18% of all UK transport CO_2 emissions and 5% of UK CO_2 emissions from all sectors.
>
> [In] 2020 aviation might produce…about 10 – 12% of total UK CO_2 emissions from all sectors. For the reasons given in the section on radiative forcing…aviation's share of total climate change effects is higher than its share of CO_2 alone."

Thus, even over 20 years, aviation is projected to increase its global warming effects markedly. International aviation is not covered by the Kyoto Protocol (see Section 9). These forecasts do of course depend on a great variety of assumptions about actions to reduce fossil fuel effects over the period, so that any figures for (say) 2050 would be very speculative.

The most recent UK Government paper assessing the implications and social costs of global warming appears to be Clarkson and Deyes [48]. This reviews several studies and concludes that the most sophisticated study was by Eyre et al [49].

4. RISK OF AIRCRAFT CRASH TO THIRD PARTIES

Aircraft crashes are rare, but their potential effects on people on the ground cannot be ignored. The risks to these third parties have been studied very carefully in the UK, and have led to changes in policies on development near to airports and been seen as important issues in planning inquiries, most especially the Heathrow Terminal 5 Inquiry. Commercial aircraft crashes generally occur because of operational factors rather than from problems with aircraft design or engine technology: aircraft design is a major safety success story over the last fifty or so years. The point of the present section is to show that such crashes are most likely to occur in areas that are close to airport runways.

Take-off and landing generally produce the most risks. Thus, the UK Government established a system of Public Safety Zones (PSZ) for the busiest airports some 40 years ago. PSZs are areas of land at the ends of the runways at the busiest airports. Within PSZs, development is restricted in order to minimise the number of people on the ground at risk of death or injury in the event of an aircraft crash. The current UK policy on PSZs is set out in DfT [50].

DfT [50] explains how the PSZ policy was developed through risk contour modelling and by setting limits on the degree of risk that is 'tolerable' for people on the ground near airports. The latter used a combination of cost benefit analysis and individual risk criteria; termed 'constrained cost-benefit analysis', this is broadly consistent with the Health and Safety Executive's tolerability of risk framework. This is a complex subject, explained in detail in DfT [50] and NATS [51].

Summarising very drastically, the main quantitative outputs are a set of individual risk contours and corresponding policy guidance. Individual risk in this context is the risk of death to an individual located at a particular place near to the airport. Risk contours are (cautiously estimated) lines of equal risk. Three standard contours are used – 10^{-4}, 10^{-5} and 10^{-6}. Thus, a person spending all their time on the 10^{-4} contour line would have a 1 in 10,000 chance of being killed per year as a consequence of an aircraft crash.

Table 2 shows the areas and population counts within the three Heathrow risk contours. These figures are some years old, but seem to be the most recently published. The risk modelling produced contours off the runway ends that are wide near the runway ends, becoming much narrower with increasing distance from the runway eventually to form a point, so are roughly triangular in shape). Heathrow's population counts within these risk contours are much larger than any other UK airports.

Risk	Area Sq km	Population (1000)
$>10^{-4}$	0.54	<0.1
$>10^{-5}$	4.60	2.2
$>10^{-6}$	31.12	47.2

Table 2. Comparison of contour areas/populations enclosed for Heathrow Individual risk calculations (adapted from Evans et al's Table 7.1 [51])

Key DfT PSZ policy recommendations include:

- Any existing housing, and other development occupied by third parties for a high proportion of the day, should be removed from within the 10^{-4} individual risk contours.
- [N]ew housing development, and most types of new non-housing development, within the 10^{-5} individual risk contour should not be approved.
- It may also be sensible to restrict development for new, sensitive or high density land uses, such as schools, hospitals, or places of assembly, somewhat beyond the 10^{-5} contour. Such restrictions should be considered on a case by case basis.

It is worth comparing the 10^{-5} and 10^{-6} figures with third party fatality rates arising from other transport industries. A useful source is RSSB [52], which lists recent (2003) Great Britain annual figures as 533 pedestrians killed by cars, 57 by buses and coaches, and 58 for rail. It is not really possible to get properly comparable figures, eg as many rail deaths arising from trespass or self-harm, worth noting that 50 fatalities per year in a population of ~50 million is a 10^{-6} annual individual rate.

5. AIRCRAFT NOISE ANNOYANCE

This section sets out information about aircraft noise disturbance. Aircraft noise can be a very technical subject, so the aim is very much to focus on key points. There are also many unanswered questions about the nature of disturbance caused by aircraft noise, so this summary is confined to what are broadly agreed facts. Heathrow Airport is a crucial example here, because a 'solution' to UK aircraft noise would certainly have to 'solve' it there.

The reference scale for noise is the decibel – dB. This is a logarithmic scale for physical quantities, so that a 'ten times' increase in noise energy produces an increase of 10 dB. It can be very confusing that dB is used for measuring quite different things, so the following text tries to spell out what precisely is being measured.

Peoples' ears and brains do not rate noises containing the same energy but with different frequencies to have the same loudness. This has led to the use of scales that 'weight' the amount of energy in the different frequencies covering the audible range. The most widely used scale is the A-weighting, so that noises on this scale are quoted in dBA.

The noise L(t) heard from an aircraft at a particular place on the ground rises to a maximum and then falls. The peak noise recorded is usually referred to as the noise level Lmax, ie is the maximum value of L(t) for a single noise event. This can be measured in dBA, but for aircraft certification a more complex measure, Effective Perceived Noise Level – EPNdB – is used. However, the Lmax (in dBA) and EPNdB values recorded for a particular aircraft are closely related. In practice there is a high correlation between the two, of approximately Lmax +13dB = EPNdB. Because the measures are highly correlated, a reduction of (say) 10 decibels in the Lmax value will correspond to approximately a 10-decibel reduction in the EPNDB value. Note that noise level here refers to a 'noise event' for a single aircraft.

People living near an airport generally hear many aircraft. Each of them generates a specific source noise depending on the aircraft type and its power settings, and (eg) wing configuration on its flightpath. These individual noise events are then attenuated through the atmosphere and along the ground. So an individual will hear many different noise events during the course of a day. How much will a particular set of aircraft events disturb him or her? What combination of these noise event parameters will best match observed disturbance? Note that 'disturbance' here does not include sleep disturbance (or difficulty getting to sleep), or possible long-term medical or psychiatric effects – to be covered in Section 6.

These are complex questions. Disturbance does not define itself. It can generally be viewed as some combination of general annoyance with that arising from interference with an individual's activities. There has been considerable research into what would constitute good disturbance measures, mainly involving social surveys near major airports. There is no single best version: examples of good indicators are the proportion of people experiencing the same noise event set who rate it very much annoying, and the proportion who rate it unacceptable. The focus here is on groups of people exposed to the same noise event set. This is because people are truly individual in their responses to aircraft noise. For a given set of noise events, most have about the same view of it, but some will find it much more disturbing and some much less. Individual psychological and physiological differences are very important. Statements about disturbance therefore usually are taken to correspond to either the average/median response or the proportion showing some kind of high response.

Research studies have shown that a good physical 'correlator' with disturbance, however measured, is 'Leq' (Brooker **(53)** gives key references). Leq is the 'Equivalent Continuous Sound Level'. It measures the total noise energy from aircraft received by the individual over a long period – the noisiest three months of the year is used in the UK. In the following equation, ** denotes 'to the power of', the i subscript denotes the i^{th} noise event, and T is the time period.

$$Leq = 10 \log \{ T^{-1} \Sigma_i \, 10^{**}(SEL_i/10) \}$$

The standard UK Leq period for T is 16 hours, which excludes night-time. Here SEL_i is the noise energy in the i^{th} aircraft noise event adjusted so that it lasts for one second. This is a mathematical short-cut, which simplifies the calculations without loss of relevant information. Thus, a constant level noise event lasting for one second at a noise level SEL contains the same noise energy as the L(t) noise event summed over its whole duration.

If all the noise events have the same level, SEL, and there are n noise events over the period, then the equation becomes:

$$Leq = 10 \log (16 \times 3600)^{-1} + 10 \log n + 10 \log \{ 10^{**}(SEL/10) \}$$

$$= SEL + 10 \log (n / 16 \times 3600)$$

A rough approximation, appropriate for most of the flights heard by people in the communities around Heathrow, is that the SEL_i value is about 10dBA higher than the $Lmax_i$ value. The actual difference between the two is mainly a function of the duration of the noise event. The approximation should be a good one for aircraft that are flying at roughly the same speed.

Figure 3 illustrates the relationship between event i's L(t), Lmax and SEL

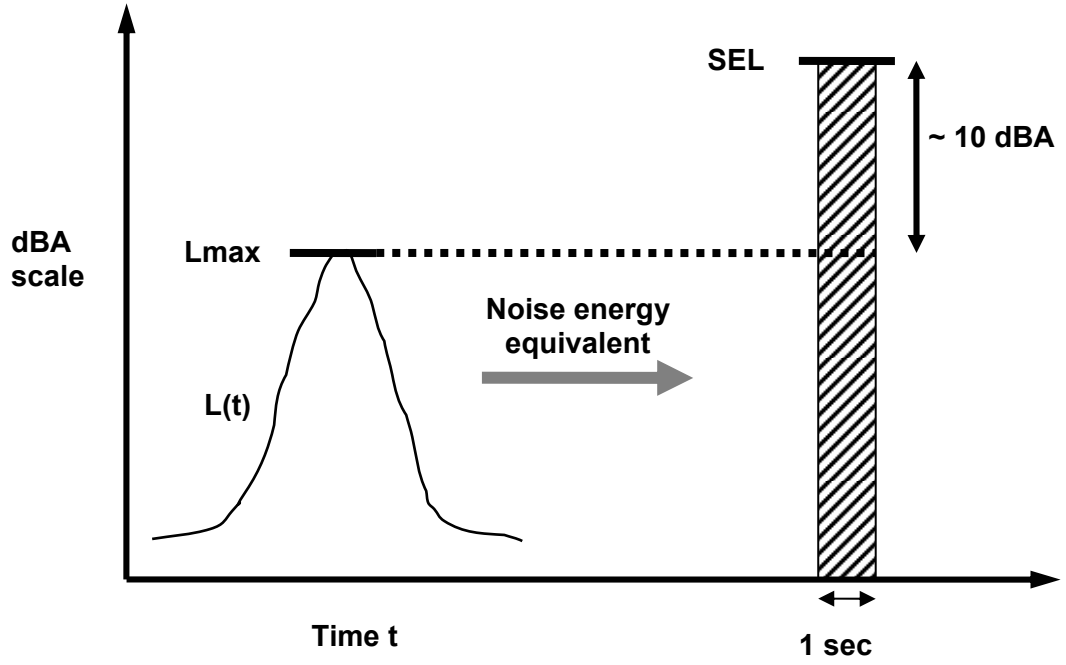


Figure 3. Noise definitions

So how does disturbance actually correlate with Leq? Figure 4 illustrates the typical variation of people saying 'Aircraft noise unacceptable' with Leq, derived from the last major UK aircraft noise study. The percentage increases from a 'threshold' of around 15% at 57 Leq to around 75% at 69 Leq, roughly in a straight line. [NB: there is a concept of 'no observable effect level', ie NOEL, that is conventionally used for 'threshold values' [(54)].]

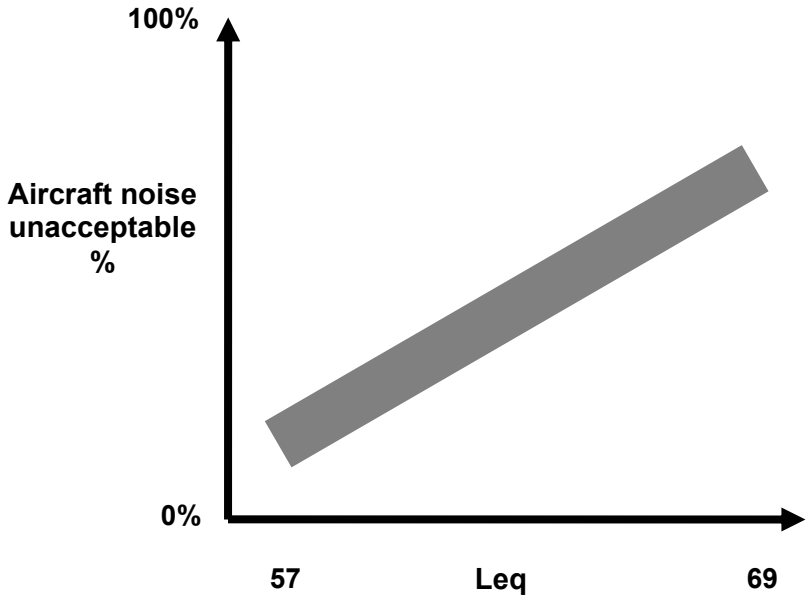


Figure 4. Percentage of survey respondents saying that levels of aircraft noise are unacceptable (rough trend approximation to Figure 9.10, ANIS Report [55])

69 Leq is used in the UK to indicate 'High' disturbance, and 57 Leq is the 'Low' – 'onset of' – disturbance. Brooker [53] indicates that the words in inverted commas are to a large extent conventions rather than absolute statements. Leq contours, which connecting places with equal Leq values, for 57 Leq and 69 Leq are produced for Heathrow, Gatwick and other UK airports. Such contours were used in planning inquiries and departmental guidance about building development. Statistics from the most recently published data for Heathrow are shown in Table 3 (Monkman et al [56])

Leq Level dBA	Area sq km	Population 000s	Log area	Predicted log Area
>72	6.5	1.4	0.81	0.85
>69	13.1	5.3	1.11	1.10
>66	24.4	20.8	1.39	1.35
>63	40.3	57.6	1.61	1.59
>60	66.1	107.3	1.82	1.84
>57	116.3	240.1	2.07	2.08

Table 3. Comparison of contour areas/populations enclosed for Heathrow (Standard contours for 2004 (Monkman et al [56])

A simple regression fit of the logarithm of the area against the Leq value is:

Predicted Log area = 6.745 – 0.08181 x Leq

This gives the predicted log Area in the right hand column of Table 3.

The Leq contours are much larger in extent than the individual risk contours of the previous section. However, they have roughly the same kind of shape, eg compare the Figures in Evans et al [51] with those in Monkman et al [56]. Just using the equation above, the 10^{-4} individual risk contour of 0.54 sq km would correspond to about 86 Leq, the 10^{-5} individual risk contour (4.60 sq km) to about 74 Leq, and the 10^{-6} individual risk contour (31.12 sq km) about 64 Leq.

Variants of Leq are often used in noise policy work. Lden is the day/evening/night noise index. Lden is the ordinary Leq except that flights in the evening have 5 dBA added to their energy value and those at night have 10 dBA added. A variant DNL has no weighting applied to the evening and a 9 (*sic)* hour night-time period. Lden has been put forward as the European Union common indicator. DNL is used in the USA. The scientific bases for these weightings are not universally agreed (eg see Brooker [53] for comments and references)

6. NOISE AND HEALTH

Aircraft noise causes annoyance and disturbs people's activities, but to what extent is it actually dangerous to their health – and what about the well being of more sensitive groups, in particular children? If it does cause significant damage, how could such effects be eliminated or mitigated?

There is a huge literature on these kinds of topic. The disciplines involved include physiological medicine, psychology, psychiatry and educational assessment. There are inherent problems in measuring possible effects because of the generally large variations in people's responses and the presence of 'statistical confounding factors'. The latter phrase is intended to cover almost anything that produces modifications to the nature or scale of people's responses.

Two simple examples of confounding factors: if people living in an area tend to work at an airport then they might be expected to react to aircraft rather differently in some aspects than people generally; if people in an area tend to live in retirement homes then their hearing will often be impaired purely through age effects, and so will tend to perceive noises differently to younger people [NB: this is 'presbycusis', which is generally significant for people from about 65 onwards, particularly men]. Moreover, there can be inherent difficulties in obtaining statistical proof of the existence of chronic effects, which may either cumulate over several years or take a long time to become measurable.

It should also be noted that the research work on health effects uses a variety of noise metrics, which can make comparisons difficult. Leq is frequently used, but so are Lmax and SEL; sometimes these are measured through the number of occasions per day, or whatever, that noise events exceed some postulated critical value. Research results for other kinds of noise do not necessarily transfer to aircraft noise, because it has different characteristics from road traffic and most other environmental noises. In particular, it concentrates noise energy in limited number of events. Thus, aircraft noise is usually studied separately.

Category	**Examples**
Mortality	reduced life expectancy
Morbidity	aggravation of disease
Adverse health effects (impairments)	chronic disturbance of sleep, concentration, performance, prolonged inflammation,
Functional/structural changes of health significance	chronic stress, immune suppression, diastolic/systolic blood pressure
Body burden	stress hormones

Table 4. Ranked health significance of adverse exposure (simplified from Hollander [(24)])

An example of the range of potential health effects of aircraft noise is shown in Table 4. The following is a selection from recent research studies and general literature reviews. In particular, Griefahn [62] is a clear summary. First, physiological health is discussed and then psychological health.

Physiological Health

Hearing Loss

Hearing Loss is well-studied and documented in the noise literature. It is generally not a concern for people living near UK airports. Formal limits are most generally used for occupational noise exposures in heavy industry or very loud recreational activities, eg target shooting. Workplace standards for protection from hearing loss usually allow a time-average level of 90 dBA over an 8-hour work period, with higher limits for shorter duration exposures. There is little possibility of hearing loss for Leqs below ~75 dBA.

Other physiological effects

Table 4 notes some physiological effects other than hearing loss. A dramatic illustration of this was reported in Meecham and Shaw [57], indicating increased mortality rates among exposed residents by using an average noise exposure level greater than 75 dB for the 'noise exposed' population. The study claimed a 15% increase in deaths due to strokes and a 100% increase in deaths due to cirrhosis of the liver. But Frerichs et al [58] reanalysis of the data did not confirm the original results. It concluded that "once the confounding effects of age, race, and sex were taken into account by direct and indirect methods of standardization, there was little difference in the mortality experience of the airport and control areas".

The number of studies into this topic has increased considerably – by 1998, Lercher et al [59] could review 30 studies in the previous 5 years (see also Stansfeld et al [60]). There are continuing research efforts, particularly in several European countries (evidenced by the geographical spread of references in Franssen et al [61]. In Griefahn's [62] review, she summarises (her reference numbers):

> "Concerning transportation noise, equivalent noise levels exceeding 70 dBA are suspected of being contributive to the causes of hypertension and levels between 65 and 70 dBA might increase the risk for ischaemic heart diseases [48]. Some authors and committees [2, 30] consider the evidence for causal relationships as sufficient whereas other [52, 53] stated that 'rigorously controlled studies which eliminate the numerous confounding factors or at least a number of them, are rare.' and that 'research has not definitely 'proved' any causal linkage between environmental noise and long term adverse health effects' but that 'it remains plausible that excessive noise might contribute to long-term adverse health effects' [3, 5]."

Friedrich [63] makes some estimates of the possible costs of such effects.

Psychological Health

Sleep Disturbance

Sleep is essential for good health, and noise could interfere with sleep even when the sleeper is not consciously awakened. Whether an individual is aroused by a noise depends upon the individual's sleep state and sleep habits, the loudness of the noise, the information value of the noise (eg alarm clock, small child), etc. Aircraft noise as received by the sleeper has been reduced by building structure and – very important – whether the room windows are open or closed. People can also adapt to some extent over time to higher levels of noise at night.

Again, this is an area in which there has been a great deal of research, with many published studies into aircraft noise and sleep disturbance over the past 40 years or so. The older studies relied on social surveys, where affected individuals filled in questionnaires or were interviewed about their recalled awakenings at home on particular nights; or through laboratory experiments using electroencephalographic (EEG) recordings or simple button pushes. Methodological issues included the large individual variations in response, potential influences of disturbance from non-noise sources, and the difficulty of avoiding bias when people 'self-report'. By the end of the 1980s, some authors were tending to suggest that there were no clear health effects associated with sleep disturbance, either by awakening or by changes sleep-state over the night (eg Pearsons et al [(64)]).

Technology enabled the use of actimetry to assess sleep disturbance. Actimeters are worn like a wristwatch, can be used to measure wrist movements, and are easily used in the home without supervision. The original research study is by Ollerhead et al [(65)]. Subsequent related UK work is by Porter et al [(66)] and Hume et al [(67)]. Section 2 of Porter et al is an extremely useful literature review and critical analysis of past research into aircraft noise and sleep disturbance. It carefully distinguishes between four levels of effect:

(i) acute responses that include immediate or direct disturbances caused by noise events,

(ii) total night effects that are aggregations of (i) over the whole night,

(iii) next day effects that are the result of (i) and (ii), and

(iv) chronic effects that are pervasive long-term consequences of (i), (ii) and (iii).

Ollerhead et al [65] showed that, once a person is asleep, it is unlikely that he or she will be awakened by a single-event noise. The study used actual in-home sleep disturbance patterns as opposed to laboratory data (and indeed was criticized because it was conducted in areas where subjects had become accustomed to aircraft noise). A minority of aircraft events affected sleep and, for most subjects, domestic and other non-aircraft factors had much greater effects. Thus, the conclusion was that, once asleep, very few people living near airports are at risk of any substantial sleep disturbance due to aircraft noise, even at high event levels. An average person was found to have a 1-in-75 chance of being awakened by aircraft noise in the outdoor range of 90 to 100 dB SEL. This conclusion represents average awakenings – some individuals in any exposed population are likely to be more sensitive to night-time noise than the 'average' person.

Ollerhead et al's studies left several questions open, which have been partly addressed in subsequent UK work. To quote Porter et al:

> "Aircraft noise can adversely affect people living near airports in many ways and concern that night-time noise is detrimental to public welfare is understandable. Employing the broad WHO definition of health, it is evident that night-time environmental noise adversely affects health by causing chronic subjective reactions. However, as yet, there appears to be no hard scientific evidence of clinically significant health impairment, ie chronic objective effects. Nevertheless, the possible existence of cause-effect relationships cannot be rejected and it seems that two fundamental questions need to be addressed in the longer term:
>
> - Can night-time aircraft noise cause clinically significant health impairment directly through physiological effects?
> - Accepting that night-time environmental noise adversely effects health by causing chronic subjective reactions, can these reactions also give rise to objective effects and thus impair health indirectly?"

In the same year, Berglund et al [68] published 'Guidelines for Community Noise', under the auspices of the World Health Organization (WHO) (see also Griefahn [60]). These demanding guidelines produced considerable debate in the acoustical and medical research communities, with questions such as: "How good is the evidence? How much credence should be paid to expert judgement?" Simplifying considerably, the current WHO [69] statement is:

> "WHO guidelines say that for good sleep, sound level should not exceed 30 dBA for continuous background noise, and individual noises events exceeding 45 dBA should be avoided."

But there is a WHO caveat that:

> "The relationships between noise exposure and sleep disturbance (following the results of the exposure-response meeting) are established only for immediate effects. Next-day or long-term effects are still not clear."

The WHO guidelines seem to be taken seriously, but with some caution. For example, the current DfT consultation into night flying restrictions at Heathrow and the other London airports [(70)] states that:

> "4.7 The environmental objective for each specific airport has been framed with reference to the 'balanced approach' required by ICAO Resolution A33/7 and taking into account the World Health Organization (WHO) 'Guidelines for Community Noise', published in 1999, in respect of night noise, as *long term targets for improving human health*." [Italics added]

Work Performance

Work performance can be affected by aircraft noise through such things as interference to speech communication and increased fatigue. People working in noisy industries have significantly higher rates of cardiovascular problems than those in quiet industries. Other studies on metabolism, body steadiness, distance judgment, and many other activities appear to show less evidence of any disturbance by noise. There are noise standards for employees in these noisy industries, but the noise exposures for people living near to airports are unlikely to reach industrial levels. There have been exceptions in the past: for example, the noise generated by Concorde is said to have affected some people living very close to the western end of the Heathrow runway.

Speech Interference

The interference of speech associated with aircraft noise is a primary source of annoyance to people exposed to aircraft noise. It is a major component of their total disturbance. In particular, the disruption of leisure activities – listening to the radio, television, music, and ordinary family conversation, etc – can give rise to considerable irritation. The psychological effects of aircraft noise interference with speech communication in normal work and leisure activities of adults are not often separately studied. Most of the research interest in this area has focused on the effects on children's learning – below.

Learning

There has been a great deal of recent research into interference with classroom activities and learning by aircraft noise. This will obviously arise from noise events that interfere with speech. Numerous schools near to Heathrow already have some degree of soundproofing because of this: normal classroom construction attenuates outdoor noise by ~12 dB with windows open, ~20 dB with windows closed. A major confounding factor is the extent to which background noise from within the classroom affects the results. Moreover, the quality of schools and socio-economic factors are very difficult to isolate and control for in rigorous statistical analyses. For example, socio-economic must be used in the widest sense, in particular to cover significant ethic group effects, eg see Schagen and Benton [(71)].

Recent research reviews include those by Stansfeld [72] and FICAN [73], from which much of the following is based. Note that FICAN is comprised of members from USA government agencies, including a representative from the Federal Aviation Administration (FAA). Table 5 illustrates the nature of children's susceptibilities and their consequences

Susceptibilities	Consequences
• critical periods in relation to learning • lack of developed coping repertoires • vulnerable tasks • vulnerable settings (schools, home)	• short term deficit followed by adaptation • lifelong impairment of learning and education

Table 5. Environmental Noise and Children's Cognitive Performance (from Stansfeld [72]

Stansfeld [72] presents a summary of the strength of evidence for effects of aircraft noise on children based on past research – Table 6. The most recent publication by Stansfeld and his colleagues [74] focuses on cognition aspects.

Health Outcome	Strength of evidence
Immune effects	Inadequate
Birth weight	Inadequate
Sleep disturbance	Inadequate / no effect
Psychiatric disorder	Inconclusive / no effect
Hypertension	Limited (weak associations)
Catecholamine secretion	Limited / inconclusive
Wellbeing/perceived stress	Sufficient / limited
Motivation	Sufficient / limited
Cognitive performance: attention	Inconclusive
Cognitive performance: *academic performance* *speech perception* *auditory discrimination* *memory* *reading*	All Sufficient
Hearing loss	Sufficient
Annoyance	Sufficient

Table 6. Health Outcome: Strength of Evidence (adapted from Stansfeld [72]

Some relevant quotes from FICAN [73], which in part reported upon a noise symposium, are:

"Recent research confirms conclusions from studies in the 1970s showing a decrement of reading when outdoor noise levels are at a Leq of 65 dB or higher. It is also possible that, for a given level of Leq, the effects of aircraft noise on classroom learning may be greater than the effects of road and railroad traffic.

Researchers are now fairly confident that a relationship between noise and its effects on some aspects of learning exist. One of the major unresolved problems, though, is identifying a level at which aircraft noise is problematic, as well as identifying levels of *change* which result in changes in learning. Most of the studies have identified students as exposed to a "noisy" or "quiet" environment, with little regard given to developing a curve which shows responses at varying noise levels. There is one dose-response function for relating reading and noise, but it is difficult to translate to DNL.

Most studies have identified "noisy" environments based on DNL or Leq – it may be that these are not appropriate metrics for two reasons: first, both DNL and Leq were developed to address issues of annoyance, not cognitive development or health; and second, DNL imposes a night time penalty which is largely irrelevant for describing classroom noise levels, and may if fact, provide a misleading measure. Perhaps we should be looking at things such as speech interference levels (SIL) and reverberation times. More research needs to be conducted to identify which noise metrics are appropriate for measuring learning responses.

Many of these studies also have a potential for confounding, for example poverty. Most of the research controls for these kinds of variables. However, what if poverty interacts with noise – what if noise, in the context of other situations, interacts with other affects to amplify them? In studies where we have controlled for socioeconomic data, we may have understated some of the effects of noise."

7. WEIGHTING THE EXTERNALITIES

Having sketched the nature of these aviation externalities, the question is: "So what?" There is little doubt of the seriousness of many of the issues sketched in earlier sections. But what relative importance should be put upon them? What are they 'worth'? Which externalities are already being progressively reduced, which need immediate action, and which can only be removed by strategic changes?

Moreover, at some point, money has to come into decision-making about what to do about significant externalities, obviously so if new aircraft need to be bought. Money is the only common currency – no pun intended – used by airlines and government; the latter standing as a proxy for all those people who have to bear the consequences of externalities. These consequences are the external costs. Somehow, these have to be brought into decision-making.

Standard economics textbooks explain the kinds of policy options that can be considered once external costs are known. These include taxes, emission charges and marketable permits – DfT [22] gives examples of these in the aviation context. But the major problem is in estimating external costs with sufficient precision.

Of the externalities discussed above, the external costs of aircraft noise have probably received the most attention over the last 30 years or so, at least in terms of the number of distinct studies carried out. Two main methods have been used, crudely summarised as:

> Hedonic pricing (HP): an off-putting phrase for a simple concept, that people's annoyance with aircraft noise is reflected in lower house prices near to an airport. The sum of these 'property losses' for residents is the external cost.
>
> Willingness to Pay (WTP): that people's views can be surveyed to find how much they would be willing to spend for hypothetical reductions in aircraft noise. Again, this is fed into information about residents' noise exposure to give the external cost.

HP studies can be traced back to the monograph by Walters [75]. A recent review by Nelson [76] identifies about 40 HP research studies, covering many countries. WTP studies are much smaller in number – see the recent review by Schipper [77].

These HP and WTP studies estimate something – but what? They can cover only those aspects of noise, eg annoyance, which people 'know' about. So they presumably would include some effects of sleep disturbance, because people experience these immediately, but less so the effects of learning impairment, because parents might not be aware of its potential longer-term importance to their children.

Similar methodologies can be used for the other kinds of externality. However, health effects need special consideration because their impact can shorten or impair life. There are obvious ethical and methodological issues raised for such aspects, eg see Chilton et al [35].

UK studies on the external costs of aviation have delivered some very valuable results, of which Clarkson and Deyes [46], DfT [21, 22], Pearce and Pearce [78], and Pearce [79] are important examples. Comparative recent estimates of external costs for Heathrow are in Table 7.

Externality	**Cost (£) per Heathrow passenger**
Aircraft noise	0.40
Air quality deterioration	0.75
Climate change	30

Table 7. Comparative external costs for Heathrow passengers

The first two rows in Table 7 are as quoted in DfT [21]. The Climate change cost uses the central estimate identified in Clarkson and Deyes [49]:

> "Therefore, in terms of UK policy design, a point estimate for the social cost of carbon emissions of £70 [per tonne of carbon] could be used as an illustrative value, with associated sensitivity range with a lower bound of £35 and an upper bound of £140, for emissions in 2000. The point estimate should then be raised by £1 for each subsequent year. It is worth mentioning here that this approach does not take into account the full uncertainty associated with estimating the social cost of carbon emissions, but it does provide a useful sensitivity analysis to reflect the disproportionate upside risk associated with climate change damages."

Pearce [79] states that in terms of additions to passenger travel costs this implies an extra £5 to £10 on short-haul flights and £40 to £50 on long-haul flights. There are currently ~30% long haul flights at Heathrow, forecast to rise to ~60% in 2015. The £30 figure in Table 7 simply assumes a 50% long haul proportion.

The obvious point from Table 7 is that the Climate change number is much larger than the other two estimates. Hence, a simply proportionate effort to eliminate or reduce these externalities (eg reduce by half) would be the wrong policy: the greatest payback is achieved by concentrating on Climate change. But is the Climate change number really the right kind of magnitude? This is not the place to answer such a question. There are major economic issues still to resolve, eg the use of a relatively low social discount rate of 3% (compare the WACC in Section 2), used to discount the long term future costs (eg see Spackman [80] and Portney and Weyant [81]). For present purposes, it should be reiterated that the £70 estimate is accepted as a reasonable one for UK policy purposes, and that the main source for this was a report [49] carried out for the European Commission.

Are the Aircraft noise and Air quality deterioration numbers about the right size? From a literature search, there does not appear to be any more recent work than the Dings et al [23] study, which contains the most up-to-date and extensive literature survey of external cost estimates of local air pollutants. The Dings et al study, carried out by a Netherlands research team, in fact confirms the major findings by the UK's Pearce and Pearce [78], arriving at external costs of the same order of magnitude.

So can the Aircraft noise external costs estimate be relied upon? The first point to note is that this estimate (from Pearce and Pearce) is largely based on HP models. The most recent review of HP studies, Nelson [76], estimates house price effects that are in broad agreement with their assumptions. [NB: these are complex statistical exercises, given the need to control for several effects, eg the positive house price effects of accessibility to an airport and its employment opportunities (eg see Tomkins et al [82].]

There are few recent WTP studies. One by Feitelson et al [83], carried out in Israel, suggested that the house price effect was about four times that of a typical HP analysis. However, this was in the context of a major airport expansion, with a noise exposure of the order of 75 Leq (compare the earlier Heathrow contours – Table 3). The most recent WTP study appears to be by van Praag and Baarsma [84], for residents near Schiphol airport in the Netherlands. This does not show such large noise effects, mainly it seems because the history of housing shortages, government regulations and comparatively large transactional costs have significant effects.

So, if studies do generally confirm the Aircraft noise number in Table 7, how much of the total aircraft noise external costs do they comprise? Some support that they contain the bulk of these costs comes from Friedrich [63], mainly drawing on work that he and colleagues have carried out in Germany and for the European Commission. The methodology described by Friedrich uses both expert economic groups to assess cost implications based on estimated exposure-response for various medical conditions (taken from the review by de Kluizenaar et al [85]). Friedrich presents some estimates for Zurich airport (Table 8), which might be expected to bear some resemblance to Heathrow proportions. Friedrich comments that "amenity loss is by far the most important source of noise impacts".

Cost category	**Value *(M€ 1998/year)***
Myocardial infarction (fatal, non-fatal) and Angina pectoris	0.375
Medical costs due to sleep disturbance (per year)	1.850
Amenity loss (ie Annoyance, house price effects)	15.500
Total	17.725

Table 8. External costs from noise exposure at Zurich airport (adapted from Friedrich [63]

Assuming that Friedrich's work paints a fair picture, this still leaves two questions arising from the discussion in Section 6. First, have the costs of impairment to children's learning been included? Second, can one be confident that the full consequences of any extra flights at night would be validly estimated? The latter is seen as particularly important in economic terms by airlines – there is a general airline desire to increase the number of night movements (eg [86]).

As already emphasized, there is ongoing research on aircraft noise and children's learning, eg Stansfeld et al [74]. The open question is the extent to which these effects can be fully mitigated by good-quality classroom sound insulation and air conditioning. If they cannot, then there a serious problem which has to be solved – but this should not wait the decades that it would take for new quieter aircraft to be designed, manufactured and brought into service.

At the Heathrow Terminal 5 Inquiry, the evidence of the main environmental group, HACAN, included the phrase 'Night flights are the single worst aspect of noise disturbance created by Heathrow Airport'. This view is probably even more strongly held today, particularly given that HACAN members have fought a long legal battle on night flight regulations all the way to the European Court of Human Rights. HACAN [87] briefing material currently states:

> "The Mayor [of London]'s Ambient Noise Strategy makes a night flight ban one of its key priorities.
>
> The Inspector at the Terminal Five Inquiry believed that a ban should be the long-term aim.
>
> A substantial number of politicians - local, national and European – back a night flight ban at Heathrow.
>
> 'Every morning between 4am and 6am, 16 passenger planes, mostly jumbo jets, arrive from Asia and America and land at Heathrow Airport. As their flight path takes them directly over central and west London, they shatter the early-morning sleep of hundreds of thousands of Londoners.' (The Economist, 17th February 2003)"

As noted in Section 6, the WHO guidelines for noise and sleep (Berglund et al [68]) are very demanding, both in terms of Leq and Lmax. Since 1999, there has been considerable further research into this topic (eg Griefahn [62]). For example, there has been increasing interest on the health consequences of poor sleep on the secondary and long-term effects of noise on sleep for children (eg see the WHO European Centre for Environment and Health meeting notes [88]).

8. SILENT AIRCRAFT

A silent aircraft is "one that is sufficiently quiet that outside the airport perimeter its noise is less than the background noise in a typical well populated environment" (Cambridge-MIT Institute [4]). Such an aircraft would, it is hoped, remove most, if not all, the external costs of noise and offer the possibility of financial benefits through changes to airport operations. Thus, they would be attractive both from a regulatory viewpoint and because airlines could derive real cash benefits by buying them. Other recent papers on ways of reducing aircraft source noise are Powell and Preisser [89], Wurzel [90], and Hepperle [91].

The silent aircraft definition immediately poses three clarifying questions: 'What is an appropriate background noise? What is the airport perimeter? Is the airport perimeter a sensible benchmark?' Again, using Heathrow for a case study enables these kinds of questions to be answered in quantitative terms.

What is the background noise in a typical well populated environment? This question is not very well-defined. It obviously depends on the amount and nature of road traffic and the distribution of major and other roads near to this 'typical' location. An easy way of producing a reasonable answer is to examine information on the variations in Leq in London. This has recently been estimated (DEFRA [92]). An extract from this document is at Table 9, which shows the Leq from road traffic during the daytime.

Leq daytime	<55	>55	>60	>65
Percentage exposed	73%	27%	20%	12%

Table 9. Proportion of Population exposed to various noise levels (adapted from Table 4.4, DEFRA [92]

It appears that a figure of 55 Leq might be a reasonable daytime figure for background noise. (Noise levels at night are extremely variable, depending very much on the frequency and distance of traffic flows. An urban area might still get 45-50 Leq at night, while suburban or semi-rural areas away from motorway traffic might get 35 Leq or even lower.)

Where near to an airport should there not be residential areas? PPG 24 [93], which is currently being reviewed by government, sets out so-called 'Noise Exposure Categories for Dwellings'. When assessing a proposal for residential development near a source of noise, local planning authorities should determine into which of the four noise exposure categories (NECs) the proposed site falls, taking account of both day and night-time noise levels – Table 10.

NEC	Guidance	Air Traffic Noise (Leq)	
		07.00 - 23.00	**23.00 - 07.00**
A	Noise need not be considered as a determining factor in granting planning permission, although the noise level at the high end of the category should not be regarded as a desirable level.	<57	<48
B	Noise should be taken into account when determining planning applications and, where appropriate, conditions imposed to ensure an adequate level of protection against noise.	57 - 66	48 - 57
C	Planning permission should not normally be granted. Where it is considered that permission should be given, for example because there are no alternative quieter sites available, conditions should be imposed to ensure a commensurate level of protection against noise.	66 - 72	57 - 66
D	Planning permission should normally be refused.	>72	>66

Table 10. Recommended Noise Exposure Categories for New Dwellings near Existing Noise Sources from ODPM [93]

What is the airport perimeter? Airport layouts do not generally have the same kind of geographical shape as their noise or risk contours. This is well illustrated by BAA [17], which shows Heathrow's land use in Drawing 1 and projected aircraft noise contours in Drawing 5. The 2004 'landtake' of Heathrow is quoted as 12.27 sq km.

Given the planning guidelines in Table 10, the effective airport perimeter in terms of residential communities is either the 66 or the 72 Leq daytime contour, depending how the guidance might be interpreted in practice. Compared with a background Leq value of 55 Leq, this would imply a reduction in aircraft source noise level by 11 dBA or 17 dBA – a substantial amount.

Benefits of Silent Aircraft

Morimoto and Hope [5] have recently published a paper making the case for developing a silent aircraft, by estimating the benefits to be gained and the external costs that would be removed. The comments here are mainly a critique of the assumptions made, particularly in respect of 'novel' financial benefits, rather than a check of their calculations.

A major problem with Morimoto and Hope is that the references used for its methodology and data appear to be selective rather than representative, and in several cases are outdated. Some examples are:

- On discount rates, which are a crucial element in the NPV calculation, Lind [94] has explicitly been superseded by Portney and Weyant [81].
- There are few references to past research work on hedonic pricing to estimate external aircraft noise costs (eg Pearce and Pearce [78], Nelson [76], Schipper [77]), although Dings et al [23] and Praag and Baarsma ([84] rather than the 2005 reference here) are included.
- The estimates of (third party?) casualties in a crash in Table A1 appear to derive from 1943, 1949 and 1951 data, whereas Evans et al [51] use comprehensive statistical data on worldwide accidents in the preceding decades, producing the individual risk results summarised earlier.
- There is no reference to the Air Travel - Greener by Design [1] work, a major omission given that it is an authoritative piece of work (probably the most important aviation community report on environmental issues in the last decade), and which is in many respects the precursor of the Silent Aircraft Initiative (Cambridge-MIT Institute [4].

Morimoto and Hope's benefits include the economic gains from additional night flights (already noted here as desirable by the airlines [86]):

> "Silent aircraft would technically allow us to have extra flights including night flights, as there will be no noise restriction. However, political issues attached to night flights would still need to be solved."

They quote ‘best guess’ assumptions, to achieve this novel benefit, of 10%, 20%, and 30% extra flights (Table A1). Are these reasonable?

Some of these extra flights might come from extra movements (ie take-offs or landings) during the day, although it is worth noting that the arrival capacity of the current Heathrow operation is determined by radar/wake vortex and runway occupancy considerations rather than noise constraints. Suppose the 10% figure refers solely to extra flights at night. Currently, there are about 1250 movements a day at Heathrow [(56)]. Ten percent of 1250 is 125. But there is currently an average of about 16 movements during the ‘night quota’ period [(70)]. An addition of 125 movements would therefore be a 700+% increase.

The phrase ‘political issues’ in the quoted text is much too mild. Given the concerns expressed by residents living close to airports and the continuing programmes of research into night disturbance, particularly as it affects children, it is difficult to see that such an increase could be implemented. The 10 dBA night-time weighting in Leq-based indices, the generally low background noise at night, and the WHO guidelines would provide substantial ammunition in battles against such additional activity at night. Note that the current DfT Heathrow proposal [(70)], already the subject of campaigning by environmental groups, concerns a ~10% increase in movements at night, within an Leq constraint (eg see HACAN [(87)]). Thus, the Morimoto and Hope estimates benefit from additional night flights appear extremely optimistic.

A substantial part of Morimoto and Hope’s estimated benefits arise because of air port relocation, to quote:

> “Once the proportion of aircraft that are silent has exceeded a threshold, new airports could start being introduced over time nearer to city centres, giving ground travel benefits as well as extra casualty costs if a plane crashes. One of the reasons the model assumes such a long time for airport relocation is that present trends are rather different. This silent aircraft technology would allow us to expand city airports or provide prospects of building a new airport closer to cities.”

This would certainly be a novel financial benefit – but does it make practical sense?

As noted in Section 5, the 2004 ‘landtake’ of Heathrow is quoted as 12.27 sq km. Major single runway airports use about half this area, eg other BAA documents quote the current Gatwick landtake as 6.78 sq km (not all yet developed). The landtake is required for both the operational part of the airport, ie runways, parallel taxiways and sufficiently separated aircraft stands and aprons, etc, and for passenger facilities, ie terminal buildings (including commercial activities), car parks, etc. For comparison, London tourist information says the areas of the largest London parks are Richmond Park – 9.55 sq km (but hardly in the city centre), and Regent’s Park – 1.97 sq km. It is hardly likely that permission would be granted for a major park to be converted into an airport, so the attention has to shift to the demolition of central offices, industry and homes

The large railway stations in central London are a factor of 10-20 less in area than Regents Park. So, a new Gatwick-like airport in central London would cover an area roughly equivalent to all the existing rail stations. These stations were mainly constructed in the early part of the 19th century when planning policy and popular democracy were in their infancy compared with today. But even then there was great public concern about the destruction their creation caused to communities – 'destroying homes and families both literally and figuratively' (eg see Dickens' 'Dombey and Son' [95]). It would hardly be less significant today. Moreover, given the existing congestion in the present London road, rail and underground networks, the Morimoto and Hope vision of reduced ground travel costs also appears very optimistic.

Morimoto and Hope note particularly the success of London City Airport as a city centre airport. [The author agrees that the airport is a success, particularly now that there are light rail links into central London.] But this airport was created on derelict land on a unique London site, following the closure of a large area of docklands activity. It is a stolport, which operates a limited range of small/medium airliners because of the restricted physical dimensions of the runway, eg the ATR42, BAe-146, Dornier 328, Fokker 50 and Saab 2000. Looking away from London, note that Paris, Madrid, Amsterdam, Berlin, Moscow, and New York do not have an equivalent stolport – nor indeed does any other major metropolitan city in the world. London City is certainly not a Gatwick equivalent: currently it is limited to a potential of about 5 million passengers compared to Gatwick's actual 30+ million. London City Airport would surely complement Heathrow and Gatwick in the future rather than replacing them.

There are also some methodological issues with Morimoto and Hope's calculations. For example, quoting 5%/95% range for net benefits might seem a worthwhile thing to do, but, in truth, this expresses something about the ranges of the parameters chosen rather than any kind of statistical significance level about the real world.

The conclusion has to be that Morimoto and Hope's estimates for these novel benefits, even their 'lower bounds' are far too optimistic. Thus, the financial case for development of a silent aircraft is not convincingly made. To reiterate, this case study analysis here has largely focused on Heathrow (and London), because of the availability of data about these real places, but some of the lessons here are more widely applicable.

9. SUSTAINABLE AVIATION INITIATIVE

Some of the most substantial and innovative ideas about the design of future aircraft have been produced by the 'Air Travel - Greener by Design' team [1] (see also Green [2]), the subsequent 'Sustainable Aviation' initiative [3], and NASA work (eg Kumar and Hefner [96]). The Sustainable Aviation initiative proposes a variety of specific objectives and targets to be monitored – Table 11 is a summary. Are these targets the right ones when assessed in terms of their estimated external costs and the financial implications for airlines?

Aircraft noise Lowering the perceived external noise of new aircraft by 50 per cent by 2020 compared with their 2000 equivalents. Percentage achievement of continuous descent approaches at individual airports.
Air quality Improving air quality by reducing nitrogen oxide (NOx) emissions by 80 per cent over the same period.
Climate change Limiting climate change impact by improving fuel efficiency and CO_2 emissions of new aircraft by 50 per cent per seat kilometre by 2020 compared with 2000 levels. Establishing a common system for the reporting of total CO_2 emissions and fleet fuel efficiency by the end of 2005, and pressing for aviation's inclusion in the EU emissions trading scheme at the earliest possible date.

Table 11. Summary of Sustainable Aviation targets

The first group of targets deals with aircraft noise. The first part is an aircraft design target. [As with most of the quantitative targets, it actually appears to have originated from the Advisory Council for Aeronautical Research in Europe (ACARE [(97)]) report produced in 2002. ACARE, SBAC and other design targets are compared by DfT [(42)].]

The first noise target is to lower "the perceived external noise of new aircraft by 50 per cent by 2020 compared with their 2000 equivalents". This is actually not very precisely phrased. The word 'perceived' would suggest that a unit such as EPNdB is being used, in which case a reduction of 50% would correspond to a reduction of 3 dB. This would be consistent with a 50% 'reduction in noise emissions', a phrase that is used in some documents discussing ACARE. However, it appears from recent technical references (eg Rolls-Royce [(98)]) that the 50% reduction is of source 'loudness', where loudness is as defined in the acoustics literature. This equates to a 10 dB reduction in the source noise level.

Rolls-Royce [(98)]) shows that progress has already been made to produce substantial source reductions, from comparisons of the performance of different marques of the Trent engine series. Press reports suggest that the A380 will be at least 3dB quieter than current nearest analogue, the B747-400. But is this at an environmental price, because of potentially negative impacts on other aircraft design requirements? RAE [(99)] offers the comment:

> "For example, the new Airbus A380 was designed to meet the most stringent QC2 rule for noise and as a consequence carries a fuel consumption penalty of up to 2% thereby worsening its economics and increasing emissions to the atmosphere."

Note that the Airbus 380 is being designed to ensure that it will meet all the current and planned ICAO/UK noise and LTO emissions rules for normal operations at an airport such as Heathrow.

The second noise target is operational, and concerns the achievement of continuous descent approaches (CDA). These require an aircraft to descend from 6000 ft altitude to interception of the ILS glideslope without recourse to level flight1. This operating procedure enables, for example, a Boeing 747-400 to reduce noise on the ground by up to 5dBA. However, CDA benefits typically accrue at distances between 10 and 25 miles from the landing threshold (eg see Kershaw et al [(100)]). Thus, the benefits are only marginally noticeable at the 57 Leq contours (both 2004 and 2015) discussed in Section 5, and have no benefit for people living at the higher Leq values.

Kershaw et al [(100)] quote the percentage success for CDA at Heathrow at 45%, which might well be seen as a low proportion given its noise benefits. They discuss some of the actions that will be required if markedly higher success is to be achieved. Morris [(101)] is a very relevant recent reference here. As noted, the technical difficulties involved in progressively reducing source noise are considerable, so it is important to 'deliver the goods' in terms of operating practices and improved ATM. SBAC [(3)] notes that 'Operational procedures to reduce aircraft noise have been developed and refined over a long period of time' – but does not mention that a 'long period' is actually more than 25 years ago [(102)]. There are several other possible ways of reducing noise operationally, eg see Air Travel - Greener by Design [(B1)], Hepperle [(91)]. The crucial question is if they can do this whilst ensuring the necessary safety (eg Brooker [(103)]).

The air quality target, to reduce nitrogen oxide emissions by 80 per cent by 2020 seems a very demanding one. What is the argument for such a large reduction? As noted in Section 7, an examination of external costs for air quality does not produce a large number in comparison with climate change's large external costs. It has been noted that some of the UK government department and parliamentary documents on air quality do not even mention aviation – the bulk of their attention is on road traffic. Again, there is a design tension between the ACARE and SBAC targets. To quote Rolls-Royce [(98)]:

> "Although there has been encouraging progress on lean-burn technology towards our NOx targets, a considerable challenge remains to demonstrate all the technical attributes required for a flight-worthy system. To achieve the ACARE goal will require further advances in this NOx reduction technology, along with improvements in fuel efficiency. Fuel efficiency can be improved by increasing the overall engine pressure ratio, which increases the propensity for NOx formation. The design of future engines will have to balance these competing factors."

For example, NOx emissions are strongly related to the engine operating temperature (the 'Zeldovich chain'), whereas CO_2 emissions depend on the type of fuel and its rate of burn: so reduced operating temperatures would reduce NOx emissions…

Thus, the basic problem is that measures to improve fuel economy and climate changing emissions are likely to become increasingly in conflict with measures to reduce noise and air quality emissions. Design compromises would then mean that, while it would be possible to achieve the individual improvement targets separately, they might prove not to be achievable together. This means that it is vital to focus on those improvements that will deliver the greater benefits, ie to reassess the targets in terms of their contribution to reduced external costs.

What about the actual fuel efficiency and CO_2 emissions target – 50 per cent per seat kilometre? The discussion and references in Section 7 show how important it is for aviation to reduce carbon emissions – and presumably also aviation's RFI. However, as noted in the section on externalities, CO_2 is by no means the only greenhouse gas, ozone and methane being generated from NOx emissions; while indirect effects from contrails and induced cirrus clouds are now judged to be very significant contributors. This shows the importance of the Rolls-Royce quote above. It implies that there should not just be a focus on CO_2, but on the totality of all RFI contributions [(104)]. It further implies the need to be able to assess the CO_2, NOx, contrail and cirrus impacts of an aircraft flight.

International aviation will presumably at some point be covered by the successors to the Kyoto Protocol (eg see RCEP [(28)]) and emissions trading arrangements. The Kyoto Protocol base year is 1990, whereas the SBAC targets are for 2020 compared with 2000. The SBAC targets are for new aircraft, not the actual fleet mix in 2020, so the 50% reduction in climate-affecting emissions translates to a very small reduction in aviation's contribution for the year 2020. It might be better to focus quantitative attention on the fleet replacement cycle time, probably of the order of 30 years. If aviation CO_2 etc emissions were to grow at 3% per annum, then this would equates to a factor of ~2.5, ie even more demanding than the present target.

If governments agree that climate change is a very serious negative aviation externality, then there will be increasing regulatory pressure through ICAO to include aviation in emissions targets, to introduce improved fuel efficiency aircraft types, and to reduce aviation's radiative forcing index. The difficulty is to estimate when the aviation consensus that would be required internationally might be achieved. Presumably, a pattern of consistent strong facts, such as an increased frequency of extreme weather events (eg intense heat waves) and effects on agricultural production, would eventually serve to convince people. The USA's Environmental Protection Agency has already made state-by-state projections of climate change effects: eg for Texas see EPA [(105)].

Another important factor would be continuing increases in the real price of oil. If the costs of fossil fuels increase markedly over the long term, then there will be real advantages to airlines in purchasing fuel efficient types. This goes right back to Section 2, that the focus of airlines will, all other things being equal, be on hard cash.

10. CONCLUSIONS

A variety of related questions has been posed, including:

(i) Are the right priorities for future aircraft design being set now?

(ii) If new civil aircraft types are ‘silent’, ie make much less noise than current types, will they then immediately be bought by airlines?

(iii) If they are ‘green’, ie safeguard the environment, will they then be introduced quickly through business decisions?

(iv) Is silent as important as green? How much should aircraft noise reduction influence engine design?

The answers are straightforward, based on generally accepted estimates of aviation’s externality costs:

(a) Future aircraft design should focus on substantial reductions on climate change impact.

(b) It is vital to avoid design compromises that prejudice this primary goal.

(c) If governments agree that climate change is a serious negative aviation externality, then there will be increasing regulatory pressure both to measure and to reduce aviation’s radiative forcing index – the totality of all aviation RFI contributions – and to include aviation in emissions targets.

(d) If the costs of fossil fuels increase markedly over the long term, then there will be real advantages to airlines in purchasing fuel efficient types.

(e) The local air quality targets proposed by the Sustainable Aviation initiative appear very ambitious. LTO cycle emission reductions should be pursued only to the extent that they do not affect improved fuel efficiency and reduced climate changing emissions.

(f) Good progress has already been made on the aircraft noise targets proposed by the Sustainable Aviation initiative, but again they should be pursued only to the extent that they do not affect improved fuel efficiency and reductions in climate changing emissions.

(g) The financial case for designing to reduce aircraft noise in order to deliver novel financial benefits, eg increase airport flights at night and/or relocate airports, is weak.

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