
The Economics of Aircraft Noise Suppression

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1. INTRODUCTION

Discussions on aircraft noise problems, unfortunately, result too often in inconclusive statements of good intentions on the one hand from those who are connected with making the noise, or emotional recrimination on the other from those who have to suffer it. Administrators, and even eminent aircraft designers, protest ignorance of acoustic technology, while sufferers from noise show a marked reluctance to face the most elementary economic facts. Perhaps one of the reasons why many people are still suspicious of technology in this country is that we have not yet mastered the art of presenting all the factors, and particularly the economic factors, in a technological problem in such a way as to make it possible to see clearly the issues involved. This paper is an attempt to give a better understanding of the interactions between the technical, economic and political sides of the aircraft noise problem. It is meant to show how these interactions might be studied, rather than to give definite answers to specific problems. Anyone needing such answers will be in a position to use much more accurate data than the author's crude approximations.

The author wishes to thank Rolls-Royce Limited and the Ministry of Aviation for permission to publish this paper, but to emphasise that the views expressed are entirely his own — although they have certainly been influenced by his participation in some of the activities of the S.A.E. in the United States, in particular a large programme of work on this very subject.

2. THE COST OF AIRCRAFT NOISE

Aircraft engineers have no difficulty in understanding the economics of the noise problems *inside* aircraft. Their customers, the airlines, will not buy

their products unless they are quiet enough for passengers to tolerate travelling in them. The same problem exists for the Railways and for the 'Tubes', and the solution is subject to the same economic pressures in so far as in every case a vehicle is only made quiet enough for the passengers not to take their custom elsewhere. Nor is there any need to discuss the noise environment of the aircraft itself and the resultant structural fatigue effects. Again in this case, it is easy to understand the issues involved, of safety and of the relative economics of moving engines elsewhere *versus* stiffening the structure. This paper therefore discusses the noise made by aircraft as it affects the people living around airports.

The value of an amenity

The major difficulty in this discussion is that it deals with an advance in technology which impinges on an amenity. Professor Buchanan faced this problem in his fascinating study of traffic in towns, in which he examined the impact of traffic growth on the amenity of living in cities which were never designed for the motor car. It is obviously difficult to put a value on the amenity of living in a pleasant city area, such as for example, Chelsea, rather than in an arid waste of parking lots such as in downtown Los Angeles. However, the relative costs of maintaining various arbitrary levels of amenity can be found and used to influence a community's decision as to the level it wishes to maintain. Doctor Beeching's mandate for rationalising the railways in the U.K., for example, could have included some consideration of the costs of maintaining various levels of the amenity of convenient rail travel. In our case we are trying to put a value on the amenity of a quiet background to life.

Another difficulty is that there are few precedents to go by, because no other machine inflicts quite such a high level of noise on the community, or is so critically affected in its economics by measures adopted to make it quieter. Legislation is just being introduced to regulate the noise from motor vehicles, for example, but the levels of noise which are being specified will not be too difficult to meet and the measures needed to meet them will not hurt the economics too seriously. There is no talk yet of buying up property along-side the roads as a possible alternative to making the vehicles quieter, whereas this is being considered very seriously around airports.

An economic analogy

The kind of arguments to use when making economic comparisons on aircraft noise problems can perhaps be illustrated in more familiar terms when considering the economics of runway length. The present generation of large jet aircraft probably cost about £1m a year each to operate. If they

had been designed for take-off from rather longer runways they could have had higher wing loadings, or lower thrust loadings, or some combination of the two. A simple parametric study suggests that if they had been designed for runways 2000 ft longer they would have had about 3% less direct operating cost. There are about 800 of these aircraft flying around so that the total saving in direct operating cost would have been of the order of £24m per year. On the other hand a round figure for the cost of acquiring land for such a runway extension, levelling it, laying the runway and the taxi-ways, and lighting them etc. is £½m for 1000 ft. This figure has been extracted from a very comprehensive study published by the Port of New York Authority in 1961 on the factors influencing their choice of the position of a new airport in the New York area. Assuming that there are 75 airports which would benefit from such a runway extension, and that each would want (on average) to put the 2000 ft on to each of two runways, the total cost of doing this would be £150m. To repay the loans needed for this over the ten year life of the aircraft would mean spending perhaps 40% more than this figure altogether, corresponding to about £21m per year. This simple comparison shows numbers of the same order so that it would not have been possible to arrive at a decision from them without considering other factors, such as landing conditions — but it is an illustration of the type of calculation needed for noise problems.

Aircraft noise

Let us consider now the noise situation around a noise-critical airport, such as London Airport, on the introduction of these same jets. From some figures in the Wilson report on Noise published in 1963, it is possible to deduce that there were in 1961 some 20,000 people living round London Airport who were highly disturbed by aircraft noise, and for whom life would have been quite intolerable if these jets had not been fitted with silencers giving noise reductions of some 10 dB. An alternative to fitting silencers, as far as London Airport was concerned therefore, would have been to buy up these people's houses, say 6000 houses at £3300 each, costing about £20m. Assuming that there were 15 such noise-critical airports at which the same order of expenditure would have been needed, this would have meant a total cost of £300m, although in this case the expenditure could probably have been laid out over the 10 year life of the aircraft, therefore costing £30m per year. If this were recovered in landing fees on an average of 50 aircraft per day on each of the 15 airports, this would amount to £110 per landing, compared with the present-day landing fee for a 707 at London of about £250.

On the other hand what has fitting the silencers cost the airlines? One American operator who was quoted in the Wilson Report, American Airlines, gave a figure of £43,000 per year per aircraft, while BOAC gave

£16,500. Taking the mean of these figures, and assuming that the silencers would have been fitted on all 800 aircraft operating today, the estimated cost would have been £24m a year. (This assumes that every aircraft has to operate out of a noise-critical airport some time or other and, of course, ignores the fact that new technologies have produced new ways of achieving the same object as the silencers, at lower cost.) To put this figure into perspective, an airline might hope to obtain a 15% return on its investment of £2½m in each large jet aircraft, *i.e.* a return of £375,000 per year, so that an additional cost of £43,000 amounts to a significant proportion of this.

The costs of the alternatives of buying up property and fitting silencers are again of the same order of magnitude. It would again have been impossible to decide on the right course of action from them alone, but the expectation of the new technologies obviously made it right to choose the silencers in this situation. The conclusion can also be drawn that the cost to the western world of life not too disturbed by aircraft noise is around £3m per dB per year.

International aspects

Both these comparisons concerning runway length and noise illustrate the international aspects of all such civil air transport problems. It is clearly impossible for an individual country to weigh up alternatives of this sort on its own in isolation. On the other hand, while it may be desirable to work towards international agreement on, for example, noise limits, it is at the same time quite reasonable unilaterally *not* to conform with the agreement, to set noise limits around London Airport 5 dB below an internationally agreed figure, for example, provided that it was recognised that £10m worth of property would equally unilaterally have to be bought up as a result. It would obviously not be reasonable to expect the world's airlines to put £120m on to their operating costs in order to save London Airport this £10m.

3. THE MEASUREMENT OF ANNOYANCE

The fact that these cost figures are so large means that aircraft will always be operating at the limit of what populations around airports will tolerate in the way of noise, and explains why so much effort has gone into determining as accurately as possible the way to measure this tolerance, or rather intolerance.

Noise spectrum

The first significant step in this direction was the recognition by the Port of New York Authority that existing measures were not adequate for com-

parisons of aircraft noises having very different spectra, *i.e.* with very different distribution of noise energy over the audible frequency range, and their introduction of the unit of noise called the 'Perceived Noise Level' measured in PNdB. This bore some resemblance to the old 'phon' scale of loudness, but took into account the fact that people seem to be even more annoyed by the high frequencies in the noise than the phon scale would suggest.

Number of times heard

It has since been learnt that it is not only the spectrum of the noise which defines its annoyance but also, among other things, the number of times it is heard. There is some experimental evidence to show that this can be taken into account by just adding up logarithmically the number heard, but there is some contrary evidence from the 1961 social survey around London Airport which is described in the Wilson Report. This led to the development of a 'Noise and Number Index' which took into account both the peak PNdB level of the aircraft heard and also the number heard per day (*N*), by the addition to the PNdB figure of $15 \log N$ as shown in Fig. 1 taken from the Report (the -80 is an arbitrary constant put in to make the curve go roughly through zero). The significance of the 15 is that the annoyance appeared to increase more rapidly than by just the simple addition of the number of noises heard, *i.e.* by the equivalent of $4\frac{1}{2}$ PNdB for a doubling of the number heard, instead of the simple 3 PNdB. The corresponding contours

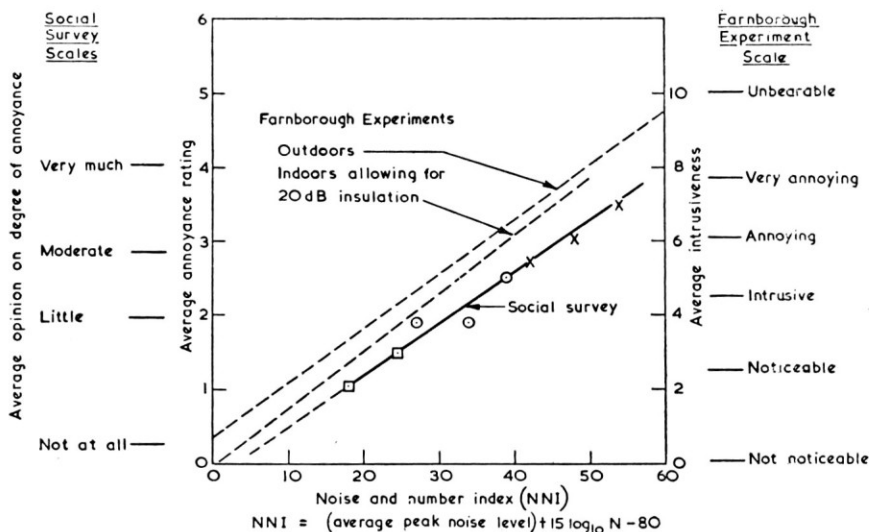
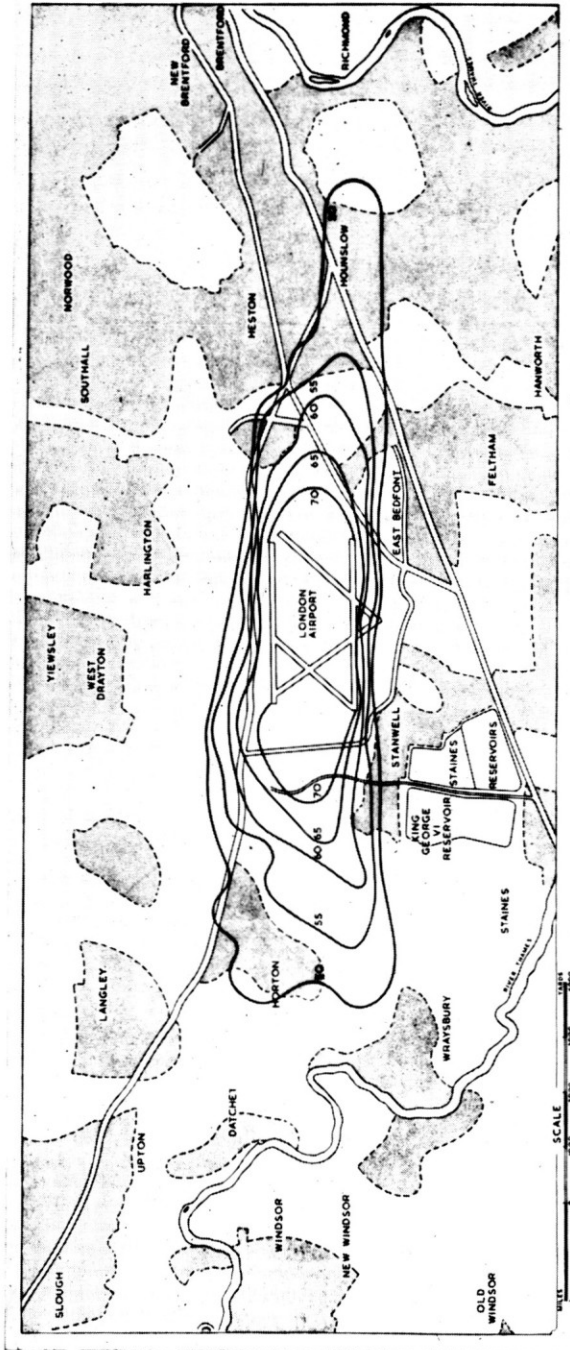


FIG. 1 — Relations between annoyance rating and Noise and Number Index obtained from social survey and Farnborough experiments



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FIG. 2 — Approximate Noise and Number Index 1961

of equal Noise and Number Index round London Airport for 1961 were as shown in Fig. 2, also from the Wilson Report. (Both these figures are reproduced by permission of Her Majesty's Stationery Office.) It was estimated at that time that there were 'perhaps 20,000 to 40,000 people living inside the 50 NNI contour, of whom two-thirds were highly disturbed by the noise'. The crude estimate of life being intolerable for 20,000 people if the noise had been 10 dB louder was based on the assumption that these 20,000 people lived between the 50 and 60 NNI contours, and led to the figure of £3m per dB per year for the amenity of a tolerably quiet life.

Duration

There are two further factors which are being considered at the moment with a view to incorporating them into a more refined measure of annoyance. The first of these is the duration of the noise, which is usually defined as the time during which it is within 10 dB of its maximum value. There is plenty of evidence that the duration has a significant effect. It is, for example, probably the factor which makes the noise from aircraft on landing almost as tolerable as that from aircraft taking off, the greater noise from the much lower aircraft being compensated by its shorter duration; and there is also some American laboratory work directly quantifying this effect in the same sort of way as for the number of aircraft heard. However, there is not yet sufficient agreement about these numbers to incorporate them into a generally accepted formula. Nevertheless, this implies the acceptance in due course of the fact that for any given aircraft the effect of altitude is not as beneficial as was once thought. Annoyance will only be reduced in proportion to the altitude (somewhat more in fact due to the extra atmospheric attenuation of high frequencies) rather than as the square, due to duration increasing roughly in proportion to altitude.

Discrete frequencies

The second factor being investigated concerns the presence of discrete frequencies in the noise. The original PNdB formula was really concerned with noise energy distributed fairly uniformly over the frequency range, but modern engines generate discrete blade-passing frequencies as well and experimental work both in America and in this country has shown that the presence of these tones in a noise significantly adds to its annoyance. The quantifying of these effects is quite a difficult business when several tones, each with its harmonics, may or may not be present, or even 50 or more sub-harmonics if the compressor blades happen to be irregularly spaced, and that the Döppler shift in frequency as the aircraft flies overhead is of the order of 2 to 1.

Total annoyance exposure

It will probably not be long before these last two factors can be worked into the measure of annoyance, which will then take into account the broad spectral distribution of the noise energy, its discrete frequency content, its duration and the number of times it is heard. The object is to find a measure of the instantaneous annoyance value of a noise (probably in terms of PNdB plus a correction for discrete frequency components), and then to integrate the total exposure to this annoyance in the given measuring period. The author hopes that this integral will continue to bear some resemblance to PNdB, the unit to which many people are accustomed, by relating the total integral to the area under an arbitrary standard noise-time curve such as that for a typical 707 take-off.

Economic aspects

The importance of these considerations can be illustrated by studying the case of an airport evaluating the effect on its surrounding community of the introduction of a new kind of aircraft, a 'jumbo-jet' perhaps. Suppose there were two competitive aircraft of identical noise characteristics, except that aircraft *A*'s noise duration was twice that of aircraft *B* — for example aircraft *A* might have wing-mounted engines, whereas aircraft *B*'s were tail-mounted and consequently, their noise might be largely shielded from the ground by the wing. A simple integration of the total time of exposure to these aircraft would show aircraft *A* to be effectively 3 PNdB more annoying than aircraft *B*. At £2m per dB as the total cost of buying up property round an airport, in order to cope with these aircraft, this would mean a difference of £6m between them in the cost of doing this. But if in fact aircraft *A* is effectively $4\frac{1}{2}$ PNdB more annoying than aircraft *B*, this would mean a difference of £9m between them in the cost of buying up property. This £3m difference between the differences arises simply from using two different measures of annoyance, and demonstrates the importance of finding the best possible measure.

4. THE 'POLITICS' OF AIRCRAFT NOISE

These remarks about the costs of aircraft noise have so far included no consideration about who should pay these costs and how this should be decided — the 'politics' of the problem. The four main protagonists concerned with this noise problem are shown in Fig. 3. The various negotiations which go on among these four are: those between the community and airport authority, concerning the annoyance to which the community is exposed,

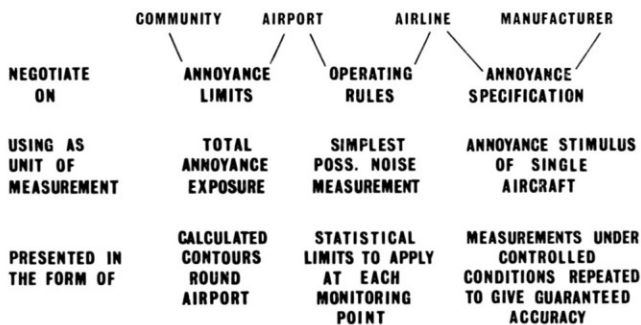


FIG. 3 — Aircraft noise negotiations

tolerable limits to this annoyance and what to do about it if these limits are exceeded anywhere; those between the airport and the airlines concerning the operating rules for their aircraft at that airport and the monitoring procedures to check that these rules are being followed; and those between the airlines and the manufacturers concerning the annoyance specification for the particular aircraft/engine combination which they are purchasing.

Basis of negotiation

In the past one single number, for instance 112 PNdB at New York, has been used as the basis for the negotiation in all three cases, but this is beginning to lead to considerable difficulty, because the requirements are different in every case. In the first case, between the community and the airport, the real measure required is the total integrated annoyance exposure, putting in all the factors described above. It seems a sensible objective to pool resources on this subject internationally to try to decide on the best measure of total annoyance exposure. As far as putting limits on this are concerned, however, this is entirely a local matter to be negotiated between an airport and its own community, as are also the local methods of adhering to these limits and, the local cost of doing so.

In the second case, between the airport and the airlines, the negotiations are concerned with the best way to operate particular aircraft/engine combinations into and out of that airport as far as noise is concerned, and subsequently to monitor that the agreed rules are being obeyed. Since this is a noise matter, it is obviously best to monitor the process in terms of noise, but it really does not matter what units the noise is measured in. It can be simply the most convenient acoustically, because there is no need to lay down a single universal figure which is applicable to all aircraft. Instead, the airport

can, and indeed should, stipulate appropriate noise limits for each aircraft/engine combination in order to keep each individual annoyance stimulus to as low a value as is reasonably possible. (Of course, in arriving at these limits the airport will take into account the true annoyance exposure produced by the aircraft in question, as negotiated with the community.) On the other hand, the way in which this limit is presented to the airline must take into account the inevitable variations in noise which occur due to atmospheric conditions, pilot differences, engine and aircraft differences, etc. and the limit should therefore be presented statistically in some form such as: 'at this monitoring point, with this aircraft/engine combination, 100 dB on such-and-such a measuring scale must not be exceeded on more than 5% of the occasions.' The particular number can be different for night-time and day-time, or for summer and winter, or can take into account any other local factors which the airport may wish to consider. It might also be desirable to quote another number, say 10 dB above this, which should never be exceeded in any circumstances, and to make the individual pilot responsible for this, the airline being responsible for the statistical figure.

Both airports and airlines are clearly interested in international agreement on the right way to do this monitoring, in order to simplify negotiations between the various airports and the various airlines in various countries, remembering always that the limiting numbers quoted may be different at every airport, or even at every monitoring point.

In the third case, negotiations between airlines and manufacturers are concerned with specifying and then measuring a guaranteed figure in the most realistic terms possible. In other words, the best method of describing the annoyance stimulus of an individual aircraft is wanted, corresponding to the unit of total annoyance exposure except for the factor concerning the number of times the aircraft is heard, and the measurements must be such as to achieve a high order of accuracy and consistency. Again, both the airlines and the manufacturers are obviously interested in international agreement on the definition (although probably not the measurement) of this annoyance stimulus, in order to simplify negotiations between the various airlines and the various manufacturers in various countries.

Economic pressures

How do the different economic pressures operate across this network? Considering first those affecting the airport, by the normal democratic processes of petitions, litigation, questions in Parliament, or by any other kind of process appropriate to the airport concerned, it should be possible for the airport to arrive at a rough idea of the level of total annoyance exposure which the community around it will tolerate, and of the costs associated with variations in this level, *i.e.* figures analogous to the 50-60 NNI

already mentioned and the £3m per dB per year for buying up property. Similarly, the airport and an airline, with all the noise and performance figures for a particular aircraft/engine combination in front of them, should be able to arrive at noise control figures for that particular aircraft at which the operation would be reasonably economic to the airline, and also the cost to the airport per dB difference from this figure arising from the airline reducing its business at the airport, or even taking its custom away altogether. It is then up to the airport to collect this information from all the airlines concerned, to fit their operations into its traffic pattern to arrive at corresponding total annoyance exposures, and to balance the airlines against the community, to achieve the best solution. 'Best' need not be the most economic, arrived at in this way alone. A country may quite legitimately subsidise the airport authority, for prestige reasons, for example.

The airline, during its discussion with the airport, will in effect have agreed an approximate annoyance stimulus figure for a particular aircraft/engine combination at which it would be reasonably economic to operate that aircraft out of that airport, and will have got an idea of the cost to the airline per dB difference from this figure arising from reducing its business at the airport. The airline will collect such information from each airport out of which it wishes to operate this aircraft, to find the total effect on the economy of operation of that aircraft. Similarly, the airline will have detailed technical discussions with the manufacturers to establish approximately the level of annoyance stimulus to which that particular aircraft/engine combination should be designed in order to give a reasonable economy, and the variation in economy per dB difference in the design figure. The airline can then weigh up these economic factors to choose the best solution, and again 'best' may not at first sight be 'most economic', because again some form of subsidy may be available for prestige reasons, or more topically, for balance-of-payment reasons. The other important factor entering into these last discussions is, of course, the competitive one. An airline may be able to make a much better deal with the airport with one manufacturer's product rather than with another's, with aircraft *B* rather than with aircraft *A* of our previous discussion, for example.

It can be seen that the interests of individual airports and individual airlines are by no means the same, and that the previous comparison of the cost of buying property in a community, versus fitting silencers to engines, omitted some important steps, although the end result was reasonable enough. The true comparisons should have been between the cost of buying property around airports *versus* the cost (in the extreme) of driving certain airlines away from these airports; and correspondingly, the cost to the airlines of giving up operation out of those certain airports *versus* fitting silencers to their engines. It follows that any community is not concerned directly with the noise specification of a given aircraft and its engines, but only with the way

in which its neighbouring airport is going to allow that aircraft to be operated; and that manufacturers are not directly concerned with annoyance exposure around airports, but with the way in which the airlines are going to be allowed to operate their aircraft. These distinctions are worth making to emphasise the most effective way in which pressures can be brought to bear on these noise problems. The community can readily bring pressure to bear on the airport, for example, but not very effectively on the manufacturers. Attempts to do the latter only lead to frustration on both sides because there are two parties, with conflicting interests, in between.

Moral issues

Are there any moral issues which might over-ride these economic issues? The author believes not. The member of a community has a moral right to a certain amount of peace and quiet, although this right is obviously to some extent qualified by his choice, for whatever reasons, to stay in the neighbourhood of the airport. Of the other three protagonists concerned, it seems that only the airport authority has a moral obligation, and that is to see that the community's rights are properly evaluated, even to the extent of testing the effect of putting the airport out of business if necessary, but this does not really over-ride the economic issue described just now, it merely extends it. The manufacturers obviously must examine and investigate possible ways of achieving less noise, even at the expense of apparently retrograde steps in economy and competitiveness, and offer these to the airlines. But in the present competitive situation this is not a moral obligation — it is a straightforward economic obligation, carried out in order to stay in business. Similarly, it is difficult to see what additional moral responsibilities the airlines can shoulder. Their job is to take what the manufacturers are able to give them, to operate how the airports will allow them and, within these limitations, to make as much money as they can for their shareholders. Only in the absence of competition between airlines and between manufacturers must moral obligations take the place of these economic pressures.

5. ADVANCES IN TECHNOLOGY

Figure 4 shows how the main components of noise from an engine vary with its thrust for the different kinds of jet engine which have been used over the past years — ignoring for a moment the fourth right-hand picture. The first three pictures represent respectively, Avon, Spey and JT3D engines. This is the peak noise in the rear arc during the fly-over. It so happens that the maximum noise heard is in this rear arc after the aircraft has flown overhead, although in some cases the noise coming out from the front, from

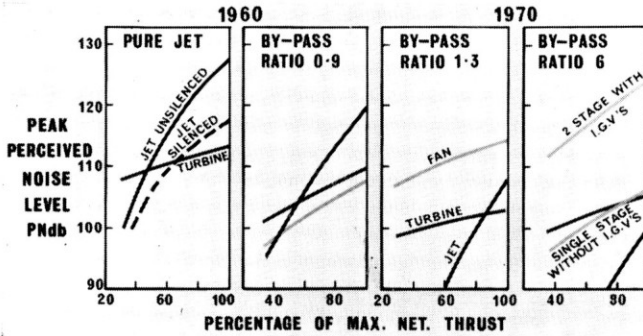


FIG. 4 — Peak noise in rear arc during fly-over.
Four engines all scaled to same thrust
(1050 ft — 185 kts)

the compressor or fan, is nearly equal in level. In the pure jet engine fan or compressor noise is quite unimportant, whereas in the next two by-pass engines it becomes more and more important; jet noise, of course, becomes less and less important; and turbine noise dominates at low thrusts on the low by-pass ratio engine. Comparing the two by-pass engines, the increase in by-pass ratio from 0.9 to 1.3 has not helped from the noise point of view. There is certainly an improvement at maximum thrust with the reduced jet noise only partially replaced by fan noise, but at thrusts lower than about 75% the fan noise of the 1.3 by-pass ratio engine is appreciably greater than the jet or turbine noise of the 0.9 by-pass ratio engine. The thrusts used after cut back and on approach are below 75%, so that the 0.9 by-pass ratio engine is the quieter.

Cost of increase in by-pass ratio

Clearly at this state of the art of engine technology the improvement in engine economy to be achieved by increasing the by-pass ratio is going to be accompanied by an increase in noise, and Fig. 5 shows the results of some typical calculations of this effect. Consider an engine of by-pass ratio 4. Reducing the by-pass ratio to 1.3 could reduce its noise by 8 dB, but this would cost 16% worsening of specific consumption. An approximate exchange rate between engine specific consumption and direct operating cost on a large, long range jet designed around such engines is that 1% increase in direct operating cost results from 2% increase in specific consumption. This 8 dB reduction in noise would, therefore, mean 8% increase in direct operating cost. Applying this to 800 of these aircraft again, each costing about £1m per year in direct operating cost, with engines at the present

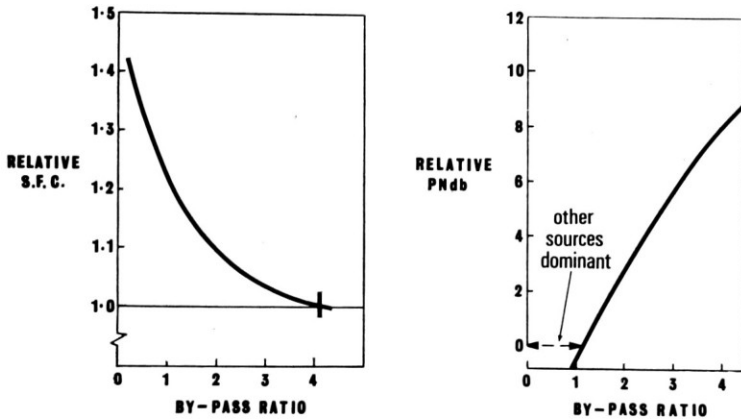


FIG. 5 — Noise penalty for improved specific fuel consumption

state of technology with by-pass ratios of 4, this method of reducing their noise would cost the airlines about £64m per year. This is £8m per dB per year, and is clearly very expensive compared with the £3m per dB per year arrived at when considering buying property around airports.

Fortunately there is a better solution. The last comparison was made with the specific weight and the specific cost of the engine remaining roughly constant as by-pass ratio was decreased. It would, however, be possible to reduce the noise at constant by-pass ratio by increasing the number of stages in the fan and its turbine, to keep the tip speeds down. This process would mean that the weight and cost of the engine would go up roughly in the manner shown in Fig. 6. In this case the reduction of 8 dB would be obtained by putting the weight and cost of the engine up by about 8%. The appropriate

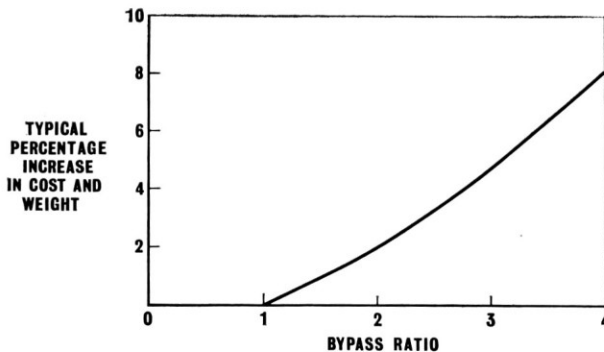


FIG. 6 — Penalty in cost and weight to restore noise to that at by-pass ratio 1

exchange rates for 1% change in direct operating cost are 10% increase in engine weight and 6% increase in engine cost. Adding these together, 8 dB would in this case cost 2% increase in direct operating cost and therefore, would cost the airlines only a quarter of the previous figure, about £2m per dB per year. This is obviously a much better proposition and the figure is now of the same order as that required for buying property around an airport to achieve the same effect.

Faced again, therefore, with a choice between the alternatives of buying property or relying on the manufacturers as with the original jet transports, it would again be right to rely on the manufacturers, in the expectation that the full cost of this would not have to be paid because of improvements in technology.

Single-stage fans

A step change in noise is, in fact, just about to be obtained from such an advance in technology, as illustrated in Fig. 4. The fourth set of curves are drawn for an engine of by-pass ratio 6, and the top curve is some 4 to 10 dB higher than the corresponding top curve for the engine of by-pass ratio 1.3. (The apparent disagreement with the previously quoted increase of 8 dB for an increase in by-pass ratio from 1.3 to 4 is only because this was based on a parametric study, whereas the curves on Fig. 4 are drawn for actual engines). The important point, however, is that multi-stage fans or low pressure compressors have been used up to this time, whereas somewhere along the by-pass ratio scale there is a point where the required fan performance can be achieved with a single stage, in the region of a by-pass ratio of 3 to 4. If the high by-pass ratio engine is designed with a single stage fan, and if at the same time it is designed without inlet guide vanes, then the enormous reduction of fan noise shown in the last diagram can be achieved. The overall result is that the new, high by-pass ratio engine is considerably quieter than any of its predecessors, without suffering any of the performance penalties discussed earlier.

The reason for this big reduction in noise can be understood by means of Fig. 7. The main noise-generating mechanism in a fan or compressor is the aerodynamic interaction of the blades with the turbulence and wakes arising from the adjacent upstream row of blades. The reduction to a single stage leaves only two such interactions, those between inlet guide vanes and rotor, and those between the rotor and outlet guide vanes. The relative air velocity on to the rotor in such a design may well be three times that on to the outlet guide vane, and since the noise generated varies as about the 6th power of this velocity, the first interaction is obviously a much more intense noise generator than the second. Removing the inlet guide vanes eliminates the first intense interaction. Figure 8 illustrates the dramatic change in the

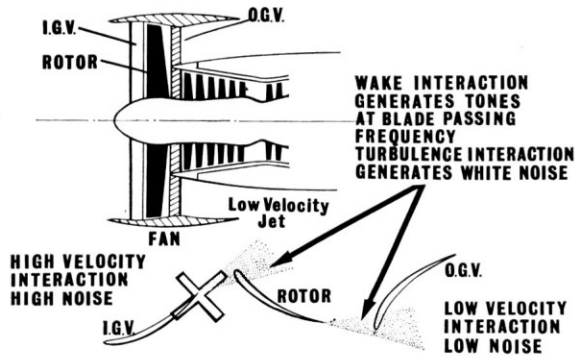


FIG. 7 — Single-stage fan noise sources

radiation patterns of the noise from the two different kinds of engine. On the left are the different components of noise for the engine with the multi-stage fan. The most prominent lobe is that of the rearwards fan noise, which clearly dominates all the others. The effect of changing to the single-stage fan without inlet guide vanes can be seen on the right. The peak noise heard along a line parallel to the engine centre line is now determined by an approximately equal mixture of rearwards fan noise and turbine noise. Incidentally, the stage has now been reached at which further reduction of fan noise alone would not be of much value.

Even if the fan noise were eliminated entirely, there would be left a turbine noise peak of almost the same amount.

Three-shaft engine

There is, however, another advance in technology which can be exploited to give another step change in the noise of this kind of high by-pass ratio

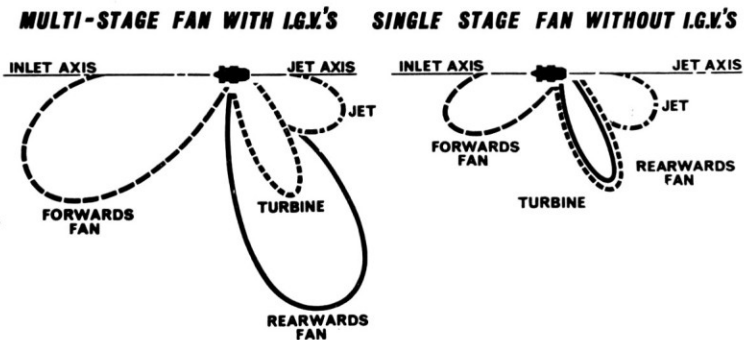


FIG. 8 — Noise sources with high by-pass ratio

engine. If it is designed as a three-shaft engine in which the fan and its turbine, the one responsible for the turbine noise, are carried on a separate shaft, the speed of this shaft can be varied independently of the other two shafts without upsetting too much the matching between the compressors and turbines throughout the engine. The fan shaft can, therefore, be slowed down during the critical noise conditions of cut-back after take-off, and approach, the loss of fan thrust being compensated by an increase in jet thrust under these conditions. A reduction of 3 or 4 PNdB can be obtained in this way, or probably even effectively 5 or 6 PNdB if the discrete frequency content is taken into account, at the cost of a variable nozzle covering a range of about 2 to 1 in area ratio.

Economic aspects

At any given state of the art of engine design, improvements in weight or cost or specific consumption seem to conflict with improvement in noise, whereas it is a change in technology (which may of course be wanted for other reasons as well) which produces an improvement. This effect is shown on Fig. 9 in which the fly-over noise for engines of different types, scaled to the same thrust, is plotted against the improvement in installed specific consumption which has been obtained over the years.

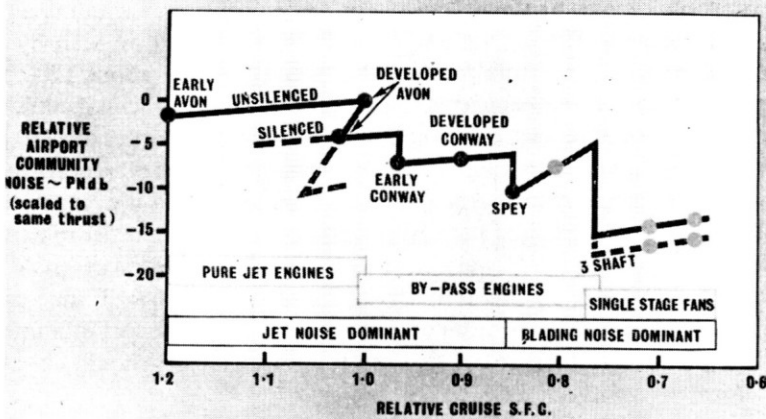


FIG. 9 — History of turbojet noise reduction

In each case the curve for a particular engine type rises, due on the left-hand side of the picture to the use of improved materials allowing higher temperatures and on the right-hand side, to increasing by-pass ratio. The reductions in noise are all due to changes in technology — the introduction

of silencers on pure jets, the change to various by-pass engines and finally, the change to the single-stage fan with no inlet guide vanes and the three-shaft engine. The net result will be a reduction of 15 dB in noise for an improvement in specific consumption of nearly 35%. The picture should be completed by adding the fact that this achievement by engine manufacturers has, to some extent, been offset by the four-fold growth in the size of transport aircraft over the same period. This growth has, of course, contributed to the overall economy, but at the expense of about 6 PNdB more noise from the correspondingly larger engines.

Clearly, it is the improvements in technology which matter from a noise point of view and which should therefore be encouraged to the utmost. And curiously enough this part of the process seems to be relatively cheap. For example, figures of millions of dollars per year were quoted as having been spent on the development of silencers in America. To put this into perspective, let us guess a round figure of 30 million dollars for the total expenditure. If this were recovered in the price of silencers supplied to the airlines, spread over 800 aircraft and a ten-year life, it would amount to only one-eighth of the £43,000 per year per aircraft quoted by American Airlines as the total cost to them of fitting these silencers.

Looking at this another way, there is a new noise test facility being built in this country at the moment, as a joint venture between Bristol-Siddeley and Rolls-Royce and largely financed by the Ministry of Aviation, specially for the purpose of investigating these engine noise problems. Including a cost figure for a steam turbine which, in fact, has been supplied on loan by the Ministry of Aviation, the total cost of this facility will be about £200,000. A sensible figure for the expenditure on research in this facility, allowing time for the proper appreciation of the results, will be of the order of £150,000 per year. If four years' work in this facility, costing £800,000 altogether, gave the means of reducing noise by, say, another 4 dB only, and if even twice as much again had to be spent on parallel engine development in order to exploit the discovery, then spread over a ten-year life this investment could be recovered on the aircraft going into service in the early '70s, 4 dB quieter, at a cost of only about £0.1m per dB per year, about $\frac{1}{20}$ th of the sort of numbers arrived at previously. It is obvious that this is how the money should be spent.

Mixture of technologies

But it is not research in pure acoustics which is needed. The contributions of acousticians as such to the improvements mentioned above have not been great. For silencers, for example, they have been confined purely to measurement, measuring the noise emitted by various shapes of jet nozzle. In the change to by-pass engines, the reduction in noise due to reduced jet velocities stems from Lighthill's classic theories of sound generated aerodynamically,

which are of course by no means pure acoustics. Similarly, the various theories of noise generated by blades in an airstream are also full of aerodynamics. And quite apart from these noise considerations, it is advances in *engine* technology which are needed. It seems, therefore, that as with so many scientific problems today, it is a mixture of technologies which is needed to make the required advances in noise reduction.

6. CONCLUSIONS

Most of this paper concerns the interactions between the different facets of the aircraft noise problem, and is therefore difficult to summarise into any conclusions. One point does, however, seem to stand out — that by far the most economic way of achieving a quiet life around airports seems to be by the encouragement to the utmost of advances in engine technology, both financially and by interesting experts in many different technologies in the engine noise problem.