516-71
N90-24869
275401
15P.

PREDICTING THE AUDIBILITY AND ANNOYANCE OF UNDUCTED FAN ENGINES

Sanford Fidell, Linda Secrist, and Marie Helweg-Larsen
BBN Systems and Technologies, Inc.
Canoga Park, California

ABSTRACT

Predictions of the prevalence of annoyance associated with aircraft noise exposure are heavily influenced by field studies conducted in urban airport neighborhoods. Flyovers heard in such relatively high ambient noise environments are composed in large part of high absolute level, broadband noise. In contrast, noise exposure created en route by aircraft powered by unducted fan engines is expected to be relatively low in level, but to contain prominent low frequency tonal energy. These tones will be readily audible in rural and other low ambient noise environments.

The annoyance of noise intrusions of low absolute level has been shown to be closely related to their audibility. Thus, one way to predict the annoyance of en route noise generated by unducted fan engines is to estimate its audibility relative to that of conventionally powered aircraft in different ambient noise environments. This may be accomplished by computing the audibility of spectra produced by an aircraft powered by unducted fan engines and comparing predicted probabilities of annoyance for them with those of conventionally powered transport aircraft.

This paper reports on analyses in progress of the annoyance of en route noise produced by aircraft equipped with unducted fan engines. The goal of these analyses is to systematically predict and compare the relative annoyance of the en route noise emissions of such aircraft and of conventionally powered transport aircraft operating under similar conditions. The analyses discussed here focus on predictions of the immediate annoyance of individual noise intrusions as the basis for more elaborate comparisons (such as Fractional Impact Analyses) yet to be completed.

Except for a few unusual cases, residential exposure to en route noise from overflights of conventionally powered transport aircraft has provoked only a fraction of the public reaction created by aircraft noise exposure in immediate airport environs. Differences between the nature of noise emissions of conventional jet engines and those of unducted fan engines (notably, the pronounced low frequency tonality of the latter) raise the possibility that the public may react more vigorously to en route noise exposure produced by aircraft equipped with unducted fan engines than to en route noise produced by conventionally powered aircraft.

If this were so, widespread adoption of unducted fan engines might exacerbate "the aircraft noise problem" in the United States, spreading it from the two million-odd people who reside in the vicinity of large airports to far larger numbers of people who reside in low population density rural areas. There is also reason for heightened concern about reactions to the noise of unducted fan engines in outdoor recreational environments.

The differences in composition of noise emissions of conventional jet engines and unducted fan engines are readily apparent in Figures 1 and 2. Figure 1 is a three dimensional representation of the noise exposure created on the ground beneath a direct overflight of an aircraft equipped with JT8D-15 engines flying at Mach .8 at 35,000 feet. The engine noise heard by an observer on the ground is composed almost exclusively of low frequency, broadband energy.

Figure 2 is a similar representation of the noise exposure produced by a comparable overflight of an aircraft equipped with an experimental unducted fan engine flying at Mach 0.7 at 30,000 feet. The most prominent feature of the noise signature of the unducted fan engine as heard on the ground is the tonal energy emitted at 200 Hz, shown in Figure 2 along with its first harmonic undergoing Doppler shifting during the course of a direct overflight.

The present analyses assess the magnitude of potential reactions to en route exposure produced by unducted fan engines in the United States; more specifically, with noise produced by such engines under cruise conditions (35,000 feet and Mach 0.8). Since unducted fan engines will not be commonplace in commercial aviation in the near future, direct experience cannot as yet provide guidance for these analyses. Instead, as is often the case, the accuracy of such analyses is limited by the large number of order-of-magnitude estimates and assumptions that must be made.

For example, estimates of en route noise exposure require assumptions about the types of aircraft that will be equipped with unducted fan engines, the rate at which such aircraft will be introduced into the fleet, the stage lengths and routes that they will fly, and their daily utilization. Likewise, estimates of community response to en route noise exposure require assumptions about ambient noise conditions and population densities in overflown areas, calculations of the audibility of such exposure, and assumptions about the relationship between the audibility and the annoyance of individual flyovers and cumulative exposure. All of these assumptions entail some amount of uncertainty.

NASA 727 - Event 3

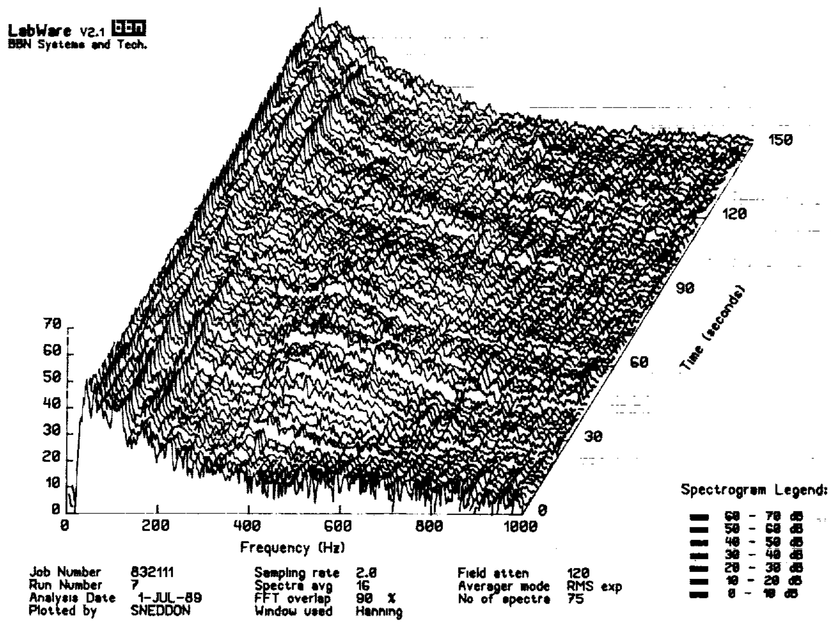


Figure 1*

NASA Propfan - Event 2

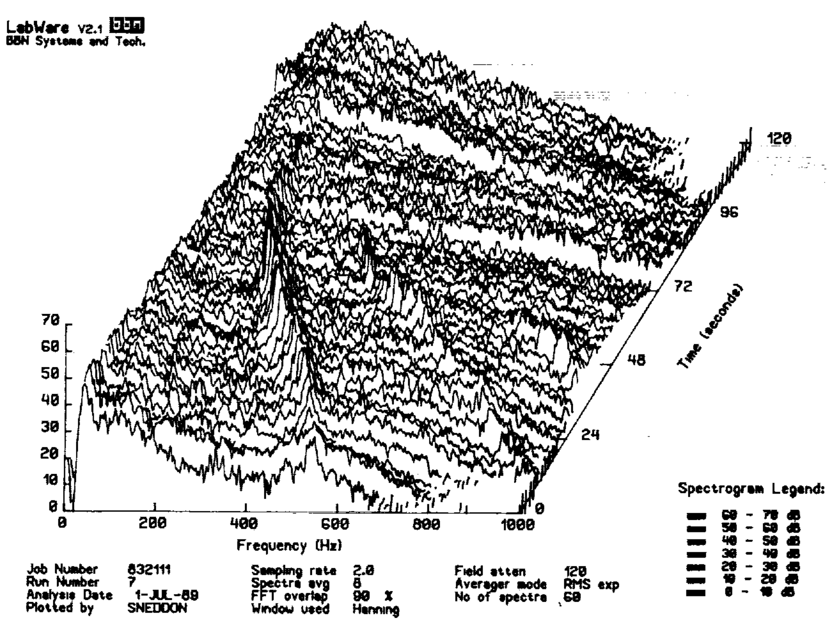


Figure 2*

* Orginial color representation of spectrogram data is shown in black and white. Color figures are available from the authors.

PREDICTION OF NOISE EXPOSURE

Operational information needed for predicting the prevalence of annoyance associated with en route noise exposure can be estimated in a reasonably straightforward manner. It was assumed for present purposes that intermediate range jet transports, such as Boeing 727 and 737 and McDonnell Douglas DC-9 series aircraft, would be those most likely to be replaced by new aircraft equipped with unducted fan engines. Given the backlog of orders that airframe manufacturers currently enjoy, it is unlikely that transport aircraft equipped with unducted fan engines could be built in consequential numbers for several years at a minimum. Furthermore, even if an immediate decision were made to introduce such aircraft into the commercial air transport fleet, the greatest rate at which they could be constructed and put into operation would probably be less than 100 per year.

The domestic commercial air transport fleet currently includes about 2600 B-727s, B-737s and DC-9s. If all of these aircraft are retired within several decades in favor of aircraft equipped with unducted fan engines, and if orders continue to be received during this time for additional intermediate range transports, a rough estimate of the greatest number of commercial transports likely to eventually fly in domestic service with unducted fan engines is 3000. Needless to say, the market for such aircraft could also prove to be far smaller - from nonexistent to perhaps a few hundred aircraft.

A less speculative datum is the total length of high altitude (that is, above 18,000 feet) jet routes in the United States. The sum a few months ago was 171,563 miles. Since new jet routes are generally created when traffic exceeds 100 flights per day per route, it is likely that this figure will climb to something on the order of 200,000 miles by the time that aircraft equipped with unducted fan engines can begin to fly on them in consequential numbers. For purposes of estimating en route noise exposure, however, 20% or so of these route miles in the vicinity of metropolitan areas are of little interest, since aircraft approach and depart cities at relatively low altitudes and speeds.

Before these high altitude route miles can be hypothetically populated with unducted fan aircraft, however, an assumption must be made about their daily utilization. DC-9s, B-737s, and B-727s currently average a bit more than seven hours per day of use in commercial service. There is little reason to believe that utilization of new intermediate range aircraft in a national hub-and-spoke network would deviate appreciably from this figure.

Secondary assumptions are also required about routes that aircraft equipped with unducted fan engines will fly and about the proportion of the time they will spend in cruise conditions. To save time, the net effect of all of these assumptions is summarized in Table 1 without further discussion.

As described later, noise levels produced on the ground during cruise at 35,000 feet are not of sufficiently high absolute level to be readily audible in geographic areas with high ambient noise levels; that is, in high population density (urban) areas. The major interest of the current analyses is therefore in estimating audibility and annoyance outside of metropolitan areas.

The current nonmetropolitan average population density in the contiguous 48 states is about 24 people per square mile, a density that is unlikely to change greatly in the near future. The figure is derived by dividing the number of people living outside the Census Bureau's standard metropolitan statistical areas (SMSAs) by the land area outside of SMSAs, parks, and wilderness areas: roughly 56 million people divided by about 2.3 million square miles. It is necessary to assume for tractable calculations that these people are uniformly distributed throughout the non-

Table 1: Summary of Worst Case Assumptions About Exposure to En Route Noise of Aircraft Equipped with Unducted Fan Engines

Eventual Maximum Number of Aircraft	3,000
Average Hours of Utilization Per Aircraft-Day	7
Total Hours of Daily Fleet Utilization	21,000
Percent of Time in Cruise Conditions	81
Statute Miles Traversed by High Altitude Routes	200,000
High Altitude Statute Route Miles Flown Daily	10,000,000
Daily Overflights of Points throughout Network	50
Maximum Noise Intrusions per hour throughout Network	4

metropolitan land area, even though in reality many of these 56 million people live in small communities.

Assuming further that the 3 dB-down points for audibility of an aircraft flyover at 35,000 feet extend four miles laterally from the flight track, it is possible to estimate an approximate land area of more or less homogeneous noise exposure in the vicinity of high altitude routes. Given a total distance of 200,000 miles for high altitude jet routes, and the assumption that nonmetropolitan areas underlie approximately 80% of distance along these routes, it follows that roughly 30 million people living within an eight mile wide corridor beneath high altitude routes may eventually be exposed to en route noise from unducted fan engines.

The conclusion about noise exposure that all of these assumptions lead to is that if all conventionally powered, intermediate range transport aircraft in the civil fleet are replaced by new aircraft equipped with unducted fan engines, roughly thirty million people residing outside of metropolitan areas of the contiguous 48 states could ultimately be exposed to noise intrusions from at most four overflights per hour throughout the hours of the day during which they are awake.

The number of hourly noise intrusions produced by aircraft equipped with unducted fan engines cannot reasonably be expected to reach this level for many years, however, until virtually all conventionally powered intermediate range transports have been retired from service. A more realistic estimate of the likely number of daily noise intrusions created by aircraft equipped with unducted fan engines within a decade of the start of operations is on the order of one per hour.

The last issue that needs to be addressed before estimates of audibility can be made is the nature of the ambient noise environment in low population density areas throughout the United States. Applying the relationship as described in reference 1 for estimating Day-Night Average Sound Level from population density,

$$L_{dn} = 10 \log (\text{population density}) + 22 \text{ dB}$$

to the present case of 24 people per square mile yields an Ldn of 36 dB. Figure 3 shows the spectral shape for the nighttime ambient noise distribution of a low population density area (5,000 people per square mile) assumed for the analyses conducted to date. Also plotted on the figure are similar spectra of assumed ambient noise distributions for inhabited areas of higher population density, and for an uninhabited area.

All of the working assumptions necessary to calculate the audibility of unducted fan engines are now in place. It should be stressed that these are in fact nothing more than working assumptions: because conclusions may be quite sensitive to these working assumptions, inferences eventually drawn from the present analyses will differ as alternative assumptions are considered. Sidestepping further discussion about the details of assumptions, however, the next step is to estimate audibility.

Audibility is defined for present purposes as bandwidth and duration adjusted signal to noise ratio, expressed in the scalar quantity d'-seconds. Following the conventions for conducting these calculations in one-third octave bands adopted in software packages such as the U.S. Army Acoustic Detection Range Prediction Model, values of d' can be calculated as

$$d' = \sqrt{\eta \quad BW} \; S/N$$

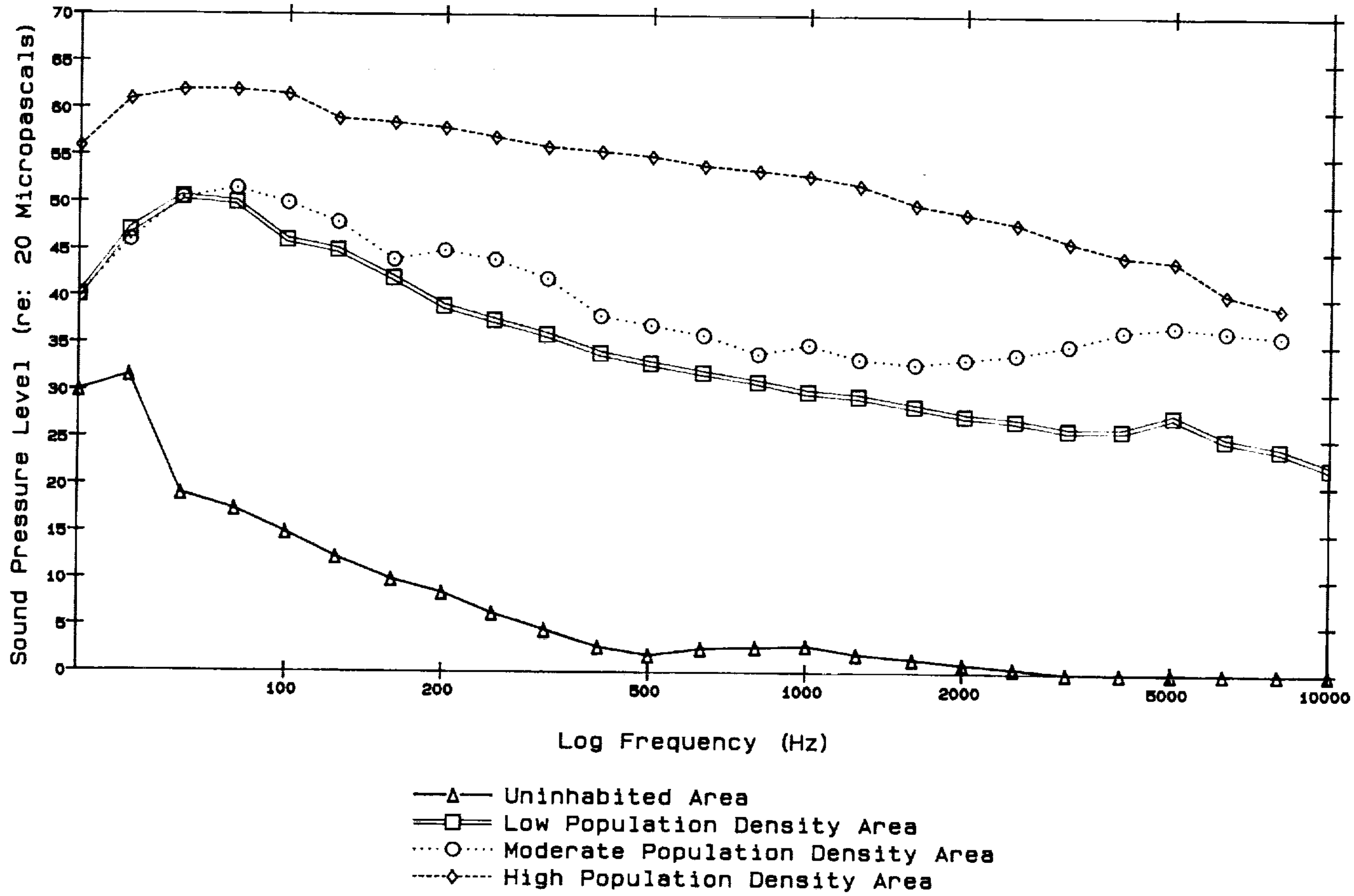


Figure 3: Assumed One-Third Octave Band Ambient Noise Spectra for Low, Moderate and High Population Density and Uninhabited Areas

where eta represents the efficiency of the observer relative to an ideal energy detector, BW is the bandwidth of the detector's passband, and S/N is the signal to noise ratio.

ASSUMPTIONS ABOUT REACTIONS TO NOISE EXPOSURE

Just as estimating en route noise exposure requires a rationale and supporting assumptions, so does the process of estimating individual and community response to the exposure. The most straightforward way to compare the annoyance of noise signatures of hypothetical aircraft powered by unducted fan engines with the annoyance of existing aircraft is to establish an equivalence in terms of the probability of immediate, short term annoyance associated with individual overflights. The equivalence in annoyance can then be manipulated to develop predictions of equivalent numbers of operations of different aircraft types, equivalent prevalence of annoyance, and other derivative measures.

The first requirement is a transfer function relating audibility to the immediate annoyance of individual overflights. Such a function can be derived from laboratory findings on the relationship between audibility and annoyance of individual noise intrusions. Two such data sets (references 2 and 3) have been analyzed to produce the averaged cumulative relationships seen in Figure 4.

These transfer functions can yield predictions of the audibility and annoyance of flyovers of any sort. Only certain flight conditions are of interest for purposes of estimating the annoyance associated with en route noise exposure, however; that is, a speed of Mach 0.8 at an altitude of 35,000 feet. Thus, aircraft recordings made under other conditions require adjustment to these conditions. The recording of an aircraft equipped with an unducted fan engine available for the present analyses produced by an aircraft at an altitude of 30,000 feet and a speed of Mach 0.7. Inverse square and atmospheric absorption adjustments were therefore made to the recorded spectrum to convert it to standard cruise conditions.

Perhaps the most obvious case for which an annoyance prediction is of interest is that of the actual noise signature of a direct overflight of an aircraft equipped with a prototype version of an unducted fan engine. The most useful interpretations of the predicted audibility and annoyance of such a flyover are in terms of the predicted audibility and annoyance of comparable flyovers of Stage II and Stage III aircraft. Accordingly, similar calculations were made for a B-727 equipped with JT8D-15 engines and for a DC-10 with its high bypass ratio engines. Inverse square and atmospheric absorption corrections were also made to recorded spectra of these Stage II and Stage III aircraft to adjust them to standard cruise conditions. The resulting flyover spectra are seen in Figure 5.

As may be seen in Figure 6, the audibility of the aircraft powered by an unducted fan engine in the very low ambient noise environment assumed to be characteristic of uninhabited areas is so great that it is a certainty that the noise intrusion would be judged highly annoying. The odds are about even that the overflight would be judged highly annoying in the ambient noise environment assumed for low population density area, roughly two to one against a highly annoying judgment in an area of moderate population density, and about ten to one against a highly annoying judgment in a densely populated metropolitan area. Figures 7 and 8 display comparable information for Stage II and Stage III aircraft.

Generalizations about the annoyance of en route noise produced by aircraft equipped with unducted fan engines should not be based solely upon an analysis of a single flyover. In particular, it is unclear whether production engines would be as noisy as the prototype engine. Furthermore,

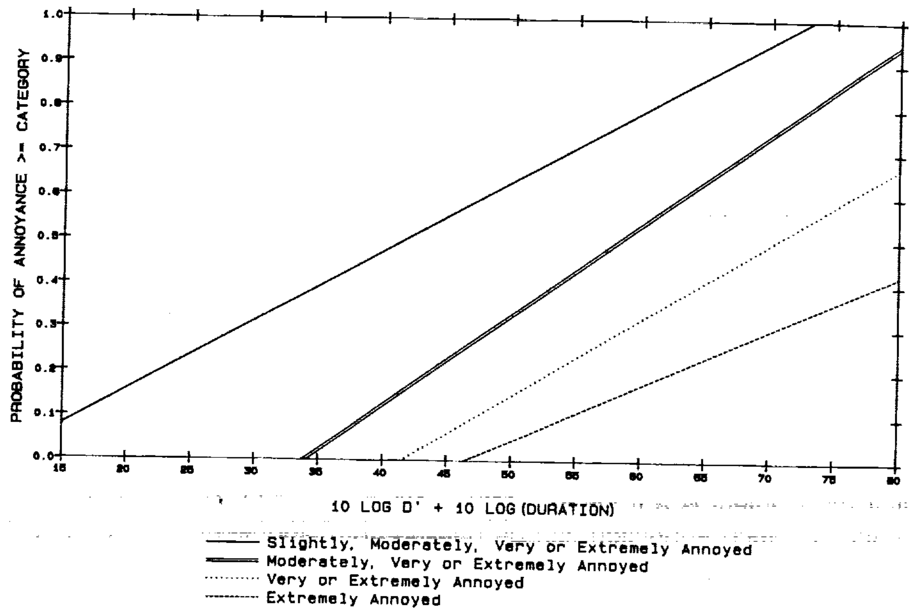


Figure 4: Average Least-Squares Fits to Cumulative Distribution of Annoyance Ratings (From Fidell and Teffeteller (1981) and Fidell, Silvati and Secrist (1989))

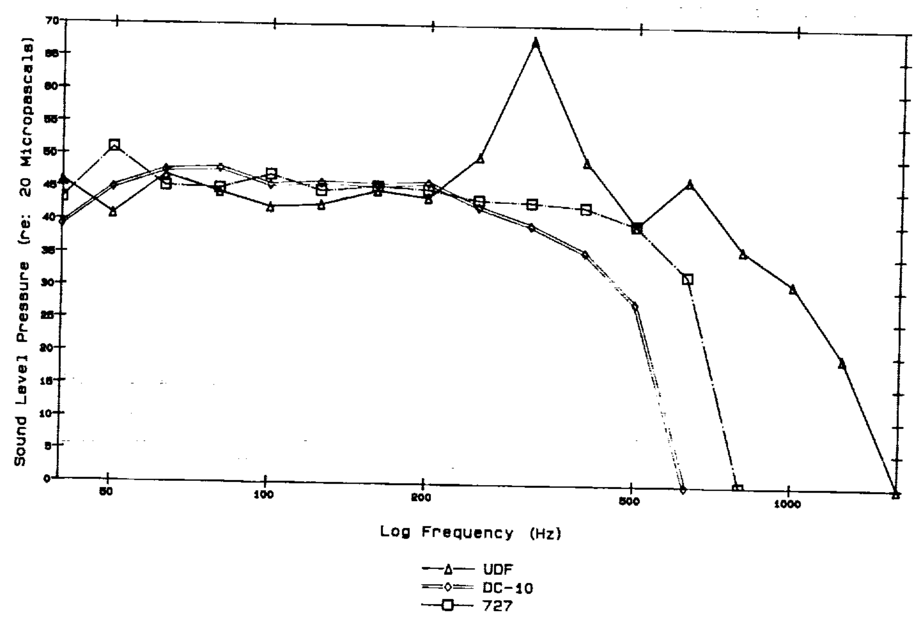
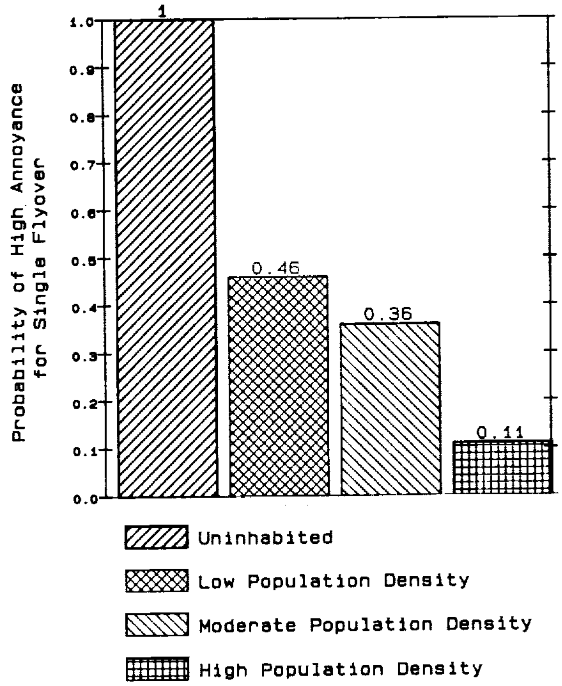
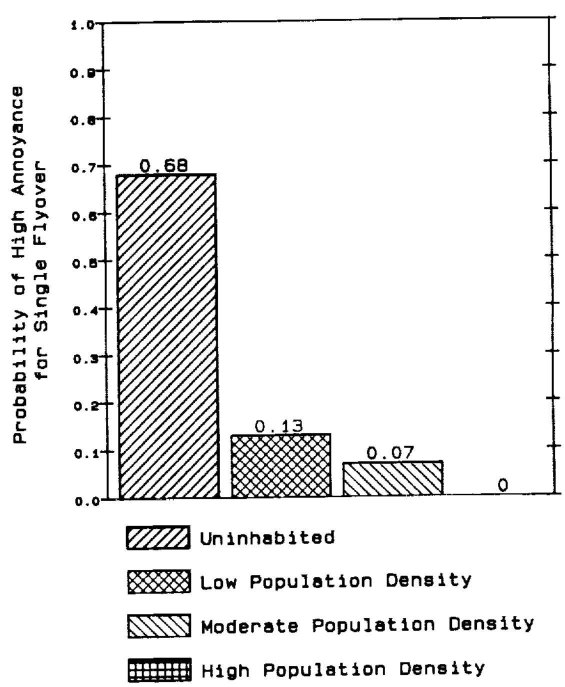


Figure 5: One-Third Octave Band Spectra of En Route Noise Emissions of B-727, DC-10 and UDF-Powered Aircraft at CPA (Adjusted to 35,000')



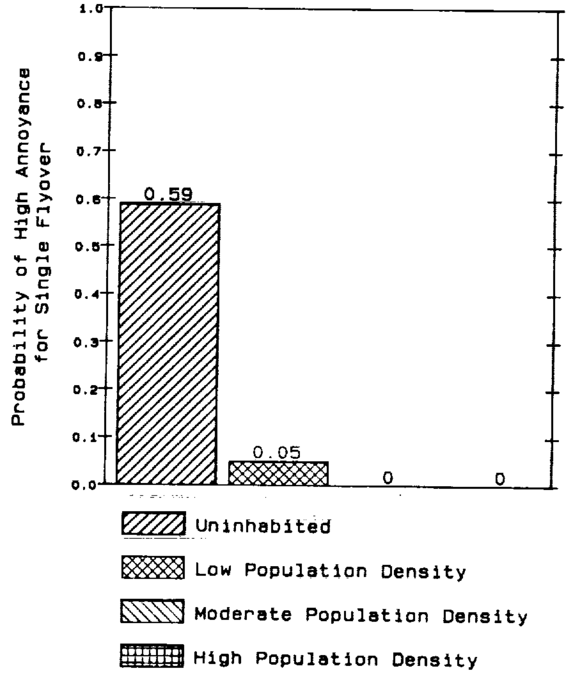
*Adjusted to 35,000'

Figure 6: Predicted Probability of High Annoyance Associated with an Actual Overflight* of UDF-Powered Aircraft (A-Level = 64.9 dB)



*Adjusted to 35,000'

Figure 7: Predicted Probability of High Annoyance Associated with an Actual Overflight* of JT8D-15 Powered (B-727) Aircraft (A-Level = 43.6)



*Adjusted to 35,000'

Figure 8: Probability of High Annoyance Associated with an Actual Overflight* of Stage 3 (DC-10) Aircraft (A-Level = 44.7 dB)

details of assumptions and calculation procedures matter. Factors such as the criterion of audibility, the points in time during the flyover which contribute to the definition of A-weighted Sound Exposure Level, the total duration of the flyover, and corrections for Doppler shifts can all influence conclusions drawn from these analyses.

Nonetheless, it is interesting to speculate on the relative annoyance of unducted fan and conventional engines at levels other than those for which recordings are available. For example, would aircraft equipped with unducted fan engines be more or less annoying than Stage II and Stage III aircraft to an observer outdoors if they produced the same A-weighted noise signatures?

The next three figures address this issue. Figures 9, 10, and 11 show the predicted probability of annoyance associated with single overflights of the three aircraft types at different A-weighted sound pressure levels in different ambient noise environments. The trends shown in the figures are not surprising: the probability of annoyance is greatest in the lowest population density ambient noise environment and rises with A-weighted sound pressure level in all ambient noise environments. It is interesting to note, however, that although the predicted probability of annoyance of an overflight of an aircraft powered by an unducted fan engine is greater than that of a Stage III aircraft such as a DC-10, it does not differ substantially from that of a Stage II aircraft such a B-727.

The next step in the analyses now in progress is to apply the equivalences established between the short term annoyance of flyovers of aircraft equipped with unducted fan and other engines to predictions of long term annoyance made with reference to a dosage-effect relationship such as that described in reference 4. Among the additional factors to be considered in the coming months are the effects of numbers of occurrences of flights (as discussed, for example, by in references 5 and 6), the sensitivity of conclusions to minor changes in assumptions, and the definition of exposure zones for Fractional Impact Analyses.

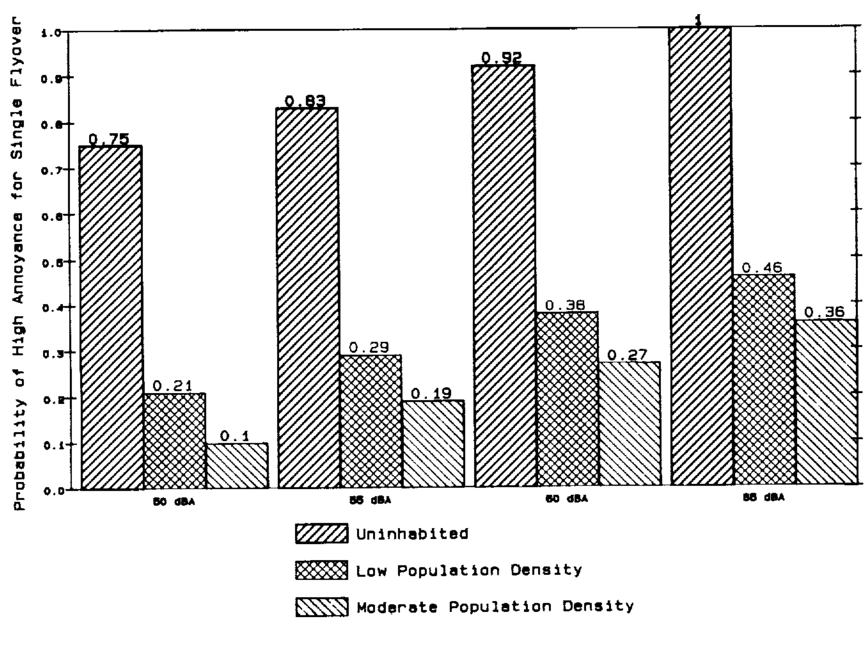


Figure 9: Predicted Probability of High Annoyance Associated with an Individual Overflight of UDF-Powered Aircraft

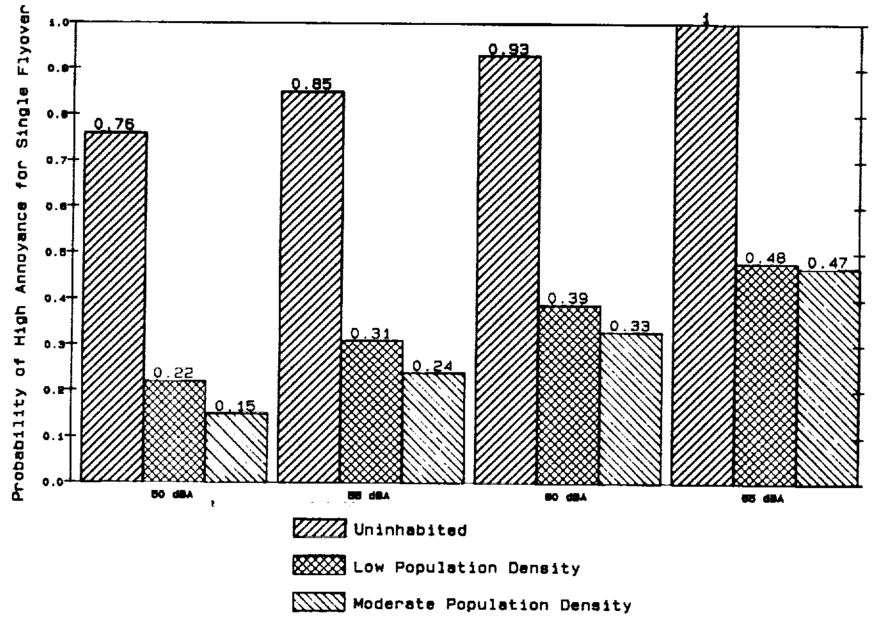


Figure 10: Predicted Probability of High Annoyance Associated with an Individual Overflight of JT8D-15 Powered (B-727) Aircraft

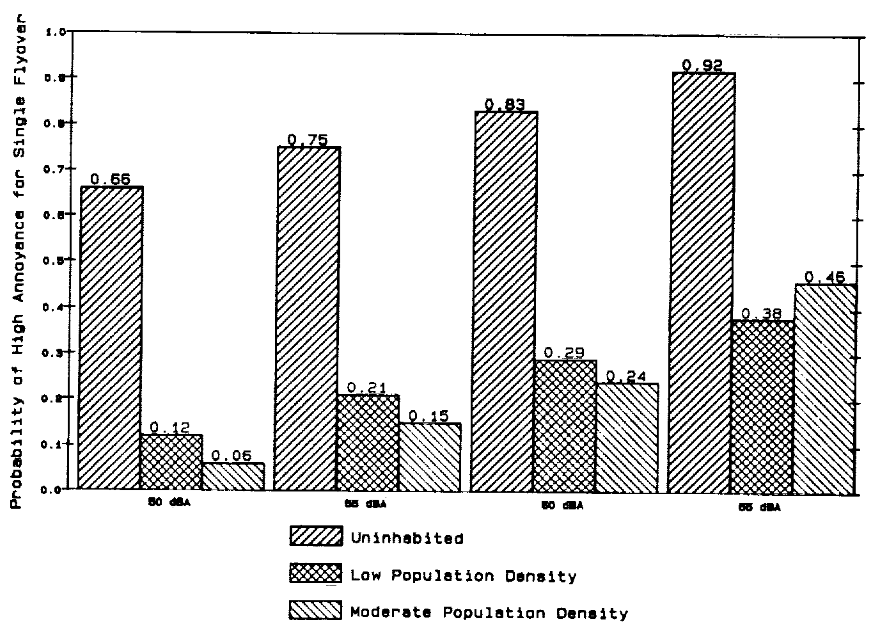


Figure 11: Predicted Probability of High Annoyance Associated with an Individual Overflight of Stage 3 (DC-10) Aircraft

References

1. Galloway, W.G.; Eldred, K. McK.; and Simpson, M. A.: Population Distribution of the United States as a Function of Outdoor Noise Level. Report No. 2592, Bolt Beranek and Newman, Inc., to U.S. Environmental Protection Agency, Office of Noise Abatement and Control, Washington, D.C., 1974

2. Fidell, S.; and Teffeteller, S.: Scaling the Annoyance of Intrusive Sounds, Journal of Sound and Vibration, 78(2), 291-298, 1981.

3. Fidell, S.; Silvati, L.; and Secrist, L.: Laboratory Tests of Hypotheses Derived from a Decision-Theoretical Model of Noise-Induced Annoyance, Report No. 6739, Bolt Beranek and Newman, Inc., to Noise and Sonic Boom Impact Techology (NSBIT), Ohio 1989.

4. Schultz, T.J.: Synthesis of Social Surveys on Noise Annoyance. Journal of Acoustical Society of America 64(2), 377-405, 1978.

5. Fields, J. M.: The Effect of Number of Noise Events on People's Reaction to Noise: An Analysis of Existing Survey Data, Journal of Acoustical Society of America 75(2), 447-467.

6. Rice, C. G. Trade-off Effects of Aircraft Noise and Number of Events. Proceedings of the Third International Congress on Noise as a Public Health Problem, ASHA Rep. 10 (American Speech-Language-Hearing Association, MD, April 1980), 495-510, 1980.

Acknowledgments

The authors are grateful to Dr. William Galloway for technical discussions and suggestions throughout the conduct of the effort summarized in this paper, and to Messrs. James Densmore, Robert Krull and Edward Rickley of FAA for making available information needed to perform these analyses. This effort was funded through the Noise and Sonic Boom Impact Technology Program of the U.S. Air Force under Contract F33615-86-C-0530. The NSBIT program is directed by Captain Robert Kull, Jr. Mr. Lawrence Finegold is the Technical Monitor for the current effort.