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16. Abstract

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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 high altitude overflights by aircraft equipped with unducted fan engines is to estimate their audibility relative to that of conventionally powered aircraft in various ambient noise conditions. These predictions may be converted into estimates of the probability of high annoyance by means of a dosage-response relationship derived from laboratory data about the annoyance of individual noise intrusions. The latter estimates may in turn be applied to populations exposed to unducted fan engine noise over a range of assumed exposure levels.

Application of these procedures to several assumed exposure cases suggests that millions of people in rural areas of the United States would be likely to be highly annoyed by the noise of aircraft powered by unducted fan engines. Keywords.

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Foreword

This report was prepared under Contract F33615-86-C-0530 of the Noise and Sonic Boom Impact Technology (NSBIT) program. The NSBIT program is conducted by the United States Air Force Systems Command, Human Systems Division, under the direction of Major Robert Kull, Jr., Program Manager.

The work described in this report was conducted under Task Order 0017 (started 15 June 1989).

Executive Summary

Aircraft flyovers heard in high ambient noise urban 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 may be readily audible in low ambient noise rural 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 high altitude overflights by aircraft equipped with unducted fan engines is to estimate their audibility relative to that of conventionally powered aircraft in various ambient noise conditions. These predictions may be converted into estimates of the probability of high annoyance by means of a dosage-response relationship derived from laboratory data about the annoyance of individual noise intrusions. The latter estimates may in turn be applied to populations exposed to unducted fan engine noise over a range of assumed exposure levels.

Application of these procedures to several assumed exposure cases suggests that millions of people in rural areas of the United States would be likely to be highly annoyed by the noise of aircraft powered by unducted fan engines.

1. Introduction

This report develops and applies procedures for comparing the annoyance associated with noise intrusions produced by transport aircraft equipped with unducted fan engines and low and high bypass ratio jet engines which power Stage II and Stage III aircraft. These analyses differ from standard aircraft noise impact assessments (1) in their focus on low single event and integrated levels of en route noise rather than on the much higher levels of aircraft noise in airport environs and (2) in their concern with noise emissions from aircraft not yet in production. The principal differences between the current analyses and more familiar ones are the low absolute levels of exposure and the consequent importance of the ambient noise environment in which en route noise is heard.

More specifically, the methods and analyses reported here are limited to assessments of the annoyance associated with noise exposure created nationwide by large transport aircraft in cruise conditions (defined for present purposes as Mach 0.8 at 35,000 feet). Since aircraft equipped with unducted fan engines have not yet entered service, experience provides no guidance for predicting the annoyance of their en route noise emissions. The strategy adopted in this report for making such predictions takes advantage of a relationship between the audibility and annoyance of low level noise intrusions.

The next chapter provides a background discussion to assist readers in following the rationale of the present analyses. Chapter 3 makes explicit the many assumptions required for these analyses, while Chapter 4 presents the results of the analyses.

2. Background

Except in 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. As heard on the ground miles below a large subsonic jet transport in cruise, en route noise lacks distinctive character: it is composed almost exclusively of low frequency, broadband energy with slow onset and decay times. En route noise is so much lower in absolute level than flyovers in airport neighborhoods that it may not even be audible above the din of urban background noise. It may thus escape notice in many high population density areas. Even if noticed, en route noise may not be recognized as such because of its nondescript character, and is unlikely to be considered among the more prominent noise sources to which people are routinely exposed in urban settings.

Lower population density areas, including both suburban and rural settings, generally enjoy ambient noise levels considerably lower than those of airport neighborhoods, as well as fewer local (high level) noise sources. Thus, the same en route noise which may be inaudible in high population density areas may be more audible, noticeable, recognizable and annoying in lower population density areas.

Furthermore, 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 might react more vigorously to en route noise exposure produced by aircraft equipped with unducted fan engines than to similar exposure produced by conventionally powered aircraft. If this were so, widespread adoption of unducted fan engines could exacerbate "the aircraft noise problem" in the United States, expanding it from the two million-odd people who reside in airport environs to far larger numbers of people who reside in low population density rural areas. Public Law 100-91 also raises concerns about the audibility and annoyance of high altitude overflights of park and wilderness areas by aircraft equipped with unducted fan and other engines.

2.1 Comparison of Noise Emissions of Unducted Fan and Low and High Bypass Ratio Jet Engines

The noise emissions of unducted fan engines differ markedly from those of low and high bypass ratio jet engines which power Stage II and Stage III commercial transports, as is apparent in Figures 2-1, 2-2 and 2-3. Figure 2-1 is a three dimensional (time, frequency, and energy) representation of the noise exposure created on the ground beneath a direct overflight of a Stage II 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.

Likewise, as seen in Figure 2-2, noise produced by Stage III aircraft also consists almost entirely of low frequency, broadband energy. The so-called "buzz tones" (multiple closely spaced tones within a relatively narrow spectral region) which are audible during takeoff of aircraft equipped with high bypass ratio engines are absent from the ground level noise signature of Stage III aircraft during cruise.

Figure 2-3 is a similar representation of the noise exposure produced by an overflight of an aircraft equipped with a single experimental unducted fan engine flying at Mach 0.7 at 30,000 feet. The most distinctive 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 2-3 along with its first harmonic undergoing Doppler shifting during the course of a direct overflight.

2.2 Conventional Approach to Predicting Annoyance of Aircraft Noise Exposure in Airport Environs

Aircraft noise impact assessments conducted within the last decade generally confine themselves to a single measure of annoyance: the prevalence in a community of a consequential degree of self-reported annoyance. The metric used for representing noise exposure and predicting annoyance is the Day Night Average Sound Level, DNL.

DNL embodies a set of decisions about (1) how to deal with the spectral content of noise intrusions (i.e., the distribution of energy over frequency); and (2) how to represent the duration and number of noise intrusions over a specified period of time. Consensus was reached fifteen years ago (EPA, 1974) on a set of assumptions that permits construction of a family of measurements adequate for most regulatory purposes. First, a frequency weighting network which resembles the inverse of human auditory sensitivity (the A-weighting network) is now

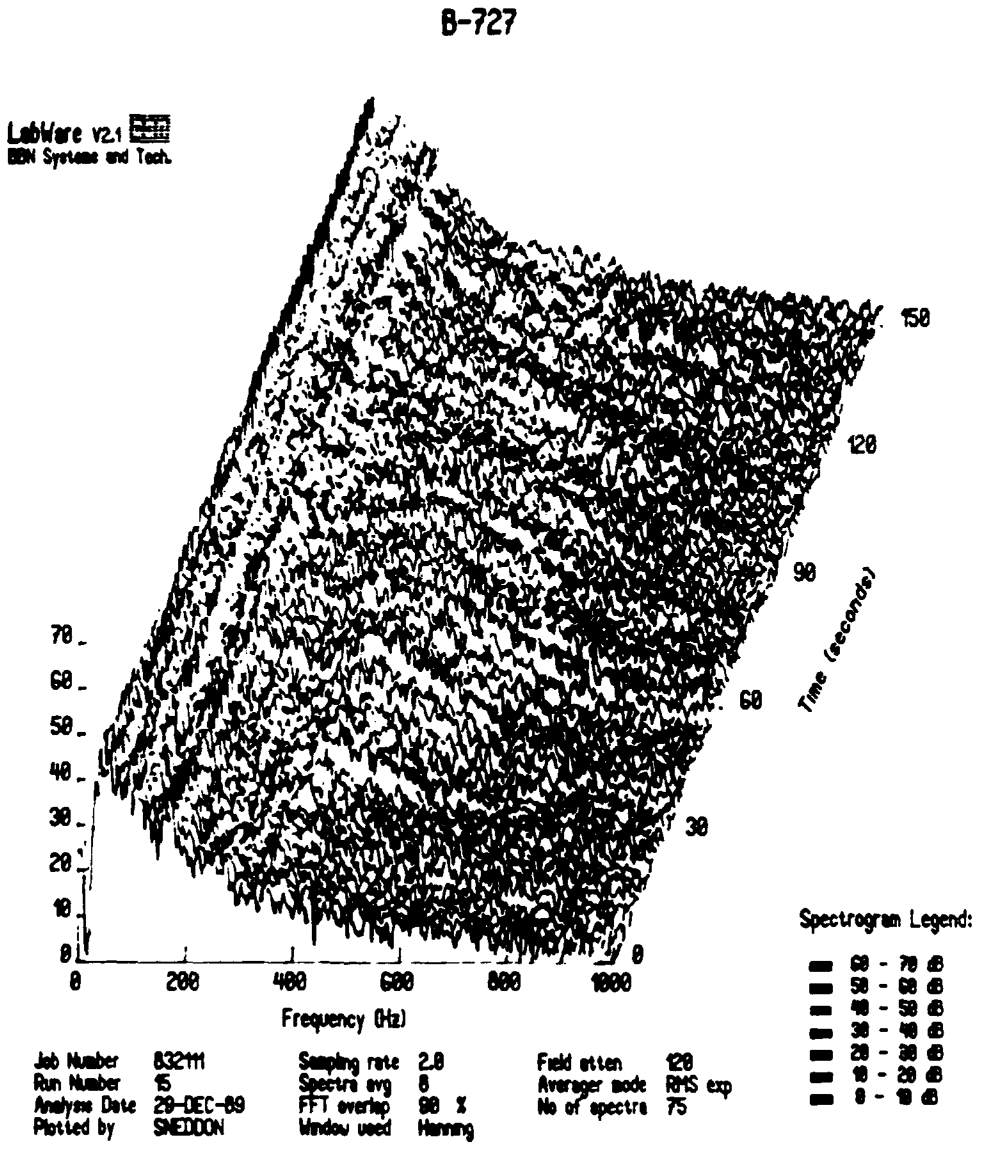

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Figure 2-1: Ground Signature of an Overflight by a Stage II Aircraft at 35,000 Feet at Mach .8

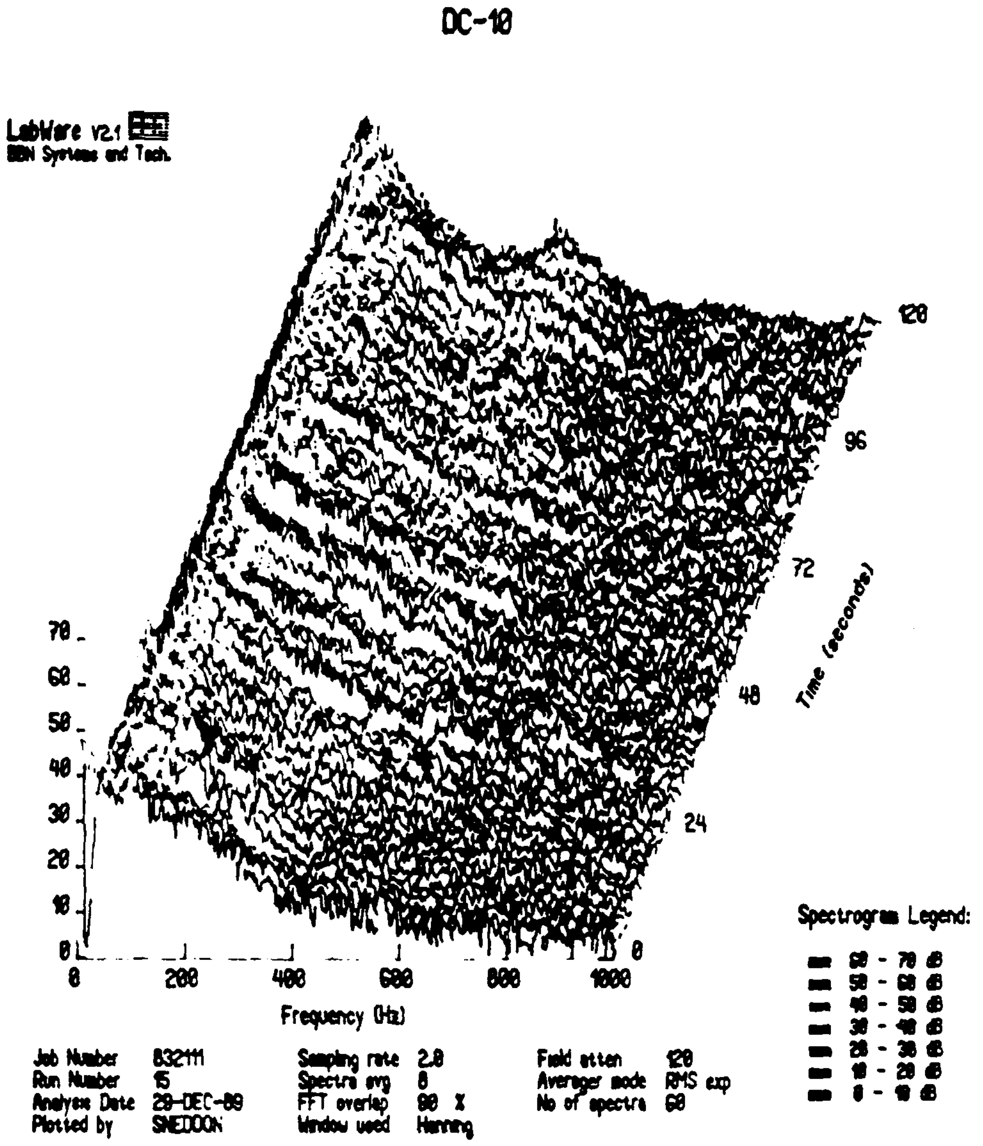

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Figure 2-2: Ground Signature of an Overflight by a Stage III Aircraft at 35,000 Feet at Mach .8

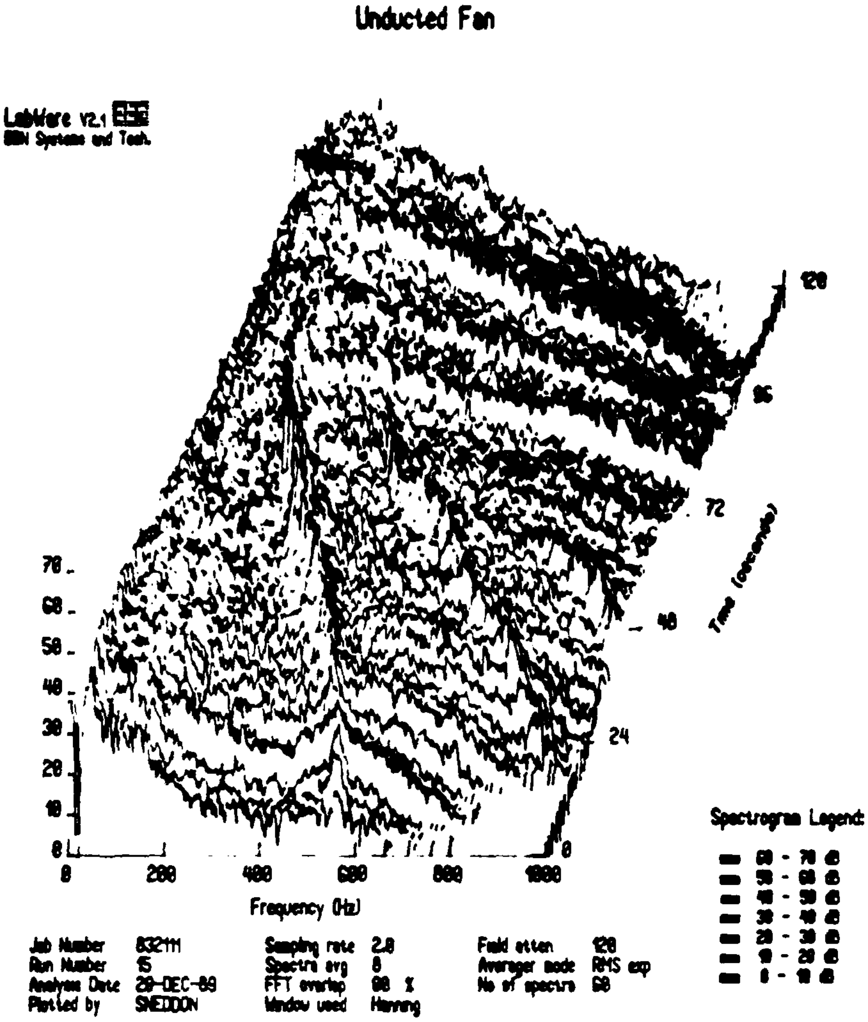

Figure 2-3: Ground Signature of an Overflight by an Aircraft Equipped with a Single Unducted Fan Engine Flying at 30,000 feet at Mach .7

universally accepted, at least as a starting point for more elaborate measurement schemes. Second, simple energy integration (10 log duration) is the process adopted to account for duration and number of events.

These two assumptions suffice to represent the total A-weighted sound energy of a time varying flyover, normalized to a nominal one second period of time, as a Sound Exposure Level (SEL). SEL values are expressed in decibel notation (ten times the logarithm of the ratio of the squared sound pressure to an agreed upon reference level of 20 μPa). Sound Exposure Levels can be logarithmically summed over specified time periods to produce Equivalent Levels (represented symbolically as L_{eq}). Hourly equivalent levels can be summed independently for daytime (0700 - 2200) and nighttime hours into the Day Night Average Sound Level (represented symbolically as L_{dn} but usually abbreviated as DNL) in which noise exposure occurring during nighttime hours is treated as though it were of a magnitude ten times greater than noise exposure occurring during daytime hours.

The most widely accepted basis for predicting the prevalence of annoyance associated with non-impulsive aircraft noise exposure is a quantitative dosage-response relationship originally synthesized by Schultz (1978) and recently updated by Fidell, Barber and Schultz (1989), as shown in Figure 2-4. DNL is the metric of the independent variable (noise exposure) of the relationship.

This empirical dosage-response relationship is an interpretation and summary of the findings of 34 data sets extracted from social surveys on the self-reported annoyance of commonplace transportation noise sources, such as the noise of aircraft takeoffs and landings at large civil airports and military airfields and the noise of vehicular street traffic. The basic information produced by the different social surveys is the percentage of respondents who describe themselves as annoyed in some consequential degree by some amount of residential noise exposure.

2.3 Limitations of Conventional Annoyance Prediction Methods for Present Purposes

It is difficult for a number of reasons to develop predictions of the annoyance of en route unducted fan engines directly from existing methods of predicting the prevalence of noise-induced annoyance. Some of the principal difficulties are (1) the pronounced tonal character of the noise emitted by unducted fan engines may create greater annoyance than otherwise expected; (2) cumulative exposure levels may be lower than those identified by EPA as adequate to protect public health and welfare; (3) differences between circumstances of exposure in airport

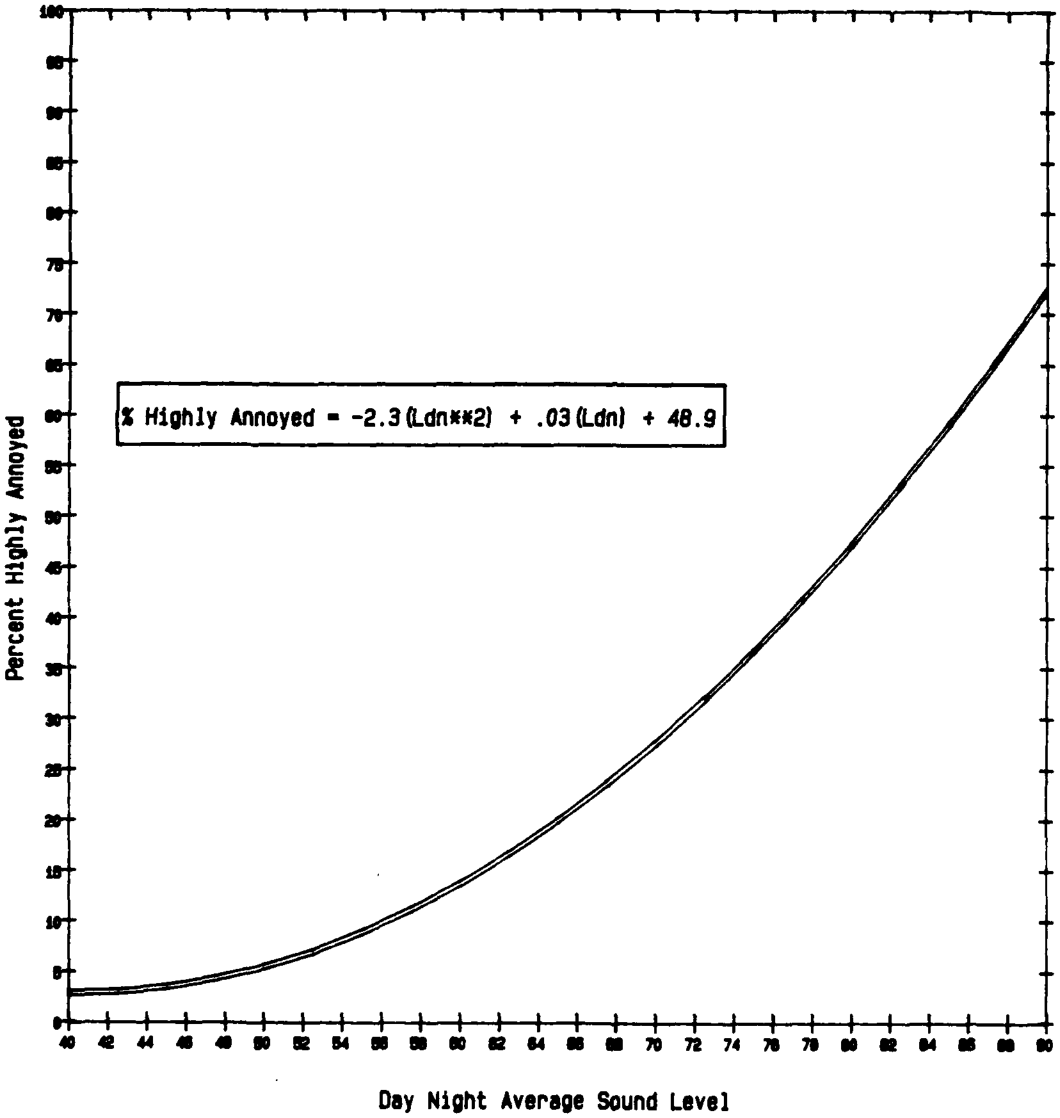

Figure 2-4: Updated Dosage-Response Relationship between Transportation Noise Exposure and the Prevalence of Annoyance (Fidell, Barber and Schultz, 1989)

environs and those encountered en route may be substantial; and (4) standard methods of predicting annoyance rely on a metric of exposure which is insensitive to the ambient noise distribution in which exposure occurs.

2.3.1 Tonal Character of Unducted Fan Engine Emissions

Procedures worked out under FAR Part 36 for certifying noise emissions of transport aircraft incorporate adjustments for the presence of tones in calculations of Effective Perceived Noise Levels. These adjustments do not generally exceed 3 dB at frequencies in the vicinity of the blade passage rate of the propellers of unducted fan engines.[1] The purpose for making such adjustments is to account for the incremental annoyance of aircraft spectra containing distinct tones. The data from which these adjustments were developed are not entirely conclusive, however, and are not fully applicable to the case at hand.

According to Scharf, Hellman and Bauer (1977) and to Scharf and Hellman (1979), tone corrections do not necessarily improve predictions of the annoyance of aircraft noise. Kryter (1970) also notes that tone corrections are not always useful in estimating perceived noisiness. The applicability of data on the contributions of tones to the annoyance of aircraft flyovers to the en route noise case (e.g., Pearsons, 1968) is also questionable, since the absolute levels and bandwidths of test signals commonly employed in laboratory tests differ considerably from those of the en route case.

2.3.2 Low Levels of Cumulative Exposure

A principal finding of EPA's Levels Document (EPA, 1974), prepared under the legislative mandate of the Noise Control Act of 1972, is that noise exposure at levels lower than L_{dn} = 45 dB has no discernible adverse effects on public health and welfare[2]. By this standard, much en route aircraft noise cannot be said to be annoying at all.

As noted by Dunholter et al. (1989), high altitude flyovers often produce A-weighted sound pressure levels on the order of 45 - 50 dBA on the ground, which can be readily heard in many low ambient noise settings. With durations of roughly 30 - 60 seconds, flyovers of this sort produce SEL values of approximately 65 dB. The number of such flyovers required during

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[1] The adjustments, made by an algorithm which searches for spectral irregularities among adjacent one-third octave bands, may sometimes be attributable to ground reflections rather than bona fide tonal energy.

[2] The term "welfare" was interpreted by EPA to include noise exposure effects such as activity and communication interference as well as annoyance.

daytime hours to produce a value of L_{dn} = 45 dB is 1000. Since air traffic on a single high altitude route is limited to about 100 flights per day, flyovers on any one high altitude route alone cannot create enough noise exposure to affect public health and welfare from EPA's perspective, even though they might be audible every few minutes throughout the day.

Although it may be tempting to define the en route noise problem out of existence by rote appeal to the findings of the Levels Document, experience with complaints and attendant political pressures associated with low level aircraft noise exposure makes it impossible to dismiss en route noise problems out of hand.

2.3.3 Differences in Circumstances of Exposure

En route aircraft noise exposure can differ from that experienced in airport neighborhoods in several ways:

- While aircraft operations in airport environs are quite predictable in time and space, en route activity audible at any one location can be considerably more variable (for example, as alternative high altitude routings change with prevailing winds);
- En route noise is generally audible at considerably greater distances than in airport neighborhoods, and thus is inherently more susceptible to variability in level due to the vagaries of long distance acoustic propagation; and
- The numbers of en route operations audible at a single point on the ground is typically considerably smaller than the numbers of approaches and departures heard in the vicinity of major airports.

Furthermore, the lifestyles of the populations exposed to airport and en route noise exposure can differ dramatically. En route noise is often experienced in low population density areas in which people may spend appreciably more time outdoors than in urban (residential) settings. The locations (with respect to flight tracks) of individuals in rural areas be much more difficult to predict and consider than in the urban case.

2.3.4 Insensitivity of DNL to Ambient Noise

Perhaps the most obvious limitation of DNL as a predictor of annoyance due to en route noise is that the metric takes no account of the ambient noise environment in which exposure occurs. Given the prevailing concern with airport and urban noise pollution when the metric was developed, this limitation is hardly surprising. The commonly acknowledged view that a given level of intrusive noise is less disturbing in locations with high background noise than in quiet locations is informally incorporated in schemes for predicting effects of noise exposure dating back as far as the original Composite Noise Rating (1953).

In the years since publication of EPA's Levels Document, it has become clear that the ambient noise in which exposure occurs can have a major influence on its annoyance. In particular, it has been shown that the audibility of low level noise intrusions is a good predictor of their annoyance. The physical basis for predictions of audibility (and through audibility, annoyance) of individual low level noise intrusions is derived from a line of research based on the psychophysical Theory of Signal Detectability (Green and Swets, 1966). Some key findings of this research include the following:

1. The audibility of broadband, low level environmental noise intrusions (such as distant aircraft flyovers) can be systematically predicted from measurements of bandwidth-adjusted signal to noise ratios (Fidell, Pearsons and Bennett, 1974).
2. The annoyance of low level noise intrusions in different ambient noise environments can be predicted with useful precision on the basis of predicted audibility (Fidell, Teffeteller, Horonjeff, and Green, 1979); and
3. The intrusiveness of low level noise intrusions can be scaled in decibel-like units of audibility (10 log d') (Fidell and Teffeteller, 1981).

Taken together, these findings suggest a simple line of reasoning leading from characterization of sounds by bandwidth-adjusted signal to noise ratios to predictions of annoyance. Three ranges of signal to noise ratio may be identified: those necessary for audibility alone, those capable of capturing enough attention to be noticed, and those capable of annoying people. Sounds with signal to noise ratios insufficient to be detected by human observers cannot be meaningfully considered to be annoying. To intrude upon the awareness of people engaged in activities other than specifically listening for noise intrusions, sounds must have even greater signal to noise ratios than those which are barely audible. To be considered annoying, sounds must have yet greater signal to noise ratios than those adequate to occasion notice.

This reasoning also suggests that integrated detectability, expressed in decibel-like units such as 10 log (d'-seconds), can serve as a metric useful for predicting the annoyance of exposure to low level aircraft noise.

3. Method

The basic information available for the present analyses consisted of ground level recordings made in low ambient noise conditions of three high altitude flyovers of aircraft in cruise conditions: one by an experimental aircraft equipped with a single prototype unducted fan engine, one by a B-727 equipped with low bypass ratio engines, and one by a DC-10 equipped with high bypass ratio engines.

The relative annoyance of the noise produced en route by these three aircraft was assessed in four steps.

1. A number of adjustments were made to the recorded noise signatures:
    - Since the altitudes and airspeeds of the three flyovers differed slightly, the actual noise signatures were adjusted to comparable cruise conditions (Mach .8 at 35,000 feet) by application of inverse square and atmospheric absorption corrections.
    - Since the experimental aircraft was equipped with a single unducted fan engine, an additional 3 dB was added in the low frequency spectral region to simulate the noise signature produced by a hypothetical twin engine production aircraft.
    - Because the noise emissions of the prototype unducted fan engine may differ from those of production engines, different constants were added to the spectra of the three aircraft at the closest point of approach (directly overhead) to normalize them to various A-weighted sound pressure levels (50 dBA, 55 dBA, 60 dBA, and 65 dBA). This normalization facilitates direct comparisons of the annoyance of noise intrusions created by the unducted fan, Stage II, and Stage III aircraft.
2. Integrated audibility of the adjusted noise signatures was estimated as described in Section 3.6.1.
3. Estimates of per-event annoyance were developed by applying a dosage-effect relationship described in Section 3.6.2.
4. These estimates of per-event annoyance were interpreted in terms of numbers of people likely to be exposed to en route noise in areas of differing population density.

The following sections develop the assumptions needed for each step and discuss their implications. The results of the analyses are presented in Chapter 4.

3.1 Development of Assumptions

Assumptions are the coin with which conclusions are purchased. The present analyses are contingent upon assumptions about many variables, including the following:

- representative cruise noise signatures of en route aircraft;
- the type of aircraft which may be powered by unducted fan engines;
- the number of such aircraft;
- the rate of introduction of such aircraft into the civil air fleet;
- routes and stage lengths to be flown by aircraft equipped with unducted fan engines;
- daily utilization and time of day of operation of such aircraft;
- ambient noise levels of communities and land areas exposed to en route noise;
- population densities of areas in which en route noise is audible; and
- the relationship between the audibility and annoyance of individual noise intrusions.

Sources of information relied upon to develop these assumptions include the U. S. Bureau of the Census (1986), the U. S. Department of Transportation (February 1989, May 1989), and the U. S. Geological Survey (January 1987). Given the inherent uncertainty of estimates about some of the above factors, order of magnitude estimates are the most appropriate level of analysis for present purposes. Neither calculations nor conclusions reported here should be considered exact.

3.2 Assumptions about Noise Exposure

3.2.1 Assumptions about Noise Signatures

The spectra considered as representative of 1) a hypothetical twin engine version of a production aircraft powered by unducted fan engines, 2) a typical Stage II aircraft, and 3) a typical Stage III aircraft are shown in Table 3-1 and Figure 3-1. These are assumed to represent en route cruise noise emissions of the three aircraft types at the point at which they are directly overhead.

Table 3-1: Spectra Representing Ground Signatures of Unducted Fan, Stage I, Stage II and Stage III Transport Aircraft in Cruise Conditions (Normalized to 50 dBA)

One-third Octave Band Center Frequency (Hz)	*Unducted Fan (dB re 20 μPa)*	*Stage II (dB re 20 μPa)*	*Stage III (dB re 20 μPa)*
50	34.3	54.3	50.7
63	40.6	48.6	52.2
80	38.6	52.1	50.8
100	34.2	53.6	50.8
125	36.6	50.3	50.6
160	34.3	48.7	51.5
200	33.8	47.2	51.1
250	38.5	44.6	48.4
315	59.2	42.3	50.8
400	33.9	39.9	44.8
500	26.0	38.0	36.8
630	30.1	30.8	-

3.2.2 Assumptions about Type and Number of Aircraft to be Equipped with Unducted Fan Engines

It was assumed 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 powered by 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 no greater than about 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

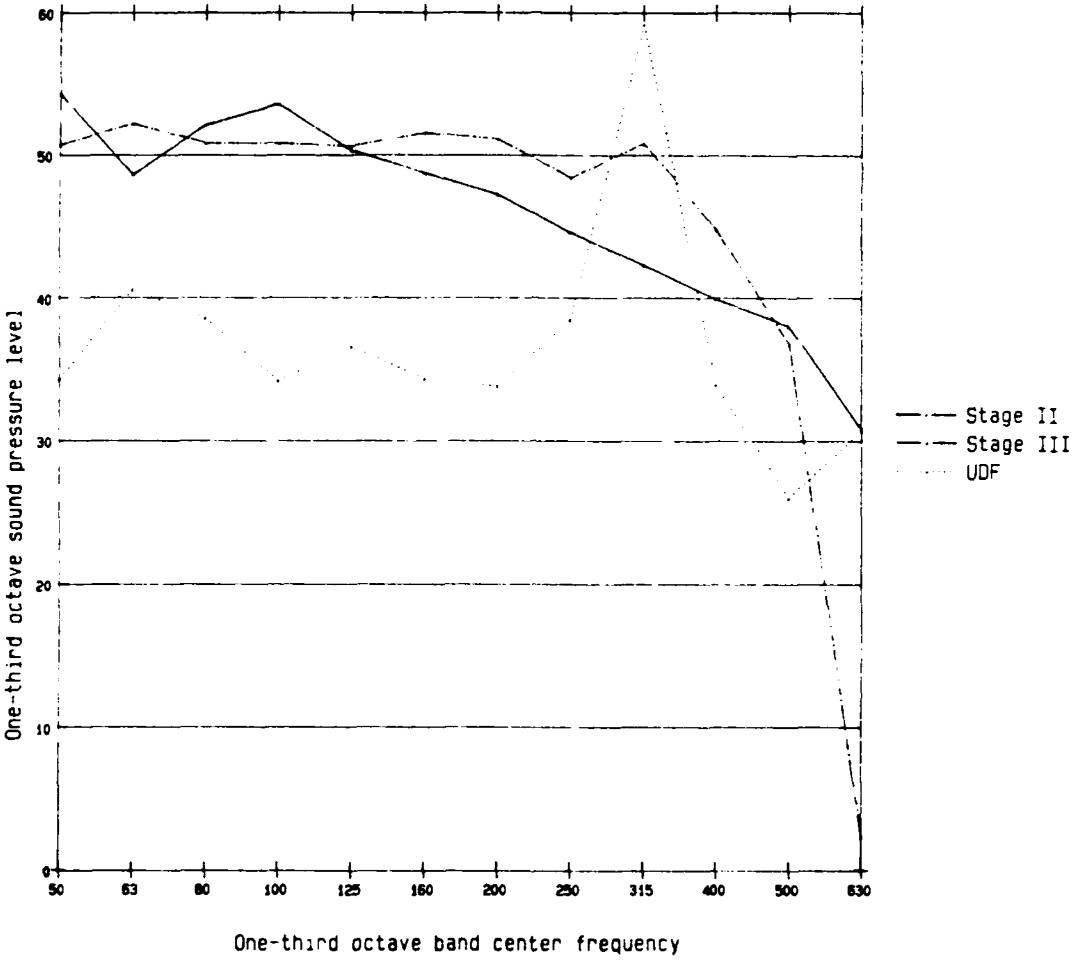

Figure 3-1: Spectral Shapes Assumed for Unducted Fan, Stage II, and Stage III Aircraft in Cruise Conditions, Normalized to 50 dBA

intermediate range transports, a rough estimate of the greatest number of commercial transports which might 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 non-existent to a perhaps a few hundred aircraft. Since there is no straightforward means of anticipating the vagaries of the commercial market for such aircraft, a figure of 300 aircraft is adopted as a lower bound on the size of a fleet of unducted fan transport aircraft. It is unlikely that airframe manufacturers would start production of unducted fan transports without orders for at least this many aircraft. The order of magnitude difference in fleet sizes between the minimum and maximum production cases also brackets the range of likely fleet sizes.

3.2.3 Assumptions about Total Route Lengths

A less speculative issue is the total length of high altitude (that is, above 18,000 feet) jet routes in the United States on which transport aircraft operate in cruise conditions. Although this figure increases slowly over time, a recent total is 171,563 miles. Since new jet routes are generally created when traffic exceeds 100 flights per day on an existing 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 could 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. Furthermore, ambient noise in metropolitan areas is sufficient to render noise from high altitude flyovers inaudible, as discussed in Section 3.3.1. This leaves approximately 160,000 miles of high altitude routes on which transport aircraft produce audible en route noise in cruise conditions.

3.2.4 Assumptions about Aircraft Utilization and Time Spent in Cruise Conditions

An assumption must be made about the daily utilization of aircraft powered by unducted fan engines before high altitude route miles can be hypothetically populated with them. According to the U. S. Department of Transportation (February 1989), the total daily utilization of DC-9s, B-737s, and B-727s is 18,839 hours, an average of slightly more than seven hours per aircraft per day 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.

Since a maximum of about 3,000 unducted fan engine aircraft might eventually be in service approximately 7 hours per day, daily utilization could not exceed about 21,000 hours. About 20% of this flight time would occur over metropolitan areas and/or in approach and departure, so that the greatest amount of time spent daily in cruise conditions over non-metropolitan areas is roughly 17,000 aircraft-hours. The comparable figure for the minimal fleet is 1,700 aircraft-hours per day.

3.2.5 Summary of Assumptions about Noise Exposure

Table 3-2 summarizes and extends the assumptions about en route noise exposure associated with the largest fleet of transport aircraft equipped with unducted fan engines. A maximum of about 9,000,000 high altitude statute miles are flown daily over non-metropolitan areas in 17,000 aircraft-hours of cruise operations at approximately 530 mph. Of some 200,000 statute miles traversed by high altitude routes, about 81% or 162,000 overfly non-metropolitan areas. On average each point in the network is overflown about 56 (9,000,000/162,000) times daily[3]. Since most flights occur between 7:00 AM and 10:00 PM, on the basis of maximum-production case assumptions, the greatest number of overflights should not exceed 4 per hour during daytime hours.

Table 3-3 summarizes and extends the assumptions about en route noise exposure associated with a minimal fleet of transport aircraft equipped with unducted fan engines.

3.3 Assumptions about Population Exposed to En Route Noise

A rationale for estimating the population exposed to en route noise is developed in the following sub-sections.

3.3.1 Assumptions about Population by which En Route Noise May Be Audible

Given that ambient noise levels in inhabited places are closely related to population density, and that en route noise emissions of transport aircraft in cruise conditions are sufficiently low in absolute level that their audibility is strongly affected by their relationship to ambient noise levels, it follows that en route noise is differentially audible in areas of differing population density. Ambient noise levels in high population density (urban) areas generally limit the probability of aural detection of high altitude aircraft noise to negligibly small values.

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[3] Differences in utilization of specific routes may be ignored for the present (comparative) purposes.

Table 3-2: Summary of Assumptions About En Route Noise of Aircraft Equipped with Unducted Fan Engines for Largest Assumed Fleet

Eventual Maximum Number of Aircraft	3000
Average Hours of Utilization Per Aircraft-Day	7
Total Hours of Daily Fleet Utilization	21,000
Percent of Time in Cruise Conditions	80
Statute Miles Traversed by Non-metropolitan portions of High Altitude Routes	160,000
Non-metropolitan High Altitude Statute Route Miles Flown Daily	9,000,000
Daily Overflights of Non-metropolitan Points throughout Network	56
Average Noise Intrusions per hour in Non-metropolitan Areas throughout Network	4

Table 3-3: Summary of Assumptions About En Route Noise of Aircraft Equipped with Unducted Fan Engines for Smallest Assumed Fleet

Eventual Maximum Number of Aircraft	300
Average Hours of Utilization Per Aircraft-Day	7
Total Hours of Daily Fleet Utilization	2,100
Percent of Time in Cruise Conditions	80
Statute Miles Traversed by Non-metropolitan portions of High Altitude Routes	160,000
Non-metropolitan High Altitude Statute Route Miles Flown Daily	900,000
Daily Overflights of Non-metropolitan Points throughout Network	6
Average Noise Intrusions per hour in Non-metropolitan Areas throughout Network	.25

One of the more straightforward ways to derive an order of magnitude estimate of the total population to which en route noise emissions are audible is thus to subtract the population residing in Standard Metropolitan Statistical Areas (SMSAs) from the total U.S. population. Based on information in U.S. Bureau of the Census (1986), the resulting estimate of the non-metropolitan population of the United States is 56,000,000 people.

3.3.2 Assumptions about Average Population Density of Non-Metropolitan Areas

The total land area of the United States is 3.54 x 10^6 square miles. Excluding the land area of Alaska and Hawaii (relatively little of which is overflown by high altitude jetways) reduces this figure to about 2.96 x 10^6 square miles. Reducing this figure further by subtracting both urban and uninhabited land areas (including park and wilderness areas) yields an estimate of 2.34 x 10^6 square miles, or roughly 80% of the land area of the contiguous 48 states.

Dividing the non-metropolitan population of 56 million people by this latter area estimate yields an average population density of about 24 people per square mile in non-metropolitan areas of the contiguous 48 states.

3.3.3 Assumption about Distribution of Non-Metropolitan Population with Respect to High Altitude Routes

It is assumed for the sake of tractable calculations that people living in non-metropolitan areas who can hear en route aircraft noise are uniformly distributed throughout the non-metropolitan land area, even though in reality many of these 56 million people live in small communities.

3.3.4 Assumptions about Land Areas Exposed to En Route Noise

It is assumed that levels produced by aircraft flyovers at 35,000 feet remain within ±3 dB of their value at the center of the ground track within an 8 mile corridor centered on the ground track (±4 miles laterally from the flight track).

Given a total length of 200,000 miles for high altitude jet routes and the assumption that non-metropolitan areas underlie approximately 80% (160,000 miles) of the distance along these routes, it follows that roughly 30 million people (24 per square mile over 1.28 x 10^6 square miles) living within an eight mile wide corridor beneath high altitude routes are exposed to en route noise.

3.4 Assumptions about Spectral Shapes of Ambient Noise Environments

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. Table 3-4 shows population densities found throughout the country.

Table 3-4: Characterizations of Areas by Population Density

Density (people/mi^2)	*Nature of Area*
0	Uninhabited
24	Average rural density
500	Quiet suburb or small town
5,000	Median density for urban areas
50,000	High density downtown area

Galloway, Eldred, and Simpson (1974) have shown that outdoor noise exposure grows directly with population density:

$$L_{dn} = 10 \log \rho + 22 \text{ dB}$$

where ρ is population density in people per square mile and L_{dn} is the symbolic representation of Day-Night Average Sound Level (DNL).

In short, people and their machines make noise; the more people there are per unit area, the more noise is produced. The mean DNL in uninhabited areas is often on the order of 30 dB or lower. In sparsely settled areas (ρ less than or equal to 100) DNL values of 35-40 dB are common; for rural areas (ρ about 500), the estimate is on the order of 50 dB; and in low density suburban areas (ρ about 2,500), the estimate is about 55 dB. In industrial society, transportation noise -- both individual vehicle passbys, and traffic on distant roads -- is the major source of community noise exposure. DNL values in the 60-70 dB range are common in major urban areas, and values as high as 80-85 dB have been observed in the vicinity of major urban airports.

The seeming unpredictability of moment-to-moment fluctuations in urban noise levels is underlain by considerable regularity. The distribution of ambient levels observed at any given location in an inhabited area may be regarded as the sum of two noise processes (Fidell, Horonjeff and Green, 1981). One of these (the distant process) has a low mean and variance, while the other (the local process) has a high mean and variance. The former is composed of noises from a multitude of noise sources remote from the point of observation. The latter is composed of noises produced by a relatively small number of sources in proximity to the point of observation.

At times of day when human activity is greatest in inhabited areas, the mean of the local process can exceed that of the distant process by 10 dB or more, thus dominating integrated metrics of noise exposure. At times of minimal activity (late night/early morning), the distant process predominates much of the time. There are also many times, however, when there is considerable momentary overlap between the distant and local processes. For example, if the mean of the distant process is 50 dBA and its standard deviation is 5 dB, and if the mean of the local process is 65 dBA and its standard deviation is 10 dB, then sounds on the order of 55 dBA are fairly likely to occur both in the distant and local processes.

In areas of very high population density, the mean of the local process may not be much greater than that of the distant process, so that the total range of variability in exposure levels throughout the day is greatly reduced in comparison with the variability observed in areas of low population density. At all times of day and over all population densities, there is less variability in low frequency noise levels than in the high frequency levels. This is particularly true for the distant noise process, because long distance propagation of acoustic energy through the atmosphere favors low frequencies.

Running water, interactions of wind and precipitation with foliage, and animal (especially insect and bird) sounds are responsible for much of the ambient noise audible in sparsely populated areas and uninhabited places. In remote arid areas lacking vegetative ground cover and large insect populations, ambient noise levels as low as 20 dBA are not uncommon, with diurnal standard deviations as small as 1 to 2 dB. Wind, water, and animal sounds in temperate climates may increase these levels to about 30 to 40 dBA, with diurnal standard deviations of 5 to 10 dB. Even higher ambient noise levels may be observed in proximity to surf and waterfalls and in environments hospitable to large seasonal insect populations.

In fact, ambient noise environments in low population density and uninhabited areas can vary in level from the nearly inaudible to the very noisy. Absent insect, water and wind noise, ambient levels in arid areas in much of the American West may be lower in level than the human threshold of hearing (the internal noise floor of human observers), especially at frequencies above 1 kHz. Such noise levels are difficult to measure without taking extreme measures to avoid instrumentation noise floors and other forms of self-noise. On the other hand, large insect and animal populations in more temperate climate zones can create ambient sound distributions at some times of day and seasons of the year rivaling those of inhabited areas.

Figure 3-2 plots spectral distributions of ambient noise over a range of population density conditions. The spectra for the higher population density cases reflect extensive empirical measurements. The spectra for the lower population density cases are composites constructed from smaller numbers of empirical measurements and extrapolations of trends observable in the higher density cases.

3.5 Implications of Assumptions about Exposed Populations

One inference that can be drawn from noise exposure assumptions made for the largest fleet case is that if and when 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.[4] The number of hourly noise intrusions produced at any one spot 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. Even under optimistic assumptions about the rate of adoption of unducted fan engines into the fleet, a more reasonable estimate of the likely number of daily noise intrusions created at any one spot by aircraft equipped with unducted fan engines within a decade of the start of operations is on the order of one per hour. In the short term (say, within a few years of entry into service of aircraft equipped with unducted fan engines), it is unlikely that individuals would hear more than a few such aircraft per day.

3.6 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 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

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[4] This estimate embodies the further assumption that relatively few air transport operations will occur during night time hours, and that the relatively low absolute levels produced en route are unlikely to awaken people (Pearsons, Barber and Tabachnick, 1989).

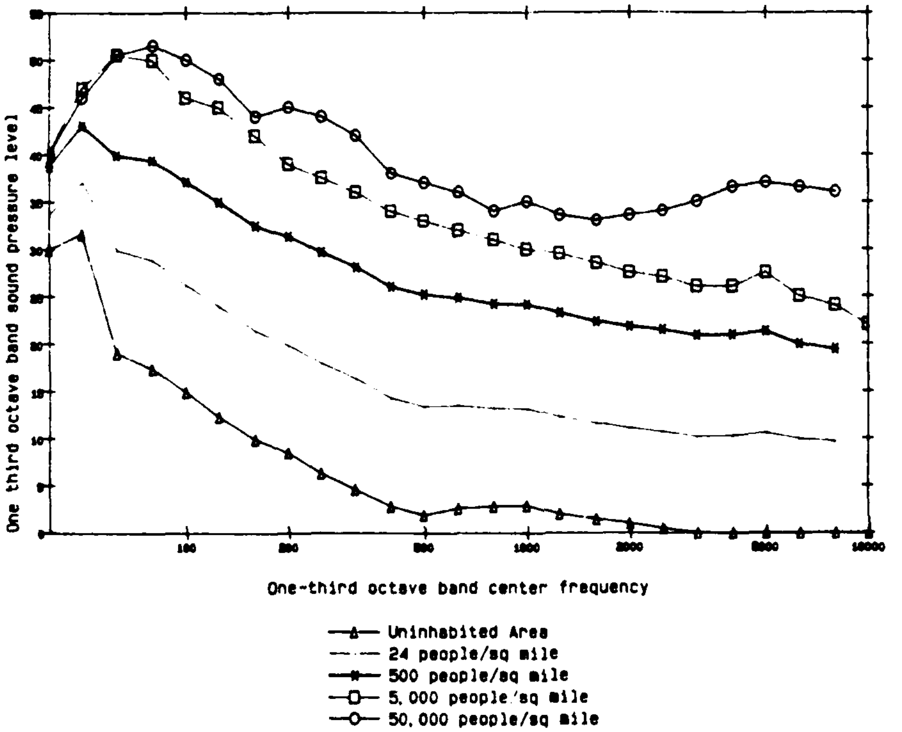

Figure 3-2: Long-Term Average Ambient Levels as Functions of Population Density

predictions of equivalent numbers of operations of different aircraft types, equivalent prevalence of annoyance, and other derivative measures.

This strategy was implemented in two steps. First, the integrated audibility of each flyover spectrum was calculated as described in Section 3.6.1. Second, the integrated audibility estimates were transformed through a dosage-effect relationship into predicted probabilities of annoyance, as described in Section 3.6.2.

3.6.1 Estimating Audibility

Existing software utilizing algorithms described by Fidell, Secrist, Harris, and Sneddon (1989) was modified to perform the audibility calculations needed to support the present analyses. All calculations were carried out with a frequency resolution of one-third octave band and a temporal resolution of half a second. Predictions of audibility were generated for the three aircraft signatures normalized to four A-weighted sound pressure levels in five ambient noise environments.

The software adjusted each half-second sample throughout the course of each flyover by the difference between the maximum A-level of the flyover and the four normalization levels (50, 55, 60, and 65 dBA). A further adjustment of -1.5 dB was made in all frequency bands of all spectra to represent average exposure levels throughout the eight mile wide corridor defining the 3 dB down exposure zone about the flight track.

A Doppler-shifting algorithm adjusted the emitted frequency of the tone of the unducted fan engine at half-second intervals to the frequency observed at a single point on the ground directly underneath the flight track. These Doppler-compensated half-second spectra were further adjusted by addition of constants needed to adjust the broadband audibility estimates for tonal signals, as described by Fidell and Horonjeff (1982).

The audibility of the resulting spectra was predicted by procedures originally developed in the early 1970s (cf. Fidell, Pearsons and Bennett, 1974). The procedures model the human observer as a simple energy detector of fixed sensitivity, whose performance can be fully specified in terms of the ratio of probabilities of hits (assertions that a signal is present when in fact it is) to false alarms (assertions that a signal is present when in fact it is not - in statistical parlance, a Type I error). The detector operates according to Bayes' Law of Inverse Probability; that is, by inferring which of two distributions is more likely to have generated its input.

The input to the observer is a sample of sound which may have been generated by a noise process alone or by a combination of a noise and a signal process. The observer's task is to decide whether the input is more likely to have been generated by the noise process alone or by the signal plus noise process. The observer makes this decision by calculating a likelihood ratio (a ratio of the probabilities that the input was generated by the distribution of noise alone and that the input was generated by the distribution of signal plus noise), and interpreting this likelihood with respect to a decision criterion based on the a priori odds of occurrence of the signal and the costs and payoffs of correct and incorrect decisions. The more closely the distributions of noise alone and signal plus noise resemble one another, the more the observer's performance (ratio of hits to false alarms) is degraded. Green and Swets (1966) provide a detailed discussion of the theoretical foundations of this approach.

A scalar quantity known as d' completely describes the sensitivity of the observer and can be used to calculate a criterion (that is, a degree) of audibility. The calculation of d' is performed by determining the difference between two normal deviates: one for the distributions of noise alone and one for the distribution of signal plus noise. The standard assumptions about normality of distribution and homogeneity of variance in the noise alone and signal plus noise distributions are made (cf. Elliott, 1966).

As described by Fidell and Bishop (1974), the acoustic basis for detection decisions is the bandwidth-adjusted signal-to-noise ratio at the ear, calculated for each frequency band within the observer's frequency sensitivity limits:

$$d' = \eta \; S/N \; W^{.5}$$

where η is a parameter that reflects the efficiency of the detector with respect to an ideal energy detector, S is the signal level in a one- third octave band, N is the external (to the ear) ambient noise level in the same one-third octave band, and W is the width of the first stage human auditory input filter.

This relationship can be expressed in logarithmic form as

$$10 \; log(d') = 10 \; log \; (\eta \; S/N \; W^{.5})$$

Algebraic manipulation of the logarithmic form of the expression for calculating d' from acoustic quantities yields a more convenient form of the expression for computational purposes:

$$10 \; log \; (S/N) = 10 \; log \; d'/\eta W^{.5}$$

Human auditory bandwidths (sometimes called "critical bands") are proportional to one-third octave bandwidths at frequencies above about 250 Hz, but are wider than one-third octave bands at lower frequencies (Fidell, Horonjeff, Teffeteller, and Green, 1983). Prediction of audibility of aircraft noise intrusions is sufficiently computationally intensive that it is generally accomplished by standard software, such as the U.S. Army Tank-Automotive Command's Acoustic Detection Range Prediction Model (Fidell, Secrist, Harris, and Sneddon, 1989).

A measure of integrated audibility (a duration-adjusted index in units of d'-seconds) was developed from successive half-second sampled spectra throughout each aircraft overflight as shown below:

$$d'\text{-}seconds = 10 \; log_{10} \; \frac{1}{2} \sum_{i=1}^{n} d'_i \; + \; 10 \; log_{10} \frac{n}{2}$$

where d'_i is the maximum d' for a single half-second sample and n is the total number of half-second samples.

3.6.2 Development of Function Relating Audibility to Annoyance

The estimates of integrated audibility of aircraft noise intrusions were interpreted by means of a transfer function relating audibility to the immediate annoyance of individual overflights. Although relatively little empirical information is available about the relationship between the audibility and annoyance of low level noise intrusions, it is nonetheless possible to construct dosage-response relationships for varying degrees of audibility and annoyance as described below.

Relationships between audibility and annoyance have been explicitly investigated in three data sets. The first of these data sets (Fidell and Teffeteller, 1981) explored the annoyance reported by ten test subjects playing a video game when exposed under free field listening conditions to noise intrusions produced by ten familiar noise sources. The ambient noise distribution in the anechoic chamber in which the test subjects were seated was composed of Gaussian noise with a spectral shape similar to PNC-40. Noise intrusions were presented in ascending and descending staircases with 1 s risers and 20 s treads. Signal presentation levels ranged over 50 dB in 2 dB steps.

Subjects were asked to indicate when they first noticed a noise intrusion, and to rate the annoyance of the noise intrusion on an absolute judgment scale composed of the following five categories: Not at all Annoying, Slightly Annoying, Moderately Annoying, Very Annoying, and Extremely Annoying. Frequencies of annoyance ratings in each response category were tabulated in 5 dB increments.

The next two data sets were collected in a two part study conducted by Fidell, Silvati, and Secrist (1989). A total of 39 subjects rated the annoyance of 10 transportation noise and synthetic noise sources while engaged in a demanding proofreading task. The test signal levels ranged in level from 60 dBA to 90 dBA in Part 1 of the study, and from 66 dBA to 96 dBA in Part 2 of the study. Signal durations were 9.3 seconds in each part of the study. Signals were presented at random levels in counterbalanced blocks of 25 trials. Signals were presented on half of all trials at random. Both the response scale and the background noise in the anechoic chamber were identical to those employed in the study of Fidell and Teffeteller (1981). Frequencies of annoyance ratings in each annoyance category were summarized across five levels of signal presentation.

The audibility of noise intrusions in both studies was quantified as described in Section 3.6.1. The difference in durations of signal presentations between the former and the latter studies was accounted for by a 10 log duration adjustment.

Probabilities of annoyance responses in each scale category were summarized in cumulative probability distributions describing the relative frequency of occurrence of responses in categories of increasing annoyance. These were plotted (on the ordinate) against 10 log d' + 10 log duration (on the abscissa) separately for each study. These plots display the probability of a report of annoyance for each response category or greater in 5 dB-wide increments of audibility. Least-squares regressions were then calculated for the distributions about each annoyance category for each study.

The slopes of the regressions observed by Fidell and Teffeteller were appreciably steeper than those of the latter study. The probability of reporting slight or moderate annoyance to a noise intrusion in this study doubled over a range of 6.1 dB. The rates of increase of annoyance with audibility observed in the latter study were considerably shallower, doubling over 9.7 dB and 15 dB, respectively. These differences in the rates of growth of annoyance with audibility were interpreted in the context of a probabilistic model of annoyance (Fidell, Green, Schultz, and Pearsons, 1988) as functions of two variables: the attention demand of ongoing activity and the affective state of the test subjects at the time of occurrence of the noise intrusion.

For simplicity of interpretation and to avoid the arbitrariness of weighting the regression coefficients for the relationships observed in the three studies, a dose-response relationship was defined by the average slopes and intercepts observed in the three studies. Figure 3-3 plots these relationships. The regression equation for the probability of high annoyance (that is, a self report of "very" or "extremely" annoying) is:

$$p(\text{High Annoyance}) = .0173(10 \log d'\text{-seconds}) - .7166$$

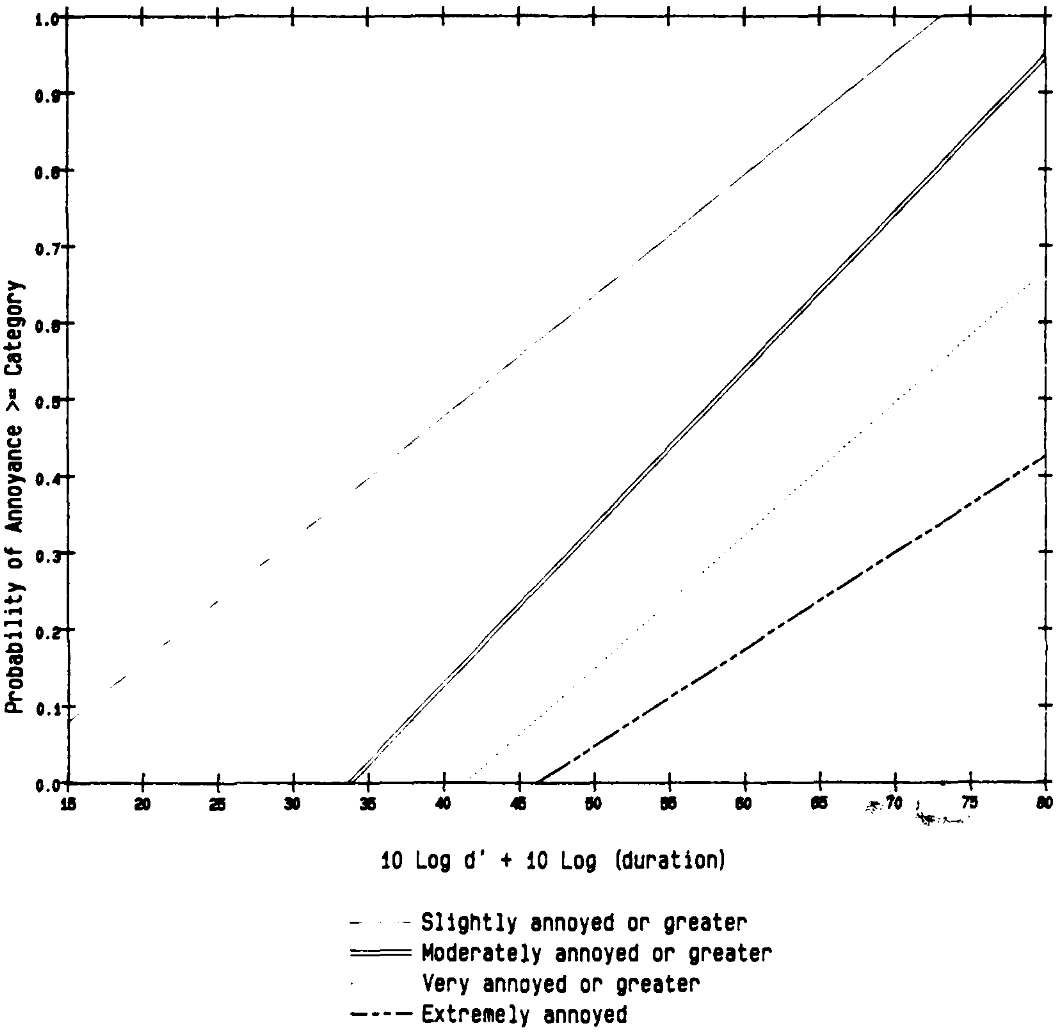

Figure 3-3: Dosage-Response Relationships between Integrated Audibility and Probability of Annoyance in Varying Degrees

4. Results

4.1 Results of Audibility Calculations

Figures 4-1 through 4-4 compare the predicted audibility of individual overflights of aircraft powered by unducted fan, Stage II (B-727), and Stage III (DC-10) engines in ambient noise environments representative of the range of population densities listed in Table 3-4. Each figure illustrates audibility estimates for single overflights of the three aircraft types for one assumed cruise noise level (50, 55, 60, and 65 dBA). For example, Figure 4-1 shows the audibility of the three types of aircraft at an assumed level of 50 dBA. Aircraft powered by the unducted fan engines are more audible in all population density conditions than aircraft powered by Stage II engines, which in turn are more audible than aircraft powered by Stage III engines. This relationship is consistent for higher levels of cruise noise exposure as well, as seen in Figures 4-2 through 4-4.

4.2 Results of Single Event Annoyance Calculations

Figures 4-5 through 4-8 parallel Figures 4-1 through 4-4 by illustrating the probability of high annoyance associated with single overflights by aircraft equipped with unducted fan, Stage II, and Stage III engines in the same range of ambient noise environments. For example, Figure 4-5 shows that the probability of high annoyance is greatest in uninhabited areas for the unducted fan engine, lower for low bypass ratio engines, and lowest for high bypass ratio engines. The same relationship holds in the average rural population density case. In the background noise environment assumed for a quiet suburb, only the unducted fan engine is audible enough to create a non-zero probability of high annoyance. These trends persist at higher levels of cruise noise exposure as well, as seen in Figures 4-6 through 4-8.

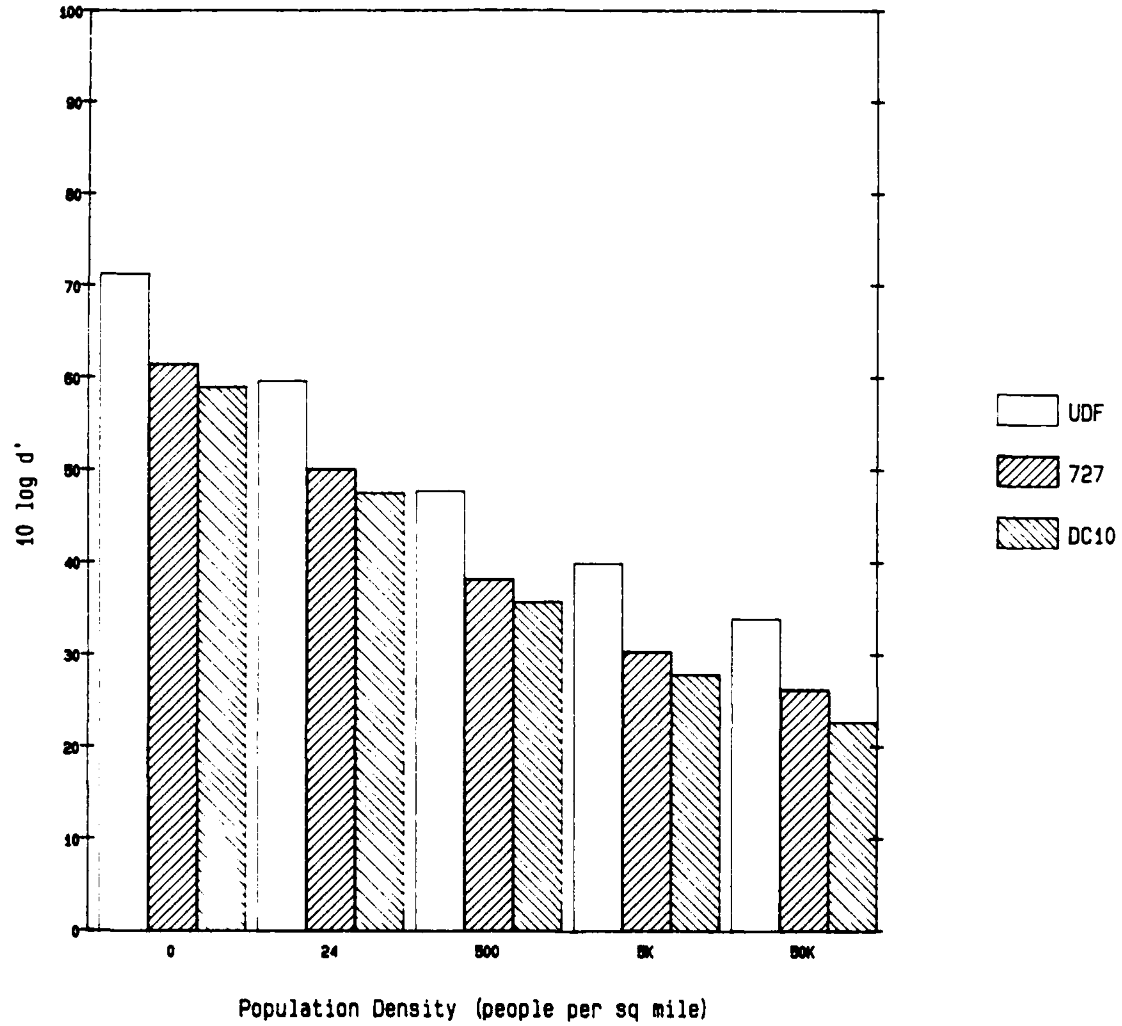

Figure 4-1: Comparison of Predicted Audibility of Three Types of En Route Aircraft Noise and Five Levels of Population Density (Cruise Noise Level Normalized to 50 dBA)

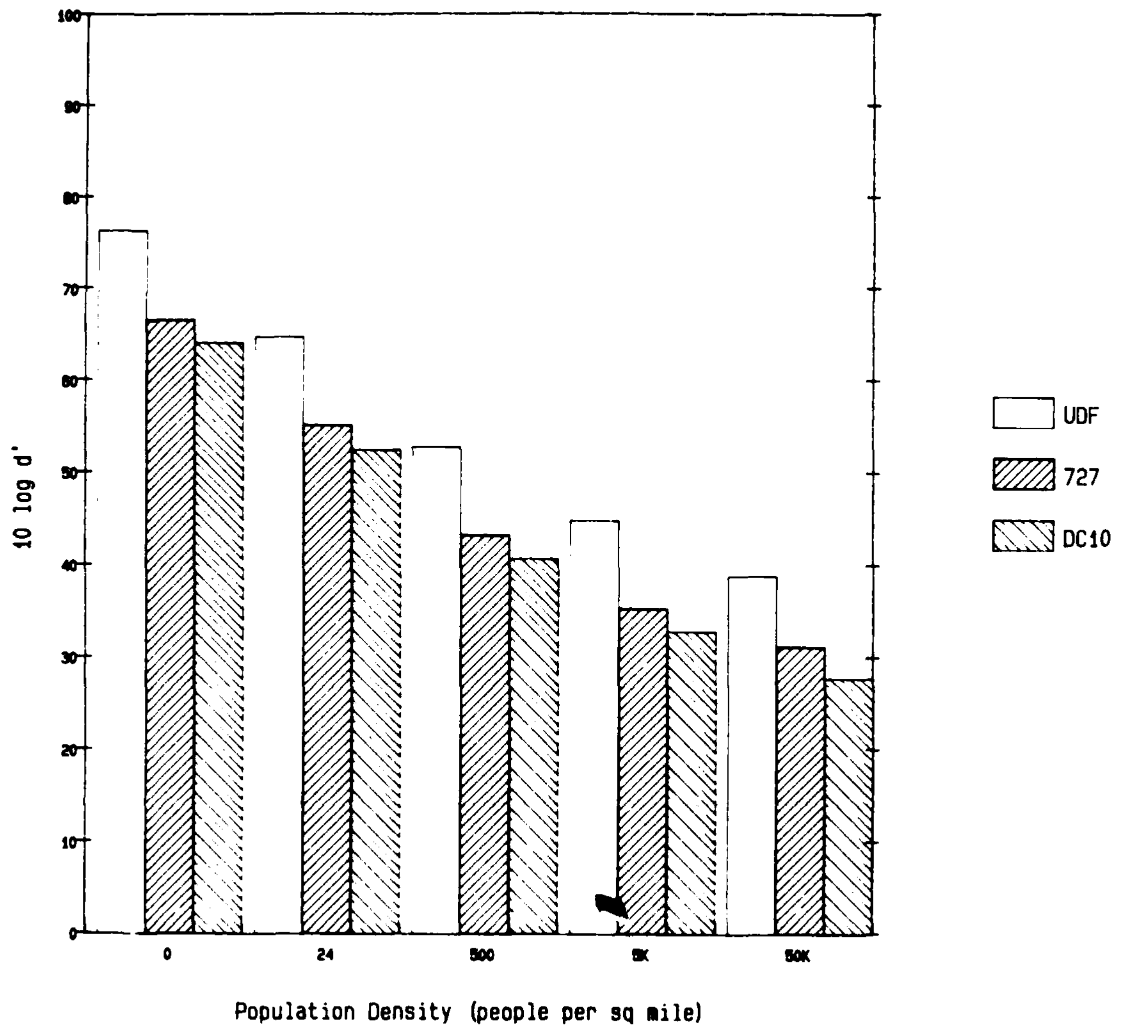

Figure 4-2: Comparison of Predicted Audibility of Three Types of En Route Aircraft Noise and Five Levels of Population Density (Cruise Noise Level Normalized to 55 dBA)

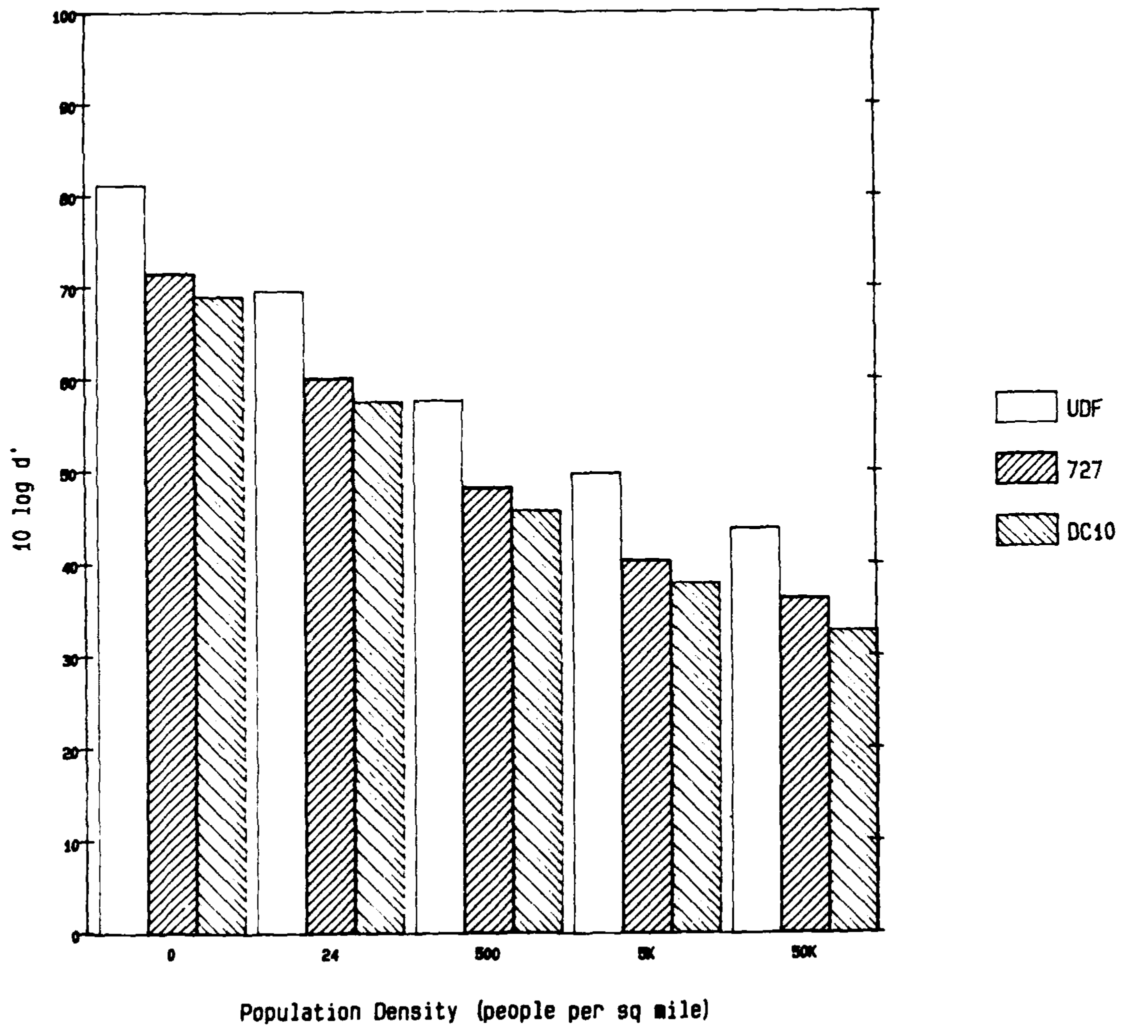

Figure 4-3: Comparison of Predicted Audibility of Three Types of En Route Aircraft Noise and Five Levels of Population Density (Cruise Noise Level Normalized to 60 dBA)

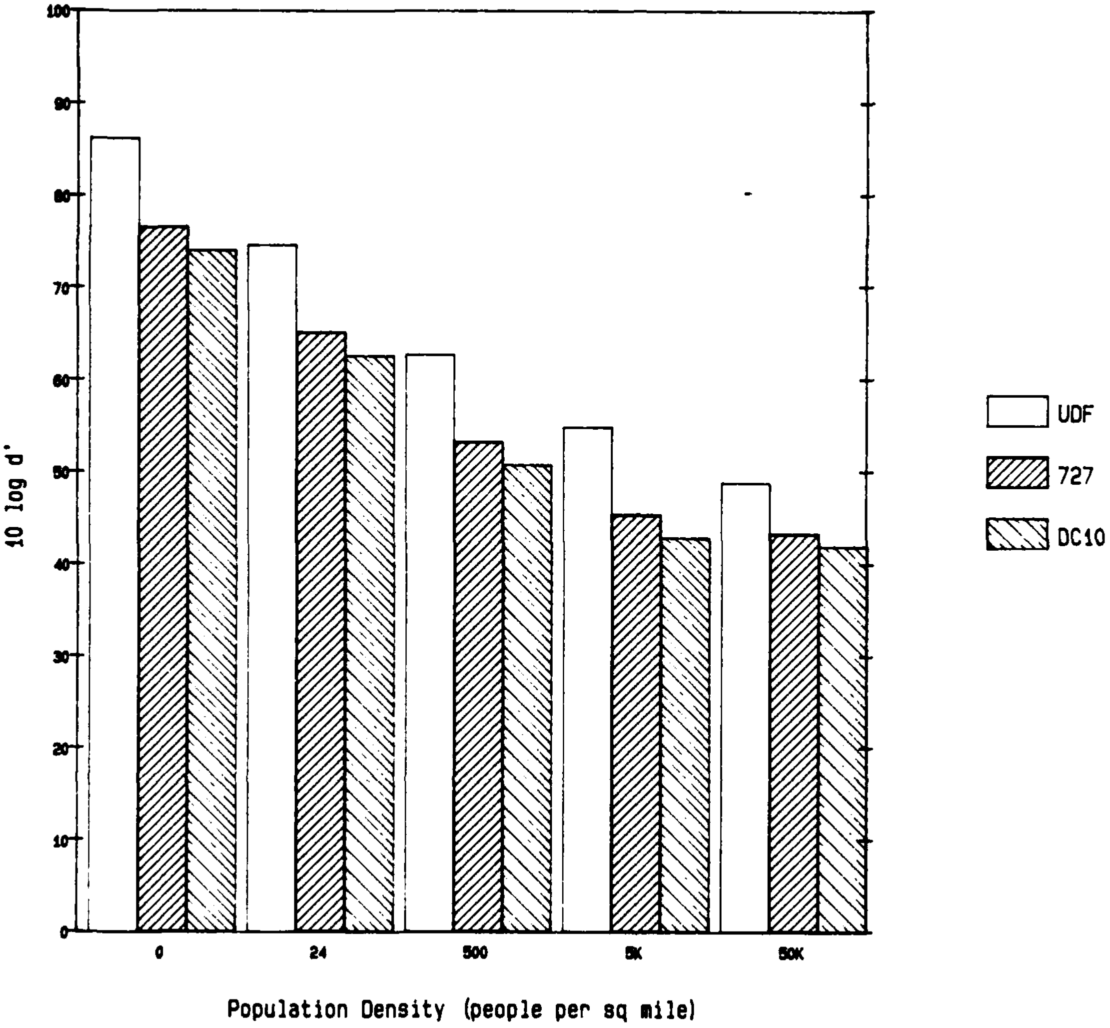

Figure 4-4: Comparison of Predicted Audibility of Three Types of En Route Aircraft Noise and Five Levels of Population Density (Cruise Noise Level Normalized to 65 dBA)

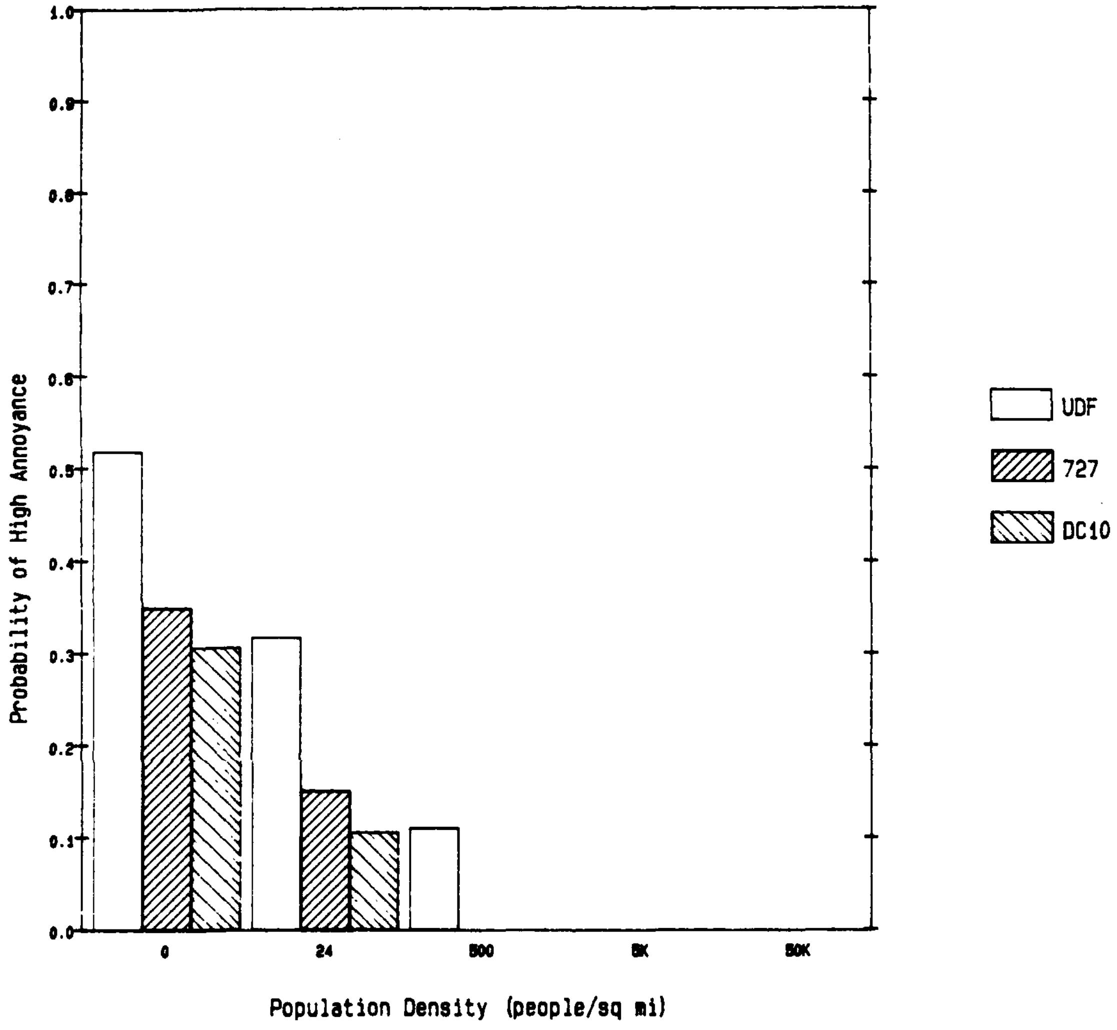

Figure 4-5: Comparison of Predicted Annoyance of Three Types of En Route Aircraft Overflights and Five Levels of Population Density for Cruise Noise at 50 dBA

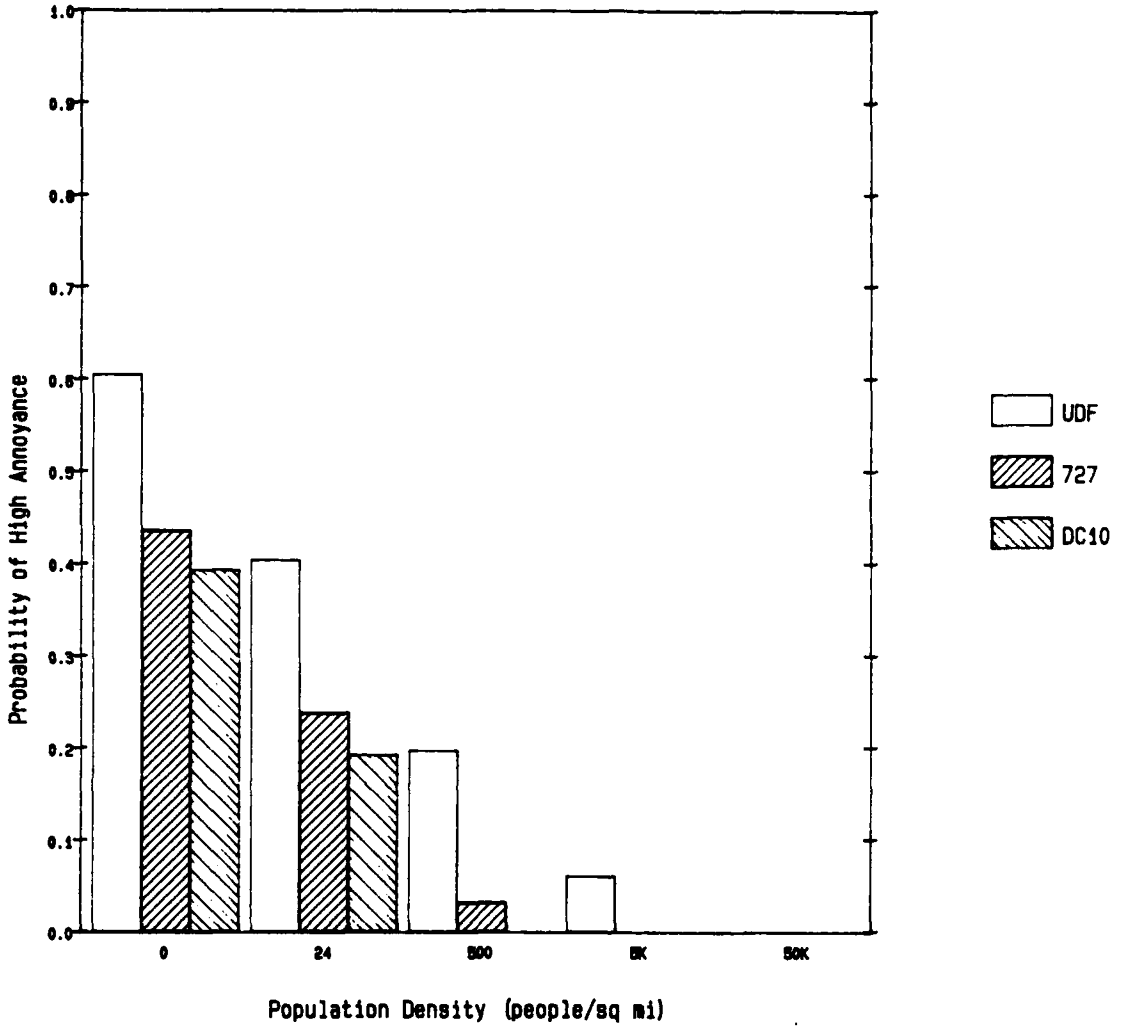

Figure 4-6: Comparison of Predicted Annoyance of Three Types of En Route Aircraft Overflights and Five Levels of Population Density for Cruise Noise at 55 dBA

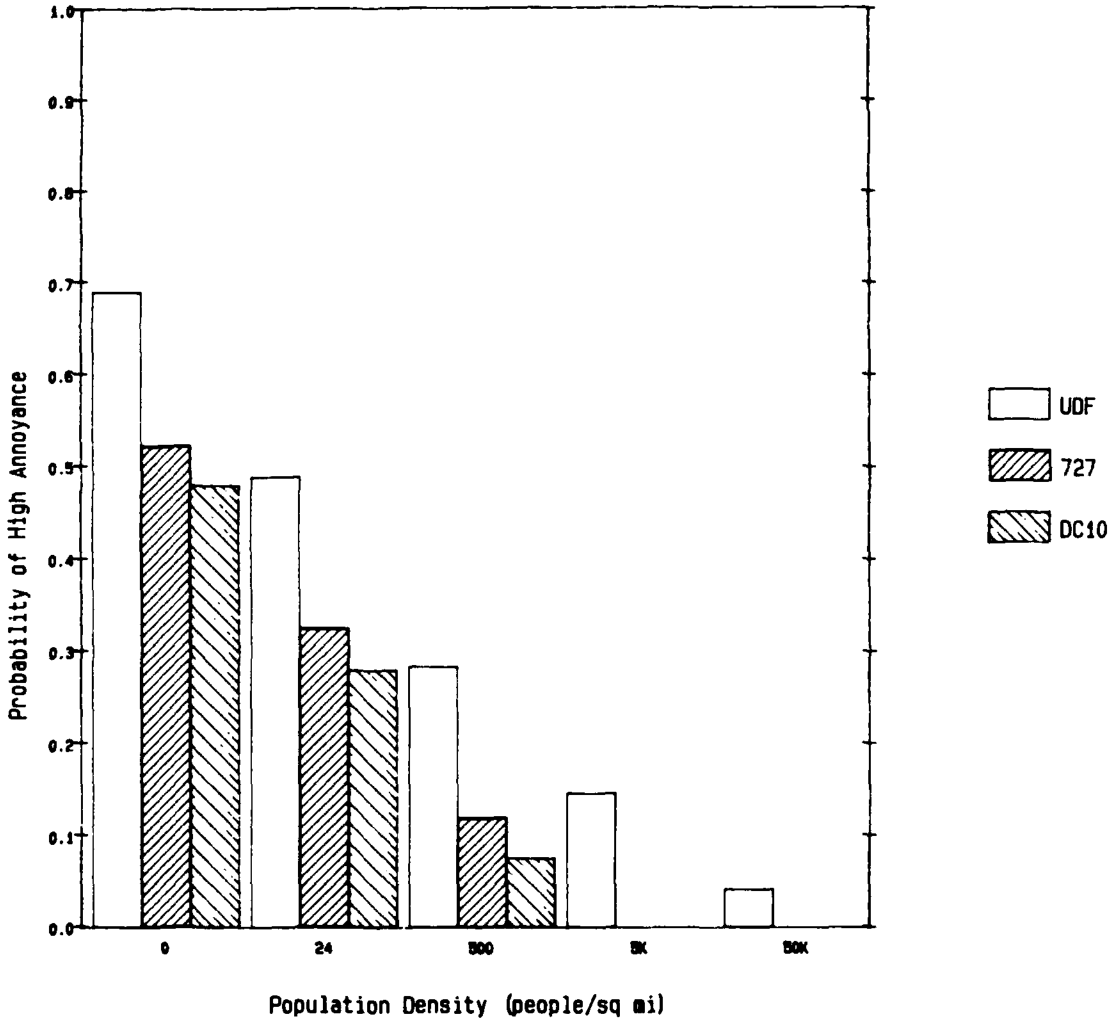

Figure 4-7: Comparison of Predicted Annoyance of Three Types of En Route Aircraft Overflights and Five Levels of Population Density for Cruise Noise at 60 dBA

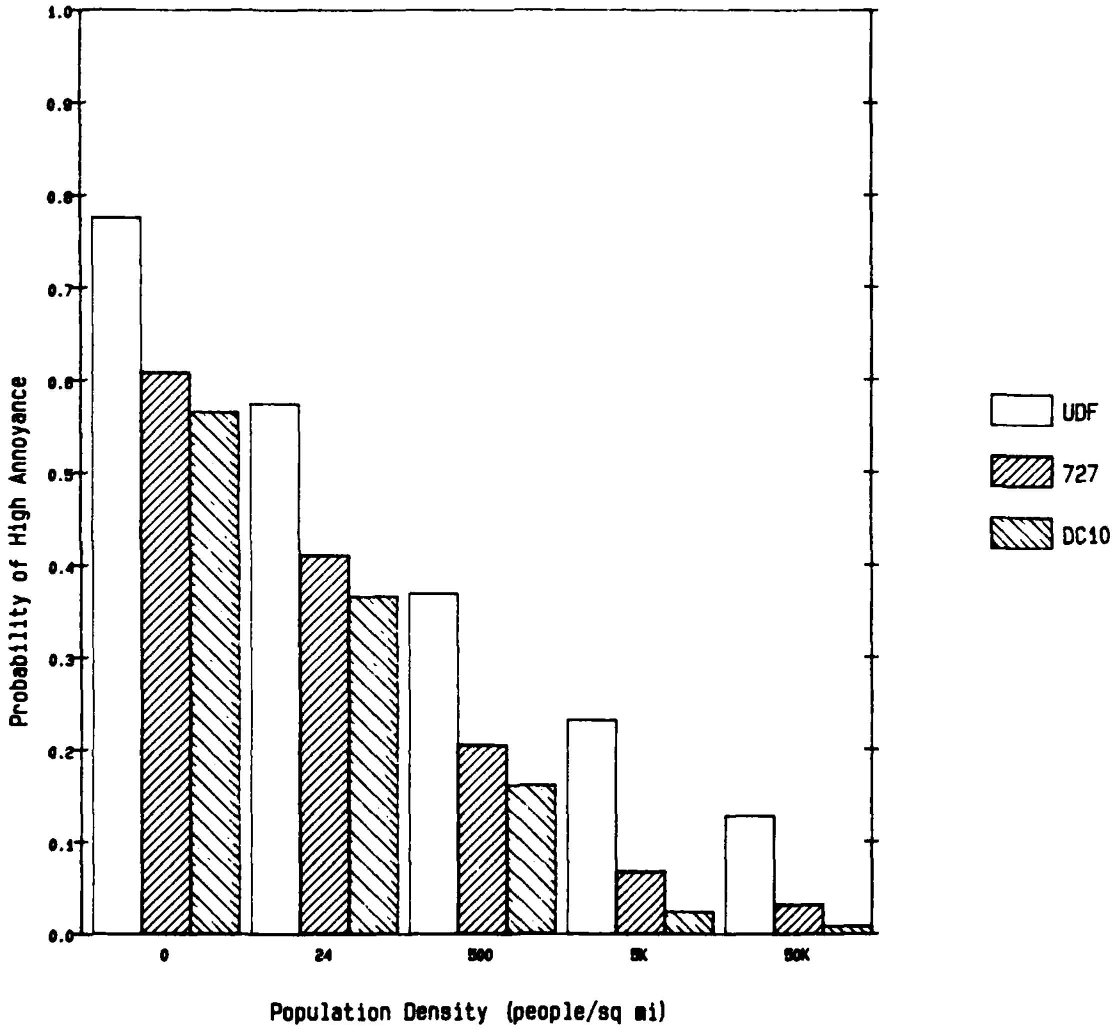

Figure 4-8: Comparison of Predicted Annoyance of Three Types of En Route Aircraft Overflights and Five Levels of Population Density for Cruise Noise at 65 dBA

4.3 Expectations of Single Event Annoyance by Exposed Population

A population-based interpretation of community response to en route noise produced by high altitude overflights may be developed by applying the per-event annoyance estimates developed in the preceding section to a specified population. This is done in Table 4-1 for the case of the total population in areas outside of SMSAs. The probabilities of annoyance shown in Figures 4-5 through 4-6 are treated as binomial proportions to derive the estimates of Table 4-1. Each person is assumed to be either highly annoyed (p) or not highly annoyed (q = 1-p) by each flyover. The expectation of the binomial distribution in simply Np, or the product of the number of people exposed and the probability of high annoyance per flyover. The figures in Table 4-1 are expectations based on a population of 30 x 10^6 people (cf. Sections 3.3.1 through 3.3.3).

It is clear from Table 4-1 that more people will be highly annoyed by individual overflights of aircraft powered by unducted fan engines than by overflights of Stage II and Stage III aircraft at all levels of exposure.

Table 4-1: Predicted Number of People (in millions) Living Outside of SMSAs Highly Annoyed by Individual High Altitude Flyovers

A-Level of Individual Flyover (dB re 20 μPa)	*Unducted Fan*	*Stage II*	*Stage III*
50	9	5.1	3.9
55	12.6	7.5	6.3
60	15	10	8.7
65	17.4	12.6	11.4

5. Discussion

The figures presented in Table 4-1 suggest not only that large numbers of people might be annoyed by high altitude overflights of aircraft powered by unducted fan engines, but also that millions of people are currently highly annoyed by high altitude overflights of Stage II and Stage III aircraft. Since the figures presented in Table 4-1 are expectations of self-reports of annoyance per overflight, however, they may not be interpreted directly as numbers of people who would report long term annoyance with exposure to the noise of unducted fan engines. These figures are not, therefore, comparable with those predicted by relationships derived from social survey findings (e.g., the dosage-response relationship derived by Schultz, 1978).

In fact, despite considerable study of the relationship between numbers of events and cumulative annoyance (cf. Rice, 1980 and Fields, 1984), it remains unclear how long-term attitudes are related to the annoyance of individual overflights. Thus, the most straightforward interpretation of the figures presented in Table 4-1 may simply be in terms of relative percentages of highly annoyed people, as shown in Figure 5-1.

As shown in Table 5-1, sizable increases may be expected in the percentage of people in rural areas who are highly annoyed by high altitude overflights of aircraft equipped with unducted fan engines with respect to the numbers of people currently annoyed by overflights of aircraft equipped with low and high bypass ratio jet engines.

Table 5-1: Percent Increase in Prevalence of Annoyance of Exposure to Noise of Unducted Fan Engines with Respect to Exposure to Low and High Bypass Ratio Engines

A-Level of Individual Flyover (dB re 20 μPa)	*Unducted Fan versus Stage II*	*Unducted Fan versus Stage III*
50	176	231
55	168	200
60	150	172
65	138	153

Absolute increases in numbers of people highly annoyed by en route noise of unducted fan engines are more difficult to predict for several reasons:

- The mere novelty of the noise source the may attract attention upon its introduction into service;
- The difference between the nondescript character of conventional cruise noise and the readily-recognizable tones of unducted fan engines may increase the identifiability of en route noise created by unducted fan engines; and
- Other nonacoustic factors (as discussed by Fidell, Green, Schultz, and Pearsons, 1988) may increase the likelihood that unducted fan engine noise will be considered annoying.

6. Summary of Findings

Analyses of the audibility of en route noise emissions of high altitude overflights of aircraft powered by unducted fan engines and by low and high bypass ratio engines require numerous assumptions about fleet composition, utilization, and routes, as well as about overflown populations and ambient noise distributions. The net effect of all of these assumptions is to produce a plausible range of an order of magnitude in terms of numbers of overflights per hour: from .25 to 4 overflights per hour, corresponding to fleets of 300 to 3000 transport aircraft.

Since the ground level cruise noise signature of production aircraft equipped with unducted fan engines can only be approximated from the emissions of an experimental aircraft, comparisons of the relative annoyance of a hypothetical twin engine aircraft powered by unducted fan engines and of Stage II and Stage III aircraft were made at four A-weighted sound pressure levels: 50, 55, 60, and 65 dBA. It was found that the noise signature of a hypothetical twin engine transport aircraft powered by unducted fan engines was more audible than those of Stage II and Stage III aircraft powered by low and high bypass ratio engines. The differences in audibility were attributable in large part to the presence of tones in the emissions of the unducted fan engines. The differences in audibility are reflected in similar differences in predicted annoyance derived from a dosage-response relationship based on laboratory data.

Population-based extrapolations of the predicted annoyance estimates indicate that millions of people living in rural areas of the United States could be highly annoyed by en route noise emissions of aircraft equipped with unducted fan engines.

Acknowledgments

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