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Improved Aircraft Acoustic Technology and its Effect on Airport Community Noise Impact

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Introduction

The growth of commercial aviation since the introduction of jet-powered aircraft has been immense. Over that time period the concerns of residents regarding noise in the vicinity of airports have continued despite large reductions in the noise associated with individual aircraft. Figure 1 shows noise levels of many aircraft types at the time they received FAA certification. The levels are derived from data that is acquired in accordance with FAA and ICAO noise certification rules and procedures [1, 2]. These rules require measurements to be made at three locations (on approach to landing, sideline on takeoff, and cut-back on takeoff) that span a range of engine thrust conditions and aircraft configuration settings (e.g., flaps and landing gear). Figure 1 plots the average of the three measurements and also shows the noise limits that were in effect at the time of certification, referred to as Chapters 2, 3, 4, and 14 in the ICAO regulations. It is clear that noise levels and regulatory requirements have steadily changed from the 1950s until the present day.

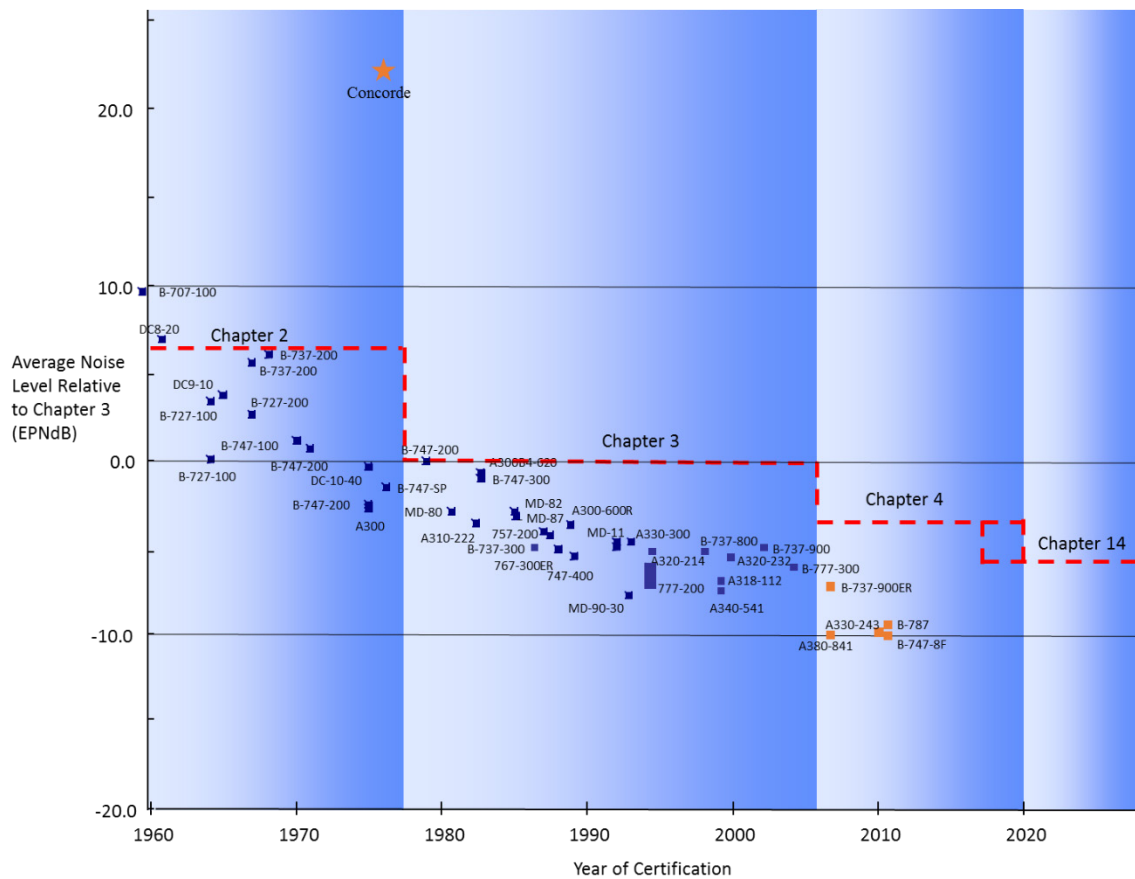


Figure 1: Certified noise levels for selected aircraft and the year of certification.

Many airports make efforts to work with their neighboring communities, publishing noise exposure contours, providing information on their operations, and often providing noise data acquired using permanent noise monitors. The production of noise exposure contours at an airport typically involves the use of sophisticated models and highly-detailed information regarding aircraft ground tracks and trajectories and precise information regarding aircraft and engine types [3]. Flight schedules enable the generation of annual average noise estimates using a variety of noise metrics, the most common of which is Day Night Level (DNL) [4].

The focus of this paper is the development of a simple, empirical model to describe the effects of improvements in acoustic technology and of traffic growth on airport noise and impacted populations. It is aimed at macroscopic analyses and takes advantage of noise analyses performed at many individual airports to form an aggregated picture, which attempts to describe systemwide effects.

Model Development

The simplest building block of an airport noise prediction begins with a single aircraft operation, as depicted in Figure 2. The sound field associated with this aircraft is assumed to be axisymmetric, a cylinder of radius R centered on a constant climb or descent path. The intersection of this cylinder with the ground surface produces (one-half of) an ellipse, a contour of a given noise level determined by distance R from the aircraft. Airport noise contours are composed of numerous operations of many aircraft types with different operating weights and engine thrust settings, all of which are expected to produce elliptical contours of varying sizes, the sum of which is similarly elliptical. This simple model ignores the vagaries of ground tracks, trajectories, flight speeds, etc. and assumes that the “average” aircraft follows a flight track with approximately constant climb/descent angle. In addition, the noise associated with runway operations (takeoff and landing roll, thrust reversers and taxiing) is ignored. It is also assumed that the multitude of component noise sources associated with an aircraft (e.g., fans, jets, airframe, etc.) are, in aggregate, axisymmetric. This is a reasonable assumption due to the similarity of aircraft in the modern fleet, most of which are twin-engined, underwing, configurations. In the event that the fleet became dominated by a radically different configuration, for example one with engines mounted above a flying wing, noise contour shapes would change significantly, likely becoming shorter and wider.

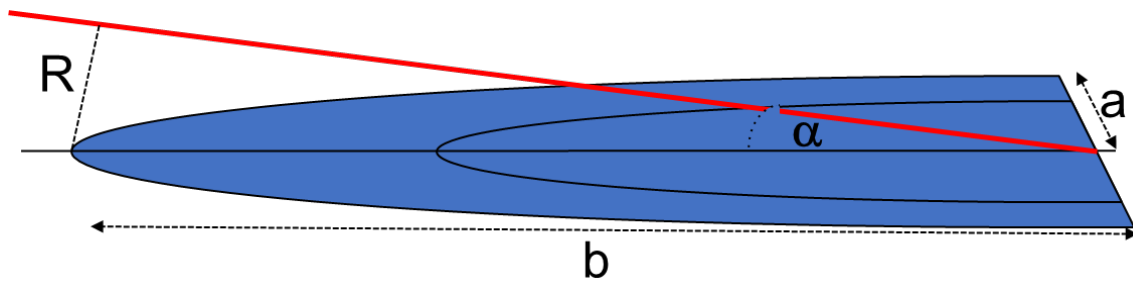


Figure 2: Nominal noise contours associated with an aircraft landing or departing.

Airports with significant numbers of commercial jet aircraft operate in much the same way as one another, with 3-degree aircraft descent angles on approach to each runway and one or more ground tracks on departure from each runway. Runway lengths are similar and can accommodate similar fleet mixes, although the numbers of operations vary considerably between airports, as does the number of runways. Inspection of many published airport noise contours indicates that they closely resemble a set of concentric semi-ellipses, some of which are curved due to ground tracks not being straight in and/or out. This observation regarding contour shapes serves two purposes; first it supports the simplifying assumptions that have been made in the model, and second, it enables estimates of contour areas to be made using published graphics. The area of half an ellipse in Figure 2 is given by

$$A = \frac{\pi R^2}{2 \sin \alpha} = \frac{\pi ab}{2} .$$

It should be noted that the climb/descent angle does not appear in the final expression so there is no necessity to differentiate between noise contours associated with the arriving and departing aircraft. A

large set of such contours was obtained from published sources, mostly online, for a range of large U.S. and European airports from various time periods. Contour areas were calculated at each airport for each ground track, typically for noise levels of 55 dB DNL (or equivalent) and higher. Ratios of contour areas (e.g., contours 10 dB apart) were computed for each ground track and at each airport. The number of such ratios that could be computed varied considerably from one airport to another, and depended on the size of the airport, the number of runways and the complexity of the airspace.

Before describing the analyses of published airport noise contours, there are some important assumptions that will be made that require explanation. Airport noise contours (expressed in DNL) are derived from a summation of individual aircraft events. The DNL value for a given observer location can be represented as a summation:

$$DNL = 10 \log_{10} \left\{ \sum_i N_i * 10^{\frac{SEL_i}{10}} \right\} - 49.4$$

where the subscript i represents a class of aircraft operations (e.g., B737-800, landing, daytime) and where N is the number of such operations in a day and SEL is the sound level at the particular observer location for a single flyover. The 10 dB penalty applied to nighttime operations in the DNL metric is captured in the SEL value. Consider observers located at the tips of two DNL contours associated with a given ground track and let the contours be separated by an interval of Δ dB. The most reasonable, and simple, assumption is that, on average, the SEL values associated with each class of aircraft operations will differ by the same Δ dB for the two observer locations.

A further assumption is that the flight path angle and the aircraft's acoustical characteristics remain constant over the distance associated with the two contours. Although this may not be the case for some aircraft operations (e.g., engine throttle "jockeying" on final approach), it must be remembered that the prediction models used to generate airport noise contours do not include such effects; the models implicitly assume that such variation "averages out" over the course of numerous flight operations. There is one characteristic of aircraft operations that can be captured in airport noise models that potentially violates the assumption regarding constant flight path angle and acoustical characteristics; that is noise abatement departure profiles, specifically engine power cutbacks. This would be problematic for analysis of airports at which large power reductions are used to protect specific areas on the ground. The best-known example is probably John Wayne Airport in Orange County, California, which, in years gone by, mandated deep power cutbacks over certain locations close to the airport. Today's quieter aircraft execute little or no power reduction when departing the airport [5]. This lack of power cutback behavior is common to the vast majority of airports.

Almost all airports and aircraft employ a 3 degree glide slope on final approach to landing. However, aircraft differ in their departure profiles, the number of engines being a primary factor because transport category aircraft must be capable of achieving a specified minimum climb rate should an engine failure occur. This requirement results in twin-engined aircraft having a steeper departure profile than three- or four-engined aircraft. For the current analyses, this is of little concern since twin-engined aircraft vastly outnumber other aircraft and hence they control airport noise exposure.

The ratio of airport contour areas was found to be, on average, 5.9 for DNL contours separated by 10 dB. It is expected that the ratio of SEL contour areas would, on average, be the same. More generally, let Z_1 and Z_2 be the SEL values of the inner and outer contours, respectively (i.e., $Z_1 > Z_2$). As shown in Figure 2, the SEL value for a particular aircraft operation is determined by distance R . Let R_1 and R_2 denote the distances associated with the inner and outer contours (Z_1 and Z_2), respectively.

The relationship between SEL and distance is controlled by several physical phenomena (e.g., geometrical spreading, atmospheric absorption, ground effects). It is assumed that these phenomena can be represented by:

$$\text{SEL} \propto 10 \log_{10} \left(\frac{1}{R^x} \right)$$

Then,

$$Z_1 - Z_2 = 10 \log_{10} \left(\frac{R_2}{R_1} \right)^x \quad \text{or} \quad \frac{R_2}{R_1} = 10^{\left\{ \frac{(Z_1 - Z_2)}{10x} \right\}}$$

The area, A , of a contour is proportional to R^2 , thus:

$$\frac{A_2}{A_1} = \left(\frac{R_2}{R_1} \right)^2 = \left(10^{\left\{ \frac{(Z_1 - Z_2)}{10x} \right\}} \right)^2 = 10^{\left\{ \frac{(Z_1 - Z_2)}{5x} \right\}}$$

As noted above, the area ratio of contours 10 dB apart was found to be 5.9. Thus, for $Z_1 - Z_2 = 10$ and $A_2/A_1 = 5.9$, x is found to be equal to 2.6.

An alternate formulation is:

$$Z_1 - Z_2 = 13 \log_{10} \left(\frac{A_2}{A_1} \right).$$

This result indicates that SEL is proportional to $10 \log_{10} (1/R^{2.6})$. In the absence of atmospheric sound absorption, and for an omnidirectional noise source, it is expected that SEL be proportional to $10 \log_{10} (1/R)$. This would result in contours 10 dB apart having area ratios of 100. Fortunately, this is not the case since atmospheric sound absorption is considerable, particularly at higher frequencies.

It is recognized that the form of the derived expressions above has no firm, physical basis and is purely empirical. As such, it likely will not be applicable to situations and conditions far removed from those used to generate it.

Some Observations Derived from the Model

Contour Areas

There are several observations that can be made regarding this simple, empirical model. Contours that are 10 dB apart have an area ratio of 5.9. Another observation concerns a scenario in which noise levels increase by 1 dB, a change often considered to be imperceptible. This change will result in a 19.4% increase in contour area, a significant change if the context is determining numbers of households eligible for sound proofing. This change is also in accord with the “rule-of-thumb”, well known to airport noise model practitioners, that a 1 dB change results in an approximate 20% change in area [6, 7].

Growth in Air Traffic

Recall that the empirical model is based on predicted DNL contours, and that DNL at any observer location may be thought of as being the summation of noise events (flyovers) associated with a number of aircraft types and operations (e.g., “N₁” flyovers of B737s on approach and “N₂” flyovers of A340s on

departure, etc.). It is a simple matter to examine changes in noise contours due to growth in air traffic. Assuming that the fleet mix stays constant and all operational parameters remain unchanged, then a doubling of the number of operations will simply increase noise exposure by 3 dB for all observer locations. This will cause noise contour areas to increase by a factor of 1.7, a 70% change. It is interesting to note that had the additional doubling of traffic been assigned to a new runway, or to a new airport, then the noise contours around the new runway would be identical to those around the original and the total contour area would be double the original. By this measure, contour area, concentrating traffic on fewer runways and at fewer airports is beneficial. In reality, other factors largely determine how traffic is assigned to runways and airports.

Improvements in Noise Technology

The empirical model can also be used to assess changes in noise due to improvements in technology. As illustrated in Figure 1, there has been steady improvement in the noise from individual aircraft, but there has also been growth in the size of the aircraft fleet over the same time period. Improvements in individual aircraft noise levels have benefited residents at all airports more-or-less equally. The growth in numbers of operations and their effect on noise exposure is far less uniform, with some airports experiencing large growth in traffic volume and others less so. The empirical model was used to illustrate aggregate effects that will not apply to any particular airport but will reflect air transport system-level changes due to improved technology and growth. Growth in numbers of operations will cause DNL to increase by $10 \log_{10} (1 + P)$, where P is the fractional increase in the number of operations. For example, a 5% increase would yield a change of $10 \log_{10} (1.05) = 0.2$ dB. Changes in noise due to improvements in technology (Figure 1) over the past 25 years have amounted to approximately 7 dB (0.3 dB per year) when noise levels are expressed as the average of the three noise certification values¹. The arithmetic sum of these three values, often referred to as the “cumulative” level, has decreased approximately 0.9 dB per year.

Table 1 presents some examples of predictions that can be provided by the empirical model. A time horizon of 25 years has been chosen for this example because it is important to recognize that changes in technology and fleet size occur quite slowly, aircraft production runs are long, and aircraft service lives are also long. In other words, changes are slow to have an effect on aggregate noise exposure, but once made, they are equally hard to reverse. The first row of Table 1 assumes that the fleet mix is static, and although unrealistic, indicates that absent new technology, the growth in traffic will inevitably cause large changes in noise contour areas. The second row assumes that acoustic technology stagnates and that older, noisier aircraft are replaced by aircraft with current-production technology, but with no further technology advances. The service life of each aircraft is assumed to be 25 years. These assumptions result in a very small annual increase that accumulates to a significant change over 25 years. The third row in the table assumes, perhaps optimistically, that technology continues its historical trend, the net result being a small annual decrease. A comparison of the second and third rows illustrates the extreme sensitivity of noise contour areas to changes in technology.

¹ Airport noise contours are derived using the SEL metric for individual aircraft flyovers. This is in contrast to the noise certification metric EPNL. It is assumed that a change of Δ dB in one metric will affect the other metric similarly. In the absence of strong tonal components, a useful empirical formula is $EPNL, \text{ dB} = SEL + 4$ [4].

Table 1: Growth and airport noise contour areas.

Scenario	Annual Change		25 year change	
	dB	Contour area	dB	Contour area
5% annual growth in # operations (no change to fleet mix)	0.21	3.8%	5.25	253%
5% annual growth 4% annual fleet replacement (in-hand technology)	0.05	0.9%	1.25	126%
5% annual growth 4% annual fleet replacement (new technology*)	-0.01	-0.2%	-2.6	63%

* Assumes historical trend of 7 dB/25 years

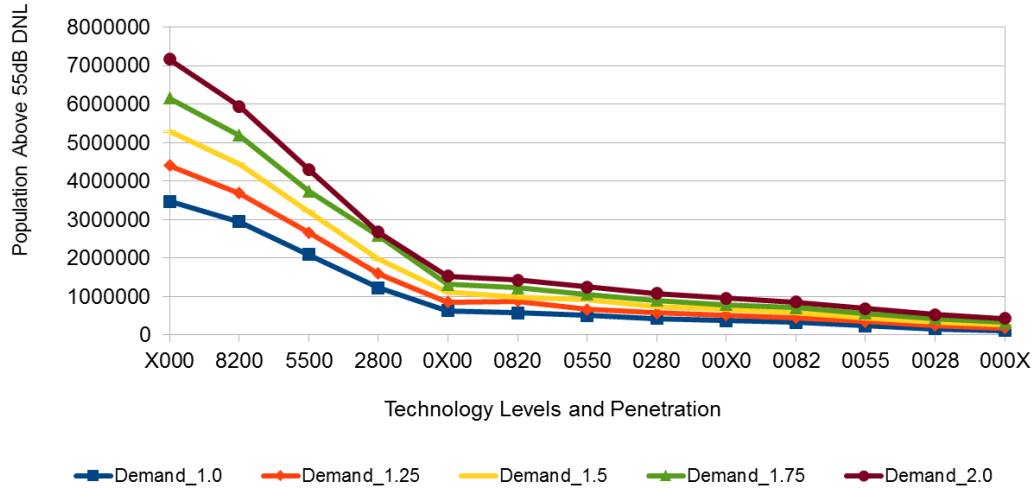
Effects of Fleet Growth and Technology on Impacted Population

The foregoing discussions have concerned noise contour areas and have implicitly assumed that contour area is a reasonable surrogate for the population within a contour, this being the quantity of real interest. An opportunity to examine impacts on population is provided by Thompson et al. [8] in which detailed analyses were conducted at all major U.S. airports and included a range of future acoustic technology levels and future traffic levels. In brief, the Thompson et al. study had the following key characteristics:

- The 55 U.S. airports in the FAA’s Future Airport Capacity Task 2 study [9] were used.
- Population distributions within a radius of 25 miles from each airport were extracted from the 2010 U.S. Census using block-level locations (centroids).
- For each airport, the 2010 flight schedule was used. Each aircraft type in the schedule was assigned to one of a number of categories depending on its size and propulsion type (e.g., jets with seating capacity between 150 and 210). A representative aircraft was assigned to represent all aircraft in each category and was “best-in-class” from an acoustical perspective.
- Noise performance of the representative aircraft types were set at four levels: current, “N+1”, “N+2”, and “N+3”. The last three correspond to Stage 4 – K certification levels expressed in cumulative values with $K = -32, -42, \text{ and } -71$ dB, respectively. The “current” fleet can be characterized by a K value of -6 dB.
- DNL was calculated at each population centroid at each airport using the FAA’s Noise Integrated Routing System and total population was determined for $\text{DNL} \geq 55$ dB and $\text{DNL} \geq 65$ dB, both at individual airports and aggregated across all 55 airports. This was accomplished for each value of K .
- Growth in air traffic was modeled by increasing the number of operations uniformly, with no consideration being given to runway or airport capacity, up to a factor of two beyond the 2010 baseline schedule.

A representative result of the study by Thompson et al. is shown in Figure 3, in which the total population above DNL 55 dB for the 55 airports is shown as a function of technology level. The four-character scale on the abscissa represents the fleet mix, with the first character being “current” and the next three

representing improved acoustic performance ($K = -32, -42, -71$ dB). The “X” indicates that the fleet is 100% at a single technology level. The numbers 2, 5, and 8 indicate that the technology level is applied to 20%, 50%, or 80% of the fleet, respectively. For example, the point on the abscissa labeled “0550” corresponds to 50% of the fleet being N+1 technology and 50% being N+2 technology. The lowest curve on the figure represents the baseline fleet size in 2010 and the others represent increased demand, up to twice the baseline.



Technology Level Code (Number represents 10 x percentage; X = 100%)

1st character: Current

2nd Character: N+1 (Stage 4 – 32 dB)

3rd character: N+2 (Stage 4 – 42 dB)

4th character: N+3 (Stage 4 – 71 dB)

Example: “0550” = 50% N+1 aircraft and 50% N+2 aircraft

Figure 3: Aggregate population exposed to DNL above 55 dB for various technology levels and growth (demand) levels.

The trends in Figure 3 are as expected, with the impacted population decreasing with technology improvements and increasing with air traffic growth. However, it is impossible to compare these trends with those that can be predicted by the model described above. Such a comparison requires that the abscissa in Figure 3 be converted into a decibel scale consistent with that used in the development of the empirical model. For those cases in Figure 3 for which the entire fleet is at the same technology level (e.g., 0X00, 00X0, and 000X), the average level below Stage 4 is simply the cumulative value, K , divided by three. Noise levels for fleets composed of mixtures of technology levels (e.g., 0550) can be calculated as follows:

$$\text{Fleet noise level, dB} = 10 \log_{10} \left\{ \sum_i P_i * 10^{K_i/30} \right\}$$

P = proportion of fleet (between 0 and 1)

K = cumulative level relative to Stage 4

$i = 1$ to 4, corresponding to technology levels “current”, N+1, N+2, and N+3.

i.e., $K = -6, -32, -42, -71$ dB for $i = 1$ to 4.

with results as shown in Table 2. It is clear from the table that the technology levels presented in Figure 3 are far from evenly-spaced when expressed in decibels; the intervals range from less than 1 dB (moving from 0820-0550) to more than 4 dB (moving from 0028-000X). The baseline population data from Figure 3 (no growth) has been replotted in Figure 4 on a logarithmic ordinate axis along with noise levels expressed relative to Stage 4 on the abscissa.

Table 2: Fleet technology mix and average noise level expressed as cumulative certification level divided by 3.

Technology Level	Noise Level re. Stage 4 (average, cum/3)
X000	-2
8200	-2.8
5500	-4.46
2800	-7.1
0X00	-10.67
0820	-11.16
0550	-12
0280	-13.1
00X0	-14
0082	-14.85
0055	-16.56
0028	-19.43
000X	-23.67

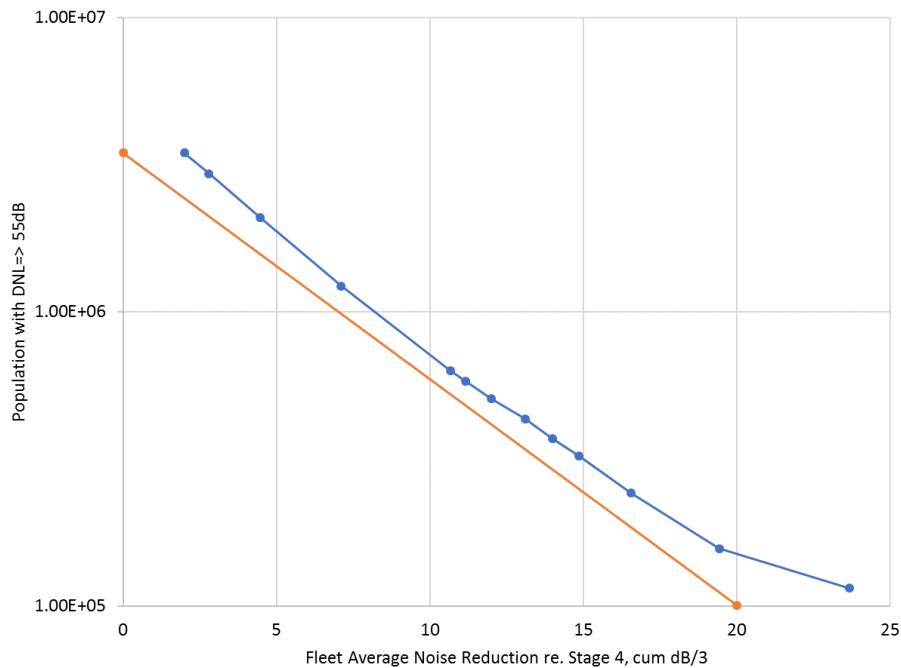


Figure 4: Population data from Figure 3 (demand 1.0 – no growth) replotted as a function of fleet average noise reduction. The lower line represents the slope of the empirical model relating contour area (a surrogate for population) and noise reduction.

As predicted by the simple model, the relationship is approximately linear, except for a divergence at the largest values of noise reduction. Furthermore, the slope of this observed linear relationship is very similar to that predicted by the empirical model, shown as the straight line in Figure 4. In other words, populations contained within a given noise contour are proportional to contour area, implying that population density is approximately uniform when aggregated across the 55 airports. The deviation from linearity in the data at high levels of noise reduction can be due to a number of factors. Under these extreme conditions the affected population is very close to the runway. Recall that the empirical model ignores noise associated with the aircraft whilst on the runway; the population data is placed at the centroids of census blocks and likely has insufficient spatial resolution when contours are very small; the assumption that aggregated population density is uniform must inevitably break down in the near vicinity of airports where sensible land-use planning is most prevalent.

It should be noted that the simple model utilized data obtained from analyses that used SEL and DNL, both of which are based on A-weighted sound levels. In contrast, technology levels are based on noise certification levels expressed in EPNdB. An implicit assumption has been made that A-weighted levels and EPNL can be used interchangeably. Analyses of noise levels from many aircraft types has shown this to be a reasonable assumption. Bennett and Pearsons [4] indicate that EPNL is approximately equal to SEL plus 4 dB for cases where “audible tones in the noise event are not excessive.” Powell (Ref. [10], Table 8 and Figure 7) analyzed a wide range of jet aircraft types and showed an extremely high correlation between noise levels expressed in SEL and EPNL.

Summary

Two independent analyses, one based on published noise contours associated with some of the larger U.S. and European airports, the other based on noise and population modeling at 55 U.S. airports, have shown that simple relationships between noise levels, noise contour areas and impacted populations can be described. Furthermore, growth in air traffic and improvements in aircraft noise technology can also be examined. An example is shown in Figure 5, which replots the data from Figure 4 with the addition of another curve, which represents the likely change in impacted population due to growth in air traffic. This 5 dB offset is the result of an assumed 3% annual growth over a period from 2010 (the baseline year) to 2050. The year 2050 was chosen in order to determine a long-range noise reduction technology goal that would result in an order of magnitude reduction in the U.S. population exposed to aircraft noise levels above DNL 55 dB. The far-term goal is shown by the horizontal line and indicates that approximately 17 dB (52 dB cumulative r.t. Stage 4) would be necessary to achieve the order of magnitude reduction in impacted population. This is a challenging goal since it requires an improvement in production aircraft noise levels from approximately Stage 4 – 6 dB (cumulative) in 2010 to Stage 4 – 52 dB (cumulative) in 2050. This will require an additional 10 dB beyond the historical rate of 0.9 dB per year.

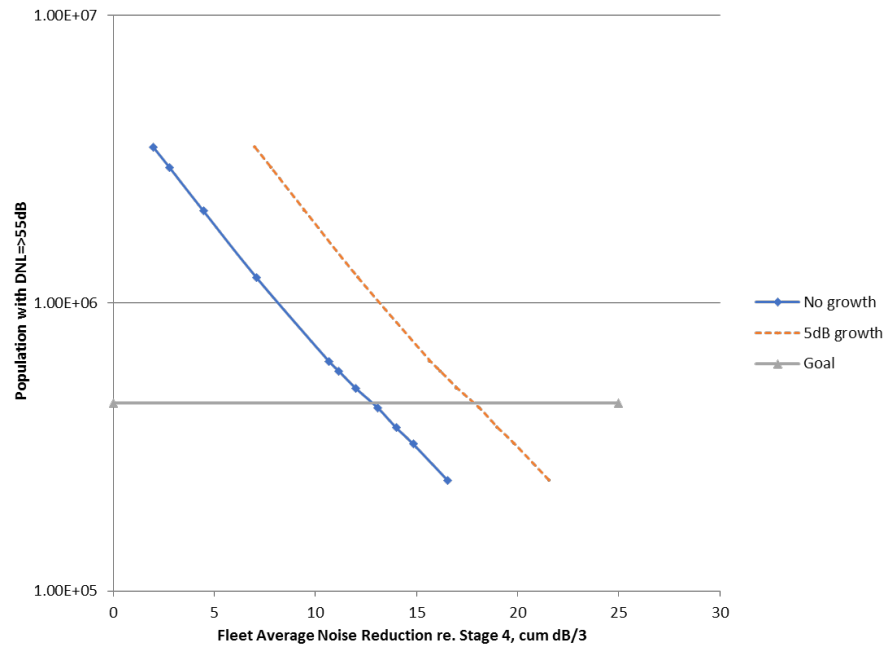


Figure 5: Aggregate population exposed to DNL above 55 dB as a function of fleet noise reduction, with and without growth.

Other analyses that can be performed using the simple relationships described above concern the implications of changes to policies regarding land use planning and mitigation measures such as sound proofing of residences. If, for example, the noise criterion for a particular land use or for sound proofing were to be lowered by 1, 3, or 5 dB, this would result in increases in contour areas of 19%, 70% and 140%, respectively. Perhaps the most useful insight concerns the delicate balance between the desire for continued growth in aviation and the needed investment in noise technology to enable reduced environmental impact.

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14. ABSTRACT The focus of this paper is the development of a simple, empirical model to describe the effects of improvements in acoustic technology and of traffic growth on airport noise and impacted populations. It is aimed at macroscopic analyses and takes advantage of noise analyses performed at many individual airports to form an aggregated picture which attempts to describe system-wide effects.					
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