2 TECHNICAL DISCUSSION

Metrics in common use for predicting noise impacts are largely expedient in nature. They are not supported by theory-based understanding of the causes of community reaction to noise, but rather on historical studies of perception of loudness, convenience of measurement, and on custom that has been codified in regulation. This section examines the rationales for use of common noise metrics as predictors of community reaction. Without such rationales, suggestions for alternative noise metrics are little more than *ad hoc* speculation, and are not likely to yield systematic improvements over current expedient methods.

2.1 Rationales for equivalent-energy and threshold-based noise metrics

As described in Section 1.2, measures of transportation noise that are intended to predict community response embody tacit theories about the origins of annoyance. One major way in which the single event and cumulative metrics described in Section 11 differ from one another is whether they adopt equivalent energy- or threshold-based views of the origins of community response to noise.

The tacit theory underlying equivalent-energy noise metrics is that each of the physical properties of noise exposure that could reasonably give rise to annoyance - level, duration, and number of noise events - does so in equal measure, so that level in decibel units, logarithm base 10 of duration, and logarithm base 10 of the time weighted numbers of noise events are fully interchangeable determinants of annoyance. For example, 3 dB changes in level, as well as doubling or halving of numbers of events or event durations, all give rise to 3 dB changes in equivalent levels.[6] In other words, integrated energy metrics assume that people integrate noise exposure in the same manner that an integrating sound level meter does.

Although this continuous integration view leads to convenient metrics (notably, the SEL/L_{eq}/DNL family), it cannot be strictly correct in the limit. People's annoyance judgments can not be based on a continuous and perfect integration of sound energy (from all sources, second by second, year after year, over indefinitely long time periods), because if the annoyance of noise exposure depended on a process of continuous and perfect integration, everyone would eventually become highly annoyed by ongoing neighborhood noise exposure after a long enough period of time.

The process of transforming sound energy into annoyance must involve some form of "leaky" integration. The integration might be level- or source-specific, or reset following some period of time, such as during absence from residential settings. If the manner in which annoyance varies with noise exposure is analogous to charging a capacitor, perhaps the charge created by daytime residential exposure dissipates during periods when exposure is low - say, at

[6] Proposals in prior decades for noise metrics employing a constant other than 10 as a multiplier for $\log_{10}$(number of events) were typically based on analyses of the findings of individual social surveys, and provided little improvement on 10 log(n) predictions in accuracy of prediction of annoyance prevalence rates when applied to the findings of other social surveys.

night. Very little is quantitatively known, however, about the time constants of arousal and decay of annoyance with transportation noise exposure (*cf.* Fidell *et al.*, 1985).

Gjestland (1984) has suggested an "interrupted integration" variant to the continuous integration rationale, in which annoyance judgments are based not on a continuous integration of sound energy, but on an integration of only the energy in excess of some threshold. The rationale for the suggestion is that environmental noise metrics should reflect only noises that people commonly notice and attend to, rather than all acoustic energy. Thus, for example, in densely populated areas where street traffic noise controls urban ambient noise levels at most times of day, a "traffic noise" metric might be sensitive only to the sounds of the noisier vehicles, such as heavy trucks and motorcycles.

Such a threshold of integration could be specified in absolute terms (*e.g.*, an A-weighted value of 45 dB), in centile based terms (*e.g.*, the L_{90} value of a distribution of source-specific noises), or in relative terms (*e.g.*, 5 dB above an ambient or median noise level). A threshold of integration could also be specified on an event basis, in terms of the SEL or minimum instantaneous level that must be exceeded. The threshold could be a constant or even a variable depending on the noise source, ambient conditions, and even the time sequence of noise events. California's Hourly Noise Level, HNL (California Administrative Code Title 21, Subchapter 6) is an example of one form that such a metric might take.

In contrast to the continuous integration view, the threshold-based ("time-above", "number-above", and "interrupted integration") views assert that some noises – those which fall below some type of threshold - do not contribute at all to annoyance, and that only the duration or number of noise events in excess of the threshold contribute to annoyance. Thus, for example, the only overflights that contribute to the annoyance of airport vicinity residents might be those whose maximum values exceed some threshold, or whose SELs are 10 dB greater than the median levels of all flights.

2.2 Rationale for noise metrics sensitive to variability in the temporal domain

Several noise metrics sensitive to variability in temporal distributions of noise events were identified in earlier decades, in the general belief that people judge steady-state circumstances of noise exposure to be less annoying than those with fluctuating noise levels. These included Robinson's (1969) Noise Pollution Level, Munteanu's (1979) pollution level (LNP) index, and derivative (that is, rate of change of level)-based indices described by Matschat *et al*. (1977) and Johnston (undated).

Although all of these metrics have fallen out of favor as needlessly complex, they remain of interest for the insights that they might provide about the origins of annoyance judgments. Two forms of temporal variability may be distinguished. One form is a property of the noise environment itself, while the other is a property of listeners. The first is the rate of occurrence of discrete noise events, while the second ("rate of response") reflects the manner in which people sum the annoyance of multiple events.

Aircraft noise exposure experienced in households under flight tracks to and from heavily used runways is generally composed of a fairly regular sequence of discrete noise

events occurring at intervals as short as every two minutes. In the vicinity of hub airports, high frequency of occurrence periods of overflights may recur as many as a dozen times a day, at intervals of 45 minutes to an hour, corresponding to banks of connecting flights. Even though the noise levels of individual overflights may not be egregiously high (for example, those of commuter jets rather than long range transports), their unrelenting and repetitive nature may be judged as more annoying than the same quantity of acoustic energy distributed in some other manner.

If distraction of attention is the mechanism that gives rise to annoyance, frequent interruptions (of concentration, conversation, TV or radio listening, etc.) might give rise to greater annoyance than the same quantity of acoustic energy distributed in other ways – for example, as smaller numbers of discrete noise intrusions of higher level, or even as greater numbers of noise intrusions spread out over the course of the day. Preferential runway use schemes, which modify the manner in which aircraft overflight noise is packaged during different time periods, may mitigate community reaction by providing several hours of respite from continuous, repetitive noise intrusions.

Schomer and Wagner (1996) and Schomer (1996) conducted a study in which test participants completed a brief questionnaire every time they heard an outdoor sound that they considered bothersome or annoying. The entire questionnaire included only three items: (1) What sound did you hear?; (2) How annoying was the sound?; and (3) What were you doing when you noticed the sound?

The largest number of test participants answered these questions as though they were sensitive simply to the integrated energy of their noise exposure. Individuals in this group noticed all noise events in excess of some personal threshold, and judged the annoyance of each event proportionately to their SELs.

A large group of test participants answered these questions with annoyance judgments that were constant for specific types of noise sources. The annoyance judgments of these latter test participants varied from source to source, but not with the SEL of a given source. For example, these test participants might have judged aircraft to be moderately annoying all the time, and motorcycles to be very annoying all the time, without regard for the SEL values of each exposure incident. Respondents who followed this pattern increased their rate of notice with increasing SEL, however.

In other words, the annoyance judgments of some test participants appeared to reflect merely the total energy of their noise exposure, while the annoyance judgments of others appeared to reflect a greater degree of cognitive involvement. Test participants whose response rate varied with SEL appeared to first notice the sound, then to classify it, and then to assign level-invariant categorical annoyance judgment to different classes of noise sources.

Noise metrics developed from assumptions about cognitive processing of environmental sounds are inherently more complex than those based solely on acoustic measurements. The case in favor of developing such metrics for regulation of aircraft noise depends to a large

extent on the inability of more familiar noise metrics to account for the better part of the variance in community response to aircraft noise exposure. Although research on the bases of individual annoyance judgments is of interest for academic reasons, it remains to be seen how necessary or pragmatically useful metrics derived from such research prove to be.

2.3 Adaptation level hypothesis

Adaptation level theory (Helson, 1964; Parducci, 1995) suggests another rationale for prediction of annoyance induced by noise exposure. In essence, the adaptation level view asserts that people eventually habituate to familiar noise environments, and are consequentially annoyed only by changes in them.[7] From this perspective, community reaction to aircraft noise is essentially a change detection process. The critical quantity that an aircraft noise metric must characterize in order to predict noise impacts from this perspective is *not* the absolute level of exposure, but the degree of *change* in exposure levels, or in effective loudness of exposure, or in some similar quantity.

The adaptation level perspective helps to explain the often expressed (but simplistic) observation that people who choose to live near airports cannot reasonably complain about aircraft noise. In many cases, long time residents of an airport neighborhood may have chosen to live near an airport with limited numbers of runways, limited numbers of nighttime and total operations, seemingly immutable approach and departure paths, and a particular fleet mix. Over time, the airport may have grown by adding runways, operations, larger aircraft types, new approach and departure paths, greater street traffic congestion and air pollution, *etc*. Such growth could readily convert once familiar and tolerable noise exposure levels into noise patterns judged as highly annoying.

FAA policy for evaluating noise impacts already reflects a rudimentary version of the adaptation level hypothesis. Even in settings where noise exposure levels do not exceed DNL values greater than 65 dB (*i.e.*, those with noise exposures as great as 5 dB lower than the defined threshold of significant noise impacts), impact assessments are required for anticipated increases in noise exposure of as little as 3 dB.[8]

It may be difficult to fully test adaptation level hypotheses in realistic settings, however, because people who are unable to adapt to a given distribution of noise exposure either move

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[7] Aircraft noise exposure is episodic in nature, since it is generated by a sequence of noise events created by individual overflights. Other forms of transportation noise, such as high volume road traffic noise, are more nearly continuous. Even though the adaptation level perspective is most easily understood in the context of more-or-less continuous noise sources, it could arguably be an appropriate model for annoyance in neighborhoods near airports with large numbers of operations. The adaptation level perspective is also a useful one for explaining large differences in aircraft noise-induced awakenings from airport to airport, *per* section 4.8 of this document.

[8] Clause 3.4, page 3-5 of FICON (1992), Scope of Airport Noise Analysis between DNL 60 dB and 65 dB, states that "If screening analysis shows that noise-sensitive areas will be at or above DNL 1.5 dB or more, further analysis should be conducted of noise-sensitive areas between DNL 60-65 dB having an increase of DNL 3 dB or more due to the proposed airport noise exposure." See also Section 14.4c of FAA Order 1050-1E.

away from neighborhoods with personally unacceptable noise environments, or never consider living in such neighborhoods in the first place. In either event, such people are unavailable for interview in social surveys, and thus do not contribute to estimates of noise-induced annoyance prevalence rates.

2.4 Limitations of A-weighted metrics as predictors of aircraft noise effects

Most metrics routinely used to predict aircraft noise effects rely on the A-weighting network to express the spectral content of aircraft noise as a single-valued index. In an effort to reflect human auditory sensitivity to sounds of various frequencies as summarized in the 1933 Fletcher-Munson curves, the A-weighting network intentionally discriminates against both low and high frequency sounds. The A-weighting network was originally recommended for application to sounds of relatively low absolute level. The B- and C-weighting networks, which discriminate less against very low and very high frequencies, were intended for application to sounds of increasing absolute level. The B-weighting network found little favor in transportation noise analyses, however, and was eventually dropped from the sound level meter standard.

The rationale for favoring A-weighted noise metrics can be traced to the very first community noise survey (Fletcher *et al.*, 1930), and to convenience of manufacture of passive filter networks for analog sound level meters. This rationale can no longer be justified on the basis of technological convenience. Contemporary digital sound level meters can as easily estimate frequency **and** level-dependent noise metrics as noise metrics that are sensitive only to frequency.

When the annoyance of aircraft noise exposure is attributable to secondary emissions (that is, rattling sounds inside residences that are caused by high levels of low-frequency aircraft noise, such as those in runway sideline areas and behind departure runways), the rationale for A-weighting aircraft noise measurements is inapplicable. The rationale may also be inappropriate for related reasons for predictions of the annoyance of highly impulsive aircraft noise (such as that created by helicopter operations, and by supersonic flight).

2.5 Amplitude- and frequency-dependent metrics

All of the simple frequency weighting networks (such as the A-, B-, and C-weightings) are sensitive only to the spectral content of sounds, irrespective of sound amplitude.[9] In other words, they are defined and act as conventional analog frequency filters. Human perception of sounds (and some noise metrics), however, are both amplitude- and frequency-dependent. Noise metrics currently in use that are sensitive to both frequency and amplitude of sounds

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[9] These frequency weighting networks were originally developed during the 1930s as inverted reflections of the Fletcher-Munson equal loudness curves. The A-weighting network, for example, was intended to mirror the 40 phon curve, while the B- and C-weighting networks were intended to reflect human frequency sensitivity to higher amplitude sounds. Analog technology for designing practicable filters from passive components limited the complexity of the resulting weighting networks.

include Zwicker loudness (LLZ), defined by ISO 532b and more recent modifications; Perceived Noise Level (PNL); tone corrected Perceived Noise Level (PNLT); and Effective Perceived Noise Level (EPNL). These metrics, which are derived from human loudness (or annoyance) judgments, require computations that are more complex than those that can be achieved by passive filters.

Loudness metrics seek to characterize an input-output process for which sound levels are inputs and subjective loudness or annoyance judgments are outputs. When applied to prediction of annoyance as judged in laboratory testing, they have not demonstrated consistently better prediction over A-weighting, however (Scharf and Hellman, 1980; Zwicker, 1985; Hellman and Zwicker, 1987). This may be due in part to inadequacies and inconsistencies in subjective testing methods and measurement.

Applications of loudness level metrics to noise sources in real world settings are further complicated by the differences between laboratory and residential settings. The principal acoustical difference in the two settings is the insertion loss of residences. Subjective judgments made in laboratory settings represent reactions to sounds presented directly to test participants. Their judgments of the loudness and annoyance of sounds correspond to their spectral content as heard in the laboratory, not to their spectral content as measured outside a residence.

In laboratory studies of the annoyance of transportation noise, test sounds presented for subjective judgment are often low-pass filtered so that they resemble sounds as heard inside residences. In social surveys, however, transportation noise is conventionally measured outdoors, even though the listening conditions of primary interest are indoors. The (highly frequency-dependent) insertion loss of residences introduces substantial differences in the spectral content of sounds as heard outdoors and indoors.[10] The A-weighted levels of transportation noise sources as measured outdoors simply do not correspond to the low-pass filtered sounds that survey respondents hear inside residences. In other words, it makes little sense to expect sound levels measured outdoors to predict their loudness as heard indoors, so outdoor noisiness cannot be expected to closely predict residential (that is, indoor) annoyance.[11]

Schomer (2004) treats the equal loudness contours of ISO (226-1987) as a filter that varies with both frequency and amplitude. Such a filter appears to account for some of the differences in annoyance of different transportation noise sources and operation types (*e.g.*, takeoffs *vs.* landings). In other words, it is the low frequencies, as heard indoors, that drive much of the human response to the transportation noise heard indoors. Schomer's proposal essentially substitutes "loudness-level weighting" for A-weighting in the computation of DNL. The log

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[10] Schomer (2004) has shown that it is only the low-frequency sound energy of transportation and other environmental noise sources that is heard indoors, because atmospheric absorption and the insertion loss of homes effectively remove the mid- and high frequency energy. Schomer suggests a standard “house filter” that corresponds to windows open about 5 cm to minimize difference among residential construction types.

[11] Social survey questionnaires are rarely designed to assess the relative contributions of outdoor and indoor exposure circumstances to overall residential annoyance. Receiver-oriented noise mitigation efforts, such as residential sound insulation programs, however, are clearly intended to ameliorate only indoor exposure.

base 10 arithmetic is maintained. That is, a doubling of operations is equivalent to a doubling of sone-seconds, and a change of 10 phon is equivalent to a 10 fold change in operations.

Schomer's proposal amounts to an incremental improvement over A-weighting. It maintains the concept of DNL, merely substituting the frequency and amplitude dependent filter designated by the equal loudness level contours for the simpler A-weighted filter. The concept of SEL remains the same, the concept of DNL remains the same, the log base 10 summation process remains the same, the time of day and day of the week adjustments remain the same (an optional feature of the DENL, a variation of DNL gaining common use in the European Union), and the factors that account for community expectations remain the same.

It is quite possible that better results could be obtained using one of the newly proposed time varying loudness calculations in place of Schomer's use of loudness level contours. Schomer *et al*. (2001) performed an initial analysis of this issue. Unfortunately, however, the summation process used log base 2 arithmetic for the loudness calculations rather than log base 10. In that study, the loudness-level weighting was found to be superior to calculations based upon loudness, largely because of the log base 2 arithmetic. Fastl (Fastl, 2000), who recommends the use of loudness with log base 2 arithmetic, uses the upper 5% - 10% of the loudness distribution over time to correlate with annoyance. The exact percentage is dependent on the type of noise source. None of these problems exists with log base 10 arithmetic because the sum calculated is automatically extremely dependent on the peaks in the stimulus signal.

2.6 The unreliability of measurements of centile levels and thresholds

Practical measurements of centile levels are problematic and highly uncertain. Consider, for example, an analysis of a 30 minute recording of sound levels near a semi-rural roadway. The LAeq for the 30 minute period is 42.9 dB, the $L10$ is 44.7 dB and the $L90$ is 39.4 dB. These findings seem credible and precise - until the uncertainty of real field measurements using a sound level meter is taken into consideration. Clause 4.0, Table 1, of ISO 1996-2:2007, “Acoustics – Description, measurement and assessment of environmental noise – Part 2: Determination of environmental noise levels” gives the 95% confidence interval for field measurements with a Type 1 meter as about ±2 dB, and about ±3 dB for a Type 2 meter.

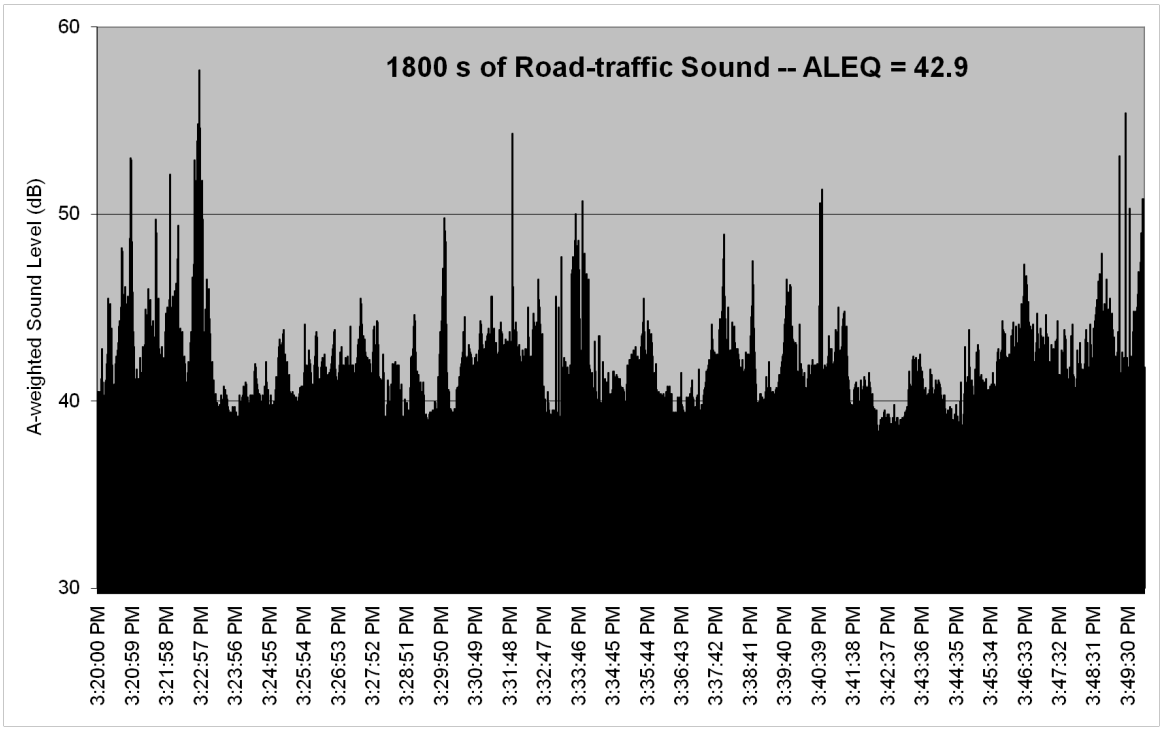

Figure 2-1. 30 minutes of semi-rural road-traffic sound

What does this uncertainty imply for real measurements or predictions? Assume the 1800 seconds of data shown in Figure 2-1 are absolutely correct, so that the L_{10} and L_{90} are precisely as given above. Then, as shown in Figure 2-2, with a ±1 dB uncertainty, the "L_{10}" can range from 43.7 to 45.7 dB, and the "L90" can range from 38.4 to 40.4 dB with corresponding percentages ranging from 6 to 17% and from 74 to 99%, respectively. For a measurement of L_{10} made with a Type 1 meter having a±2 dB uncertainty (see Figure 2-3), the 95% confidence limits extend from actually measuring the L_{28} to L_4. For measurement of L_{90} (a common definition of the ambient level), the 95% confidence limits for a Type 1 meter measurement extend from actually measuring the L_{100} to L_{65}. For a Type 2 meter (Figure 2-4), the same confidence limits range from L_{47} to L_3, and from L_{100} to L_{35}, respectively. In other words, for this commonplace sort of field noise measurement, as shown in Figure 2-1, a Type 2 meter can measure an L_{10} that is lower than another measurement of L_{90} at the same site over the same time period.

"Time above" measurements are similarly uncertain. When the threshold for the "time above" measurement is near L_{10}, one person may measure the time above L_5 while another person at the same site measures time above L_{20}. The estimated durations of these two time-above measurements could well differ markedly.

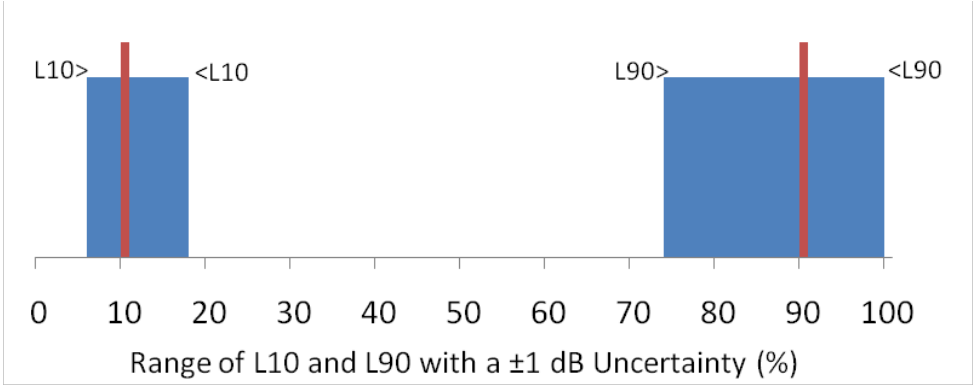

Figure 2-2. Uncertainty of Plus or Minus 1 dB

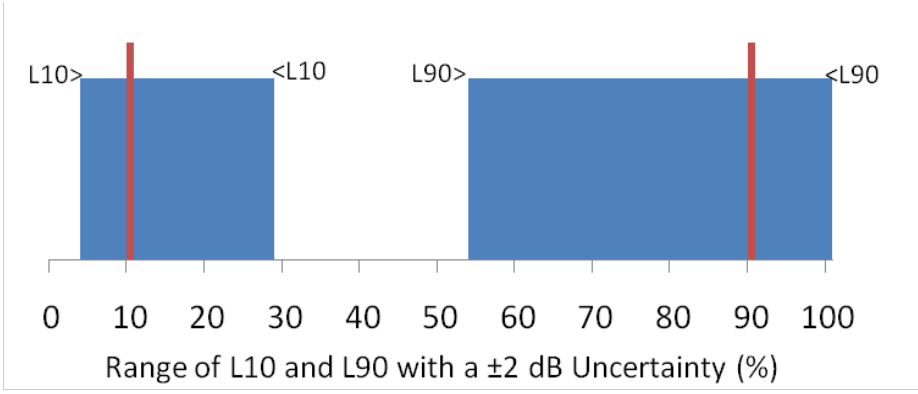

Figure 2-3. Uncertainty of Plus or Minus 2 dB.

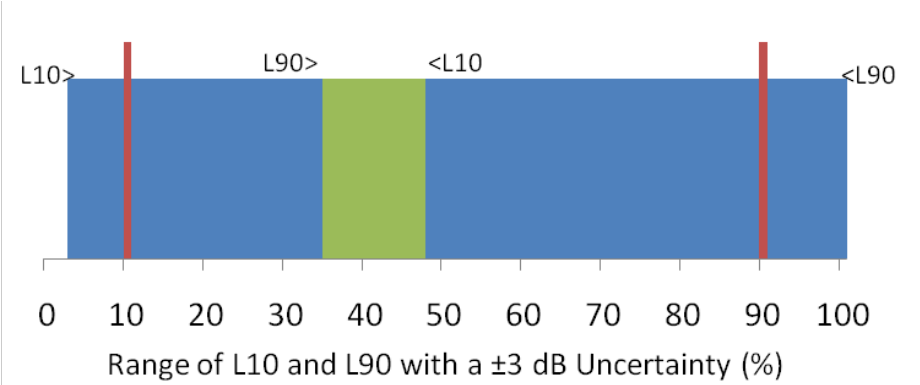

Figure 2-4. Uncertainty of Plus or Minus 3 dB.

2.7 Speech interference metrics

Quantification of speech intelligibility was a major psychoacoustic research concern throughout the World War II era (*cf.* French and Steinberg, 1947). Since speech intelligibility

was replaced by annoyance as a primary indication of aircraft noise impacts in the late 1970s, however, relatively little new effort has gone into prediction of speech intelligibility in the presence of time varying environmental noise. It is thus not surprising that long-established indices of speech intelligibility, such as Articulation Index and Speech Interference Level remain in common use, and appear adequate for most assessments of aircraft noise impacts.

EPA's 1974 "Levels Document" identified an A-weighted level of 65 dB as a *de facto* threshold of effect for indoor speech intelligibility in the presence of continuous, steady state ambient noise. EPA judged that at least 95% of sentences were intelligible in the presence of lower levels of ambient noise. This criterion is a somewhat simplified characterization of a satisfactory conversational environment, based on general assumptions about customary vocal levels, speaking distances, and linguistic competence. Although Pearsons *et al.* (1977) conducted extensive field measurements of typical speech levels in a variety of communicating environments, little effort has been made to formulate more detailed criteria for aircraft noise-induced speech interference.

2.8 Sleep disturbance metrics

Aircraft noise-induced sleep disturbance has been long studied by U.S. and European researchers, largely in small-scale and limited duration studies. Nevertheless, quantitative relationships between aircraft noise and sleep disturbance remain so poorly documented that there is little realistic, near-term prospect for reliable, acoustically-based prediction of sleep disturbance. The numerous impediments to such prediction include the following:

1) The entire stock of the most relevant field data on the ability of aircraft noise intrusions to awaken people sleeping in familiar quarters consists of a handful of studies of limited scope conducted at a few airports. The self-selected test participants in these studies are relatively few, and of unknown representativeness of broader populations. Findings of laboratory studies of noise-induced sleep disturbance differ greatly from those of field studies in which test participants sleep in their own beds (Pearsons *et al.*, 1995).

2) A recent review of the literature on prediction of noise induced sleep disturbance (Fidell *et al.*, 2010, p. 80) describes the results of half a dozen efforts to establish quantitative relationships from the findings of field studies of sleep disturbance due to aircraft noise intrusions into familiar sleeping quarters. None of these efforts has yielded an accurate and reliable relationship that accounts for substantial amounts of variance in the association between aircraft noise and behavioral awakening.

3) Agreement among researchers on such basic matters as definitions of sleep "disturbance", appropriate research methods, and preferred measures of noise exposure is poor. Thus, for example, some researchers prefer to measure only maximum A-weighted measures of single events, others prefer sound exposure levels, and yet others favor long term equivalent levels such as L_{night}.

4) The most pragmatically useful information for regulatory purposes (*i.e.*, the findings of behavioral awakening studies) indicates that aircraft noise intrusions

only occasionally disturb sleep. Most of the dosage-effect relationships based on behavioral awakening field data have very shallow slopes. Further, they predict that the prevalence of awakening does not exceed 5% until indoor sound exposure levels of intruding noises exceed 90 dB. (Corresponding *outdoor* levels of aircraft noise events may be as much as two orders of magnitude greater.)

6) Findings of other (actimetric and electrophysiological) studies of noise-induced sleep disturbance suggest many more instances of sleep disturbance, but are very difficult to interpret for regulatory purposes.

7) Sizable, airport-specific differences in median sound exposure levels that awaken test participants are apparent in studies which attempt to compare awakening data from different airports (*e.g.*, Anderson and Miller, 2007).

Fidell *et al.* (2010) conclude as follows:

> "Epidemiological evidence does not yet support reliable prediction of noise-induced sleep disturbance, nor well-informed policy debate, much less a plausible technical rationale for regulatory action. The practical, population-level implications of noise-induced sleep disturbance and its consequences remain poorly understood due to design and other limitations of field studies of noise-induced sleep disturbance already undertaken, and to limitations of the statistical analyses performed to date. Published relationships used to assess the probability or prevalence of noise-induced awakening remain highly uncertain and unhelpfully imprecise. Considerable caution must be exercised in extrapolating conclusions about sleep disturbance that have been inferred from the behavior of relatively small and purposive samples of people living near a few airports to the general population."
>
> "Additional findings from large-scale, long duration field studies of the effects of a wide range of environmental noise exposure on behaviorally confirmed awakenings could improve understanding of relationships between noise and sleep disturbance. It is doubtful, however, that further analyses of the results of studies that are similar in design to those already conducted will meaningfully improve understanding of noise-induced sleep disturbance. New analytic approaches must systematically account for non-acoustic factors such as the source and meaning of noise intrusions and sleepers' familiarity with them, and must provide a context for distinguishing between incidence rates of spontaneous (non-noise related) and prevalence rates of bona fide noise-induced sleep disturbance."

In other words, if major improvements are sought in the ability to predict awakenings from aircraft noise intrusions into sleeping quarters, a much larger corpus of field research findings than is currently available will be required. More field studies of the same type that have already been conducted are unlikely to yield useful new information, however. Novel study designs are required for new field studies, and theory-based methods for analyzing their findings will be necessary as well.

3 SUPPLEMENTAL NOISE METRICS

As described in Section 1.7, supplemental noise metrics are defined for present purposes as those which may improve public understanding of the characterization of aircraft noise or changes in aircraft noise. Such metrics do not necessarily improve the accuracy, precision, or credibility of noise impact predictions, however.

3.1 Arcane nature of aircraft noise metrics

The general public typically encounters detailed discussions of DNL and other noise metrics in the context of environmental impact disclosure documents or land use compatibility studies. Full comprehension of aircraft noise exposure estimates expressed in units of DNL requires familiarity with logarithmic notation, decibel arithmetic, time-weighting and temporal normalization, and frequency-weighting networks. A meaningful understanding of the prospective noise modeling from which DNL-based exposure estimates are derived requires further understandings of aircraft noise emissions, aircraft and airport operations, aviation demand forecasting, statistical manipulations of acoustic and operational quantities, long range acoustic propagation, and the nature of isopleths (geo-referenced noise exposure contours.) Most of these specialized understandings are outside the everyday experience of the general public.

Noise metrics in such documents quantify the *acoustic* consequences of proposed actions such as airport expansion projects. Some consider noise metrics expressed in units other than integrated exposure as useful supplements to DNL for improving public appreciation of the meaning and practical implications of varying degrees of aircraft noise exposure. It is far from clear, however, how much supplemental noise metrics actually improve public understanding of noise *impacts*. In fact, it is far from clear that supplemental descriptions of various properties of aircraft noise distributions actually improve public understanding of noise *impacts*.

3.2 Role of noise metrics in environmental impact disclosure documents

Quantitative descriptions of existing and anticipated aircraft noise environments are obviously necessary in environmental impact disclosure documents. However, the acoustical engineering approach to "explaining" noise impacts primarily in arcane units is not only insufficient, but sometimes inappropriate. Explanations of noise impacts in terms of noise metrics, rather than in terms of the consequences of exposure to noise, are indirect at best.

Consider, for example, the units adopted for expressing the "significance" of noise exposure. For regulatory purposes, FAA considers changes of 1.5 dB or more at exposures greater than or equal to L_{dn} = 65 dB as a threshold of significance of aircraft noise impacts. FAA land use compatibility guidelines recommend that residential land use is acceptable at noise exposures as high as L_{dn} = 65 dB. FICON (1992), however, declares that *annoyance,* not DNL, is its preferred "summary measure of the general adverse reaction of people to noise," and that "the percentage of the area population characterized as 'highly annoyed' by long-term exposure to noise" is its preferred measure of annoyance. In other words, according to FICON, the prevalence of a consequential degree of annoyance is its preferred measure of adverse

reaction to noise, not a time-weighted average sound exposure level. This preferred summary measure is expressed in units of population percentages, not in units of decibels (ten times the logarithm of a ratio of sound pressures with respect to 20 μPa).

The linkage FICON endorses between the prevalence of a consequential degree of noise-induced annoyance and a DNL value is given by a mathematical transform:

$$\%HA = 100/(1+e^{(11.13-0.141L_{dn})}) \qquad [1]$$

For noise regulatory purposes, "community response" has no deeper meaning than this equation. The essential purpose of an environmental *impact* disclosure, however, is to describe noise impacts, not noise levels. Aviation noise studies including environmental disclosure documents rarely dwell on the fact that an L_{dn} = 65 dB threshold of significance represents an expressly *non*-technical value judgment that a "significant" noise impact percentage occurs only when 12.3% or more of the population is highly annoyed by aircraft noise.

In a similar vein, various land uses are asserted to be "compatible" with continued airport operation when their noise exposures do not exceed certain values of DNL. Expressing "land use compatibility" in units of decibels is a form of circular reasoning that is more a matter of administrative convenience than of logic. "Compatibility" of aircraft noise with land uses is obviously capable of varying by degree, and is most fundamentally a measure of the ability of noise-exposed land to support its intended uses.[12]

3.3 Omission of acoustic jargon from environmental impact disclosures

The most straightforward means for demystifying the results of aircraft noise impact analyses is to express them directly, in terms of impacts, rather than indirectly, in terms of acoustic quantities. This observation is consistent with that of Eagan (2007), who characterizes complex exposure metrics as "obscure" to the general public. Given that the purpose of quantifying noise in the first place is merely to predict annoyance, no real need exists for burdening the public with the chore of understanding acoustic jargon. For purposes of quantifying noise to support policies about land use compatibility, neither a need nor a system of units exists to require or support public understanding of the nuances of acoustic metrics.

Thus, for example, the public is likely to more readily comprehend graphics which display the percentage of neighborhood residents who may be expected to be highly annoyed by aircraft noise in different neighborhoods, than to make sense of sets of DNL contours. Furthermore, rather than creating a misleading impression of empty precision of noise exposure estimates by means of thin contour lines, graphics displaying annoyance prevalence rates should focus on

[12] A further confusion sometimes arises about the regulatory meaning of the term "land use compatibility". In common use, "compatibility" suggests a reciprocal balance of interests. In regulatory parlance, the term is defined unidirectionally, as land uses that are consistent with continued operation and expansion of *airport* operations, without consideration for neighborhood amenities.

gradations of color coded community reactions. Figures 3-1 and 3-2 illustrate the difference. Figure 3-2 could equally well represent gradations in prevalence of annoyance as of noise exposure.

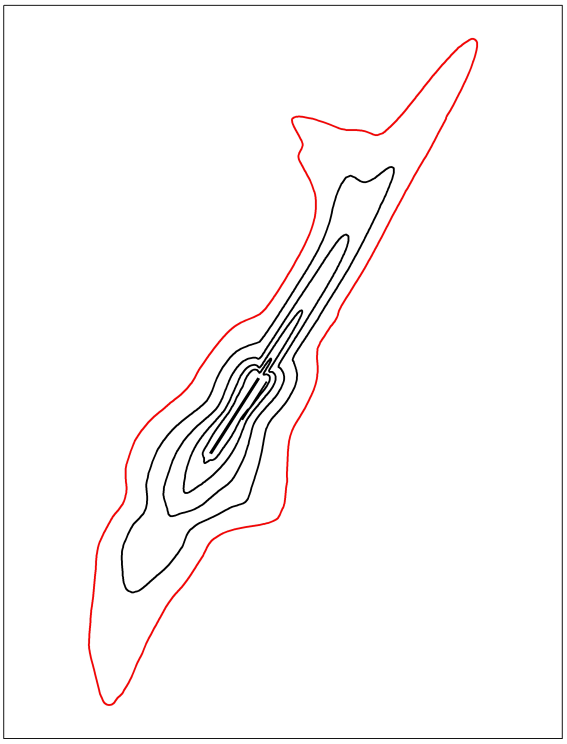

Figure 3-1. Typical DNL contours in 5 dB intervals, mistakenly interpretable as indicative of step changes in noise.

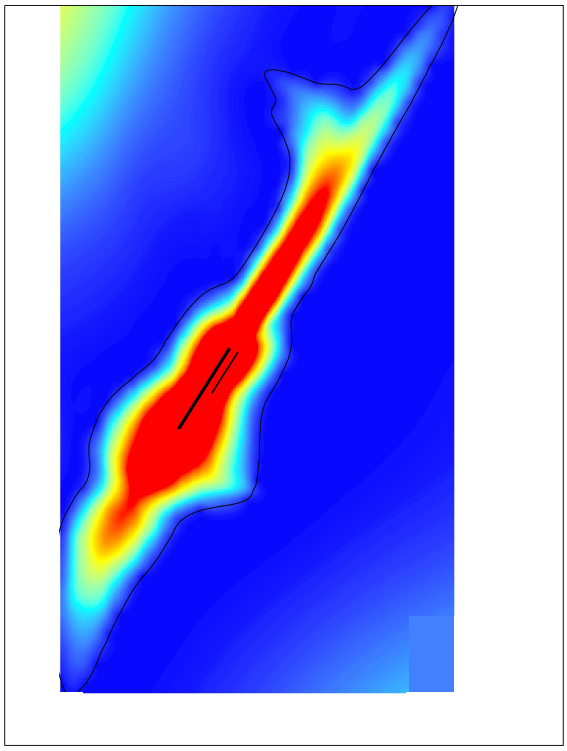

Figure 3-2. DNL depicted as graduated shading, suggestive of continuous variation in noise level.

Administrative decisions can still be based on conventional DNL contours, as land use compatibility issues would be difficult to resolve with shaded noise level maps. The point is that the public would more readily and realistically comprehend the gradual change in noise in the airport environs.

3.4 Pseudo-terrain mapping of complaint density information

Local and federal perspectives on community response to aircraft noise can differ considerably (*cf.* Fidell, 2003.) For purposes of federal regulatory policy, FICON (1992) treats "community response" as a mathematical transformation of DNL which predicts the prevalence of noise-induced annoyance in a community. On a day-to-day basis, airport administrations tend to be more focused on complaint behavior. This is due in part to the cost and inconvenience of direct assessment of annoyance prevalence rates via social survey, and in part to a view that the attitude of annoyance (a covert mental process) is somehow less valid than freely offered, directly countable complaints.

The reliability of complaints as an indicator of community response to aircraft noise is discounted by FICON (1992), on the grounds 1) that "Annoyance can exist without complaints and, conversely, complaints may exist without high levels of annoyance"; 2) that small numbers of complainants are usually responsible for seemingly disproportionate numbers of complaints; and 3) complaints are not readily predictable from noise exposure.

Historical objections to complaints as measures of community reaction should be reevaluated given recent improvements in the state of the art of collecting and reporting noise complaint data. Modern airport noise management systems (ANMS) and geographic information system (GIS) software can be used to make better uses of complaint information than traditional "pin-in-the-map" representations of complaint patterns. ANMS software at scores of major airports has been accumulating detailed information about complaints that can be conveniently geo-referenced and compellingly represented by GIS software. The resulting graphics provide insights into the origins of complaints that corroborate and complement annoyance-based metrics of community response to aircraft noise, and can be more readily understood by the general public.

Consider, for example, the geographic pattern of noise complaints associated with start of takeoff roll noise at San Francisco International Airport shown in Figure 3-3.[13] An airport-sponsored analysis (Pearsons *et al.,* 2000) of noise complaints lodged over a period of 6 years was conducted by geo-coding street addresses of complainants to contour complaint densities. Figure 3-3 shows these complaint densities coded as false elevation. The peaks of the pseudo-terrain show two concentrations of complaints, located behind and roughly 45° to the sides of the extended centerlines of the airport's primary departure runways. These locations correspond to the lobes of the directivity patterns of jet engine exhaust noise of aircraft departing on these runways. The complaint concentrations are located well beyond the airport's L_{dn}= 65 dB cumulative noise exposure contour.

An airport-sponsored complaint analysis conducted at Naples Municipal Airport in Florida documents a mismatch between overt community reaction to aircraft noise and land use compatibility recommendations premised on annoyance prevalence rates. Figure 3-4 shows two "mountains" in complaint density (rendered as false elevation) along the extended centerline of the primary departure runway at the airport. The contour draped over the complaint density pseudo-terrain that encompasses the bulk of the high ground is the 95 dB maximum A-level contour. (The airport's L_{dn} = 65 dB contour closes much nearer to the end of the runway.)

Figure 3-5 depicts noise complaints at Hanscom Field in Massachusetts. Figure 3-4 shows that peaks of complaint density remain well outside of the L_{dn}= 65 dB contour that nominally distinguish airport-compatible from airport-incompatible residential land uses. Of particular interest are the three "hills" of complaints to the east of the airport, which correspond to population concentrations overflown by straight out and turning traffic departing the airport.

[13] Portions of the following text paraphrase Fidell (2003).

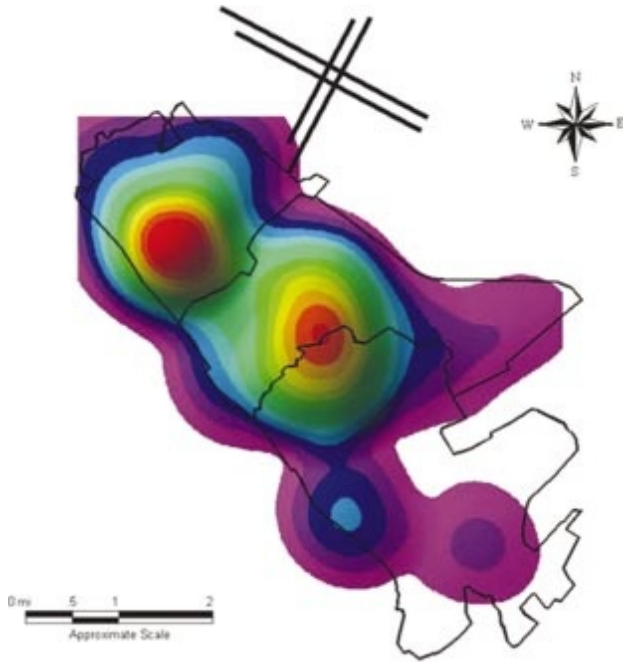

Figure 3-3. Pseudo-terrain map of noise complaints at San Francisco International Airport.

The geographic distributions of noise complaints with respect to runway ends, flight tracks, and directivity of aircraft noise sources are more consistent with proximity to flight tracks and directivity of noise sources than with DNL contour patterns typically used for assessment of transportation noise impacts. The increased interpretability of noise complaints made possible by computer-based record keeping and geo-information system software suggests a more prominent role in the future for complaint rate information in the design of aircraft noise mitigation projects and impact assessments. For example, it may be more effective to show noise complaint patterns in aircraft noise disclosure materials (intended for prospective buyers, or for consideration in land use decisions) than display contours of noise in a decibel based metric. Ironically, such a role would be reminiscent of that which complaints played in community reaction assessments prior to Schultz's 1978 synthesis work.

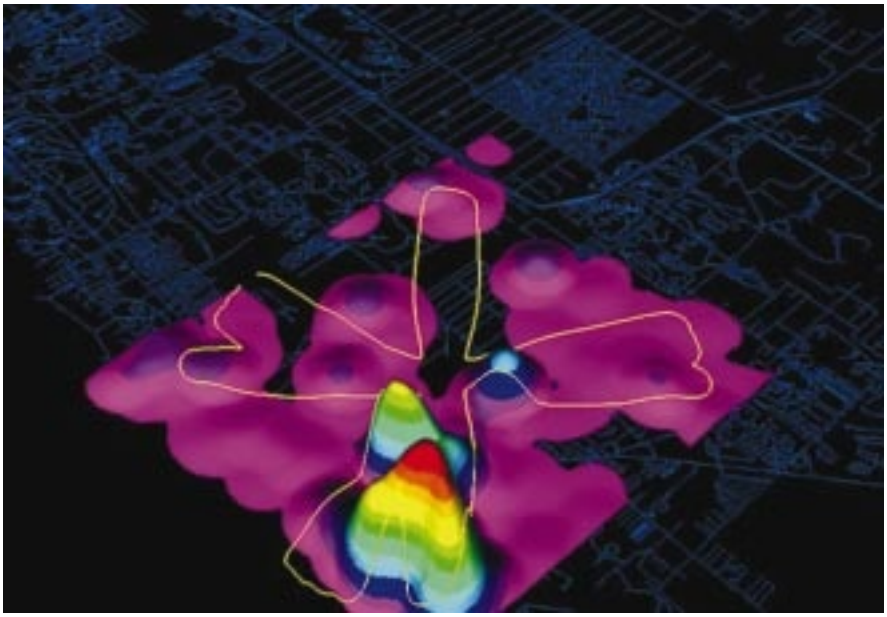

Figure 3-4. Pseudo-terrain map of noise complaints at Naples Airport.

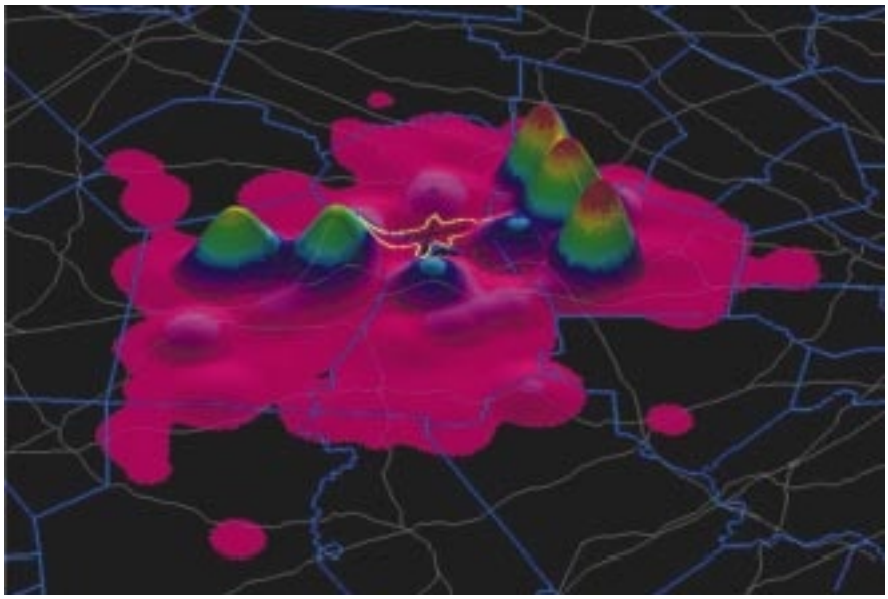

Figure 3-4. Pseudo-terrain map of noise complaints at Hanscom Field.

4 ALTERNATIVE NOISE METRICS

4.1 Gauging the potential utility of alternative noise metrics

The correlation between a proposed alternative noise metric and DNL can serve as a simple test of the potential utility of an alternative noise metric. If the product-moment correlation between a proposed alternative noise metric and DNL exceeds 0.5, for example, it is unlikely that a proposed alternative noise metric can offer more than a marginal improvement in ability to predict the prevalence of noise-induced annoyance in a community.

It is important to recognize that different correlations between DNL and alternative noise metrics may be observed in different operational and geographic settings. For example, correlations between DNL (an A-weighted noise metric by definition) and C-weighted noise metrics may be poorer at points in runway sideline communities exposed at relatively short ranges to thrust reverser and takeoff roll noise, and in communities behind departing aircraft that are exposed to predominantly low-frequency start-of-takeoff-roll noise, than in communities under approach paths. Certain alternative noise metrics may therefore be more appropriate in some settings than in others.

4.2 Stringency Issues

'Stringency' is a term that describes the apparent change in the strictness of a noise standard through a change in the numerical computation of the noise level as opposed to a change in the standard itself. For example, the FAA permits airports in the State of California to use CNEL, a metric mandated the State's Airport Noise Regulations (FAR Part 150), in lieu of DNL. CNEL values are generally about 0.6 dB higher than DNL values, so that FAA's L_{dn} = 65 dB standard is about 0.6 dB stricter in California than it is in other states[14]. In the noise metric correlations described below, most noise metrics differ from DNL by a constant. Switching to those metrics without changing the 65 dB numerical standard by a similar constant would result in a change in the stringency of the standard without changing the standard itself. The following discussions do not address changes in stringency, because a change of metric would logically imply a corresponding change in the standard for equivalency. Changes in the stringency of a standard are policy, not metrics, issues.

4.3 Description of noise modeling approach

Developing correlations between DNL and other noise metrics was approached using two different methods. The first was to use the Noisemap database (Czech and Plotkin, 1998) to develop a correlation between the A-weighted maximum noise level, Lmax, to a variety of other single event measures of noise. The second method used the Integrated Noise Model Version 7.0b (INM) to develop a correlation of DNL to a variety of single event and cumulative noise metrics. The Noisemap method was used initially because the Noisemap database includes one-third octave band noise data for a fairly wide range of civilian aircraft in addition to the military

[14] An increase in strictness of 0.6 dB may seem trivial, but 0.6 dB difference in the location of the 65 dB contour used in enforcement of a land use restriction at a large airport may represent a substantial geographic area.

aircraft database (only civilian aircraft were used in the current analysis). This allowed for the computation of a variety of noise metrics, some quite dated, that are not a part of any aircraft noise database and consider sound propagation effects over long distances. The INM method was used to correlate DNL with other metrics which can be developed from INM computations. These approaches are discussed below.

4.4 Correlations among single event aircraft noise metrics calculated from information contained in the Noisemap database

An analysis was conducted of the relationship of A-weighted aircraft sound levels to five other aircraft noise metrics. The goal was to determine whether other measures of aircraft noise differed sufficiently from A-weighted sound levels to support usefully different characterization of aircraft sound levels. The following are brief descriptions of the noise metrics compared:

A-weighted sound level: The most common frequency weighting network for expressing a broad brand sound as a single number reflecting human sensitivity to sounds of varying spectral content. The original A-weighting network was based on the Fletcher-Munson equal-loudness contour for loudness level of 30 phons [Fletcher, Munson, 1933], and was intended for application to sounds of about 30 dB. Phons were the original measure of loudness at individual frequencies.

B-weighted sound level: A frequency weighting very similar to the A-weighting network intended for noises in the range of 60 to 70 dB The B weighting has less extreme weightings at the low and high frequencies [Schultz, 1982].

C-weighted sound level: A scale very similar to the A-weighted scale, but developed for higher noise levels like the B scale and is most often used as a surrogate for the overall (un-weighted) sound pressure level. The C scale has less extreme weightings at low frequencies when compared to the A scale [Schultz, 1982].

Tone Corrected Sound Exposure Level: Sound Exposure Level, SEL, is the most common measure of the total noise exposure for a single aircraft flyover. Mathematically, it is the sum of the sound energy over the duration of a noise event or considered as an equivalent noise event with a one-second duration. SEL is almost always expressed in terms of the A-weighted sound level. In this analysis the C-weighted SEL is evaluated as a potentially independent measure of noise from the A-weighted Lmax or A-weighted SEL. Tone Corrected Sound Exposure Level, SELT, is the SEL with a correction for any discreet tonal characteristics. Tone corrections are determined by how much the noise level in any 1/3 octave bands exceeds the levels of adjacent bands.

D-weighted sound level: The D-weighting is very similar to the A-weighted scale, but was developed as alternative to rating loudness by measuring perceived noisiness from equal noisiness curves instead of equal loudness curves. It was developed as a simple alternative to measuring Perceived Noise Level (PNL) described below and for use in measuring aircraft noise. [Schultz, 1982].

Effective Perceived Noise Level (EPNL): EPNL measures the noise exposure over the total duration of an aircraft noise event, similar to the Sound Exposure Level. EPNL is based on the Perceived Noise Level (PNL) and not on the A-weighted sound level. PNL is a measure of noisiness as opposed to a measure of loudness as judged by the human observer. EPNL is the fundamental measure used to set noise standards for certifying aircraft noise levels by the aircraft manufacturer [Federal Air Regulation Part 36, International Civil Aviation Organization (ICAO) Annex 16].

Speech Interference Level (SIL): SIL is a metric designed to describe difficulty of understanding speech over an interfering noise level. It is the arithmetic sum of the octave band sound pressure levels in octave bands centered at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz [Bennett and Pearsons, 1981].

The analysis was conducted on aircraft noise measurements derived from the database of civil aircraft noise measurements contained in the Noisemap software. Noisemap is a suite of programs and databases that includes an aircraft noise database for both military and civil aircraft. Table 4-1 lists the civil aircraft included in the Noisemap aircraft noise database. For each of the aircraft listed in Table 4-1, the database includes the A-weighted L_{max}, EPNL, SEL, tone corrected SEL, and one-third octave band sound pressure levels from 50 Hz to 10,000 Hz. The Noisemap database includes information about takeoff, approach, and cruise thrust and aircraft configuration. The one-third octave band measurements were used to compute the B, C, and D-weighted maximum noise levels of the present analysis.

The current analysis established the coefficient of determination, R^2, among the A-weighted maximum noise level, L_{Amax} and each of the five other single event noise metrics noted above. The coefficient of determination is a standard measure of the shared variance of two variables, or in effect, the degree to which two variables are related to one another. Any noise metric that is highly correlated with the A-weighted sound level can not mathematically or logically support predictions of noise impacts superior to those afforded by A-weighted sound levels, even though it may differ from the A-weighted level by a constant and/or a scaling factor.

Table 4-2 displays linear regressions (slope and constant for the equation $y = mx + b$, where x = A-Weighted L_{max} and y = dependent metric) and the R^2 values for each of the noise metrics examined in this analysis. The results summarized in Table 4-2 indicate that the A-weighted sound level is highly correlated with other common measures of aircraft noise based on different frequency weighting networks, as well as with a speech interference metric based on specific frequencies. These analyses considered the spectral characteristics of a broad range of civil (primarily turbofan) aircraft, at a standard distance of 1000 feet from the source. Because these aircraft engines produce broad-band noise lacking strong tonal characteristics, these results are not particularly surprising.

Table 4-1. Civil aircraft included in Noisemap database

B-747-100 (Q)	B-727-1QN7 (Q)	LEARJET-35
B-747-200 (N)	B-727-2QN15 (Q)	LEARJET-25
B-747-100 (QN)	B-727-2D17 (Q)	SABER-80
B-747-SP (N)	A-300	CESSNA-500
DC-8-20 (Q)	B-767-CF6	CL-600
B-707-120 (Q)	B-767-JT9	GULF-GIIB
B-720 (Q)	A-310	MU-3001
B-707-320B (N)	B-737-300 B1	CL-601
B-720B (N)	B-737-300 B2	ASTRA-1125
DC-8-50 (N)	BAC-111	ELECTRA-188
DC-8-60 (N)	F-28-MK2	DHC-7
DC-8-70 (N)	F-28-MK4	CONVAIR-580
BAE-146	DC-9-30D9 (N)	BAE-HS-748
B-707-320 (QN)	DC-9-10D7 (N)	SHORTS SD3-30
DC-8-60 (QN)	B-737-D9 (N)	DHC-6
CONCORDE	DC-9-30QN9 (Q)	DC-6 R2800
DC-10-10	DC-9-10QN7 (Q)	DC-3 R2800
DC-10-30	B-737-QN9 (Q)	SAAB-340
DC-10-40	DC-9-50D17 (Q)	CESSNA-441 TPROP
L-1011	B-737-D17 (Q)	GASEPV VAR PTCH
L-1011-500	MD-81	GASEPF FIX PITCH
B-727-2D7 (N)	MD-82	BEECH BARON 58P
B-727-2D15 (N)	MD-83	HERCULES-380
B-727-2QN9 (Q)	B-757-200-RR	B-727-EM7
		B-727-EM5

Table 4-2. Noisemap-derived linear regression and coefficients of determination for relationships among A-weighted sound levels and other aircraft noise metrics

METRICS COMPARED WITH L_{AMAX}	SLOPE	CONSTANT	R^2
Effective Perceived Noise Level	.962	13.80	.97
Tone Corrected Sound Exposure Level	.963	11.50	.98
C-Weighted L_{max}	.975	6.66	.91
B-Weighted L_{max}	.995	3.33	.95
D-Weighted L_{max}	1.01	4.41	.97
Speech Interference Level	.997	-9.25	.99

The analysis described above has several limitations. The Noisemap database contains few modern aircraft engines, although it does include those which power the Boeing 757, 767 and 737-300. A further limitation is that the noise measurements in the Noisemap database are standardized to a slant range of 1000 feet. This is not an uncommon aircraft-to-observer range near the L_{dn} = 65 dB contour at a typical airport, but greater ranges are common at lower DNL values. Lower correlations among noise metrics than those observed in the current analysis are

thus conceivable at larger slant ranges. Consideration of a larger fleet of modern engines might also affect the conclusions of the Noisemap-based analysis.

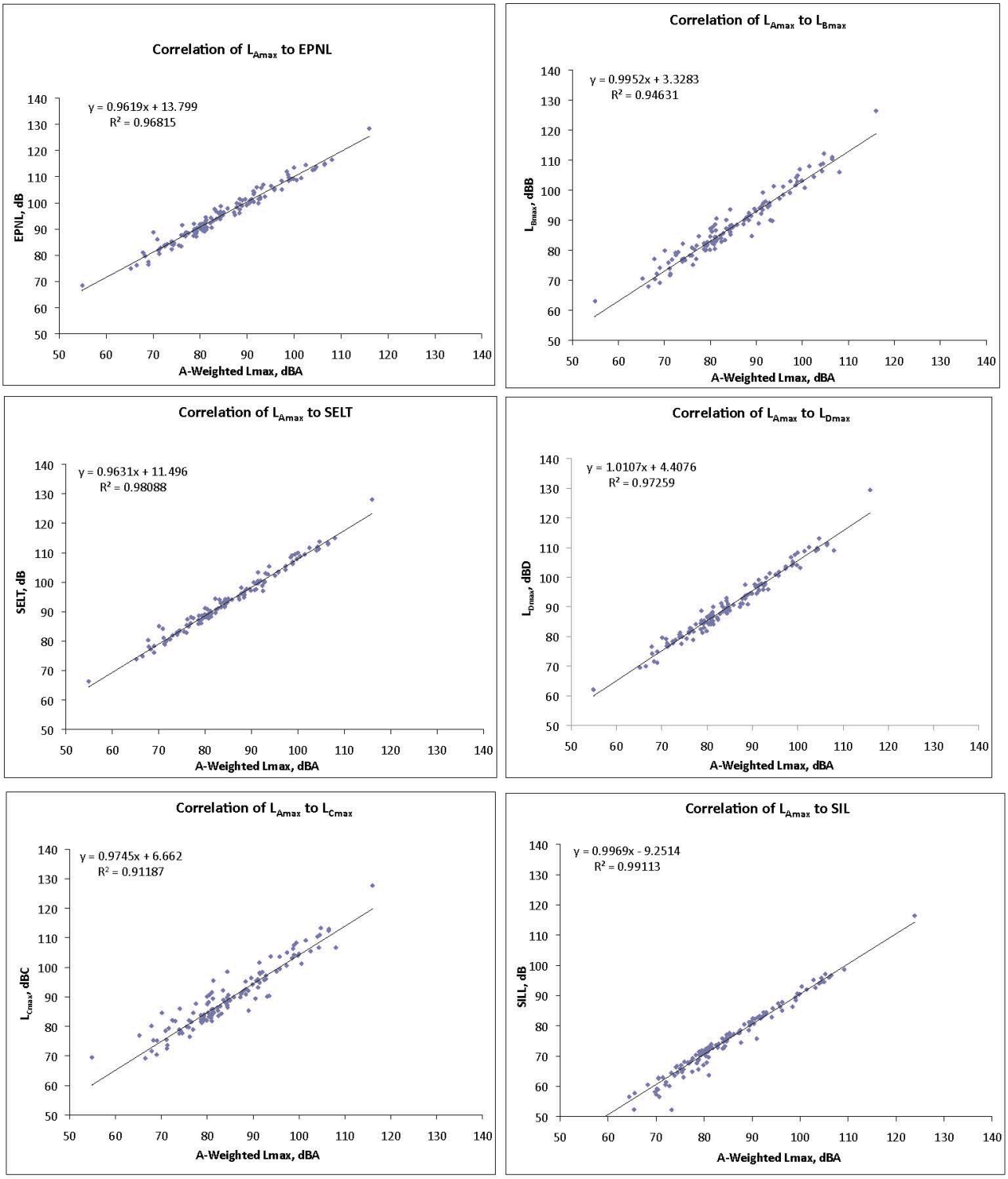

Figure 4-1. Plots of the relationships between A-Weighted Lmax and other measures of aircraft noise levels

4.5 Correlation among single event and cumulative noise metrics calculated from information contained in the Integrated Noise Model (INM) database

A second analysis was undertaken to correlate (the A-weighted) DNL with other noise metrics under a wider range of conditions than was possible using information in the Noisemap database.[15] INM was used to create a large grid of points at which INM computed values for DNL and a variety of other noise metrics.

Because DNL is a time-weighted cumulative noise metric, DNL values depend on numbers of flights, aircraft fleet mixes, time of day of flight operations, flight paths, profiles and operating procedures, and the distance from the aircraft to the receiver. An exhaustive analysis of all of the potential combinations of factors is clearly intractable. However, correlations among DNL and other noise metrics can be calculated for a typical air carrier airport, created for the sole purpose of modeling the correlation of DNL to other metrics. More specifically, this approach can help to determine whether noise metrics other than DNL could yield meaningfully different predictions of noise exposure[16] for a typical airport, and hence, support predictions of noise impacts potentially different than those produced by DNL.[17]

The hypothetical airport created for this analysis has a single, 10,000 foot, sea-level runway. The airport was surrounded by a 17 by 17 nautical mile (nm) grid with a 1nm grid point spacing, as shown in Figure 4-2. The airport's fleet mix resembles that of the current fleet operating at Seattle-Tacoma International Airport. This mix includes a substantial amount of short and medium haul flights, as well as a fair number of international flights. It also includes a mix of aircraft operated by low cost carriers, legacy carriers, and international and cargo carriers. The fleet mix at the hypothetical airport is similar to that at most U.S. airports, in that it is dominated by narrow-body twin engine aircraft.

The hypothetical single runway airport is limited in the number of operations that it can accommodate. The number of daily operations resembles that of San Diego's Lindbergh Field, a very busy single runway airport. Table 4-3 shows the fleet mix and number of operations assumed for the hypothetical airport. The flight tracks consist of straight-in and straight-out dispersed tracks with a total of six subtracks and one backbone track. The runway use is 50% in each direction, with a schedule of 75% day, 15% evening, and 10% night operations.

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[15] As noted earlier, correlations among noise metrics shown in Table 4-2 might differ if the noise sources considered included strong low frequency tones, or at greater source-to-receiver distances. As sound propagates through the atmosphere, high frequency components are preferentially absorbed by the atmosphere, so that aircraft spectra heard at greater distances contain mostly low frequency energy.

[16] A meaningfully different noise exposure prediction is one that differs from DNL by more than a constant, because correlation is indifferent to constants.

[17] Note that fixed differences in values of DNL and other metrics are irrelevant, since they can be fully accounted for by corresponding differences in interpretive criteria.

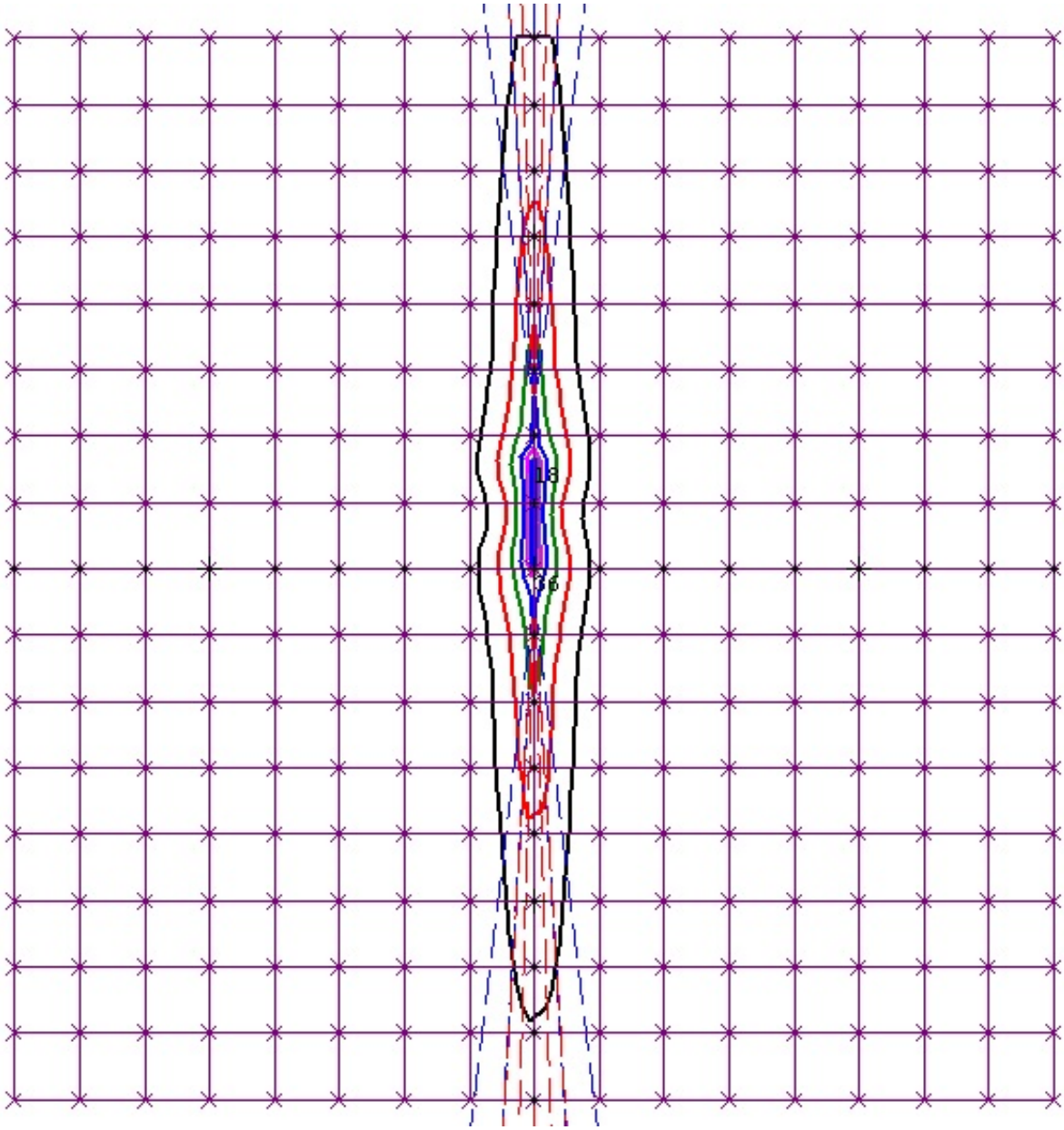

Figure 4-2: Runway, grid Points, flight tracks and DNL contours for the hypothetical arport. The outer contour is L_{dn} = 55 dB; inner contours are plotted at 5 dB increments. Grid points are spaced at 1nm intervals

Table 4-3 Fleet mix and numbers of daily operations at hypothetical airport

Airccraft Type (INM Name)	Daily Departures	Daily Approaches
DHC830	61.27	61.27
737800	55.80	55.80
737700	31.72	31.72
737400	20.50	20.50
CRJ9-ER	16.00	16.00
757PW	15.19	15.19
A320-232	9.07	9.07
737300	8.68	8.67
EMB120	7.49	7.49
A319-131	7.29	7.29
MD83	7.17	7.17
757300	5.33	5.33
A320-211	4.17	4.17
767300	2.72	2.72
747400	2.47	2.47
A330-343	2.13	2.12
777200	1.89	1.89
757RR	1.83	1.83
A321-232	1.78	1.78
CL601	1.63	1.63
737500	1.62	1.61
DC1010	1.22	1.22
GV	1.07	1.07
MD9028	0.85	0.85
DC1030	0.75	0.75
717200	0.55	0.56
A300B4-203	0.55	0.55
A330-301	0.46	0.45
CNA208	0.38	0.38
MD11GE	0.35	0.35
MU3001	0.28	0.29
A340-211	0.28	0.28
CL600	0.28	0.28
ATR42	0.27	0.28
MD11PW	0.25	0.24
777300	0.24	0.25
ATR72	0.22	0.23
LEAR35	0.19	0.19
DHC8	0.19	0.19
MD82	0.17	0.17
IA1125	0.11	0.11
CNA172	0.08	0.09
CNA750	0.08	0.08
A300-622R	0.06	0.06
CNA441	0.05	0.05
PA31	0.05	0.05
747200	0.06	0.04
737QN	0.05	0.05
CIT3	0.05	0.05
GIV	0.04	0.04
SD330	0.04	0.04
CNA500	0.04	0.04
C130	0.02	0.02
Totals	275	275

All of the noise metrics that INM can calculate were evaluated at each grid point.[18]In addition, detailed grids were computed at each grid point to determine the number of flight events above various thresholds(the so-called "number of events above (NA)" metric.) Table 4-4 shows the metrics that were calculated for this analysis and correlated to DNL.

Table 4-4. INM-calculated metrics considered in correlation analysis for hypothetical airport

Independent Metric Candidates	Slope	Constant	R^2
Community Noise Equivalent Level or Day-Evening Night Average Sound Level (CNEL/Lden)	.9999	.6399	.99998
Weighted Equivalent Continuous Perceived Noise Level(WECPNL)	1.0793	7.6323	.99951
24 Hour Average Sound Level (LA_{eq}(24 hour)	1.0001	-2.7943	.99999
Daytime Average Sound Level (LA_{eq}(day)), typically 12 hours, 7 am to 7pm.	1	-1.195	1
Effective Perceived Noise Level (EPNL)	1.0741	43.576	.9995
Tone Corrected Perceived Noise Level ($PNLT_{max}$)	1.43281	13.521	.9722
Nighttime Average Sound Level (LA_{eq}(night)	1	-8.5235	.99999
Sound Exposure Level (SEL)	1	46.582	.99999
Maximum A-weighted Noise Level (LA_{max})	1.4353	3.8479	.98381
Time Above a Tone Corrected Perceived Noise Level (TAPNL) threshold	1.7872	-54.523	.54849
C-weighted Sound Exposure Level (SELC)	.7495	67.338	.98824
Maximum C-weighted Noise Level (LC_{max})	1.2035	24.128	.97864
Time Above 65 dBA (TA 65 dBA)	.8963	-28.588	.51406
Noise Exposure Forecast (NEF)	1.074	-40.326	.99951
Time Above 65 dBC (TA65 dBC)	1.9629	-59.688	.70822
Number of Events Above 70 dBA (NA70 dBA)	12.46	-632.42	.91298

*Slope and constant from the form y = mx + b, x = A-Weighted Lmax, y = dependent metric.

Figure 4-3 plots the correlation of DNL to each of the 16 alternative metrics shown in Table 4-4. The very high DNL values calculated are of three grid points that lie directly on the runway.

[18] Recall that INM'S analysis of the relationships among DNL and other noise metrics is a geospatial one that includes the effects of atmospheric absorption and low angle of elevation overground propagation.

The only noise metrics that do **not** correlate more highly than r = 0.9 with DNL are the "time above" metrics. Note the slope very near to 1.0 and the very high R^2 for all but the TA and NA metrics.

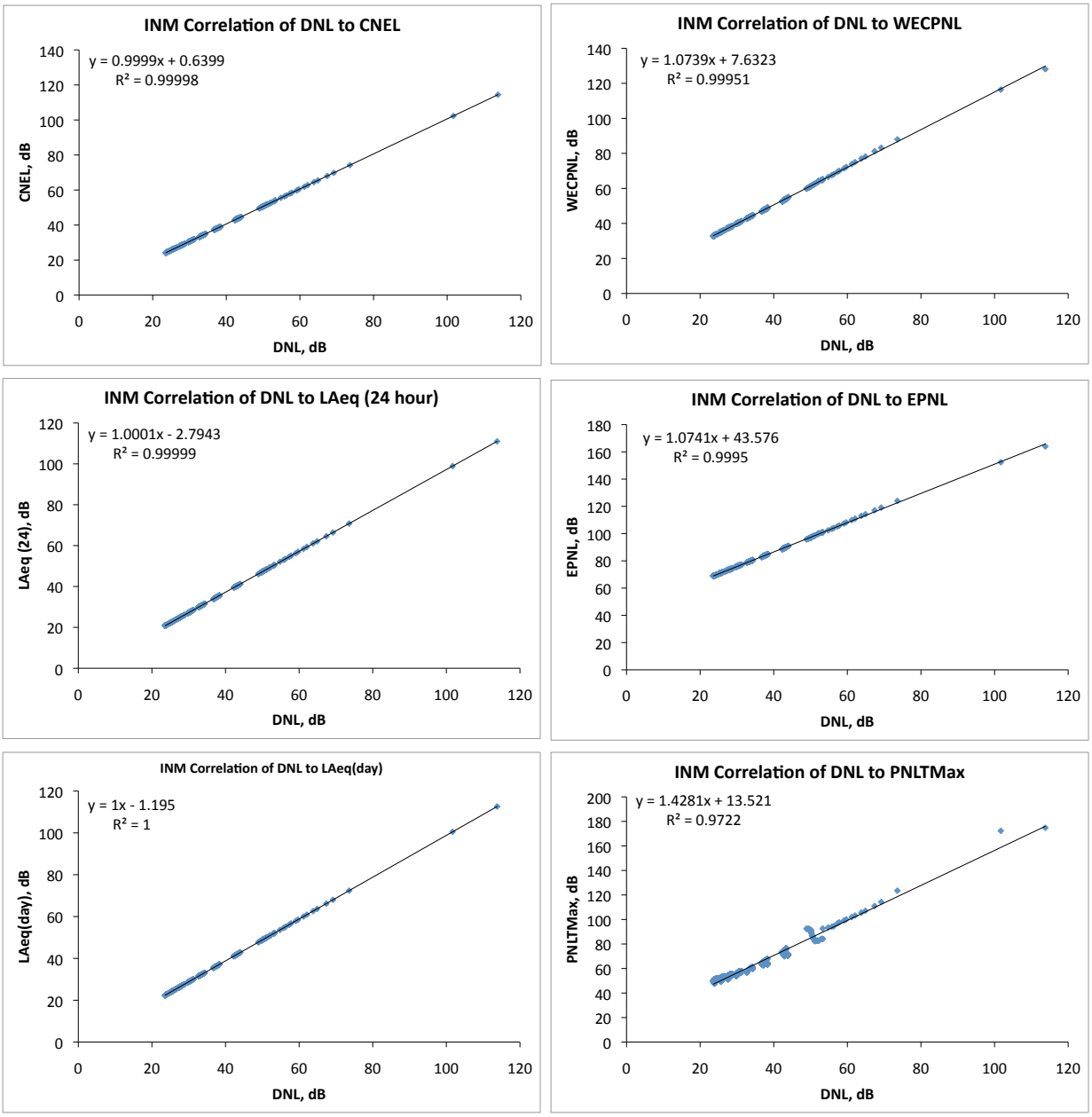

Figure 4-3. Correlation of DNL to Other Cumulative Metrics

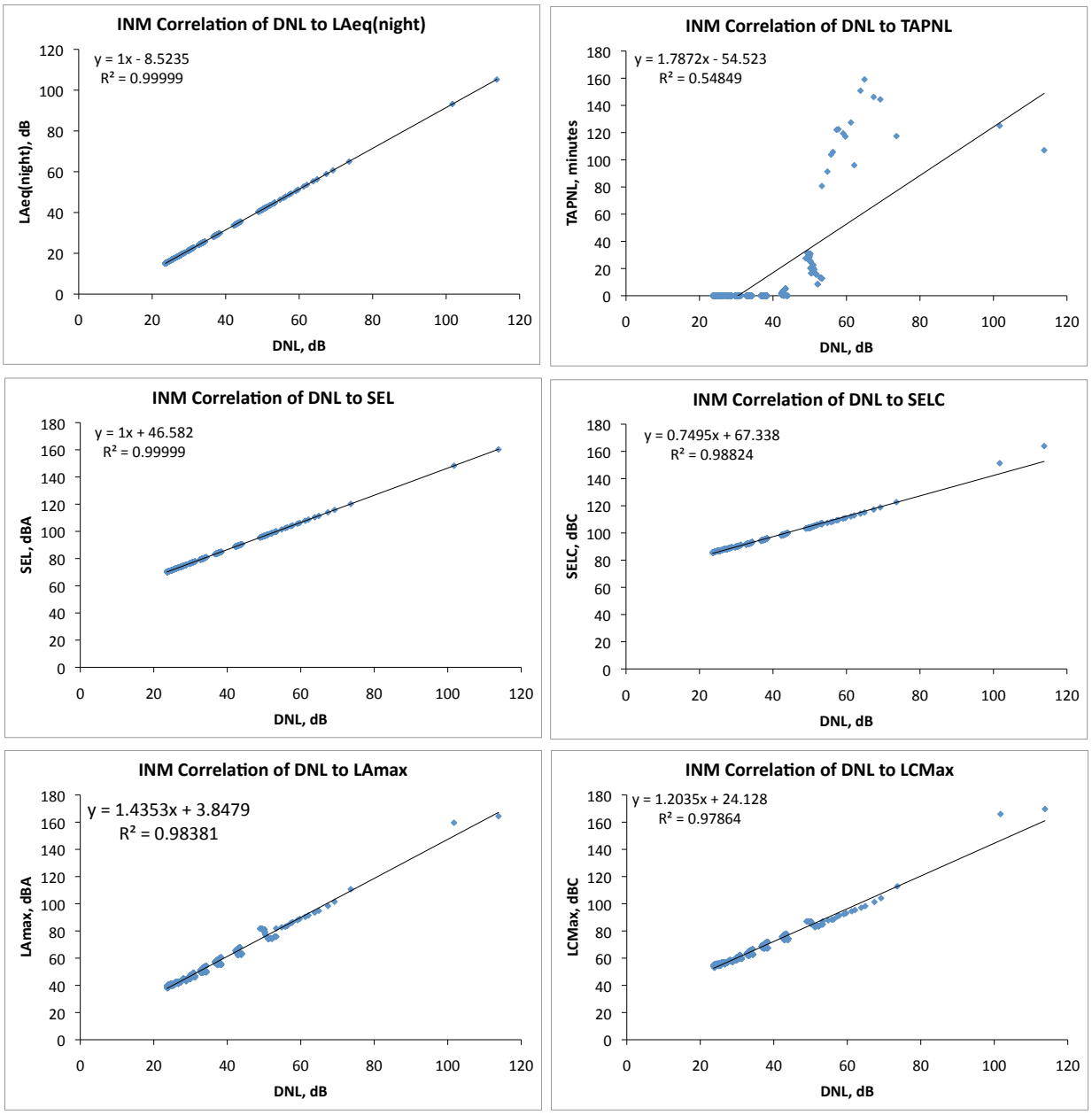

Figure 4-3. Correlation of DNL to Other Cumulative Metrics (cont'd)

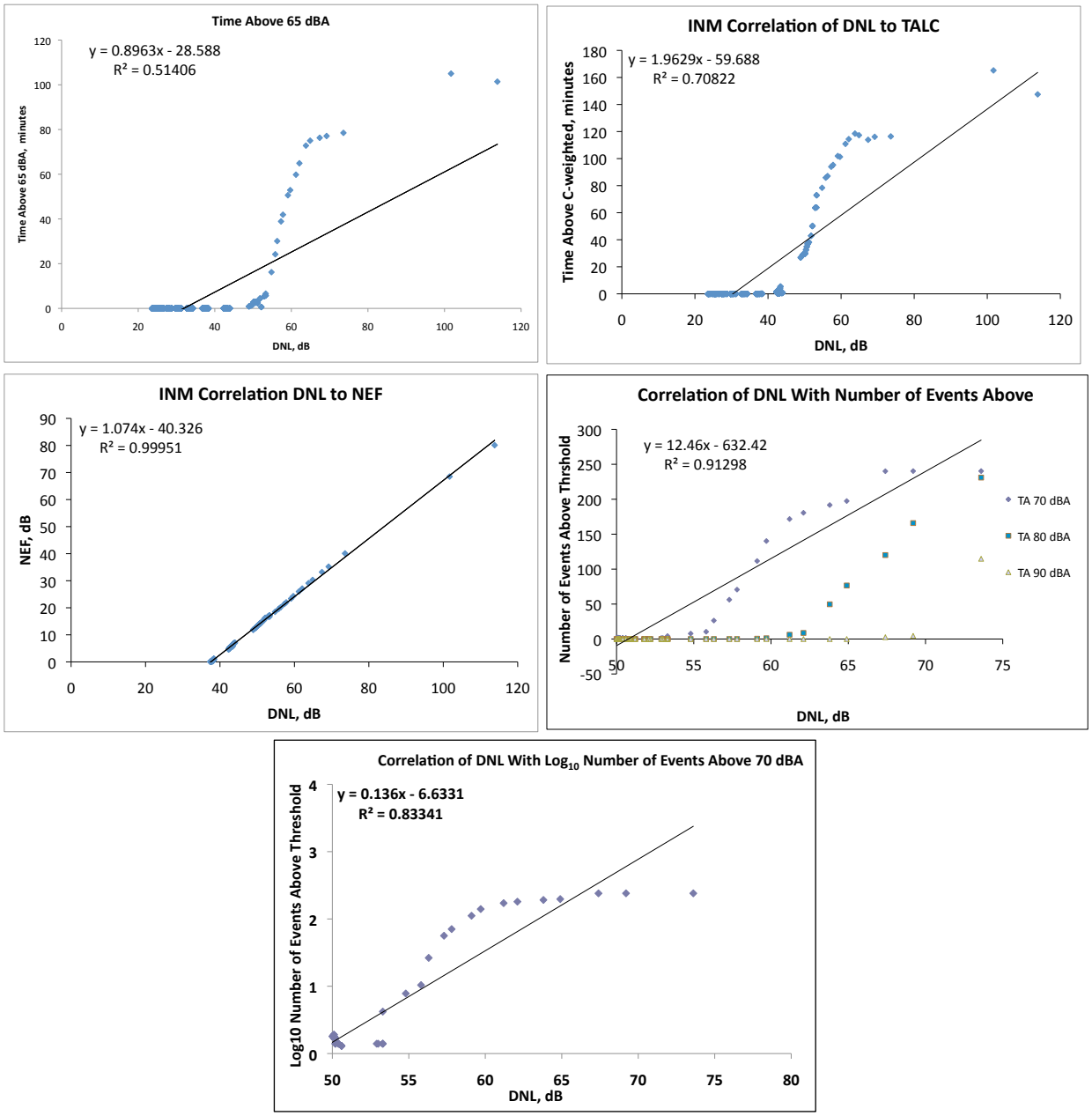

Figure 4-3. Correlation of DNL to Other Cumulative Metrics (cont'd)

4.6 Summary of correlation analysis findings

The findings of the analyses described in Sections 4.4 and 4.5 clearly document that the A-weighting-based DNL noise metric is nearly perfectly correlated with most other aircraft noise metrics, whether based on the A-, C-, or annoyance (PNL) frequency weighting networks. R^2 values between DNL and all common metrics of aircraft noise other than Time Above (TA) and Number Above (NA) exceed 0.98.[19]

In other words, all of the other common aircraft noise metrics save TA and NA differ from DNL only by a scaling constant, so that only TA and NA reflect potentially useful information that is not wholly redundant with that expressed by DNL. Thus, replacing DNL with CNEL, NEF, WECPNL, Leq(24), Leq(day) or Leq(night) will not provide any improvement in the accuracy or precision with which an aircraft noise metric can predict the prevalence of aircraft noise-induced annoyance in a community. These findings are applicable to most air carrier airports, both because the SEA fleet mix is a typical one, and because the findings are so unequivocal. It is true that for a different day/evening/night mix the relation of DNL to CNEL, DENL, NEF, Leq(24), Leq(day) and Leq(night) will change, but only the constant will change. They will remain highly correlated.

For a constant fleet mix, doubling or halving operations doubles or halves the number of events above, and hence changes DNL by 3 dB. The correlation of DNL to number of events above does not change for a constant fleet mix. For related threshold values, NA and TA are essentially the same metric, since Time Above is merely the product of Number of Events Above and the durations of the events. The shape of the relationship between DNL and time and number above metrics TA and NA have essentially the same shape.

The relationships between time and number above metrics and DNL resemble step functions. TA and NA are zero until a threshold is reached, after which they climb steeply until saturation is reached. Between the threshold value and saturation, the slope of the relationship is fairly linear. Once the threshold is exceeded, a small change in DNL can produce large changes in TA and NA. The steep slope is an artifact of the logarithmic nature of DNL but the linear nature of TA and NA.[20] In this case the fleet mix was typical of a large air carrier airport. As the fleet mix changes the shape of the TA and NA correlation to DNL will change. For example, if there were only one aircraft type in a single mode of operation the TA and NA correlation curves would be a step function. The more diverse the aircraft fleet mix, the shallower the slope of the TA and NA correlation with DNL curve.

The correlation of DNL with the log base 10 of NA was tested as well and is shown at the bottom of Figure 4-3. It does not correlate quite as well as DNL versus NA (NA 70 dBA was used for the least squares analysis is each case).

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[19] This is not a novel conclusion. Although the current demonstration is better documented than most, the conclusion has been noted, among others, by Botsford (1969), Fidell (1979), and Schultz (1982).

[20] Note that this discussion is with respect to overflight noise. Noise from ground runups may display a different pattern as the duration may be quite long from some of these events and TA and NA may behave differently under that kind of circumstance. Fleet mix will affect the correlation of TA and NA to DNL.

The conclusion of the correlation analysis is that a loudness-based metric (that is, one that is both frequency *and* level-based) metric offers the best prospects for a metric generally similar but somewhat superior to DNL. Threshold-based metrics may be of some additional utility for predictive, but not necessarily regulatory utility, due to their linear (rather than logarithmic) nature.

4.7 Low Frequency Sound Level (LFSL)

Secondary emissions (rattle sounds) associated with low frequency sounds are a special case. Predicting levels of rattling sounds is a difficult matter involving non-linear acoustic excitation of building and furnishings as a result of low frequency noise. Several communities including those around San Francisco International Airport and Minneapolis St Paul International Airport have wrestled with this issue. The most common experience with low frequency sounds are those areas directly exposed to back blast noise at the beginning of takeoff roll and the noise from thrust reverser on landing. This low frequency noise can result in rattle of building elements such as window frames and furnishings such as wall hangings and bric-a-brac.

A panel of experts commissioned by the City of Richfield and Minniapolis Metropolitan Airport Commission[21] recommended the use of a noise metric (Low Frequency Sound Level, or LFSL) tailored to the low frequency noise emissions of large jet transports. While the single event metric was disparaged in FICAN's review of the recommendation,[22]it warrants further consideration as the only metric proposed to date that addresses exclusively the consequences of residential exposure to low frequency noise produced by high power jet engines.

LFSL is defined as the sum of the levels of one-third octave band noise levels from 25 through 80 Hz (sum on energy basis). Although ANSI and ISO (ISO 1996-1) recommend considering frequencies as low as 16 Hz to account for building excitation effects, large jet engines do not produce substantial energy at such low frequencies. ISO states that "The frequency range of interest appears to be about 5 Hz to about 100 Hz. In the range below about 20 Hz, some countries use the G-weighting to assess sound. Above about 15 Hz, several countries use octave-band or one-third-octave band analysis in the range from about 16 Hz to 100 Hz." The rationale for the G-weighting network was not based on a comprehensive set of empirical measurements of either low frequency aircraft noise nor building resonances.

No comprehensive database exists of aircraft noise data at these low frequencies. For example, the Noisemap database described in Section 4.4, does not generally report noise levels below 50 Hz, except for a few military aircraft, primarily helicopters and a few fighter and

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[21] "Findings of the Low-Frequency Noise Expert Panel of the Richfield-MAC Noise Mitigation Agreement of 17 December, 1998," 25 April 2000.
[22] FICAN on the Findings of the Minneapolis-St. Paul International Airport Low Frequency Noise (LFN) Panel, April 2002.

bomber aircraft. The aircraft with low frequency data available from Noisemap are shown in Table 4-5.

The noise data for aircraft shown in Table 4.5 were used to calculate LFSL for takeoff, arrival and overflight noise at a fixed slant range distance of 1000 feet. These data were then correlated to the A-weighted noise levels for these same conditions. The correlation of LFSL to A-weighting is shown in Figure 4-3. LFSL does not correlate as highly with A-weighting (R^2 less than 0.7) as do other common frequency weightings. The scatter in the data show that A-weighting is not a useful surrogate for LFSL, and that LFSL does provide information about noise levels that are not available from the A-weighted data. If there were data at larger slant distances it is expected that the scatter would be greater and correlation even weaker.

B-2A	CH-53E
C-17	CH-46E
F-14A	ASTAR SA350D
F-14B	DAUPHIN SA365N
F-18A/C	GAZELLE SA341G
F-18E/F	PUMA SA330J
F-22	TWINSTAR SA355F
P-3C	A109
E-2C	BL212 (UH-1N)
AH-1G	BL222
AH64	CHINOOK (CH-47D)
OH58	BOELKOW BO-105
OH58D	HU500D/E (OH-6)
TH55	SK61 (CH-3A)
CH47B	SK65 (CH-53)
CH47D	SK70 (UH-60A) BLACKH
UH60A	SK76 SPIRIT

Table 4-5. Aircraft in Noisemap Database With Noise Data For Frequencies Less Than 50 Hz.

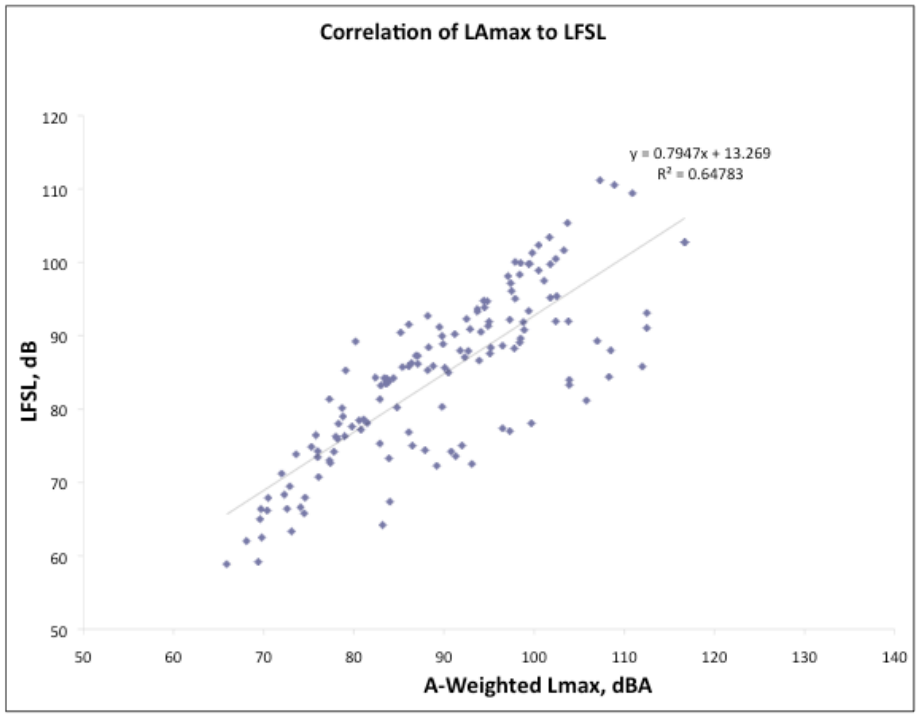

Figure 4.3. The Correlation of A-weighted Lmax to Low Frequency Sound Level (LFSL) For a Select Number of Military Aircraft.

4.8 Role of non-acoustic variables as predictors of annoyance prevalence rates

The International Standards Organization has convened a working group, ISO WG-45, that is considering a formal role and a systematic means for estimating the contribution of non-acoustic factors to annoyance prevalence rates. The method under consideration assumes that the prevalence of annoyance with transportation noise increases at the same rate as the duration-adjusted loudness of noise exposure. This growth rate is expressed as an exponential function with a fixed growth rate equal to that of the growth of loudness with sound level (Stevens, 1972). This is the growth rate of loudness implicit in the familiar rule of thumb that a change of 10 dB in sound pressure level is perceived as a factor of two change in loudness, or expressed in equation form:

$$\textit{Growth rate of loudness} = (10^{L/10})^{0.3} \qquad [2]$$

DNL values are converted into estimated noise doses, m,

$$m = (10(^{DNL/10}))^{0.3} \qquad [3]$$

Predicted annoyance prevalence rates for the calculated dose are then computed as the probability of high annoyance, p(HA):

$$p(HA) = e^{-(A/m)} \quad [4]$$

where A is a non-acoustic decision criterion, per Green and Fidell (1991).

The community-specific constant, A, is found by minimizing the least square difference between the annoyance prevalence rates predicted by an exponential function with a slope equal to the rate of growth of loudness with level ("the effective loudness function") and those observed at the interviewing sites in each community. This process slides the effective loudness function along the DNL axis to the point at which a best fit between the predicted and observed points occurs. The value of A at this point is transformed into a decibel-like index that reflects the aggregate influence of all non-dose related factors on annoyance judgments in a given set of field observations. Another way to describe the terms m and A in the function that generates the familiar sigmoid dose-response curve is that m is that variable that forces the slope and shape to conform to the known human perception of the change in loudness and A scales that dose-response curve to reflect the non-acoustic components contributing to reported high annoyance.

Fidell *et al.* (2011) selected the midpoint of the effective loudness function - the point corresponding to a 50% annoyance prevalence rate - as a convenient descriptor of the position of the effective loudness function on the DNL axis for any given community. This value of DNL is termed the "Community Tolerance Level" (CTL). CTL so defined represents a DNL value at which half of the people in a community describe themselves as "highly annoyed" by aircraft noise.

4.9 Applications of CTL to noise effects research and noise assessment methods

CTL analysis permits quantification in decibel units (of DNL or other metrics) of the effects of situational variables and varying circumstances of noise exposure on the prevalence of annoyance. Current "one size fits all" policy for defining the significance of noise impacts assumes that a single dosage-response relationship is appropriate for assessing the noise impacts of all forms of transportation noise in all communities.

CTL analysis, however, permits categorization of circumstances of noise exposure at large airports in urban areas, large airports in suburban areas, feeder airports in suburban areas, general aviation airports in rural areas, and so forth. CTL analysis could therefore facilitate more accurate assessment of noise impacts in a range of (for example) "small, medium, large, and extra large" exposure circumstances. Such research would be a combination of (1) classifying existing airports carefully into various categories to determine what categorization scheme collapsed airports into a set of homogenous groupings, and (2) performing new attitudinal surveys at a set of "verification" airports"

A second application of CTL would be to examine the efficacy of factors in assessment using DNL that are currently "assumed to be true." For example, it has been assumed, for a variety of reasons, that noise at night warrants a 10 dB penalty. Three studies (Wehrli *et al.*, 1978, Planungsbüro Obermeyer, 1983 and Fields, 1986) examined annoyance separately by

daytime and nighttime. The Swiss road traffic study suggested about three dB greater sensitivity to nighttime vs. daytime noise exposure. The German road and railroad noise study showed essentially no difference between daytime and nighttime sensitivity. Fields concluded "that studies of community response to noise will not provide a usefully accurate estimation of the time-of-day weighting parameter in the adjusted energy model." These sorts of observations suggest that a further review of the 10 dB nighttime penalty might warrant reconsideration.

4.10 Sufficiency of a single model of annoyance

A basic research issue which affects any choice of noise metric is whether a single model of annoyance is appropriate for the entire population. The standard model (time weighted average energy, or "DNL" model) assumes that all people perfectly integrate all acoustic energy at all hours of night and day to form opinions about annoyance. A number of alternative models discussed in this chapter and in the technical discussion of Chapter 2 are plausible, as is the possibility that different models are useful for representing the opinions of different segments of the population. Although the implications of imperfect integration and other models of annoyance are far-reaching for the selection of noise metrics, they are unlikely to be fully understood until much additional basic research is completed.

5 EUROPEAN PERSPECTIVE ON ROLE OF METRICS IN REGULATORY POLICY

This section summarizes recent European Union (EU) policy documents and statements concerning aircraft noise metrics, as required by Task 2 of the Statement of Work of by Volpe Purchase Order DTRT57-10-P-80191.

5.1 The Environmental Noise Directive (END) of 2002[23]

This Directive is the fundamental policy statement on environmental noise issues for the European Community (EC). The underlying principles of the directive include:

Monitoring the environmental problem by requiring competent authorities in Member States to draw up "strategic noise maps" for major roads, railways, airports and agglomerations, and by using the nominally harmonized noise indicators L_{den} (day-evening-night equivalent level) and L_{night} (night equivalent level). These maps are intended to help estimate numbers of people annoyed and sleep-disturbed throughout Europe.

Informing and consulting the public about noise exposure, its effects, and the measures considered to address noise, consistent with the principles of the Aarhus Convention.

Addressing local noise issues by requiring competent authorities to draw up action plans to reduce noise where necessary and maintain environmental noise quality where it is good. The directive does not set any limit value, nor does it prescribe the measures to be used in the action plans, which remain at the discretion of the competent authorities.

Developing a long-term EC strategy, which includes objectives to reduce the number of people affected by noise in the longer term, and provides a framework for developing existing Community policy on noise reduction from source.

The most significant aspect of this directive is the requirement to produce the mandatory strategic noise maps using the harmonized indicators Lden and Lnight. This requirement, however, should not be interpreted as implying that all other noise metrics are superseded in any EU country. In the UK for example, the Civil Aviation Authority continue to produce annual noise contours for UK airports in terms of a 16-hour daytime LAeq.[24]

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[23] The fundamental directive that describes EU policy on environmental noise may be downloaded from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2002:189:0012:0025:EN:PDF.

[24] http://webarchive.nationalarchives.gov.uk/+/http://www.dft.gov.uk/pgr/aviation/environmentalissues/nec/secnoise07/noiseheath07.pdf

The European Commission staff is responsible for directing efforts on the END Directive. A paper at Internoise 2010 (Bazals Gergely, 2010) summarizes the current position. This paper notes that in accordance with article 10 of the Directive, the European Environment Agency (EAA) and the European Commission, have established a Noise Observation and Information Service (or NOISE) database, of information reported by the Member States. NOISE is maintained by EAA and the European Topic Centre on Land Use and Spatial Information (ETC LUSI) on behalf of the European Commission.[25]

Some preliminary analyses of the NOISE database are described by Gergely (2010). Gergely also notes that, according to the Directive, the Commission shall submit to the European Parliament and the Council a report on the implementation of this Directive. The report was intended to assess the need for further EC actions on environmental noise and, if appropriate, to propose implementing strategies. The report was also to include a review of the acoustic environment quality in the EC based on the data referred to in Article 10, and to address scientific and technical progress and any other relevant information. The reduction of harmful effects and the cost effectiveness ratio were to be the main criteria for the selection of proposed strategies and measures. If appropriate, the report was also expected to include proposals for the amendment of the Directive.

The recently published report is described below.

5.2 Review of Implementation of the Environmental Noise Directive 2002/49/EC

The European Commission contracted with Milieu Ltd., Risk and Policy Analysis Ltd. (RPA) and TNO to conduct the review of implementation required by Article 11 of the Environmental Noise Directive 2002/49/EC. The three tasks of the project were as follows:

Task 1: Review implementation of the key provisions of the Directive by theMember States (EU27), and develop proposals for amendment of the Directive, as appropriate;

Task 2: Provide a comprehensive review of measures employed to manageenvironmental noise from key sources in the Member States; and

Task 3: Develop an Action Plan outlining further implementation strategies and Community action on environmental noise, if considered appropriate.

The objectives of Task 1 - the most relevant for current purposes were:

1) To review the implementation of the key provisions of the Directive with the aim of identifying the main problems and difficulties experienced by the Member States and their competent authorities in implementing the key provisions;

[25] See http://noise.eionet.europa.eu/

2) To provide the Commission with an accurate overview of the risk of non-compliance with the key provisions of the Directive; and

3) To propose amendments of the Directive and solutions with a view to ensuring a more efficient and secure implementation and to better meeting the objectives of the Directive.

The core of Task 1 reviews the implementation of the END in each of the 27 Member States. Each chapter includes a review of relevant legislation, responsible administrative bodies, designation and delimitation of agglomerations, major roads, major railways and major airports, noise limit values, quiet areas, strategic noise mapping, and action planning.

All Member States were found to use the noise indicators Lden and Lnight for strategic noise mapping, as required by the END. Some Member States chose to use additional indicators, due to national preferences regarding their suitability in assessing noise and existing experience. Details of the use of additional indicators are given in Table 5-1 from the Task 1 report.

Noise Mapping Methodologies	**Member states**
Use of Lden and Lnight indicators	Austria, Cyprus, Germany, Denmark, Estonia, Greece, Spain, Finland, France, Ireland, Lithuania, Luxembourg, Netherlands, Portugal, Romania, Sweden, Slovenia, Slovakia, United Kingdom
Use of additional indicators	Estonia: Lde, LAeq, LpAeqT, LpAmax Finland: LAeq (07-22h) and Laeq (22-07h) Ireland: LAeq, LAmax, LAmin, LA10, LA90 and LA95 Netherlands: LAeq(0-24h) Sweden: Lday and Levening Slovenia: Leq 24 hours and Lmax United Kingdom: LAeq 16h (roads, rail, airports, industry); LAeq 18h and 6h (rail); LA10 18h (roads); and Lday (in Scotland) in quiet zones within agglomerations.

Table 5-1. Use of noise indicators for noise mapping in the Member States.

5.3 Other EU Directives Concerning Aircraft Noise

The EU Europa website (http://ec.europa.eu/environment/noise/) lists other noise- related Directives as follows:

- Aircraft noise (follow-up by EC Directorate General Energy & Transport)
- Subsonic Aircraft - Directive 80/51/EEC (This deals with basic Noise Certification)
- Subsonic Jet Aeroplanes - Directive 89/629/EEC (Also on Certification)
- Limitation of the Operations of Aeroplanes - Directive 92/14/EEC
- ICAO Chapter 2 prohibition (Operating restrictions at Community airports)Directive 2002/30/EC and related Commission review (2006) (These deal with the ICAO "balanced approach" (cf. Vallet, 2008))
- Regulation of chapter 3 civil subsonic aeroplanes, Directive 2006/93/EC (Chapter 3 prohibition)

5.4 EU Aircraft Noise Studies

The EU Europa website also lists some relevant "recent studies carried out on behalf of the Commission" as follows:[26]

> Aircraft Noise Exposure at and around Community Airports: Evaluation of the Effect of Measures to Reduce Noise, October 2007.
>
> This study was designed to help the Commission review Directive 2002/30 concerning noise-related operating restrictions at EU airports, after 5 years of experience. The study includes an assessment of changes in the total impact of aircraft noise within the European Union since the entry into force of the Directive. It also includes an inventory of measures to mitigate noise at and around Community airports since its entry into force, as well as an inventory of already planned actions to mitigate aircraft noise with respect to gradual withdrawal of marginally compliant aircraft and to night flight restrictions.
>
> The report also contains a detailed analysis of the above matters to estimate how likely the Community is to achieve its objective of limiting aviation noise at and around Community airports under existing legislation, and to identify possible improvements to that legislation, in part by examining more stringent phase-out options.

[26] See http://ec.europa.eu/transport/air/studies/environment_en.htm

Sound Noise Limits - Options for a uniform noise limiting scheme for EU airports, January 2005[27]

The summary of this report is reproduced in full in Appendix C because it contains a number of references to "indicators"; *i.e.*, noise metrics. The full report not included here) also contains two relevant appendices: "Shortcomings of L_{eq} as an Indicator of Noise Impact at Night," and "Overview of supplementary metrics for transparency of noise policy." The first of these is a straightforward account of well known aspects. The second refers to a form of "number above a threshold" supplementary metrics proposed in Australia where the primary aim is to provide information that is transparent, easy to interpret and meaningful to all including the layperson. They are intended to add information to the L_{eq} contours.

5.5 The EC Working Group WG-AN

The European Commission appointed a Working Group of experts on Airport Noise ("WG-AN") in 2003. The terms of reference for the working group required development of recommendations on the following matters:

- Implementation of ISO's 'balanced approach'. ("The WG will deliver its position on the relevance and feasibility for the European Union of the related recommendations delivered by CAEP/WG2.")
- Land use planning and control
- Use of economic instruments (taxes, fiscal incentives, charges taking into account existing and planned legislation)
- Penalties for non compliance of legislation aiming to control noise (including land use planning and building legislations)
- Control of noise due to night-time flights
- Noise limits (including noise limit values) and measurable targets. The health and socioeconomic aspects of different options will be discussed, as well as the feasibility and added value of an EU common approach aiming to enforce noise limit values in this respect.
- Noise related operational restrictions: Management of flight trajectories (take off and landing) and allowed flying corridors. Low noise trajectories as well as concentration vs. dispersion of flight paths will be discussed.
- Impacts on noise climate of capacity management technologies
- Building soundproofing
- Monitoring (by measurement) and noise mapping
- Mediation and conflicts management methods
- Information and participation of the public

[27] http://ec.europa.eu/transport/air/studies/doc/environment/2005_01_sound_noise_limits.pdf

An unpublished Final Report of the WG from 2007 has been made available through the courtesy of the Chairman of the working group, Dr. Michel Vallet. Two related Internoise papers by Vallet, from 2006 and 2010, and a paper from the ICBEN 2008 Conference are also part of the literature set that has been posted at (http://www.volpe.dot.gov/acoustics/docs/2000/description-otherwise-undocumented-data-points.pdf).

The Final report was intended to summarize the main policy recommendations from the group. It particularly provides the European Commission with suggestions which could be taken into account for the preparation of the reviews on the implementation of the Directives 2002/30/EC and 2002/49/EC. The report notes that it was not possible within the group to achieve a full consensus on every policy recommendation. Some members believed that, besides dissemination of good practice and non-legally binding guidance, no new EU initiatives should be taken to regulate aircraft noise around EU airports since the 'balanced approach' together with the current EU legislation in force should – according to these members - suffice to deal with aircraft noise problems. Other members were of the opinion that there is room for international and EU initiatives to build on the current policy framework to achieve a higher level of environmental and health protection and to strike a more sustainable situation. Several WG-AN members expressed the opinion that the use of "guidelines, codes of good practice and other tools for flexibility" is not sufficient to obtain the adapted degree of noise control around airports. When rules are not mandatory, noise control is not achieved.

This report embraced the second way, according to the results of the evaluation studies of the exposure to noise around airports: the number of exposed people has not decreased as expected in the goals of the Directive 2002/3. Of the many recommendations put forward, those of most relevance to the present project concern Noise Metrics and Limits and are reproduced in full in Appendix C.

WG-AN Recommendations:

1) Require, in addition to Lden and Lnight, at least the monitoring of LAmax levels to inform the public on single events noise and encourage competent authorities in preventing, limiting and sanctioning the noisiest events., where these are unlawful, and after to have identified other noise sources in the environment of the airport.

2) Some noise limits should be set for single event noise, as already mentioned in the Directive 2002/49 (Annex 1) and be based on LAmax outdoor levels in sensitive areas; they should trigger soundproofing schemes and deterring sanctions with a particular attention to evening and night.

3) Exposure to noise related targets should be set with a view to reduce or cap the overall number of people living around the airport in dwellings exposed to air traffic noise levels Lden above 55 dB and Lnight above 50 dB. In addition, targets based on NAx metric could also be considered to steer actions aimed at reducing the noise peaks of single events.

4) The noise limits and targets above mentioned could be harmonized at EU level on the basis of WHO guidelines, in relation with health protection, and in order to avoid environmental dumping.

5) Require that statistics on the noise levels of single events (LAmax), the number of events exceeding the relevant LAmax limits (NAx) and the number of people living around the airport in dwellings exposed above the relevant levels are systematically reported to the public on a regular basis (every 5 years at least). And this to include the population of newly permitted inappropriate developments in the affected area. Such data should be also used for comparison of Noise Certification levels and measured levels, in order to validate additional noise limits.

The above recommendations are also reflected in the conclusions of Vallet (2010), as follows:

"During the decade 2000-2009 several texts have exposed possible criteria to take into account the community response to noise around airports. The EU Directive 2002/49 clearly offers the use of single event noise level as supplemental index. The ICAO-CAEP assessment of the scientific knowledge pointed out noise effects and primary metrics for airport noise: global noise indexes like L_{eq}, $L_{eq\text{-}night}$, L_{dn} or $L_{den}$and L_{max}, SEL are proposed according the effects on people. A discussion on the effects of noise on sleep is a good example to argue for a supplementary indicator, L_{max}, to be used in addition to L_{night}.

"This is a practical solution to get lower global noise level and with less peaks of noise, particularly for medium size airports with few night flights. WHO Europe, in the Guidelines dedicated to the night, proposed to consider the Lnight, that is a change compared to its previous views. This view is well adapted for major airports, where there are numerous flights at nights and very short time without noise. In a practical way, airports are providing noise levels in terms of Lmax or SEL, and for anecdote, residents can easily control (*sic*) the noise levels by using their mobile phone, (iPhone or others) that include a noise meter application or a very low cost sound meter: after that, people can address their own observations to airports' authorities, for instance on the number of aircraft that exceed the noise levels, expressed as legal or recommended limits for a single movement."

5.6 Summary observations

Much of the European Community noise regulatory and policy activity in recent years has centered around the Environmental Noise Directive and the requirements of the 27 Member States to develop and publish strategic noise maps. This has been a challenging and time consuming process even for the most scientifically advanced of the Member States. Perhaps because of the emphasis on achieving compliance with EU law and completing the mapping process and the subsequent stage of developing Noise Action Plans, there has been less of a focus on understanding the limitations or otherwise of the L_{den} indicator or metric.

A number of strong voices have campaigned, however, for a more suitable metric than L_{night} for dealing with sleep disturbance. Perhaps also because of the burden of compliance with the

Environmental Noise Directive, government sponsored research on alternative metrics has been minimal.

Thus it is fair to say that differences between U.S. and European positions on metrics tend to be matters of degree, rather than fundamental differences of opinion about the acoustic quantities worth measuring and using as bases of aircraft noise regulation. Forms of the A-weighted average continuous noise level, L_{eq}, are the primary ones in both the US and EU. Where the US has relied on DNL, the EU leans toward L_{den} and L_{night}. The chief differences among these are limited to a night only metric and an evening (California-style) weighting in the 24 hour metric. The rationale and history of developing regulatory positions in the two jurisdictions obviously differ, but the path taken to present understandings is of lesser interest for current purposes than the actual metrics used to support regulatory rationales, and the minor differences in the metrics themselves.

6 RECOMMENDATIONS AND CONCLUSIONS

6.1 General conclusions

DNL values for noise exposure created by aircraft operations correlate very highly with values of most other conventional noise metrics in most geographic and operational settings (see Sections 4.4 and 4.5). This suggests that little or no improvement in accuracy or precision of prediction of the prevalence of aircraft noise-induced annoyance may be expected from substitution of another noise metric for DNL.

Measures of the duration and numbers of noise events in excess of a threshold do not correlate as highly with DNL as other noise metrics in common use. At sub-threshold levels these metrics have a value of zero, but at supra-threshold values they tend to rise very rapidly with respect to DNL. In other words, small changes in DNL produce large changes in time above and number of events above. This implies that threshold-based metrics are likely to exhibit high uncertainties for regulatory purposes. They may nonetheless have some utility for educating the public about changes in noise environments associated with implementation of new projects or flight procedures.

Some special circumstances in which correlations between DNL and other aircraft noise metrics may be poorer include in areas behind departure ends of runways subject to start-of-takeoff-roll noise, and in runway sideline locations exposed to high levels of low-frequency noise created by thrust reverser application. Note also that conclusions about noise sources with pronounced low frequency components, such as helicopters, have not been addressed here and may vary.

6.2 Supplemental metrics

If the goal of supplemental noise metrics is to improve public understanding of aircraft noise impacts by demystifying acoustic jargon in descriptions of noise exposure, the simplest solution is to entirely omit such jargon from public statements, in favor of direct descriptions of noise impacts themselves. For example, rather than filling environmental impact disclosure documents with illustrations of aircraft noise exposure contours, such documents could show readers graduated displays of aircraft noise-induced annoyance prevalence rates, probabilities of awakenings, or other consequences of predicted noise levels.

6.3 Alternative metrics

Nearly all of the metrics reviewed in this study are highly correlated with DNL for typical airport operations. Any alternative metrics worth consideration would need to provide new information that differs from DNL by more than a constant. Community Tolerance Level is one such non-acoustic measure that may be used to characterize community response to transportation noise. Low Frequency Sound Level may be another useful alternative to DNL in settings in which low frequency noise is of particular concern. These settings include areas behind runways subject to noise from start-of-takeoff roll, and runway sideline areas subject to thrust reverser noise.