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SUPPLEMENTAL METRICS FOR DAY/NIGHT AVERAGE SOUND LEVEL AND DAY/EVENING/NIGHT AVERAGE SOUND LEVEL

Final Report

of the

I-INCE Technical Study Group on Metrics for Environmental Noise Assessment and Control (TSG 9)

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Foreword

This report is based on a study for the US Department of Transportation by Mestre *et al.* (2011). This DOT study examined the issues and opportunities for a supplemental and/or alternative metric to A-weighting. Obviously, there is a great deal of overlap between the Mestre *et al.* study and the I-INCE TSG-9 effort. TSG-9 greatly appreciates the use of the DOT study as a starting point for its work in this area.

This report primarily deals with airport noise in its examples. However, the methods and technical information contained are considered to be equally applicable to all modes of transportation and this is signified by the title which is applicable to all modes.

0 EXECUTIVE SUMMARY

Noise is measured either for regulatory purposes, or so that its effects on people can be predicted and disclosed in environmental impact analyses and used for noise/land use planning. One particular noise metric, the average sound level, uses one of two variants: Day-Night Average Sound Level (DNL), or Day-Evening-Night Sound Level (DENL);[1] one of those two metrics is commonly used as the sole predictor of annoyance - the primary effect of noise on residential populations. However, DENL is not the only predictor of the annoyance caused by that noise. Rather, potentially, other metrics can add to, improve, or replace the predictions made using DENL. This report examines options for supplementing or replacing DENL as a predictor of noise impacts.

Section 2 reviews basics of transportation noise regulatory policy, introduces the customary approach to measuring noise, and identifies the major limitations of DENL. The information presented in this section is further explained and discussed in Appendices A and B. Appendix C is an extended description of various noise metrics or indicators.

Section 3 describes the logic for measurement of noise, and the rationale necessary to predict noise effects from noise measurements. This section also contains information about limitations of the most commonly used frequency weighting for noise measurements (the A-weighting network), and about the unreliability of field measurements of noise that are not based on a time-integration of exposure.

In principle, a different noise metric or indicator can provide incremental improvements or it can provide substantial improvements to the prediction of noise impacts. However, a different metric can only provide substantial improvements if it differs meaningfully from DENL. A substantial difference between DENL and a supplemental noise metric or indicator requires a statistical correlation between DENL and the alternate noise metric that is smaller than about 0.7. Section 4 of this report shows that nearly all noise metrics or indicators correlate very highly with DENL. Most supplemental noise metrics or indicators are thus unlikely to support more than an incremental improvement over DENL. The only noise metrics or indicators that do not correlate highly with DENL, “Time Above” and “Number Above”, share other limitations that limit their usefulness as predictors of noise effects. Nevertheless, if a noise metric or indicator performs consistently better than DENL, then even a small improvement in

[1] Some countries use DNL and others use DENL (in the USA State of California , a variant of DENL, Community Noise Equivalent Level (CNEL) is used. In this report, DENL is used to represent all 3 of these, DNL, CNEL and DENL.

variance explanation can turn out to be statistically significant and can be considered to be meaningful.

Section 5 also includes conclusions from the correlation analysis of metrics, analysis of the effects of noise induced rattles, and the introduction of a systematic method for including non-acoustic influences on self-reports of annoyance, the "Community Tolerance Level."

Nearly all of the metrics reviewed in this study are highly correlated with DENL for typical airport operations. Any supplemental metrics worth consideration would need to provide new information that differs from DENL 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.

Currently, the Community Tolerance Level implicitly includes the effects of low frequency noise annoyance and noise-induced rattles. These two effects can be made more explicit by:

1) Replacing A-Weighting with a weighting that is sensitive to both amplitude and frequency can make low frequency noise and noise-induced rattles explicit factors in the total noise annoyance, rather than implicitly including them with all the other factors that make up the CTL.
2) Development of a metric that assesses the degree of rattle induced by sound and its effect on annoyance in the community, as recommended in clause 4.7.

1 INTRODUCTION AND BACKGROUND

The scope of this document is to list, describe, and compare metrics based on non-A-weighted sound levels that are potential supplements to A-weighting sound level for environmental noise assessment and control.

These metrics include:

1) supplemental or replacement noise metrics or indicators that could help to improve characterization of relationships between community annoyance and noise exposure

2) noise metrics or indicators that are *not* likely to support such improvements;

3) metrics that could be used to predict sleep disturbance and speech interference;

4) extant information useful for calculating any or all such metrics; and

5) new information useful for calculating such metrics.

As will be described in Section 2, discussion of noise measurement in isolation is somewhat artificial, since the purposes for and nature of noise measurements are closely linked to prediction of noise impacts and to regulatory policy. Although the focus of this report is on noise measurement, portions unavoidably touch on the rationale for noise measurement and its policy implications.

2 Fundamental regulatory purpose for noise measurement

As many ways to measure noises exist as reasons for making measurements. Bennett and Pearsons (1981), excerpted here and condensed in Section 10, Appendix D: Glossary, and Schultz (1982), describe many such metrics and reasons for noise measurements. Although it is easy to lose sight of the fact, noise is not measured for its own sake, but for the purpose of verifying compliance or predicting effects on individuals and communities. If noise did not annoy people and interfere with their speech and sleep, few would regard noise measurement as worth the effort.

Given the underlying purpose for noise measurement, every noise metric or indicator expresses a tacit theory: that annoyance (and/or speech interference/sleep disturbance/hearing loss/community opposition to airport operation and expansion, *etc*.) is caused by and hence predictable from the measured acoustic quantity. Explicit acknowledgement of these tacit theories can improve understanding of some of the limitations of noise metrics or indicators for implementing regulatory policy decisions.

2.1 Graphic representation of customary noise measurement systems

Figure 2-1 illustrates some of the customary physical dimensions of noise metrics or indicators. The figure analogizes common single event and cumulative noise metrics to a system of bodies (distinct noise metrics or indicators) orbiting a noise source. The distances from the noise source to the orbits of noise metrics in Figure 2-1 represent the measurement time scales. The color coding of the bodies (and the satellites orbiting them) represents their various frequency weightings. Measures with momentary or variable measurement periods cross orbital paths of the other metrics.[2]

2.2 Dominance of A-weighted equivalent energy metrics in noise measurement

For both technical and other reasons, the family of A-weighted equivalent energy metrics that was first fully described in the U.S. Environmental Protection Agency's (EPA) 1974 "Levels Document" has remained dominant in noise regulatory analyses for the last several decades. Total acoustic energy is readily and consistently measurable on time scales from

[2] Appendix B includes three spreadsheets that (1) characterize metrics from the 1960s and 1970s that remain in common use (2) integrate metrics from the 1980s, 1990s, and 2000s, and (3) include some calculations and ratings that may be of future interest.

milliseconds to days, combines all of the primary characteristics of noise (level, duration, and number) into a single-valued index, is conveniently manipulated (at least by acousticians), and demands only one appealingly simple assumption -- the so-called "equal energy hypothesis--" about the origins of annoyance. This assumption is that level in decibel units, logarithm base 10 of duration, and logarithm base 10 of the time weighted number of noise events are directly interchangeable, and hence, equally important determinants of annoyance.[3]

2.3 The Current role of DNL and DENL in prediction of annoyance due to noise

Day-Night Average Sound Level is an A- and time-weighted average sound level normalized to a 24 hour period. DNL was initially intended by EPA (1974) as an expedient means for quantifying and comparing transportation noise resulting from disparate sets of operations (for example, of operations of differing aircraft fleets at different airports, of noise exposure created by surface and air transportation, etc.). Schultz's (1978) use of DNL as the predictor variable was the first major synthesis of a relationship between environmental noise and annoyance prevalence rates and gained acceptance by the early 1980s. After FAA received Congressional direction to adopt a noise metric or indicator (Aviation Safety and Noise Abatement Act, 1978), the DNL metric was retroactively identified as the logical basis for U.S. aircraft noise regulatory policy.

In 2002, the European Commission approved the Environmental Noise Directive (Directive 2002/49/EC, 2002) demanding the production of strategic noise maps in main cities by all EU Member States. The main purpose of noise-mapping process was to evaluate size of population affected by noise issue and exposed to harmful environmental noise.

In all cities having a population first in excess of 250,000 and few years later in excess of 100,000 noise environments must be assessed by means of noise mapping. Moreover, environmental noise regarding major roads, major railways and major airports must also be reported to the EC by the EU member states. The EU chose DENL as the metric for the noise mapping with the desire to identify noise-impacted zones and ameliorate the situation. However, limit values were not globally defined but limit values mean values of DENL as determined by the Member States and the EC concluded that limit values may be different for different types of noise (road-, rail-, air-traffic noise, industrial noise, etc.), different surroundings and different noise sensitiveness of the populations. (Directive 2002/49/EC, 2002)

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[3] As noted by Fidell (2003), the empirical evidence in favor of this hypothesis is not definitive, but the theory that people integrate the acoustic energy of noise events in precisely the same manner that a sound level meter does has historically been appealing, both for its simplicity and for want of demonstrably superior hypotheses.

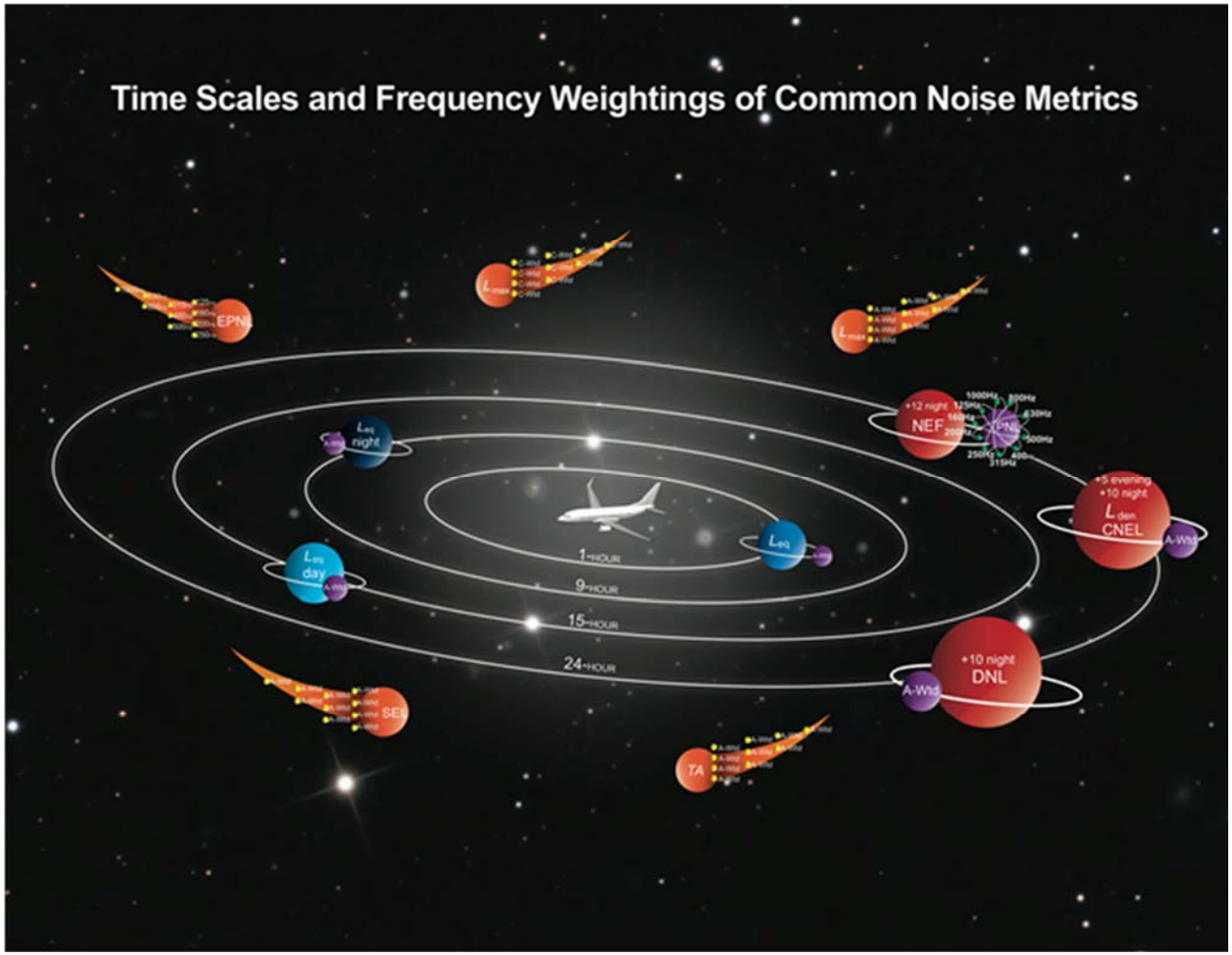

Figure 2-1: Schematic representation of common noise metrics

The USFAA cites L_{dn} = 65 dB as a guideline for defining compatible land use in the vicinity of an airport (FAR Part 150, "Noise Control and Compatibility Planning For Airports"), and as part of the definition of a threshold for defining a significant noise impact (FAR Order 1050-1E, "Environmental Impacts: Policies and Procedures"), as follows:

> *14.3 SIGNIFICANT IMPACT THRESHOLDS. A significant noise impact would occur if analysis shows that the proposed action will cause noise sensitive areas to experience an increase in noise of DNL 1.5 dB or more at or above DNL 65 dB noise exposure when compared to the no action alternative for the same timeframe.*

When the L_{dn} = 65 dB threshold of significance is exceeded, FAA policy permits, but does not require, further analysis to lower noise levels.

When the L_{dn} = 65 dB threshold of significance is exceeded the FAA policy permits, but does not require further analysis using supplemental noise metrics or indicators as appropriate to the situation:

> *14.5a. The Federal Interagency Committee on Noise (FICON) report, "Federal Agency Review of Selected Airport Noise Analysis Issues," dated August 1992, concluded that the Day- Night Average Sound Level (DNL) is the recommended metric and should continue to be used as the primary metric for aircraft noise exposure. However, DNL analysis may optionally be supplemented on a case-by-case basis to characterize specific noise effects. Because of the diversity of situations, the variety of supplemental metrics available, and the limitations of individual supplemental metrics, the FICON report concluded that the use of supplemental metrics to analyze noise should remain at the discretion of individual agencies.*
>
> FAA uses L_{dn} = 65 dB as a boundary for determining a significant noise impact with respect to an exposure-response curve which relates DNL to a nominal percentage of the population that is predicted to be "Highly Annoyed." The percent of the population predicted by the 1992 FICON curve to be highly annoyed at this exposure level is 12.3%.

In recent surveys about dose-response relationships for aircraft noise annoyance, a significant increase in annoyance of residents at a given aircraft noise exposure level over the years was observed. Thus any threshold, which relates DNL to a nominal percentage of population to be highly annoyed, must be updated from time to time (Jansen and Vos, 2011).

2.4 Pragmatic limitations of DENL

Despite DENL's dominance as a metric underlying transportation noise policy, it is ill-understood, misinterpreted, and distrusted by the public for a number of reasons:

A cumulative, 24 hour time-weighted average level is an abstract concept, far removed from common experience. A quantity of noise exposure expressed in units of DENL cannot be directly experienced by casual observation in the same sense that the maximum sound level of a single noise event can be heard.

Even though DENL values reflect all of the noise energy occurring during a 24-hour period, its very name (Day-Night *Average* Sound Level) is commonly misconstrued as implying that the measure is somehow insensitive to high level noise events.

The logarithmic arithmetic necessary to manipulate DENL values, and the normalization of the decibel notation of the units to 10log (86,400 seconds/day) are non-intuitive for non-technical audiences.[4]

Public understanding of prospective aircraft noise modeling and annual average day exposure contours - the context in which the public generally encounters DENL-based information - is weak at best.

DENL is required for use in environmental impact disclosure documents as the required metric of noise exposure. The subsequent focus on the metric in lieu of descriptive discussion of noise impacts is confusing and potentially misleading.

The public does not fully understand the linkages between DENL and interpretive criteria based on predicted noise exposure levels. In particular, the rationale for identifying L_{dn} = 65 dB as a threshold of significant noise impact is opaque.

The metric often suffers from a "shoot-the-messenger" reaction to unpopular policies that are expressed in units of DENL. This leads to a common criticism of DENL as a metric in lieu of criticism of the manner in which DENL is used.

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[4] Efforts to express acoustic quantities such as DENL in linear units, such as pascal-square seconds or "pasques", have not been widely accepted.

Quite apart from the difficulty the public experiences in grasping the concept of a time-weighted average sound exposure level expressed in decibel notation, DENL has another major practical limitation. It doesn't work particularly well as a predictor of aircraft noise impacts. FICON's 1992 relationship accounts for less than a fifth of the variance in the association between aircraft noise exposure and the prevalence of high annoyance in communities (Fidell, 2003; Fidell and Silvati, 2004). As discussed in greater detail in Section 4.8, this limitation is due in part to the fact that DENL is oblivious to the non-acoustic determinants of annoyance, in part to the expedient (non-theory based) formulation of the FICON exposure-response curve, and in part to random errors of measurement of both exposure and community response to aircraft noise exposure.

2.5 Distinction between "supplemental" and "alternative" noise metrics or indicators

For the above and other reasons, alternative and supplemental noise metrics or indicators have long been sought to complement or even replace DENL in noise impact assessments. An important distinction is drawn for current purposes between "alternative" and "supplemental" noise metrics or indicators. In the current context, a "alternative" noise metric is one that can in some way improve public understanding of the manner in which noise is characterized. In itself, public understanding of forecasted changes in noise in environmental impact disclosure documents does not advance the state of the art of predicting community reaction to noise exposure. In contrast, a "supplemental" noise metric or indicator is one that can actually improve the ability to predict noise *impacts*.

The distinction between improving public understanding on the one hand, and improving the predictability of noise impacts on the other, is an important one for present purposes. *Alternative* metrics may correlate well or poorly with DENL, because their goal is merely to improve communication with the public.[5] Thus, for example, a noise metric expressed in linear units rather than in logarithmic (decibel) form might, in principle, be more readily grasped by the public than one expressed in decibel notation, even though it might not be any more effective than DENL as a predictor of noise impacts. Likewise, the public may find counts of numbers of times per day that aircraft or other single event noise intrusions exceed some threshold more intuitively appealing than DENL values, even though no means are available for transforming such counts into predictions of community response to aircraft noise.

Logically and statistically, however, only *supplemental* metrics that do **not** correlate well with DENL can provide substantial improvement in accuracy or precision over that currently

[5] A recent U.S. Department of Defense publication (DNWG, 2009) discusses such supplemental metrics at length.

provided by DENL; metrics that correlate well with DENL can only provide incremental (if any) improvement in accuracy or precision of prediction of noise impacts.

The scope of this study group deals with supplemental metrics. However, Technical Study Group 9 believes some discussion on alternative metrics is useful and this discussion is included in Appendix A.

3 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 or indicators 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.

3.1 Rationales for equivalent-energy and threshold-based noise metrics or indicators

As described in section 2, measures of 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 7 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 or indicators 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}/DENL family), it cannot be strictly correct in the limit. People's annoyance judgments cannot 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.

[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.

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 night. Very little is quantitatively known, however, about the time constants of arousal and decay of annoyance with 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 or indicators 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.

3.2 Rationale for noise metrics or indicators sensitive to variability in the temporal domain

Several noise metrics or indicators 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, a 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 with annoyance judgments that were constant for specific types of noise sources. The annoyance judgments of these 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 response with increasing SEL.

A large group 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 proportionally to its SEL.

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 or indicators 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 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 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 will prove to be.

3.3 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 noise is essentially a change detection process. The critical quantity that a noise metric or indicator 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 a noise source such as an airport cannot reasonably complain about noise. In many cases, longtime residents of a neighborhood may have chosen to live there when it was semi-rural. Over time, the neighborhood may have grown to urban and the roadway may have been enlarged from two lanes to six lanes. Such growth could readily convert once familiar and tolerable noise exposure levels into noise patterns judged as highly annoying.

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.

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.

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

Most metrics routinely used to predict noise effects rely on the A-weighting network to express the spectral content of 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 noise analyses, however, and was eventually dropped from the sound level meter standard.

The rationale for favoring A-weighted noise metrics or indicators 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 noise exposure is attributable to secondary emissions (that is, rattling sounds inside residences that are caused by high levels of low-frequency noise, such as aircraft noise in runway sideline areas and behind departure runways), the rationale for A-weighting these 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).[8]

3.5 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

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[8] Since health effects are not within the present scope of TSG-9, the following is offered as a cautionary note for the reader. In addition to A-weighting being inappropriate for low frequency sources and highly impulsive sources among others, it also is not clear that A-weighting is appropriate for studying or describing possible health effects -- especially those that may be non-auditory effects.

[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.

words, they are defined and act as conventional analog frequency filters. Human perception of sounds (and some noise metrics or indicators), however, are both amplitude- and frequency-dependent. Noise metrics currently in use that are sensitive to both frequency and amplitude of sounds include Zwicker loudness (LLZ), defined by ISO 532 B and more recent modifications; Perceived Noise Level (PNL); tone corrected Perceived Noise Level (PNLT); and Effective Perceived Noise Level (EPNL) and time-variant loudness (N) defined by DIN 45631/A1 as well as ISO 532-1 including steady loudness and time-variant loudness (in preparation). 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 loudness judgments are outputs. When applied to prediction of annoyance as judged in laboratory testing, loudness metrics have demonstrated that they often allow a better prediction over A-weighting (Fiebig, 2013). However, loudness is correlated to a certain degree with sound pressure level indicators, and thus, loudness metrics do not always perform significantly better (Scharf and Hellman, 1980; Zwicker, 1985; Hellman and Zwicker, 1987). Moreover, in laboratory experiments, the performance of loudness metrics regarding the prediction of noise annoyance can only be investigated on the basis of short-term noise exposure and its respective response by test subjects. In residential settings, noise annoyance is usually based on long-term noise exposure and can increase over time. This aspect is not covered in laboratory experiments. Thus, loudness metrics could not prove their benefit with respect to noise annoyance caused by long term noise exposure so far.

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 as compared to 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 DENL. The log 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 tenfold change in operations.

Schomer's proposal amounts to an incremental improvement over A-weighting. It maintains the concept of DENL, 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 DENL 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 that is gaining common use in the European Union), and the factors that account for community expectations remain the same.

It is possible that better results could be obtained using one of the newly proposed time varying loudness calculations (e.g. DIN 45631/A1 or ISO 532-1-method B (in progress) in place of Schomer's use of loudness level contours, but the arithmetic base remains in question. In a 2001 study, Schomer et al. show significantly higher correlation when loudness-level weighting and base 10 arithmetic are used compared with Zwicker loudness calculated using base 2 arithmetic. For this study, Schomer did the loudness-level weighting calculations and his two co-authors, Yoiti Suzuki and his colleague Furmitaka Saito did the Zwicker loudness calculations. Fastl (2000), who recommends the use of loudness using log base 2 arithmetic, uses the upper 5% - 10% of the loudness distribution over time to correlate with perceived overall loudness (annoyance). Genuit (2013) reports much the same result. Both of these researchers conclude that the exact percentage is dependent on the type of noise source, and that their method is better. Schomer counters that 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. A single, comparative study of at least 3 formulations is required. It would include (1) loudness-level weighting, (2) loudness using base 2 arithmetic, and (3) the best loudness calculation possible while incorporating log base 10 arithmetic.

3.6 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 L_{Aeq} for the 30 minute period is 42.9 dB, the L_{10} is 44.7 dB and the L_{90} 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.

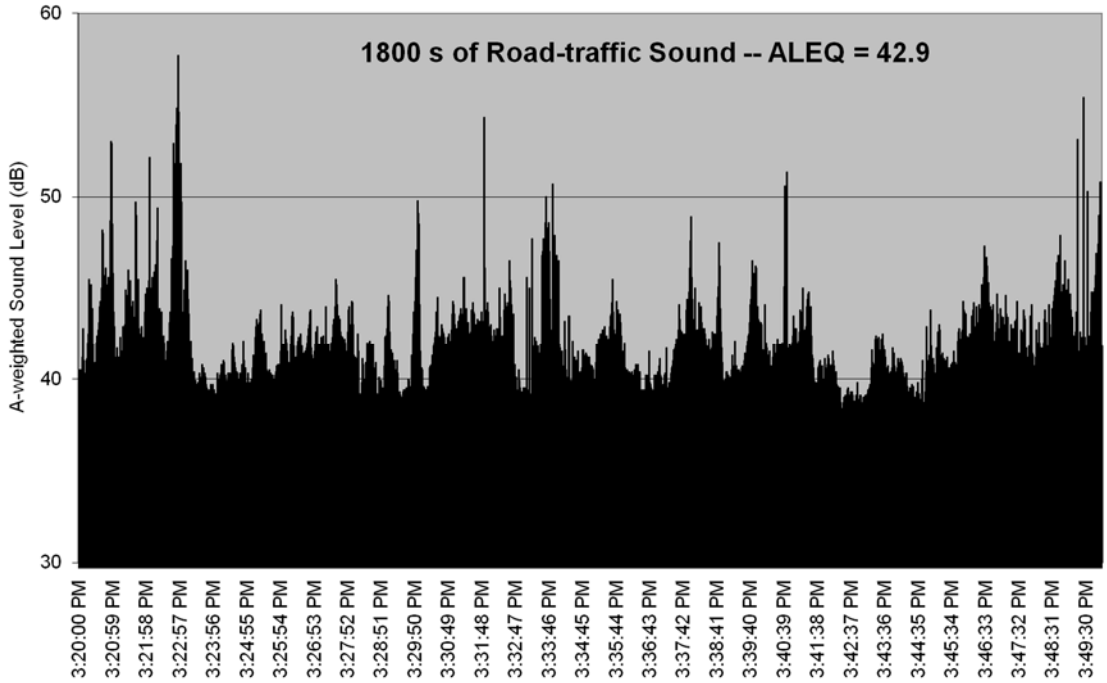

Figure 3-1: 30 minutes of semi-rural road-traffic sound

What does this uncertainty imply for real measurements or predictions? Assume the 1800 seconds of data shown in Figure 3-1 are absolutely correct, so that the L_{10} and L_{90} are precisely as given above. Then, as shown in Figure 3-2 with a ±1 dB uncertainty, the "L_{10}" can range from 43.7 to 45.7 dB, and the "L_{90}" 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 (Figure 3-3), 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 3-4), 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 3-1, one person using a first Type 2 meter can measure an L_{10} that is lower than a second person's measurement of L_{90} at the same site over the same time period using a second Type 2 meter.

"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 very well differ markedly.

This uncertainty problem should be contrasted with measurement of L_{EQ} which does not exhibit such marked uncertainty problems.

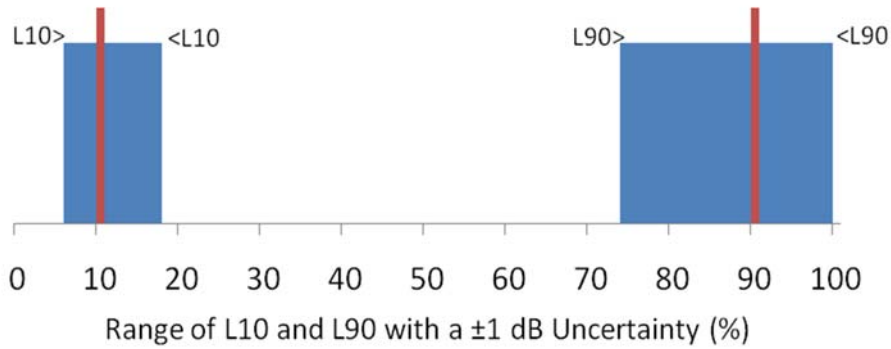

Figure 3-2: Uncertainty of plus or minus 1 dB

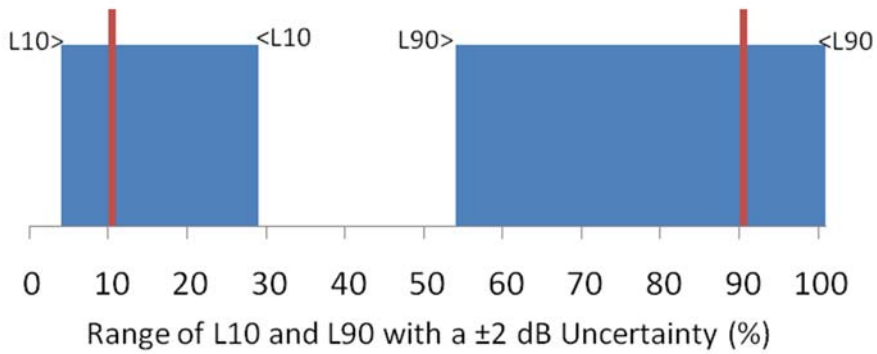

Figure 3-3: Uncertainty of plus or minus 2 dB

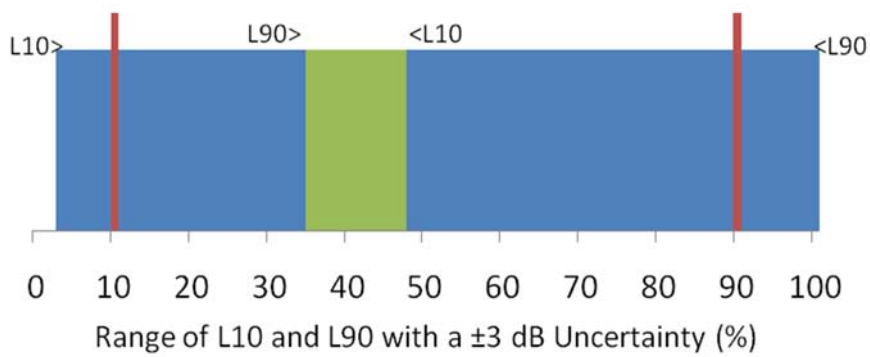

Figure 3-4: Uncertainty of plus or minus 3 dB

3.7 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 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 noise impacts.

3.8 Sleep disturbance metrics

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 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 noise intrusions to awaken people sleeping in familiar quarters consists of a handful of studies of limited scope. 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 noise intrusions into familiar sleeping quarters. None of these efforts have yielded an accurate and reliable relationship that accounts for substantial amounts of variance in the association between 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 uncommon. 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 noise intrusions only occasionally disturb sleep. Most of the dosage-effect relationships based on behavioral

awakening field data have very shallow slopes. Further, for aircraft noise, these studies 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 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) For airports, 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 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.

4 SUPPLEMENTAL NOISE METRICS OR INDICATORS

4.1 Gauging the potential utility of supplemental noise metrics or indicators

The correlation between a proposed supplemental noise metric or indicator and DENL can serve as a simple test of the potential utility of a supplemental noise metric or indicator. If the product-moment correlation between a proposed supplemental noise metric and DENL exceeds 0.5, for example, it is unlikely that the proposed supplemental noise metric or indicator 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 DENL and supplemental noise metrics or indicators may be observed in different operational and geographic settings. For example, correlations between DENL (an A-weighted noise metric or indicator by definition) and C-weighted noise metrics or indicators 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 supplemental noise metrics or indicators 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 (DENL), 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[10]. In the noise metric correlations described below, most noise metrics or indicators 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 issues, not metrics issues.

[10] 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.

4.3 Description of noise modeling approach

Developing correlations between DNL and other noise metrics or indicators 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, L_{max}, 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 or indicators. 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 aircraft database (only civilian aircraft were used in the current analysis). This allowed for the computation of a variety of noise metrics or indicators, 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 or indicators 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 or indicators. 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 40 phons [Fletcher, Munson, 1933], and was intended for application to sounds of about 24-55 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 55 to 85 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 L_{max} 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 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 average 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 aircrafts 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 or indicator that is highly correlated with the A-weighted sound level cannot 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.

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 or indicators 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. However, these results are expected to be the same for other sources that do not exhibit prominent discrete tones and which have A- weighted spectra that peak in the 500 or 1000-Hz octave bands.

Table 4-1: Civil aircrafts 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

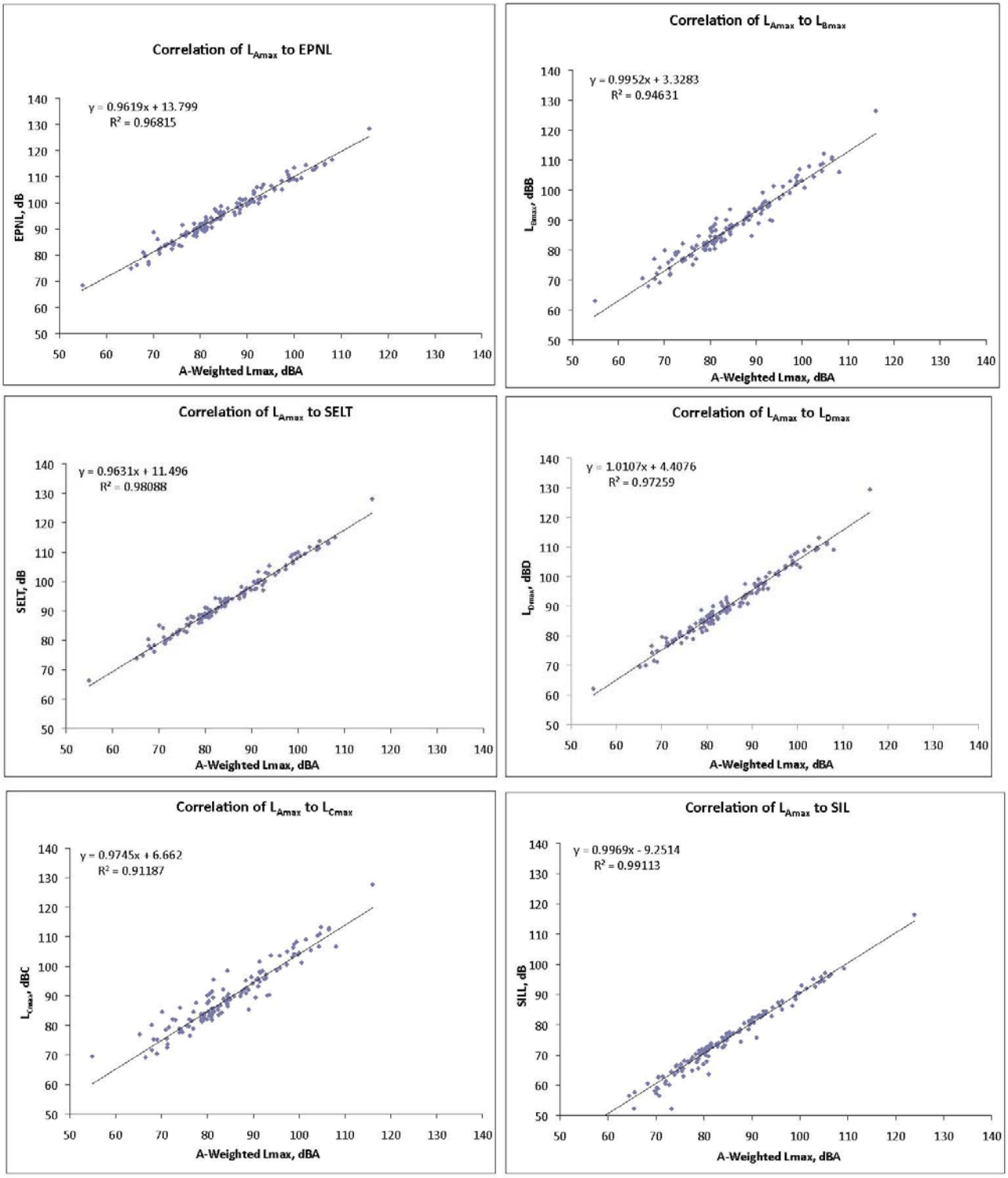

Figure 4-1: Plots of the relationships between A-Weighted L_{max} and other measures of aircraft noise levels

4.5 Correlation among single event and cumulative noise metrics or indicators 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 or indicators under a wider range of conditions than was possible using information in the Noisemap database.[11] 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 or indicators other than DNL could yield meaningfully different predictions of noise exposure[12] for a typical airport, and hence, support predictions of noise impacts potentially different than those produced by DNL.[13]

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,

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[11] 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.

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

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

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 sub-tracks and one backbone track. The runway use is 50% in each direction, with a schedule of 75% day, 15% evening, and 10% night operations.

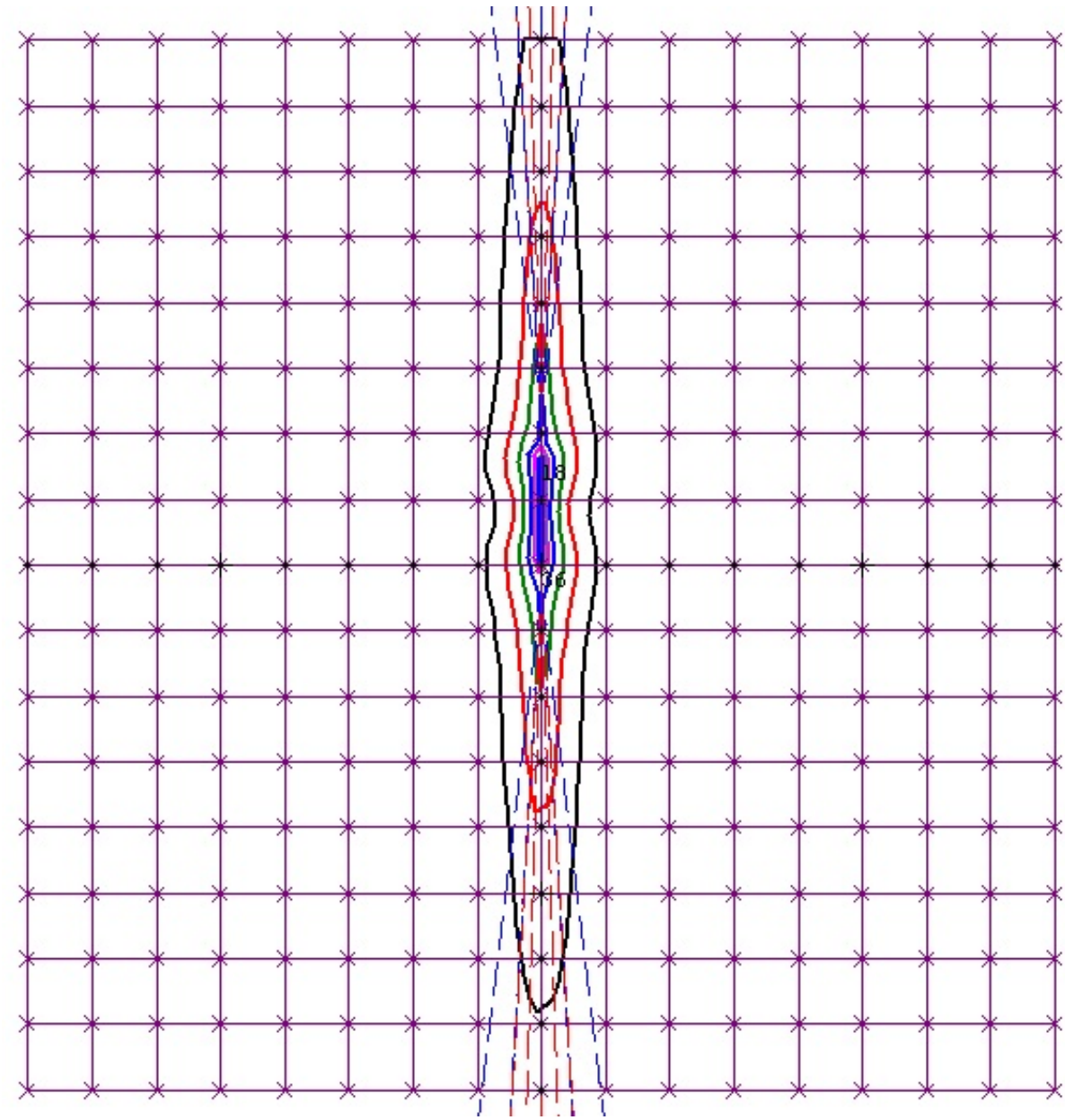

Figure 4-2: Runway, grid Points, flight tracks and DNL contours for the hypothetical airport. The outer contour is L_{dn} = 55 dB; inner contours are plotted at 5 dB increments. Grid points are spaced at 1nm intervals

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.[14]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**
a	Community Noise Equivalent Level or Day-Evening Night Average Sound Level (DENL/CNEL)	.9999	.6399	.99998
b	Weighted Equivalent Continuous Perceived Noise Level(WECPNL)	1.0793	7.6323	.99951
c	24 Hour Average Sound Level (L_{Aeq}(24 hour)	1.0001	-2.7943	.99999
d	Daytime Average Sound Level (L_{Aeq}(day)), typically 12 hours, 7 am to 7pm.	1	-1.195	1
e	Effective Perceived Noise Level (EPNL)	1.0741	43.576	.9995
f	Tone Corrected Perceived Noise Level ($PNLT_{max}$)	1.43281	13.521	.9722
g	Nighttime Average Sound Level (LA_{eq}(night)	1	-8.5235	.99999
h	Sound Exposure Level (SEL)	1	46.582	.99999
i	Maximum A-weighted Noise Level (L_{Amax})	1.4353	3.8479	.98381
j	Time Above a Tone Corrected Perceived Noise Level (TAPNL) threshold	1.7872	-54.523	.54849
k	C-weighted Sound Exposure Level (SELC)	.7495	67.338	.98824
l	Maximum C-weighted Noise Level (L_{Cmax})	1.2035	24.128	.97864
m	Time Above 65 dBA (TA 65 dBA)	.8963	-28.588	.51406
n	Noise Exposure Forecast (NEF)	1.074	-40.326	.99951
o	Time Above 65 dBC (TA65 dBC)	1.9629	-59.688	.70822
p	Number of Events Above 70 dBA (NA70 dBA)	12.46	-632.42	.91298
q	Log (number of events above 70 dBA)	.136	-6.6331	.8334

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

Figure 4-3 to Figure 4-5 plots the correlation of DNL to each of the 17 alternative metrics shown in Table 4-4. The very high DNL values calculated are of three grid points that lie directly on the runway.

The only noise metrics or indicators that do **not** correlate more highly than r =0.9 with DENL 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.

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

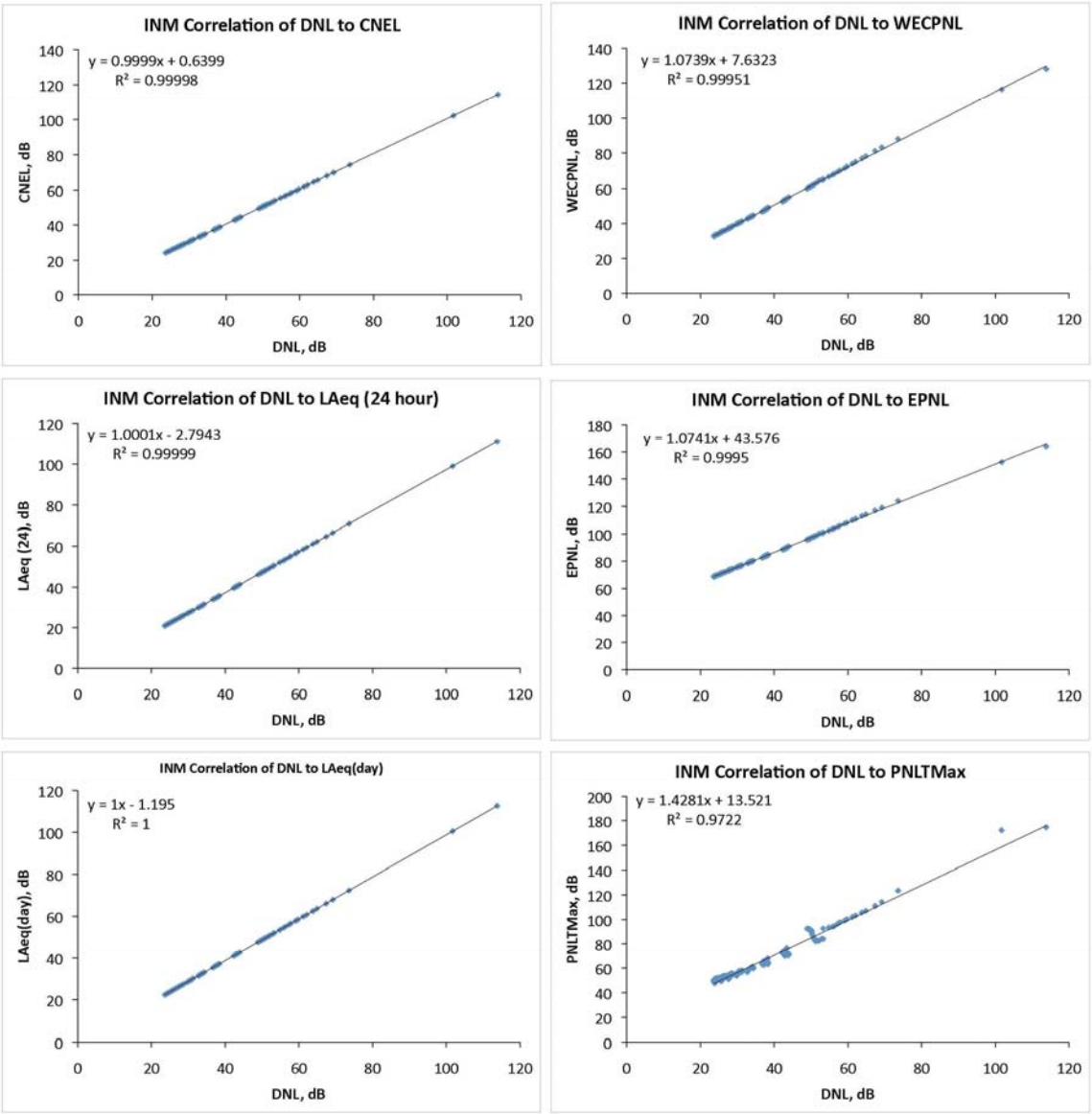

Figure 4-3: Correlation of DNL to Other Cumulative Metrics
The 6 panes represent the first 6 cases, lines a through f of Table 4-4

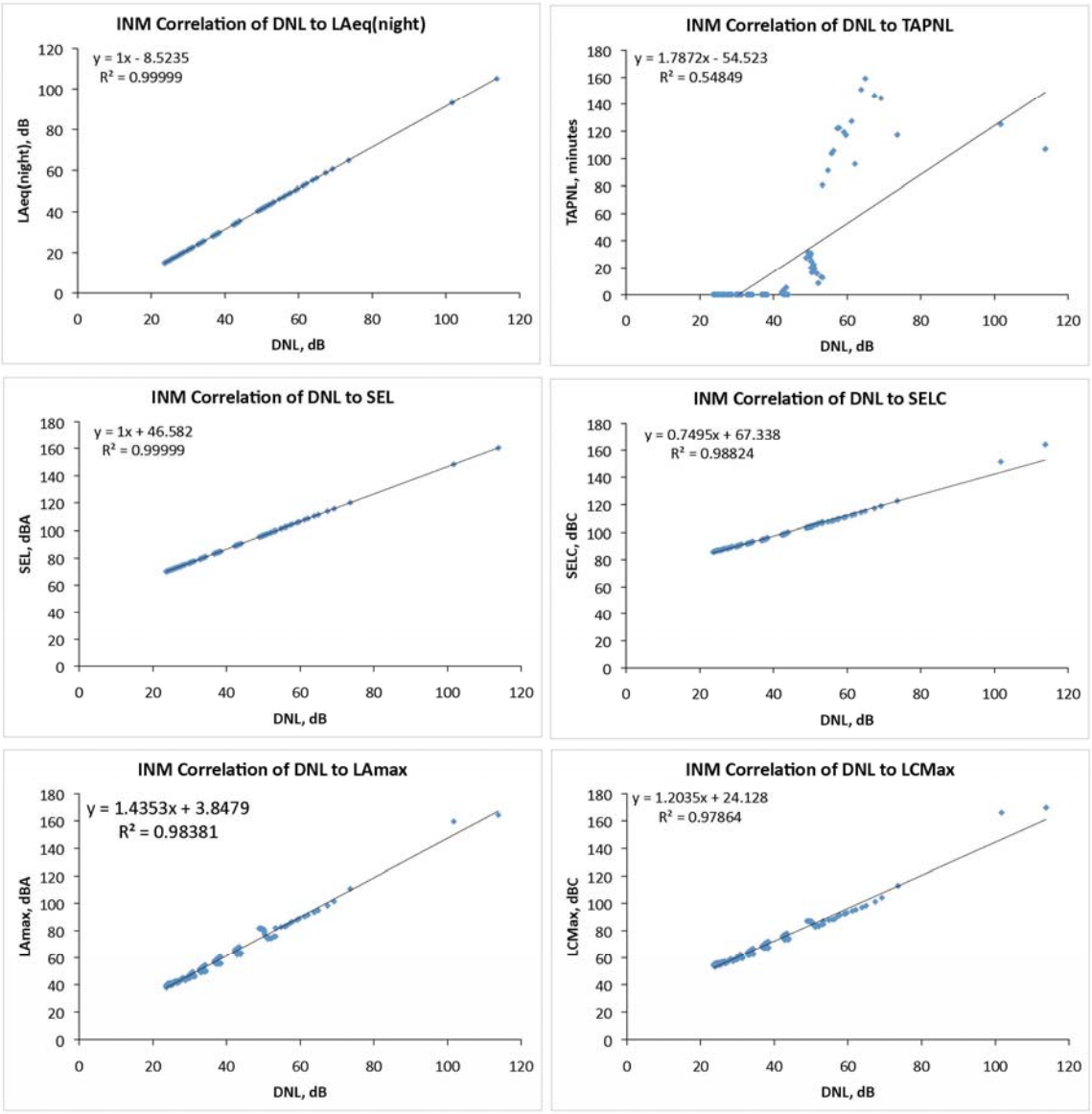

Figure 4-4: Correlation of DNL to Other Cumulative Metrics (cont'd)
The 6 panes represent the second 6 cases, lines g through l of Table 4-4

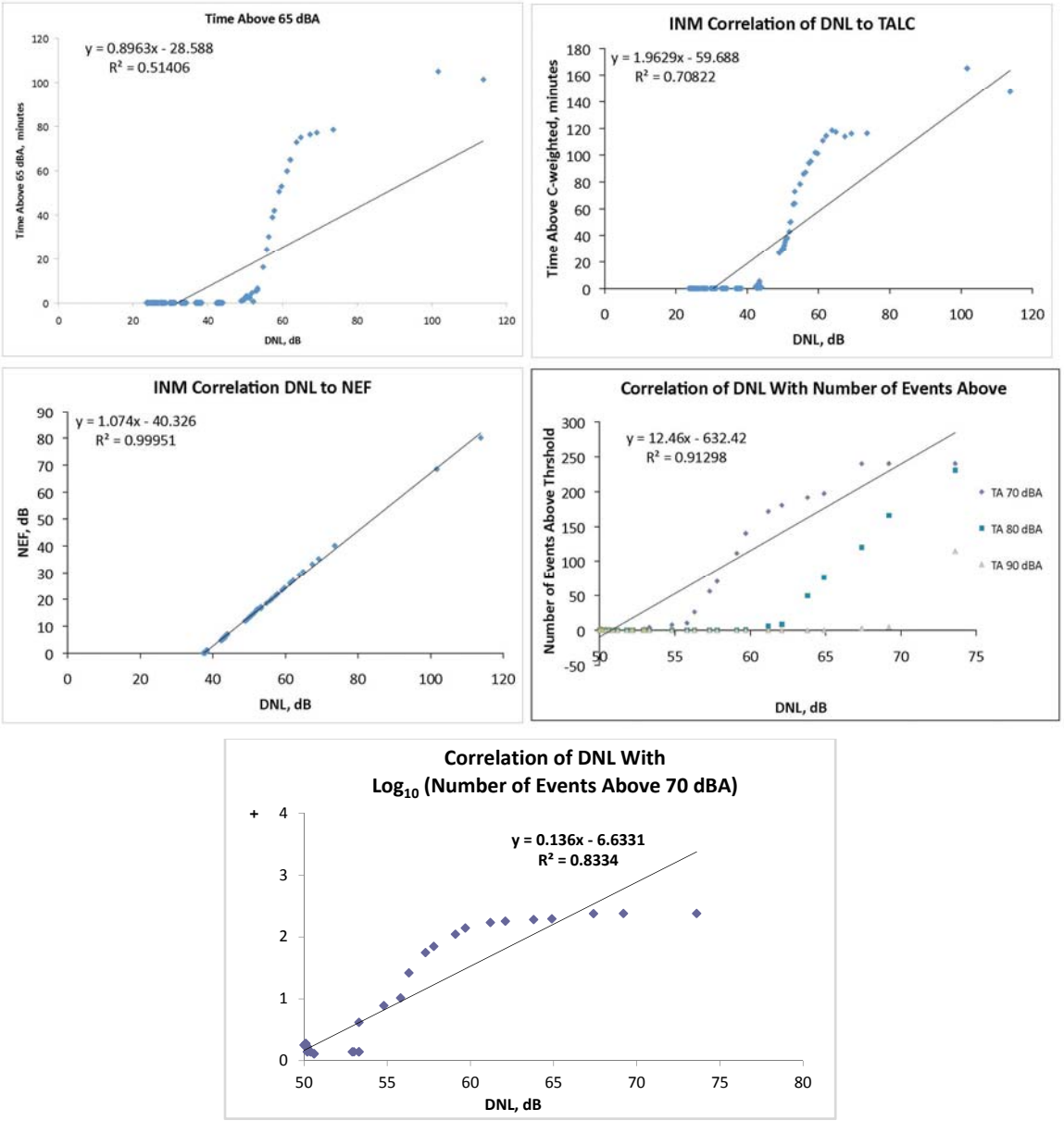

Figure 4-5: Correlation of DNL to Other Cumulative Metrics (cont'd)
The 5 panes represent the last 5 cases, lines m through q of Table 4-4

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.[15]

In other words, all of the other common aircraft noise metrics or indicators 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 DENL, NEF, WECPNL, $L_{eq}(24)$, $L_{eq}(\text{day})$ or $L_{eq}(\text{night})$ will not provide any improvement in the accuracy or precision with which an aircraft noise metric or indicator 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 DENL, DENL, NEF, $L_{eq}(24)$, $L_{eq}(\text{day})$ and $L_{eq}(\text{night})$ 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 DENL by 3 dB. The correlation of DENL 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 DENL and time and number above metrics TA and NA have essentially the same shape.

The relationships between time and number above metrics and DENL 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 DENL can produce large changes in TA and NA. The steep slope is an artifact of the logarithmic nature of DENL the linear nature of TA and NA. 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 DENL 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 DENL curve.

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[15] 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).

The results above are expected to be similar for other sources that do not exhibit prominent discrete tones and which have A-weighted spectra that peak in the 500 or 1000-Hz octave bands. For example, 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 DENL.

The correlation of DENL with the log base 10 of NA was tested as well and is shown at the bottom of Figure 4-5. It does not correlate quite as well as DENL versus NA (NA 70 dBA was used for the least squares analysis is each case).

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 DENL. 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)

Low Frequency Sound 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. There are several common noise sources that produce high levels of low frequency sound. This sound creates these rattling noises. Common sources that create rattles include: High energy impulsive sounds, such as sonic booms, mining explosions, large military weapons low frequency industrial processes, such as--gas turbine generators, wind farms, combustion processes (e.g., grain dryers, asphalt batch plants)-- helicopters, railroads, and certain aircraft operations. With respect to aircraft, 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.

Fidell *et al.* (2000) has proposed a low frequency metric for use in the vicinity of airports, but it does not go low enough in frequency to be generally used. [16] This low frequency issue is

[16] "Findings of the Low-Frequency Noise Expert Panel of the Richfield-MAC Noise Mitigation Agreement of 17 December, 1998," 25 April 2000.

a very important component to community noise assessment that is largely ignored. For example, in an experiment dealing with perception of helicopter sounds, the creation of significant rattles was equivalent to a 20-dB increase in sound level, and low levels of rattle were equivalent to a 10-dB increase (Schomer *et al.*, 1989). In another experiment, the mere existence of rattle sounds that were below the level of the sound exciting the rattles, increased the reaction of the subjects by about 6 to 13 dB. Recently, Yokoshima *et al.* (2012) have shown that conventional Japanese railroads should have a 3 dB penalty compared to road traffic, in contrast to the 5 dB bonus espoused by the European community. However, the adequacy of the railroad bonus has recently been up for discussion in the European community (Lercher, 2013). It is expected that the railway bonus will be abolished. Schomer *et al.* (2012) on the basis of a theoretical analysis of a large body of road traffic and railroad noise survey data shows that there is about a 15 dB difference in the noise assessment of trains between those that do and those that don't produce a significant amount of rattles.

Overall, it should be clear that low frequency sound is one of the biggest, if not the biggest, source of error related to the use of A-weighting. For the sources delineated here the error is a minimum of 6 dB for faint rattles, and is more typically measured to be 15-20 dB. This factor is like impulses or tones, just more important, and yet it is ignored. An explicit metric is urgently needed that can assess the degree of noise-induced rattle and predict the increase in annoyance that results from this rattle. In the interim, the Community Tolerance Level, recently developed, provides a systematic method for estimating the contribution of the various acoustic variables not assessed by A-weighting, such as the rattles discussed here, impulsivity, and tonality. Because the totality of non-A-weighted acoustic variables, and as shown in 4.8, the totality of non-acoustic variables, are all represented by the one-number metric CTL. It can be said that each of these variables is implicitly included in the total.

4.8 Role of non-acoustic variables as predictors of human and community response

The importance of non-acoustic variables, such as fear of crashes, has long been noted, but it has not received a lot of actual attention in the field. Currently, there are two schools of thought as to how to integrate non-A-weighted acoustic variables and non-acoustic variables into the prediction of human and community response. One school of thought is that the Community Tolerance Level (CTL) provides a systematic means for estimating the contribution of non-A-weighted acoustic factors and non-acoustic factors to community response as measured in terms of prevalence of annoyance. A second school of thought espouses the concept of soundscape as a means for including the contribution of all the acoustic factors and all the non-acoustic factors to total community reaction to the sonic environment.

In 4.8.1 below, the CTL methodology is explained, and in particular, the role non-A-weighted acoustic variables and non-acoustic variables play in CTL, and in 4.8.2, the soundscape methodology is explained with emphasis on the role played by the totality of variables.

4.8.1 **Community Tolerance Level**

Recently, Fidell *et al.* (2011) and Schomer *et al.* (2012) have developed the Community Tolerance Level as a systematic means for estimating the contribution of non-acoustic factors to annoyance prevalence rates.

The method 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. The function is time-integrated since it has been shown that annoyance goes up by the equivalent of 3 dB when the distinct number of transitory sources doubles or when the duration of a "continuous" source doubles. Like in a loudness calculation, the response doubles when the energies, raised to the 0.3 power, double. The 0.3 that is almost at the right edge of Eq. (5) is the factor that implements the loudness-like behavior.

Secondly, it is assumed that the community response takes the form of a transition function going asymptotically and monotonically from 0% HA at a lower noise level to 100 % HA at some higher noise level. For simplicity, the simplest transition function, e^{-x} is chosen. In mathematical terms, CTL is defined by Equation (5). For any given community, CTL is determined by varying L_{ct} in Equation (5) until the least squares fit is found. The value of CTL that yields the least squared fit is the CTL for that set of data. Creating the least squared fit involves using the CTL term to shift the function e^{-x} along the DNL axis until the best fit is found.

$$\% \text{ HA} = 100*\text{EXP}(-(1/(10\text{^}((L_{dn}-L_{ct} + 5.306)/10))0.3)) \qquad \text{(Eq. 5)}$$

where, %HA is the percent highly annoyed at a location within the community,
L_{dn} is the Day-Night Average Sound Level (dB) at that location within the community
L_{ct} is the Community Tolerance Level (CTL) for that community (dB).

As an example, Figure 4-6 shows three sets of airport community survey data and the CTL function given by Equation 5 fit to these data. In general, it is found that when the data represent a single community, then they form a reasonably good fit to the CTL function. The transition functions fit to the sets of data denoted for Figure 4-6 also are shown.

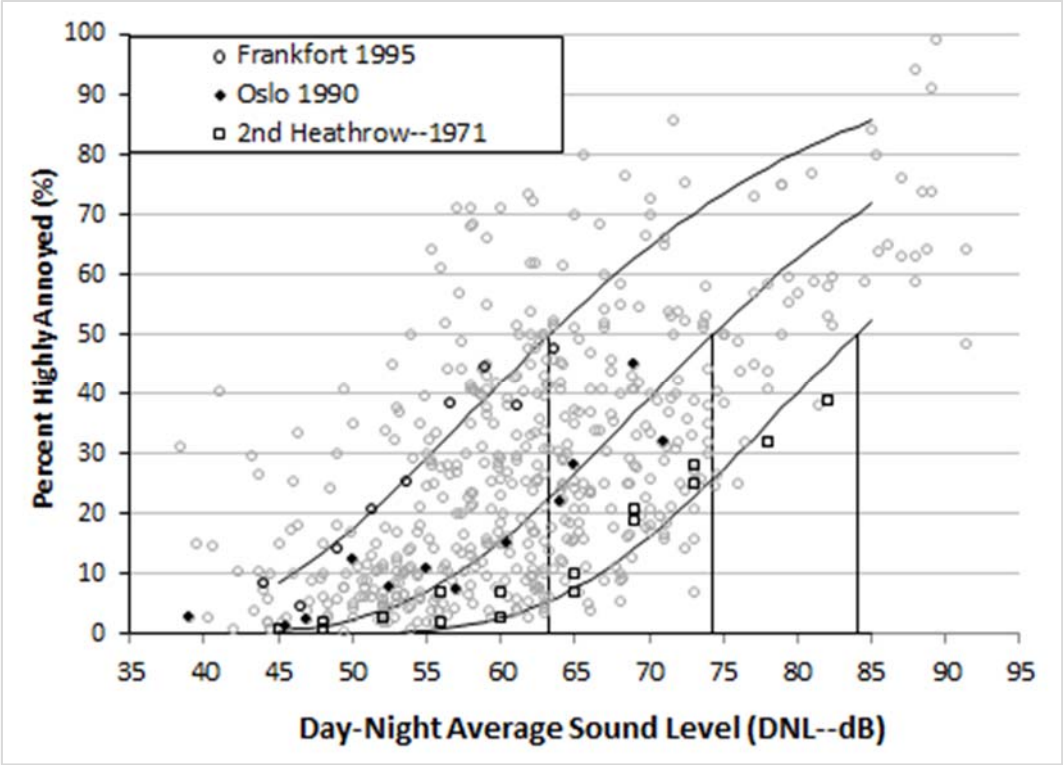

Figure 4-6: Noise surveys data from 43 airports. Three sets of airport community survey data (Frankfurt, Oslo, London) and their CTL functions are highlighted.

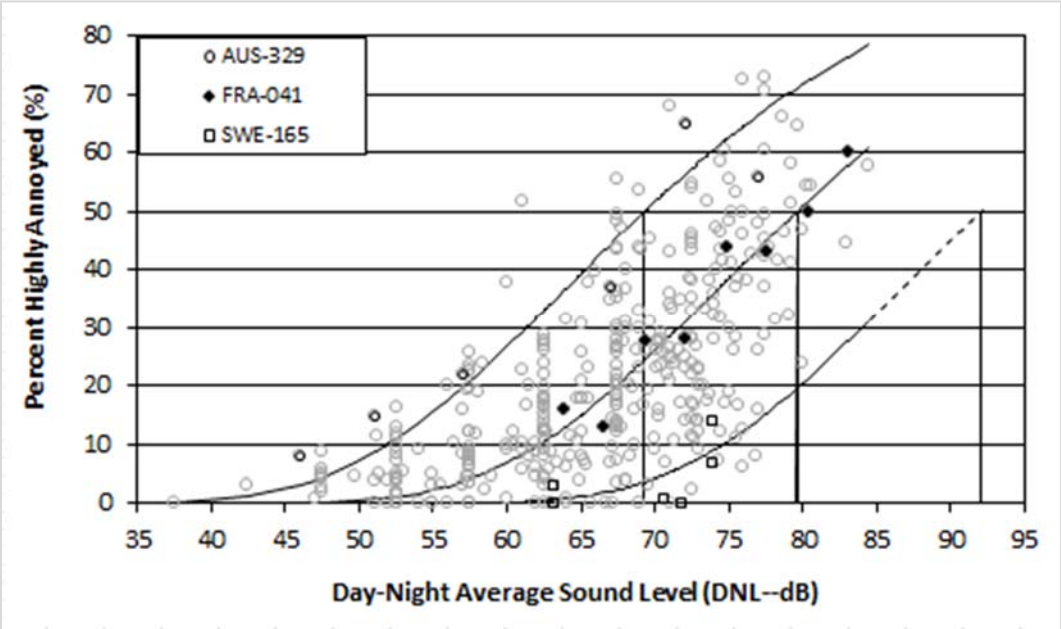

Figure 4-7: Road traffic noise surveys data from different countries. Three sets of community survey data (Australia, France, Sweden) and their CTL functions are highlighted.

The transition function represented by e^{-x} is symmetrical and goes from 0 to 100 percent. Any point on the transition function could have been used to represent this functions position along the DNL axis, but, arbitrarily, the midpoint, which corresponds to 50% HA, was chosen as the "anchor point" just because it was the midpoint. That is, the constant 5.306 in Equation 5 is chosen just so that for any value of CTL, the value of the DNL axis at the functions midpoint is the CTL for that set of data and the percent HA is at 50%. Figure 4-7 illustrates the CTL function fit to three sets of road-traffic survey data, and the results are quite similar to those in Figure 4-6.

One should note that with CTL fit to a set of community data, the focus shifts from describing a function that was fit to the total of all surveys the hypothetical whole-world average community to the description of a single, real, existing community. Figure 4-6 and Figure 4-7 each show data for three different communities. In each figure, one community is near the average, one is about 10 dB above the average (more tolerant towards the noise), and one is about 10 dB below the average (less tolerant towards the noise). CTL puts the "community" into community noise, and if there ever was any doubt, CTL shows that in terms of the response of a specific community to a specific source, one size does not fit all. CTL represents all the non-acoustic variables, and all the acoustic, but not A-weighted variables that influence the community-wide response.

4.8.2 **Soundscape**

Background

The term “soundscape” has many meanings for many people. Because the field has evolved into differing strains around the world, as well as across disciplines, there is a diversity of opinion about its purpose, definitions and use. Consequently, the use of the term ”soundscape” has become idiosyncratic and ambiguous. A recently adopted International Standard ISO 12913-1 (2014) has as its purpose the enabling of a broad international consensus on the definition of ”soundscape,” so as to provide a foundation for communication across disciplines and professions with an interest in soundscape. The standard recognizes that there are similarities between the concepts of ”landscape” and ”soundscape” as both are based on perception by people; for the purpose of the International Standard, soundscape will be understood as a perceptual construct, related to a physical phenomenon.

This new ISO standard distinguishes the perceptual construct (soundscape) from the physical phenomenon (acoustic environment), and clarifies that soundscape exists through human perception of the acoustic environment.

Current status

Soundscape research represents a paradigm shift as it relies as much or more on human and social sciences (e.g. psychology, sociology, architecture, anthropology, medicine) as on physical science. Also this same multifaceted team is needed to account for the diversity of soundscapes across countries and cultures. Noise reduction alone, which is the main focus of most environmental noise policies around the world, does not necessarily lead to improved quality of life in urban/rural areas; a new multidisciplinary approach is essential.

Soundscape as a resource

To discuss the contribution of Soundscape research into the area of community noise research means to focus on the meaning of sounds and their implicit assessments with respect to the understanding that Soundscape will evaluate noise as a resource, a source from which benefit is produced. Typically resources are materials, money, services, staff, or other assets that are transformed to produce benefit and in the process may be consumed or made unavailable. Benefits of resource utilization may include increased wealth, meeting needs or wants, proper functioning of a system, or enhanced well-being. From a human perspective, a natural resource is anything obtained from the environment to satisfy human needs and wants. The business dictionary (2014) gives the following definition to a resource: "an economic or productive factor required to accomplish an activity, or as means to undertake an enterprise and achieve a desired outcome. Three of the most basic resources are land, labor, and capital; other resources include energy, entrepreneurship, information, expertise, management, and time." (see: http://www.businessdictionary.com, 2014). The related analysis is placing sound in context, with noise and sound linked to activity at realistic study sites.

Goals and what is central to Soundscape research?

Classical noise metrics or indicators are significantly limited by certain sound source situations (e.g., multi-source environment), or by certain sound source characteristics (e.g., low-frequency noise, tonal components). The central goal of soundscape research and implementation is to better fit (correlate) the indicators used with the perception and evaluation by concerned citizens.

The main requirement and goals for soundscape are:

- To support a methodology to perform an acoustical appraisal; to evaluate what are the distinctive acoustic attributes of various different soundscapes (Why does this place sound different? What is unique?)
- To support a methodology to perform a psycho-physiological appraisal; to assess the grade and type of neurophysiologic stimulation (Is the soundscape stressing, supporting or relaxing? Which emotions are linked to it?)

- To support a methodology to perform a context appraisal; to assess the person-environment fit (Are there sounds or sound components which interfere with intentions/expectations/meaning or support these? Are there other sensory factors (visual, vibration, odors) which interact with the sounds in a supporting or distorting way? Is the meaning of this place or the attachment to this place distorted, undermined or supported?)
- To support a methodology to design and construct a soundscape as part of either a new or remedial action; to assess the holistic potential of the place (Are control/coping options available/implementable? Can new meaning/ emotions/ attachment and social interaction be created to support adaptation and meet expectations?

In practice there is still a significant gap between soundscape indicators which are used in some standardized way in measurements made by "people asking questions" and those indicators used in measurements made by "instruments". Psychoacoustic, ecological and landscape acoustics need techniques to be more tightly integrated into such studies to mediate between personal experience and group-area-society requirements and needs. Only through proper integration of these techniques can the potential of the soundscape approach be implemented in planning. By definition, the soundscape approach relies on this strategy, and in a strict sense it can be said: any study which does not use this multidisciplinary method cannot be considered a complete soundscape study.

Research and Development Needs

Besides facilitating and enhancing the involvement of different disciplines, it important to broaden the set of areas that constitute the foundation and platform of soundscape. Areas to develop or further develop include economics, noise policy-standards, combined noise source effects, common protocols, cross cultural studies, soundscape education , combined measurement procedures, and perceptive parameters-including the character of the sound. With respect to surveys, cross cultural questionnaires and the importance of survey site selection has to be emphasized. Further emphasis has to be given to multi-sector environmental health impact assessment, the Soundscape perspective on sustainable development and environmental zoning, citizen involvement, and preservation of quiet areas.

It is important to distinguish the totality of Soundscape from the limited idea of quiet zone. Consideration of "sensitive areas" and the design of "supportive environments" requires new insights into the existing annoyance data and new integrative research strategies. There is a common consensus about the necessity of additional parameters beside the A-weighted sound pressure level. Psychoacoustic parameters contribute immensely to more proper methods to measure and assess environmental sound. It will be possible to explain the contributions to annoyance that result from noise when psychoacoustic parameters, mainly based on standardized procedures of measurement and analysis, are used. To insure that Soundscape is

not just a matter of noise level reduction but that it accounts for people's concerns and well-being, it is necessary to integrate contextual and subjective variables into the evaluation procedure.

Conclusions

In environmental health impact assessments (airports, rail tracks, roads) only the upper health limits of exposure (highest noise levels) are addressed, and this has led to an administrative policy which is to "fill up" the noise exposure to the maximum allowed.

Therefore, during the last 20 years noise exposure has spread from urban centers to suburban and rural areas and from daytime to nighttime. This spread reduces the options for restoration, undisturbed communication and a healthy, non-(noise) impaired environment and environmental quality of life.

Due to this unfavorable development, recent strategy papers, guidelines and directives have stressed the need to change these administrative noise policies towards a more perception oriented and sustainable environment.

For example: it was the task of WG-3 of COST Action TD0804 to reconcile and integrate classical and soundscape oriented means ("harmonizing") and link those with quality of life and health related outcomes in order to find appropriate strategies at different scales of assessment and implementation

There is still often ignorance as to the use of soundscape techniques in noise action plans and for the protection of quiet areas. Funding agencies still hesitate to fund soundscape projects. However, this situation differs broadly from country to country.

It needs to be recognized and accepted:

- that the involvement of different disciplines is requisite to identification of the resources in both human and physical terms,
- that soundscape research is the platform for further development in economic and ecologic, as well as in noise policy standards concerning the enhancement of quality of life,
- that there is the need to linking Quality of Life and Health to soundscape.

4.9 Relationships between Soundscape and Community Tolerance Level

Schomer *et al.* (2013) suggest that non-acoustic factors reflect the context in which the sonic environment is perceived; hence, these factors constitute the judgments of a soundscape. Although contexts can be classified in a variety of ways, for the purposes of convenience Schomer *et al*. divide contexts into two broad types: (1) community-wide context, which are shared by residents of the same neighbourhood, and (2) individual context, which may be unique and unrelated to

those of other residents or neighbourhood norms. Each individual perceives his/her soundscape uniquely. While a community context reflects shared context elements and norms, it is an individual context which determine each individual's perception of the sonic environment

People respond to questionnaires in accordance with their perceptions of sounds, as considered in both community and individual contexts. Virtually every attitudinal survey may be viewed as a soundscape study because respondents have no alternative to assessing sonic environments in such contexts. Noise survey respondents report their reactions to the sound environment as it exists for them, in contexts, at the time of interviewing.

Given 1) that the attitudinal survey responses are soundscape responses about the soundscape, and that shared contexts and norms are shaping responses, and 2) that a single number index, CTL, suffices to quantify the net effect of the "non-acoustic factors or non-A-weighted factors and their interactions," it follows that CTL is a decibel-denominated parameter that summarizes and quantifies soundscapes. These two observations are only relevant for assessments of annoying sounds, however.

CTL currently lacks robust prospective methods, because until further developed, it can only be empirically estimated after the fact. If CTL is viewed as a one-number representation of the soundscape, however, it follows that results of research to measure and assess the soundscape may provide means to develop prospective estimation methods for CTL. Any techniques that can prospectively assess a soundscapes should just as readily prospectively estimate CTL values. That is, If CTL is a one-number descriptor of a soundscape, then it follows that methods developed to quantify sounds are the methods that can be adapted to prospectively evaluate CTL in a community setting.

The obvious missing information results from the fact that community noise research has almost exclusively focused on assessing environments that are too noisy. From the work of Fidell *et al.* (2011) and of Schomer *et al.* (2012), we know that one number, CTL, can quantitatively represent all of the community-wide contexts for annoying situations. It remains unclear whether CTL can do the same in settings where the goal is to create a healthy sonic environment rather than to minimize adverse effects.

Both the noise control and soundscape research perspectives may profit from synergies where the research of each can assist the other. The fact that CTL represents community contexts with a single, decibel-denominated number shows that a soundscape can be described with just one parameter. If CTL is a one-number descriptor of a soundscape, then it follows that methods developed to quantify sounds are the methods that can be adapted to prospectively evaluate CTL in a community setting.

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

CTL analysis permits quantification in decibel units (of DENL 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 DENL that are currently "assumed to be true." For example, it has long 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.

4.11 Sufficiency of a single model of annoyance

A basic research issue which affects any choice of noise metric or indicator is whether a single model of annoyance is appropriate for the entire population. The standard model (time weighted average energy, or “DENL” 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 3 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 or indicators, they are unlikely to be fully understood until much additional basic research is completed.

5 RECOMMENDATIONS AND CONCLUSIONS

5.1 General conclusions

In general, DENL values for noises that do not contain discrete tones and which have A-weighted spectra that peak in the 500 or 1000-Hz octave bands correlate very highly with values of most other conventional noise metrics or indicators in most geographic and operational settings (see Sections 4.4 and 4.5). This suggests that only a small improvement in accuracy or precision of prediction of the prevalence of aircraft noise-induced annoyance may be expected from substitution of another noise metric or indicator for DENL. But even an incremental improvement may be cost effective and warranted

Measures of the duration and numbers of noise events in excess of a threshold do not correlate as highly with DENL 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 DENL. In other words, small changes in DENL 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 DENL and other aircraft noise metrics or indicators may be poorer include in areas behind departure ends of runways subject to start-of-takeoff low-frequency noise created by thrust reverser application.

5.2 Supplemental metrics

Nearly all of the metrics considered in this study are highly correlated with DENL for typical airport operations. Any supplemental metrics worth consideration would need to provide new information that differs from DENL by more than a constant. Community Tolerance Level and Soundscape are two such non-acoustic measures that appear to be related, may be used to characterize community response to transportation noise.

As discussed above, currently the Community Tolerance Level implicitly includes the non-A-weighted acoustic variables and the non-acoustic variables by combining the totality of the variables into the one-number descriptor, CTL. The inclusion of these non-A-weighted acoustic variables, such as the effects of low frequency noise annoyance and noise induced rattles, can be made more explicit by:

1) Replacing A-Weighting with a weighting that is sensitive to both amplitude and frequency as recommended in clause 3.5.

2) Development of a metric that assesses the degree of rattle induced by sound and its effect on annoyance in the community, as recommended in clause 4.7.

Also, currently, CTL provides a simple one-number metric as a means to include the effects of all non-A-weighted acoustic variables and all non-acoustic variables, while soundscapes provide no numerical metrics. Thus, until such time as the soundscape can provide metrics--upon which decisions can be made--it would seem that CTL currently provides the greater utility.

5.3 Recommendations

The ability to predict and quantify the prevalence of annoyance engendered by non A-weighted acoustic variables has been identified as a high priority need. In particular, the role of noise induced rattles and vibration is noted, along with better assessment of more common characteristics such as impulse, tones, modes of operation of sources, etc. Here it is recommended that CTL be used to understand and quantify these variables.

The ability to predict and quantify the prevalence of annoyance engendered by non-acoustic variables has been identified as a high priority need. This capability is required for both CTL and for soundscapes and it is recommended that current and envisioned soundscape research be conducted, among other items, to fill this double need.

It is recommended that research be conducted to replace A-Weighting with a weighting that is sensitive to both amplitude and frequency and may help make low frequency noise and noise-induced rattles explicit factors in the total noise annoyance, rather than implicitly including them with all the other factors that make up the CTL.

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7 APPENDIX A: ALTERNATIVE NOISE METRICS OR INDICATORS

As described in Section 2, alternative noise metrics or indicators 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.

7.1 Arcane nature of aircraft noise metrics or indicators

The general public typically encounters detailed discussions of DENL and other noise metrics or indicators in the context of environmental impact disclosure documents or land use compatibility studies. Full comprehension of aircraft noise exposure estimates expressed in units of DENL 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 DENL-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 or indicators in such documents quantify the *acoustic* consequences of proposed actions such as airport expansion projects. Some consider noise metrics or indicators expressed in units other than integrated exposure as useful alternatives to DENL 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 alternative noise metrics or indicators actually improve public understanding of noise *impacts*. In fact, it is far from clear that alternative descriptions of various properties of aircraft noise distributions actually improve public understanding of noise *impacts*.

7.2 Role of noise metrics or indicators 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. 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 DENL. 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.[17]

7.3 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

[17] 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.

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 DENL 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 gradations of color coded community reactions. Figure 7-2 and Figure 7-1 illustrate the difference. Figure 7-1 could equally well represent gradations in prevalence of annoyance as of noise exposure.

Figure 7-2: Typical DENL contours in 5 dB intervals, mistakenly interpretable as indicative of step changes in noise

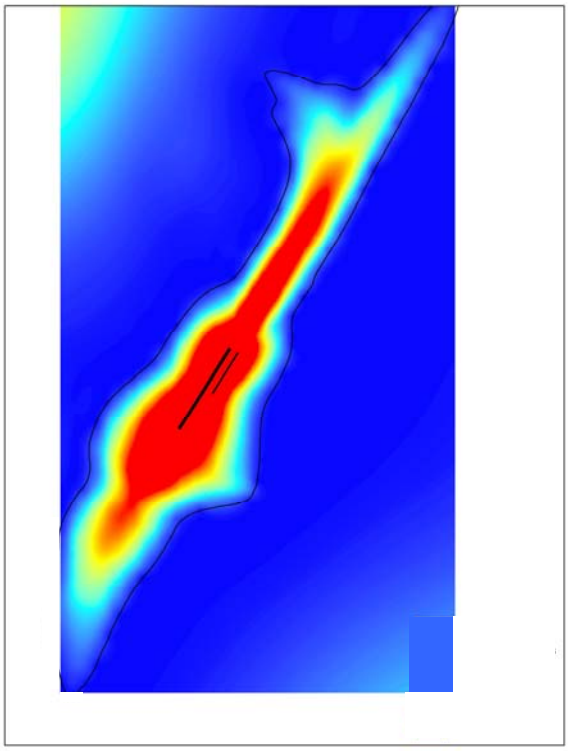

Figure 7-1: DENL depicted as graduated shading, suggestive of continuous variation in noise level

Administrative decisions can still be based on conventional DENL 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.

7.4 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 DENL 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 7-3.[18] 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.

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

Figure 7-3 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 7-4 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 7-5 depicts noise complaints at Hanscom Field in Massachusetts. Figure 7-5 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.

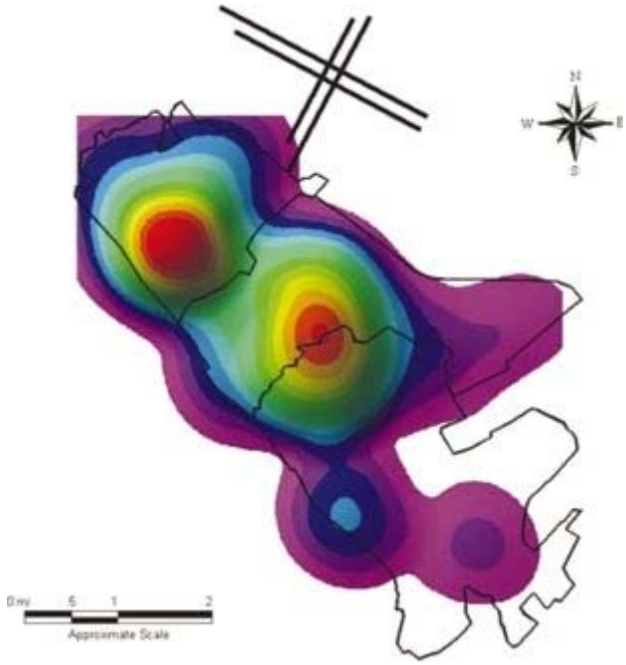

Figure 7-3: Pseudo-terrain map of noise complaints at San Francisco International Airport

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 DENL 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.

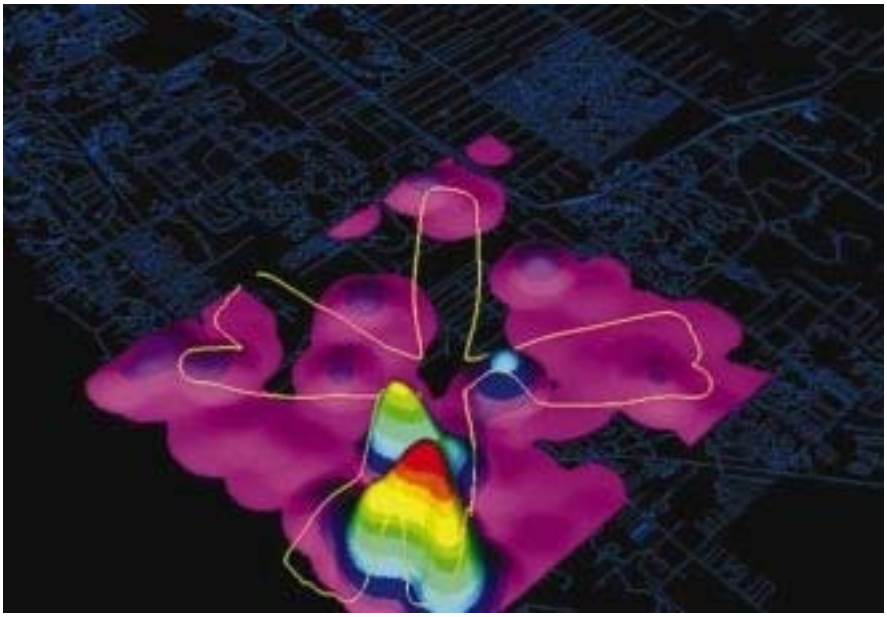

Figure 7-4: Pseudo-terrain map of noise complaints at Naples Airport

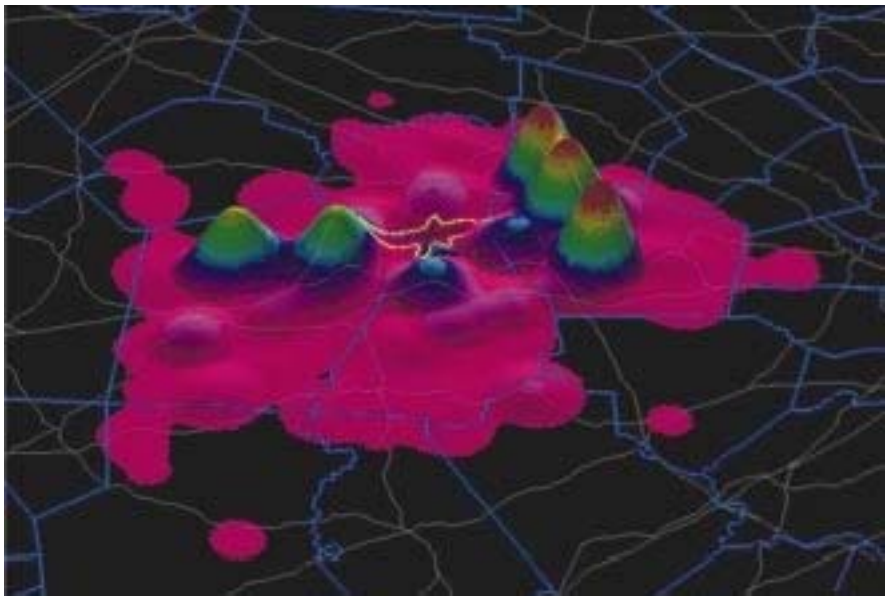

Figure 7-5: Pseudo-terrain map of noise complaints at Hanscom Field

8 APPENDIX B: FEATURES OF CONTEMPORARY CIVIL AIRCRAFT NOISE METRICS OR INDICATORS

This appendix contains three tables which systematically characterize the attributes of transportation noise metrics or indicators developed during distinct technological eras. The first table addresses metrics developed during the 1960s or earlier, some of which remain in common use (Table 8-1). Each of these metrics - other than loudness - can be measured with equipment no more sophisticated than an analog sound level meter, or an electromechanical distribution analyzer. The bottom half of the first table, addressing integrated noise metrics, is therefore largely empty. Metrics such as NNI (Noise and Number Index) are little used today. Metrics such as TA (time above a threshold) and NA (number above a threshold), date from a later era, but could have been measured with 1960s technology.

Table 8-2 addresses metrics developed mostly in the 1980s and 1990s that remain in use today. The table includes a family of temporally-integrated metrics, such as A-weighted sound exposure level (ASEL) and C-weighted equivalent level (CSEL). It also includes are integrated calculations, such as effective perceived noise level (EPNdB) and ratings such as day/night average sound level (DENL). Calculations of the more complex metrics were facilitated by standalone one-third octave band analyzers interfaced to laboratory minicomputers.

Table 8-3suggests metrics whose calculations are facilitated by contemporary digital technology. Such metrics have the potential for serving as improvements or supplements to DENL. They include a family of time and frequency-dependent integrated metrics, and alternative ("interrupted" or threshold-sensitive) integration methods such as SENEL. Table 3 also acknowledges the potential for source-specific forms of noise ratings which could be based on categorical judgments about the annoyance of particular noise sources. Such metrics could distinguish the integrated annoyance of (for example) aircraft from that of trucks, cars, motorcycles, and trains. Such metrics could also take into consideration rates of occurrence and rates of responses to noise events, as described by Schomer and Wagner (1995).

Gray areas of the tables indicate items or quantities inapplicable to the time frame or metric class. Light blue coloring delineates metric classes; light purple shading highlights examples or notes; alternating salmon and almond coloring of rows is included simply for clarity; and yellow highlighting signifies a change in the frame of reference.

Table 8-1: 1960's era analog noise metrics

PAGE 1		1960's era, analog metrics									
Name	Metric Class	Directly Measured		Calculated				Rating	Time-dependent		Counting
	General Characteristics of the Metric	Single level	Spectrum of levels	Frequency	dependent	Amplitude and frequency dependent w/o masking	Amplitude and frequency dependent with masking	"Adjusted" calculation	Centiles	Time above	Number above
	Example	max A (slow)	C--octave bands	AI	SIL	PNL	Loudness ISO 532b	PNL-t	L10-A (1-s *slow*)	TA-C (1-s *slow*)	NA 70 A
Frequency weighting (choose 1)	OASPL			●	●						
	Z					●	●	●			
	C		●							●	
	A	●							●		●
Spectrum (if applicable choose 1)	Octave Bands		●		●						
	1/3 Octave			●		●	●*	●			
	narrow bands										
Time detection (choose 1)	fast			●							●
	slow	●	●		●	●		●	●	●	
	1-s LEQ										
	other LEQ (Duration in s)										
Detection (choose 1)	maximum	●		●		●					●
	rms average		●		●		●	●	●	●	
	peak										
Integration (choose 1)	LEQ										
	LEQ + K*log(n) +f(level,number) [specify K and f]										
Summation (choose 1)	LOG2						●				
	LOG10					●		●			
Rating factors (choose all that apply; specify value)	Tone							●			
	Rattles										
	Impulse										
	Evening										
	Night										
	Weekend										
Expectations (all that apply)	Rural										
	New										
	PR										

Table 8-2: 1980's and 1990's era integrating-averaging metrics

PAGE 2	1980's era, Integrating-averaging Metrics								
	Metric Class	Directly Measured				Calculated			Rating
		Sound Exposure Level (SEL)		Equivalent Level (LEQ)					
	General Characteristics of the Metric	Single level	Spectrum of levels	Single level	Spectrum of levels	Frequency dependent	Amplitude and frequency dependent w/o masking	Amplitude and frequency dependent with masking	"Adjusted" calculation
	Example	CSEL (1-s LEQ)		1-hr ALEQ (1-s ALEQ)			EPNdB	Time-varying loudness	DENL
Frequency weighting (choose 1)	OASPL						●		
	Z		●		●			●	
	C	●							
	A			●					●
Spectrum (if applicable choose 1)	Octave Bands				●				
	1/3 Octave		●				●		●
	narrow bands							● *	
Time detection (choose 1)	fast								
	slow						●		
	1-s LEQ	●	●				●		●
	other LEQ (Duration in s)			1 ms	10 - s			2 ms	
Detection (choose 1)	maximum								
	rms average		●	●	●		●	●	●
	peak								
Integration (choose 1)	LEQ	●		●	●		●		●
	LEQ + K*log(n) +f(level,number) [specify K and f]								
Summation (choose 1)	LOG2							●	
	LOG10						●		●
Rating factors (choose all that apply; specify value)	Tone								●
	Rattles								●
	Impulse								●
	Evening								5 ●
	Night								10 ●
	Weekend								5 ●
Expectations (all that apply)	Rural								●
	New								●
	PR								●

Table 8-3: Integrating averaging metrics

PAGE 3	Integrating-averaging Ratings								
	Metric Class	Directly Measured		Existing, Calculated Ratings			Potential, Calculated Ratings**		
	General Characteristics of the Metric	"Standard" Sound Exposure Level	Thresholded Sound Exposure Level	DNL	DENL	NEF	Amplitude and frequency dependent w/o masking	Amplitude and frequency dependent with masking	DNL/DENL (using SENEL)
	Example	CSEL (1-s LEQ)	SENEL > 60				LL-SEL	Time-varying loudness	Using SENEL
Frequency weighting (choose 1)	OASPL					○			
	Z						○	○	
	C	○							
	A		○	○	○				○
Spectrum (if applicable choose 1)	Octave Bands								
	1/3 Octave Bands			○	○	○	○		○
	narrow bands							○ *	
Time detection (choose 1)	fast								
	slow					○			
	1-s LEQ	○	○	○	○				○
	other LEQ					0.5 s	50-100 ms	2 ms	
Detection (choose 1)	maximum								
	rms average		○	○	○	○	○	○	○
	peak								
Integration (choose 1)	LEQ	○		○	○	○	○	○	○
	LEQ + K*log(n)		1-s LEQ > 60						1-s LEQ > 60
Summation (choose 1)	LOG2							○	
	LOG10			○	○	○	○		○
Rating factors (choose all that apply; specify value)	Tone			○	○	○	○		○
	Rattles			○	○		○		○
	Impulse			○	○		○		○
	Evening				5 ○				
	Night			10 ○	10 ○	16.67	10 ○		10 ○
	Weekend			5 ○	5 ○		5 ○		5 ○
Expectations (all that apply)	Rural			○	○		○		○
	New			○	○		○		○
	PR			○	○		○		○
Frame of Ref:	Indoors						○	○	

* Calculations may depart from one-third octaves below about 500 Hz because the critical bands of the ear are wider than a one-third ocatave-band filter .

** Conservatively, 100,000 rating variations

9 APPENDIX C: EXCERPTS FROM EUROPEAN UNION 2005 "SOUND NOISE METRICS" REPORT

Community-level regulation of noise nuisance at European airports is a contentious issue that has been discussed for over a decade now. Against the backdrop of both 2002 noise Directives this study develops and assesses approaches to setting noise limits at larger EU airports. Harmonization of noise limit schemes within the Community may contribute to smooth functioning of the internal market. In this study, different degrees of harmonization are presented, but the pros and cons of the concept of uniformity in noise limiting schemes, though important issues, are not part of this study.

The key question that has been answered is primarily in what way could noise limits be defined. Questions like at what level such limits should be set and what mitigation measures can be applied to reach these levels have not been answered here.

The aim of setting noise limits at airports is to limit or reduce noise around them.

Limitation of noise can serve the following two goals:

- Limitation of noise impacts on people.
- Spatial limitation of noise impacts.

A noise limiting scheme consists of:

- A noise indicator.
- A method for setting the noise limits (resulting in the levels of the limits).
- A monitoring mechanism.
- Enforcement procedures.

Currently, many different types of noise limitation schemes exist. Many European airports have developed their own system for limiting noise based on different noise indicators, noise limits and monitoring methods.

The scheme we propose is composed of the following elements:

A locally set limit to the absolute number of exposed people within several L_{den} contour zones, including a supplementary measure indicating the number of annoyed people.

Locally set limits to night time noise, based on two indicators:

- An indicator limiting the number of noisy events to which anyone is exposed during the night (NAx).
- A Person Events Index (PEI) limiting the total noise load per night.

Locally set absolute limits to the number of exposed people within L_{den} contours

The first element of the proposed scheme is directed at limiting the absolute number of exposed people. It is a uniform noise indicator which adheres closely to current Community legislation. Though the indicator is uniform, thus increasing transparency and comparability, the levels of limits are determined locally.

By localizing the responsibility for setting limits to the number of exposed people, full account can be taken of the local situation. Local authorities are best equipped to do this, and also to balance the limits levels with land use issues. We propose a noise indicator based on exposure instead of one primarily based on noise emission or the adverse effects of noise (annoyance). Noise exposure relates directly to Directive 2002/49/EC and is also in line with environmental legislation in other fields. Noise exposure limits should be based on L_{den} contours, also advocated in the same Directive. Introducing a separate measure with a similar aim in mind would lead to confusion.

The scheme should limit the total number of exposed people within L_{den} contours, mainly because this most directly relates to the main problem of aircraft noise and provides a higher flexibility to airports than limiting noise exposure at a number of geographical 'reference' points on the ground. Special account can be taken of dwellings with noise insulation. A pragmatic approach would be to count these dwellings in a contour with a lower noise level. For monitoring, we suggest making primary use of calculated airport noise performance, because airport noise modeling allows a predictive approach and is well advanced, whereas reliable noise measurements are at best very labor intensive. Measurements could be used to validate calculations, to check whether aircraft certificated noise levels are accurate for in-service situations and whether best practice measures are being implemented.

Supplementary measure indicating the number of annoyed people

Using up to five noise level bands makes it hard to assess whether progress is being made. It is not clear how to appraise a reduction in one band and an increase in another. For this reason we strongly recommend using the following supplementary measure: the total number of annoyed people within the 55 dB(A) contour (*i.e.,* the lower boundary of the lowest band for which reporting requirements apply).

Based on established statistical noise-annoyance relationships for aircraft noise, the total number of annoyed people within each band can also be estimated. By summing the results for each band, an estimate of the total number of annoyed people is obtained.

This measure is not meant to provide an additional restriction, but might serve as a basis to determine limit levels for each particular band and to get insight into whether the airport is doing a good job or not with respect to noise limitation over the whole of the affected community.

Locally set limits to night time noise

Although the L_{den} measure does have a penalty factor for evening and night flights, this does not fully do justice to the specific problem of night noise. Peak noise levels are a better indicator than the L_{Aeq} based metrics, such as L_{den}. To have a good indication of the total noise exposure during the night and also provide certainty of protection to individuals, we propose to add two indicators:

- An NAx indicator to limit the number of noisy events to which any individual
- person is exposed, and

- A Person Event Index (PEI), giving a better indication of total noise exposure during the night than an NAx indicator. The PEI(x) sums the total number of instances where an individual is exposed to an aircraft noise event above a specified SEL value of x dB(A) for the night time period.

Internationally set limit based on the ratio of exposed area and some volume measure

To provide comparability between airports within the Community and to provide for reflection of the smooth functioning of the internal market, a relative indicator linking noise limits and transport volume should be part of the combined scheme. The indicators proposed above do not directly link the level of the noise limit with the transport volume.

We propose an internationally set limit defined by the exposed area per measure of transport volume. The underlying idea is that any two airports of a similar 'size' should produce broadly similar size noise contours, although they of course to some extent depend on runway layout. Noise contour size could be based on the total area within a simple 24 hour L_{eq} contour. There may be exceptions where noise contour area is not so important, for example, an airport with contours stretching over the sea or other uninhabitable areas. It could also be appropriate to subtract the area of the airport itself from the airport's contour size. This may help to prevent the airports which cover larger areas being unfairly penalized. For defining a measure of transport volume some combination of distance and actual payload, such as Maximum Zero Fuel Weight (MZFW) seems the best option. Further research is necessary for this part of the combined scheme particularly into the robustness of the relationship between noise contour area and airport size in terms of transport volume. This would also identify any deterioration in the achievement of noise limit objectives with traffic growth.

Reporting requirements

The fourth element of the framework we propose consists of extensive requirements on reporting noise policy by the local authorities responsible for setting limits. Reporting should improve transparency and provide a clear picture of what is expected in the future to all stakeholders, airlines and surrounding communities alike. This should provide a firm basis for corporate and personal planning, and that can itself help to limit annoyance.

We propose that airports should publish long term noise policy plans and associated forecasts, clearly stating their objectives and the proposed timescale for their achievement.

10 APPENDIX D: GLOSSARY

The following glossary of noise metrics or indicators was condensed from the following:

> Handbook of Aircraft Noise Metrics, Ricarda L. Bennett and Karl S. Pearsons, NASA Contractor Report 3406 N81-21871, Bolt Beranek and Newman Inc., prepared for Langley Research Center under Contract NASl-14611, 1981

In this condensed version only the metric definition, purpose and background are provided from the original text. The original document contains more background information and calculation procedure. Also, this condensed version was converted to text from using optical character recognition (OCR) software, so the reader is cautioned to refer to the original document for confirmation of the metric definition.

The metrics presented here are presented in the same order as in the original document as follows:

Frequency Weighted Metrics

1. A-Weighted Sound Level (SLA)
   A-2
2. B-Weighted Sound Level (SLB)
   A-4
3. C-Weighted Sound Level (SLC)
4. D-Weighted Sound Level (SLD)
5. E-Weighted Sound Level (SLE)

Computed Metrics

1. Perceived Noise Level (PNL)
2. Tone Corrected Perceived Noise Level (PNLT)
3. Psychoacoustic Loudness
4. Psychoacoustic Sharpness

DURATION CORRECTED SINGLE EVENT METRICS

1. Effective Perceived Noise Level (EPNL)
2. Sound Exposure Level (SEL)
3. Single Event Noise Exposure Level (SENEL)

MULTIPLE EVENT METRICS

1. Statistical Sound Level (Lx)
2. Equivalent Continuous Sound Level (LEQ)
3. Hourly Noise Level (HNL)
4. Time Above Threshold (TA)
   a. Time Above Ambient (TAA)
   b. Time Audible (TAUD)
5. Composite Noise Rating (CNR)

6. Noise Exposure Forecast (NEF)
7. Day-Night Average Sound Level (DENL).
8. Community Noise Equivalent Level (CNEL)
9. Day-Evening-Night Average Sound Level (LDEN)
10. Noise and Number Index (NNI)
11. Weighted Equivalent Continuous Perceived Noise Level (WECPNL)
12. Australian Noise Index (ANEF)
13. Number of Events Above Threshold (NAx)
14. Kostens Units (K)

SPEECH COMMUNICATION METRICS

1. Articulation Index (AI)
2. Speech Interference Level (SIL).

INDEX (Alphabetical listing)

Frequency Weighted Metrics

TITLE: **A-WEIGHTED SOUND LEVEL**

ABBREVIATION: SLA

SYMBOL: L_A

UNIT: Decibel (dB)[19]

GEOGRAPHICALUSAGE: International

DEFINITION: A-weighted sound level is sound pressure level modified to de-emphasize the low frequency portion of sounds. It is one of several such weightings (A, B, C, D) found on a sound level meter which attempts to approximate the human ear's response to sound.

PURPOSE: A-weighted sound level is used to approximate the relative "noisiness" or "annoyance" of many commonly occurring steady state or intermittent sounds. It is often employed in measuring outdoor community noise such as aircraft flyovers and vehicular traffic. However, for short impulsive
sounds, or sounds with very intense low frequency characteristics or with discrete tonal components, A-weighted sound level does not do an adequate job of accounting for people's subjective response and other more precise measures should be used.

BACKGROUND: A-weighted sound level was initially intended to be a convenient way to approximate subjectively judged loudness for measured sound levels between 24 and 55 dB. However, in practical usage it was found that A-weighted sound level correlated extremely well with human responses to many different sounds regardless of the levels.

This simple rating is a valid and reliable measure of many types of noise signals and is comparable to many of the more complex noise rating methods.
A-weighted sound level is also used as the basic frequency weighting for other measures such as the statistical measure Lx or for equivalent continuous level, (LEQ). In fact, sound level is understood to mean A-weighted sound level if no frequency weighting is specified.

An electrical network designed to provide the A-weighting has been conveniently incorporated into most sound level meters since approximately the late 1930's. This affords a simple direct method of measuring the A-level of a given noise signal. The resulting weighted spectrum is summed to obtain a single rating number.

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[19] It is often seen in the literature as dBA or dB(A). However, according to ANSI Y10.11-19?9, the correct unit is decibels without a modifier.

A-weighted sound level is widely accepted in both industrial and community noise control programs. It has been incorporated in many ordinances and regulations at both the state and federal level. And, it is often used in the rules and regulations published by several federal agencies including the Department of Labor (DOL), the Environmental Protection Agency (EPA), the Department of Transportation (DOT), and the Department of Housing and Urban Development (HUD).

TITLE: **B-WEIGHTED SOUND LEVELS**

ABBREVIATION: SLB

SYMBOL L_B

UNIT Decibel (dB)[20]

GEOGRAPHICAL USAGE: International

DEFINITION: B-weighted sound level is sound pressure level modified to de-emphasize the low frequency portion of sounds. It is one of several such weightings(A, B, C, D) found on a sound level meter which attempts to approximate the human ear's response to sound.

PURPOSE: B-weighted sound level was developed to approximate the relative loudness of medium level sounds. Currently SLB is not usually employed for noise measurement purposes.

BACKGROUND: In an effort to provide a better correlate with the loudness of sounds, three weighting networks were designed into sound level meters to modify sound pressure levels in accordance with equal loudness contours.

The B-weighting shown in Figure SLB-2 was one of the weighting networks used. The B-weighting network has the response characteristics that are approximately the inverse of the 70 phon equal loudness contour for pure tones. The B-weighting was to be used if the readings on the sound level meter were between 55 to 85 dB.

[20] It is often seen in the literature as dBB or dB(B). However, according to ANSI/IEEE 260.4-1996 , the correct unit is decibels without a modifier.

TITLE: C-WEIGHTED SOUND LEVEL

ABBREVIATION: SLC

SYMBOL: L_C

UNIT: Decibel (dB)[21]

GEOGRAPHICAL USAGE: International

DEFINITION: C-weighted sound level is sound pressure level modified to limit the low and high frequency portion of sounds. It is one of several such weightings (A, B, C, D) found on a sound level meter which attempts to approximate the human ear's response to sound.

PURPOSE: The C-weighted sound level was developed to approximate the relative loudness level of high level sounds. Currently it is primarily used to approximate overall sound pressure level where the frequency range of interest is between 31.5 Hz and 8000 Hz. Frequency weightings are 3 dB or less in that range.

BACKGROUND: In an effort to provide a better correlate with the loudness of sounds, three weighting networks were designed into sound level meters to modify sound pressure levels in accordance with equal loudness contours.

The C-weighting is essentially flat and therefore provides a reasonable approximation for estimating the loudness level of high level sounds. Like the A-weighting and B-weighting, the C-weighting relates to the equal loudness contours. Specifically, it is the inverse of the 100 phon loudness contour. Initially the C-weighting was to be used If readings on the sound level meter were above 85 dB.

The C-weighting scale is fairly uniform in response from 31.5 Hz to 8000 Hz; It must be noted that the weighting factors will yield a slightly different result from measurements done with a linear scale which contains no corrections. However, if the sound level meter does not have a linear scale selection, it would be fairly safe to use the C-weighting as an estimate of the overall sound pressure level.

[21] It is often seen in the literature as dBC or dB(C). However, according to ANSI/IEEE 260.4-1996, the correct unit is decibels without a modifier.

TITLE: D-WEIGHTED SOUND LEVEL

ABBREVIATION: SLD

SYMBOL: L_D

UNIT: Decibel (dB)[22]

GEOGRAPHICAL USAGE: International

DEFINITION: D-weighted sound level is sound pressure level modified to de-emphasize the low frequency and emphasize the high frequency portion of sounds. It is one of several such weightings (A, B, C, D) found on a sound level meter which attempts to approximate the human ear's response to sound.

PURPOSE: D-weighted sound level was developed as a simple approximation of perceived noise level. Further, it was intended to be a more precise measure than A-weighted sound level to approximate the relative noisiness or annoyance of many commonly occurring sounds.

BACKGROUND: Because the calculation procedures for perceived noise level (PNL) is fairly complicated, it was thought that a similar more direct measure that would allow an immediate estimate of the effect of an aircraft flyover should be developed. This measure was initially designated as N-level and was to be incorporated into a sound level meter, like the A-, B-and C-weightings. The weighting network for this new measure was the inverse of the 40 noy contour developed by K. Kryter. However, the N-weighting, unlike A, B and C, had no reference at 1000 Hz. Thus the measurements made with the N-weighting had to be calibrated by determining N-level and PNL from several aircraft flyovers and
using the average difference for subsequent N-level measurements. Average N-levels were then, by definition, equal to PNL values.

To eliminate the uncertainty in the N-level, it was suggested that the inverse noy curve weighting be equal to 0 at 1000 Hz (similar to A, B and C), and the Technical Committee No. 29 (Electroacoustics) of the International Electrotechnlcal Commission (IEC/TC29) further suggested that the letter "D" be adopted to replace the "N". This recommendation has been implemented.

[22] It is often seen in the literature as dBD or dB(D). However, according to ANSI/IEEE 260.4-1996 , the correct unit is decibels without a modifier.

TITLE: E-WEIGHTED SOUND LEVEL

ABBREVIATION: SLE

SYMBOL: LE

UNIT: Decibel (dB)

GEOGRAPHICAL USAGE: Limited

DEFINITION: E-weighted sound level is sound pressure level modified to de-emphasize the low frequency and emphasize the high frequency portion of a sound. This measure has been proposed as another attempt to approximate the human ear's response to sound in a manner very similar to D-weighted sound level.

PURPOSE: E-weighted sound level, in its proposed form, was designed to provide a close estimate to Stevens' (Ref. I) perceived level. It was designed to measure the noisiness or loudness of sounds such as aircraft flyovers.

BACKGROUND: The concept of E-weighted sound level was proposed by Stevens In his work on perceived level in 1972. He had found that sound measured with this "ear-weighted" frequency response was closely related (± 2 dB) to the perceived level calculated according to Stevens' Mark VII procedure. E-weighting reflects the basic 20 sone contour used In Mark VII with a standard reference band at 1000 Hz. The accuracy of the E-weighting to predict perceived level is particularly good for sounds of medium level. E-weighting is as yet a draft standard only recently published by the American National Standard Institute in August of 1978 for comments and criticism. No proposal was made in this draft to incorporate E-weighting as an addition to the American Standard sound level meter. It was merely specified as a frequency weighting which could be used with any general sound measurement system which has a flat frequency response over the frequency range of interest to the experimenter.

TITLE: PERCEIVED NOISE LEVEL

ABBREVIATION: PNL

SYMBOL: L_{PN}

UNIT: Decibel(dB)[23]

GEOGRAPHICAL USAGE: International

DEFINITION: Perceived noise level (PNL) is a rating of the noisiness of a sound calculated from acoustic measurements. It is computed from sound pressure levels measured in octave or one-third octave frequency bands. The PNL of a given sound is intended to be numerically equal to the level of an octave band of noise centered at 1000 Hz which is judged equally noisy to the given sound.

PURPOSE: PNL was developed as a method for ranking the noisiness of sounds of widely differing spectral character. It is used mainly for ranking the relative annoyance or disturbance caused by aircraft flyover noise.

BACKGROUND: Karl Kryter introduced the perceived noise level method when it was found that loudness level calculated by Stevens' method underestimated the Judged noisiness of Jet aircraft relative to that of reciprocating engine aircraft. The determination of PNL is patterned after Stevens' loudness level, except that equal noisiness curves were employed instead of equal loudness curves. Two sounds of equal noisiness mean that people would be willing to accept one sound as much as the other "occurring periodically 20-30 times during the day and night at their home". The equal noisiness curves shown in Figure PNL-2 were developed by determining the levels of equal noisiness of various bands of noise at different frequencies.

The unit noy is used for the scale of perceived noisiness. The numerical value of 1 noy was assigned to the perceived noisiness of an octave band of random noise centered at 1000 Hz and corresponding to a sound pressure level of 40 dB. Similarly, 2 noys corresponded to a sound pressure level of an octave band of random noise at 50 dB.

Thus, above the 1 noy value, an increase of l0 dB is equivalent to a doubling of the perceived noisiness as measured in noys, similar to the growth of loudness suggested by Stevens. Values less than 1 noy do not grow in the same manner, but again follow the same pattern as suggested by Stevens for the loudness measure.

Validation tests for the perceived noise level using a variety of sounds indicated that the calculation procedure did not account for the effects of pure tones such as those often present in

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[23] The unit for the scale of perceived noisiness is the noy, while the unit for perceived noise level is the decibel. It is seen in the literature as PNdB.

turbofan aircraft flyovers, nor did it take into consideration the effect of the duration of a sound, since it was mainly used to rank the judged noisiness for sounds of equal duration. For these reasons, further research was conducted which eventually provided tone corrected perceived noise level (PNLT) and effective perceived noise level (EPNL), which attempt to include the effects of pure tone and duration as indicated elsewhere in this Handbook.

The method uses octave or one-third octave band noise levels. However, for certain types of sounds that vary with time, the manner in which the octave or one-third octave band levels are determined is important. Originally, the band levels were determined as the maximum levels in each band under measurement regardless of the time In which they occurred. When calculated in this manner, the result is called composite PNL(PNLC). With the advent of computer calculations for perceived noise level, band levels are determined for each point in time and perceived noise levels calculated from these measurements. In both cases, maximum perceived noise levels are determined, but differences of as much as 2 dB are observed for the different techniques.

TITLE: TONE CORRECTED PERCEIVED NOISE LEVEL

ABBREVIATION: PNLT

SYMBOL: L_{TPN}

UNIT: Decibel (dB)*[24]

GEOGRAPHICAL USAGE: International

DEFINITION: Tone corrected perceived noise level is perceived noise level with the addition of a tone correction factor. This tone correction factor is intended to account for the added annoyance due to spectrum irregularity or discrete frequency components, such as tones.

PURPOSE: Tone corrected perceived noise level was developed to improve the noisiness assessment for those sounds with prominent discrete frequencies. Like perceived noise level, it is used in assessing the subjective response to single event aircraft fly-overs which commonly contain pure tones, such as in turbo-fan Jet aircraft. However, when aircraft noise is being evaluated, EPNL is more commonly employed because it takes duration as well as discrete frequency effects into accouter.

BACKGROUND: With the advent of turbo-fan Jet aircraft, it became evident that perceived noise level could not evaluate the effects of the pure tone "whine" that is sometimes present in the sound from these Jets. Therefore after developing the perceived noise level procedure, Kryter and Pearsons worked on a method which would compensate for these pure tones often heard in a Jet aircraft flyover. Several researchers developed various schemes for compensating for the additional noisiness of these discrete frequency components. After reviewing the various correction techniques, a tone-correction procedure was finally adopted by the Federal Aviation Administration and incorporated into the FAR Part 36 in 1969.

[24] The unit for the scale of perceived noisiness is the noy, while the unit for perceived noise level is the decibel. It is seen in the literature as PNdB.

TITLE: EFFECTIVE PERCEIVED NOISE LEVEL

ABBREVIATION: EPNL

SYMBOL: L_{EPN}

UNIT: Decibel (dB)[25]

GEOGRAPHICAL USAGE: International

DEFINITION: Effective perceived noise level is perceived noise level (PNL) of a single event adjusted for the added annoyance due to duration and for the presence of discrete frequencies (tones).

PURPOSE: Effective perceived noise level assesses the noisiness of a single noise event. Since EPNL takes into consideration both the tone and duration components of a noise, it is a convenient rating for measuring sub-sonic aircraft flyovers. The FAA has designated this rating scheme as the basis for its aircraft noise certification procedure.

BACKGROUND: Effective perceived noise level evolved in response to the new technological designs of Jet engines. Several individuals and sponsoring organizations worked independently and together on the development of this single number rating method which uses objective acoustic measurements to estimate the effective "noisiness" response to a single aircraft flyover. Finally, through Joint negotiations with FAA, ISO, and SAE, an ad hoc working committee (SAE A21) generated the procedure which computes effective perceived noise level.

The rationale for the development of this measure is based upon the results from several subjective judgment tests which indicated that as the duration of a sound or aircraft flyover increased, it was judged noisier. Further, the sounds with identifiable discrete tones were judged noisier than sounds without audible tonal components. Thus, it was evident that adjustment factors should be added to the perceived noise level rating to compensate for the perceived noisiness attributable to the signal time history and the presence of audible discrete frequency components.

Effective perceived noise level is calculated over the time history of a flyover at a time sequence (usually 0.5 sec. intervals) of tone-adjusted perceived noise levels which are calculated from one-third octave band noise spectra. The tone adjustments are determined from one-third octave band spectra by a procedure described under PNLT. The integration procedure results in adding 3 dB for each doubling of signal duration.

[25] The unit of effective perceived noise level is the decibel; it is commonly seen in literature as EPNdB.

TITLE: SOUND EXPOSURE LEVEL

ABBREVIATION: SEL

SYMBOL: LAE[26]

UNIT: Decibel (dB)

GEOGRAPHICAL USAGE: International

DEFINITION: Sound exposure level is energy averaged A-weighted sound level over a specified period of time or single event, with a reference duration of 1 second.

BACKGROUND: Sound exposure level was developed to provide a means of measuring both the duration and the sound level associated with a particular time period or event measured at a specific site. SEL was designed to include duration because it was found from the results of subjective noise studies that longer duration noises were judged more annoying than shorter duration noises. Thus, the SEL included the entire range of A-weighted sound levels over the period or event of interest. However, for practical purposes, when attempting to characterize an event such as an aircraft flyover by SEL, it is only necessary to measure the sound levels which are within l0 or 20 dB of the maximum A-level.

Relation to Single Event Noise Exposure Level (SENEL) (California)

SENEL is a special sub-set of SEL and was developed to be used exclusively in the California state airport regulations to limit excessively noisy aircraft operations. SENEL is calculated exactly like SEL but is based upon only the measured A-weighted sound levels above a threshold level. This threshold level is determined by some type of legislative or administrative action. A Federal court decision held that the Federal law pre-empted the State's power to regulate noisy aircraft operations with SENEL. The same decision noted that the airport proprietor's power to set noise limits was not affected. Conceivably, the individual proprietor, whether city or private, could still use a SENEL criteria to govern aircraft flyover noise.

[26] Sound exposure level is sometimes referred to as noise exposure (NEL).

TITLE: STATISTICAL SOUND LEVEL

SYMBOL: Lx

UNIT: Decibel (dB)

GEOGRAPHICAL USAGE: International

DEFINITION: The statistical sound level is a descriptor of a noise environment measured In some time period. It is that noise level which is exceeded x percent of the time.

PURPOSE: Statistical sound level (often referred to as centile level) provides a means of assessing the fluctuating noise levels at a point of interest. For example, it is commonly used to characterize the noise at a community location that is exposed to vehicular traffic.

BACKGROUND: The sound levels in most communities fluctuate depending upon, among other things, the noise source, the time of day, or the season of the year. The noise level within an hour, for example, could fluctuate from very quiet to extremely loud. Therefore, a good way to describe the levels that are present during the day at a site, or the noise exposure of that site, is to use a statistical measure which takes the time varying characteristics of the sound into account. The measure, statistical sound level, or centile level, does just that by considering the proportion of time certain noise levels are exceeded.

The relationship between time and levels exceeded is represented as a cumulative distribution of sound levels as seen in Figure Lx-1. The curve in this figure shows what percent of the observation period each level is exceeded. The time period can be any length, but typically it is for 1 hour or more. Further, the sound levels can be measured using various weighting factors, but usually A-weighted sound level is used.

Common practice has dictated that L10, L50, and L90 are most often used as statistical descriptors of the noise environment to designate levels exceeded l0 percent, 50 percent and 90 percent of the time. However, it should be noted that any other centile levels can be used such as L1 (1 percent) to L99 (99 percent). The sound pressure level exceeded 10 percent of the time, expressed as L10, gives an approximate measure of high level and short duration noises. A measure of the median sound level is L50 and represents the level exceeded 50 percent of the time. The background ambient level is estimated by L90 which is the sound level exceeded 90 percent of the time. The choice of L90 to represent the ambient noise and L10 as the dividing line for the peak levels is somewhat arbitrary. Other countries, such as Australia, have chosen instead to designate L95 and L5 as background and peak levels.

The difference between L10 – L9O indicates range within which the noise levels spend 80 percent of the time. The standard deviation of the noise levels over the defined time period is a common measure of the statistical fluctuation.

Statistical sound level measures serve as the basis for other measures which were developed to examine how the fluctuating noise relates to subjective annoyance. The traffic noise index (TNI)

and noise pollution level (NPL) are both ratings which require a knowledge of statistical parameters such as the 90, 50, and l0 percent levels of cumulative distribution.

Highway traffic noise most often lends itself to a statistical distribution type measure. Early criteria used for highway noise are expressed in terms of L_{10} values. In high density traffic situations the statistical distribution of sound levels can be represented by a Gaussian distribution. The L_{10} value can be estimated by the median (L50) and the standard deviation of the noise levels (s), and is given by:

TITLE: EQUIVALENT CONTINUOUS SOUND LEVEL

ABBREVIATION: QL[27]

SYMBOL: L_{eq}

UNIT: Decibel (dB)

GEOGRAPHICAL USAGE: International

DEFINITION: Equivalent continuous sound level is the level of the A-weighted sound energy averaged over a specified period of time.

PURPOSE: Equivalent continuous sound level was developed to provide a measure of time varying or fluctuating noise. It has proven to be an effective tool for assessing people's reactions to aircraft and vehicular traffic noise. It also correlates well with the degree of annoyance, hearing loss, speech and sleep interference that is generated by different levels of noise exposure.

BACKGROUND: Equivalent continuous sound level is one of the ratings which addresses the problem of measuring a time varying noise. It is a single number descriptor that quantifies the combination of noise magnitude, duration, and frequency response of the ear. This is achieved by averaging (that is, converting decibel levels to relative sound power, averaging, and then changing back into resultant levels in decibels) A-weighted sound level over stated period of time. This has also been called 'energy averaging' the sound levels.

This concept of energy averaging or integrating over time is the basis of equivalent continuous sound level. This is defined as the A-weighted sound level of a constant or steady state sound which contains the acoustical energy equivalent to the actual fluctuating noise existing at the location over the observation period.

Equivalent continuous sound level may be calculated for any desired time period such as 24 hours, 8 hours, 1 hour, daytime, or nighttime. It is often seen In the literature as $L_{eq}(24)$, $L_{eq}(8)$, $L_{eq}(1\ )$, L_d and L_n, respectively. It is essential to always indicate the time period over which equivalent sound level

Equivalent continuous sound level is familiar to scientists in the United States and in Europe. In 1957, it was used in the original U.S. Air Force Planning Guide for noise from aircraft operations. It was also referred to in the 1955 report on criteria for short term exposure of personnel to high intensity jet aircraft noise, which was the forerunner of the 1956 Air Force Regulation on "Hazardous Noise Exposure".

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[27] Equivalent continuous sound level is also referred to as average sound level. ANSI, in proposed terminology, will symbolize average sound level or equivalent continuous sound level at L_T, where T is the time period over which the average is taken; previously it was symbolized as $L_{eq}(T)$.

In 1965 it was used in Germany as a rating to evaluate the impact of aircraft noise upon the communities near airports. Other countries such as Austria, East and West Germany, and Sweden have recognized its applicability for assessing the subjective effects of time varying noises of all kinds, including street traffic, railroad traffic, canal and river ship traffic, aircraft, industrial operations, playground, etc.

Equivalent continuous sound level is the primary metric for several more complex noise ratings. Notably it is used in community noise equivalent level (CNEL) in the form of hourly noise level which is L_{eq}. Likewise, QL is the fundamental metric for day-night average sound level (DENL). DENL, like CNEL, has a weighting adjustment for sound levels occurring during different hours of the day.

TITLE: HOURLY NOISE LEVEL

ABBREVIATION: HNL

SYMBOL: L_h

UNIT: Decibel (dB)

GEOGRAPHICAL USAGE: State of California

DEFINITION: Hourly noise level is the level of the mean-square A-weighted sound pressure over an hour period.

PURPOSE: Hourly noise level is used to characterize the time varying noise environment on an hourly basis.

BACKGROUND: Hourly noise level is identical to equivalent continuous sound level (QL) for an hourly period. HNL can be calculated for 1 hour or more and identified by 1HNL (L_{lh}) or 2HNL (L_{2h}). If HNL is computed for different time periods within a day, they are referred to in literature as HNLD (L_{hd}), HNLE (L_{he}) and HNLN (L_{hn}) (Ref. 1). Hourly noise level is the basis for one of the computational formulas for California's community noise equivalent level (CNEL).

TITLE: TIME ABOVE THRESHOLD

ABBREVIATION: TA

SYMBOL: TA

UNIT: Minutes

GEOGRAPHICAL USAGE: United States

DEFINITION: Time above threshold is the time of noise exposure above some pre-selected threshold of A-weighted sound level. For comparison purposes both the threshold level and the observational period must be stated.

PURPOSE: The time above threshold method was designed as a means of describing the noise exposure at locations of interest using units of measure (minutes) that could be comprehended by non-acoustics as well as acoustic experts.

BACKGROUND: The time above threshold method was initially incorporated into an approach called Aircraft Sound Description System (ASDS) developed by the Federal Aviation Administration (FAA) as part of an effort to provide an objective approach for describing aircraft sound levels at geographical locations around an airport. The ASDS concept used two means to carry out this approach: l) the time above a specified threshold (TA), and 2) the situation index (SI). The time above threshold rating accounted for both the A-weighted sound levels of the aircraft events and the time that the sound levels were in excess of a specified 85 dB threshold value. The second aspect of the ASDS method, the situation index, provided a description of the noise exposure in terms of the amount of geographical area that was affected by the noise, and was expressed in units of acres-per-minute.

The ASDS method as a whole was not widely accepted. That part of the method dealing with the situation index concept was eliminated but the time above threshold rating was retained and incorporated by the FAA into the Integrated Noise Model (INM) computer program. This program is used in airport planning whenever it is necessary to consider the environmental impact. The threshold levels for time above in the INM program are specified from 65 to 115 dB in 10 dB increments. The standard observational time periods are 24 hours, evening (1900-2200) and night (2200-0700).

Time above threshold method provides information on the direct effects of noise generating activities such as aircraft flyovers. It enables one to obtain useful information on the total duration of a potentially interfering sound in order to analyze the effects on speech, sleep, or television viewing or determine the number of times during the day in which the interference occurs and the duration of each interference. The information on duration and intensity of sound that become fused into a single number cumulative rating (e.g., noise exposure forecast) can be differentiated by the time above threshold method.

The TA describes the noise exposure experienced at a specified geographical location; however, it is not correlated with estimates of community reaction for noise events above a certain threshold. Instead, the FAA emphasized the objective basis of TA and has not sponsored any research to qualify or interpret these numerical values in order to predict people's subjective annoyance reactions.

TITLE: COMPOSITE NOISE RATING FOR AIRCRAFT

ABBREVIATION: CNR

SYMBOL: L_{CNR}

UNIT: DECIBEL (dB)

GEOGRAPHICAL USAGE: UNITED STATES

DEFINITION: Composite noise rating is a calculated rating based upon perceived noise level of all events occurring within a 24-hour period. Adjustments are made for time of day, type of aircraft, and numbers of aircraft operations occurring over an annual period. Two composite noise ratings are calculated: one for flight and one for run-up aircraft operations.

PURPOSE: Composite noise rating is a method used for rating the noise exposure from aircraft operations and for estimating community reactions. This measure takes into consideration noise associated with both ground run-up and airborne operations in an attempt to predict community response.

BACKGROUND: Tracing the development of CNR over the years provides an insight into the evolution of a single measure which could be used to estimate human reactions to specific noise sources. CNR was the forerunner to other community noise prediction measures, but today is no longer used and has essentially been replaced by day-night average sound level (DENL).

The 1952 CNR and the later 1955 version was designed to predict community reaction to any noise source not exclusively aircraft noise. This
CNR method contained a series of rating curves plotted approximately 5 dB apart and labeled with letters (a through m) as a means of identifying the level rank of the measured noise source in question. After the level rank of a noise was determined from these curves, it was adjusted for the effects of community background level, time of day and how often the noise occurred, the presence of pure tone components, impulse noise characteristics, the previous noise exposure history of the community, and the season of the year. Each of these adjustments had an associated 'correction number' which raised or lowered the level rank of the measured noise.

The 1957 CNR procedure focused on predicting the effects of aircraft ground run-ups and flight operations on the adjacent community without the necessity of field measurements. In this modification of CNR, Stevens and Pietrasanta attempted to describe the physical nature of the noise source itself. They found that in most instances the equivalent level for the 300 to 600 Hz frequency band of an aircraft flyover controlled the level rank referred to in the earlier CNR version.

The correction factor for tone and impulse characteristics of the aircraft noise source was eliminated from the 1957 version of CNR because they were not present or rarely occurred in these particular types of military aircraft. However, an effective duration correction for the time-varying attributes of an aircraft flyover was added. The time of day (modified into three periods:

0600-1800; 1800-2300; 2300-0600), seasons of the year, and background corrections consistent with the previous CNR method were retained. Certain sociological correction factors were carried over from the 1952 CNR and refined, such as characterization of the neighborhood (i.e., suburban, urban, or rural) and emphasis on the community's previous noise exposure and current predisposition towards the airbase.

Stevens and Pietransanta also developed a technique which would allow the prediction of a noise rating and corresponding community reaction given the information on the operational characteristics of the aircraft. They, along with Galloway, developed two sets of basic L_{eq}(300-600 Hz) contours, one for ground run-ups and the other for airborne operations. A table was also developed which would allow for modification of these contours depending upon the specific aircraft under consideration. The contours could then be combined and overlaid on a map of the air base to determine the L_{eq} (300-600 Hz) at any point on the base.

A subcommittee of the Committee on Hearing and Bioacoustics of the National Academy of Science/National Research Council recommended that CNR be rewritten to incorporate a new psychoacoustic measure called perceived noise level (PNL). And, in 1963, Galloway and Pietrasanta produced "Land Use Planning with Respect to Aircraft Noise". This time the contours were based upon maximum PNL instead of L_{eq} (300-600 Hz). And the noise contours were produced for both takeoff and approach conditions as well as ground run-ups for different aircraft classified on the basis of aircraft type, engine type, and performance.

The 1963-1964 CNR, like the previous versions, contained adjustments which took into consideration the factors that affected community reaction to the total airport operations. The total duration of noise over a specific period of time was accounted for by considering the number of aircraft operation of each class of aircraft on each runway. The time of day correction factor was modified to require only two time periods (0700-2200 and 2200-0700) instead of the previous three time periods (Tables CNR-1 and CNR-2). And in contrast to the 1957 CNR calculation procedure, the 1963 CNR eliminated the seasonal corrections, and contained no adjustment for background noise levels nor community attitude towards the aircraft flyover operations. It was decided that such attitudinal assessments were difficult to quantify and at best would merely cloud the results.

Remember that the CNR values for airborne and run-up operations are treated separately. However before they can be computed, the 'partial' CNRs must be determined for each type and class of aircraft and for runway utilization with appropriate time of day adjustments. The 'partial' CNRs are then combined to yield a final CNR value for flight and a CNR for run-up operations. These final CNR results are then correlated with descriptions of expected community reaction.

TITLE: NOISE EXPOSURE FORECAST

ABBREVIATION: NEF

SYMBOL: LNEF

UNIT: Decibel (dB)

GEOGRAPHICAL USAGE: International

DEFINITION: Noise exposure forecast is a rating based upon effective perceived noise level measurements taken over a 24 hour period. Adjustments are made for time of day and for the daily number of aircraft operations averaged over an annual period.

PURPOSE: Noise exposure forecast is used to estimate community reaction to the noise resulting from aircraft operations. The NEF levels at various locations in a community adjacent to an airport act as guidelines for establishing compatible land use development and zoning regulations.

BACKGROUND: Noise exposure forecast was developed as an improvement on the 1963-1964 composite noise rating (CNR) measure but was to apply to civilian and not military aircraft. However, like CNR it is no longer currently used by airport or community planners in the United States and has been replaced by day-night average sound level (DENL).

A brief comparison of CNR and NEF is useful to gain an historical perspective over these types of single number community noise measures. Both measures account for the number of aircraft operations. However, NEF uses effective perceived noise level as its basic metric which allows a better assessment of the tone and duration components associated with turbofan aircraft flyovers. The EPNL computations are more involved than the method found in CNR. Therefore, computer techniques are required to analyze the discrete tone and duration parameters at each time interval in a flyover time pattern.

NEF also incorporates a time of day adjustment, dividing the hours into two periods (0700-2200 and 2200-0700), the same as CNR. It is interesting to note that this correction factor in NEF adds 12.2 dB to the measured levels of the nighttime events. That is because the multiplier of the number of nighttime events is 16.67. Compare this report to the correction factor of only i0 dB used in community noise equivalent level (CNEL) and day-night average sound level (DENL) for the same purpose, namely, to estimate the increased annoyance associated with nighttime aircraft operations.

As was done with CNR, NEF results are correlated with community reactions to noise from aircraft operations. Guided by the responses associated with CNR values, in particular, the boundaries between categories of CNR 100 and 115, a new set of response categories was developed for the NEF values.

TITLE: DAY-NIGHT AVERAGE SOUND LEVEL

ABBREVIATION: DENL

SYMBOL: L_{dn}

UNIT: Decibel (dB)

GEOGRAPHICAL USAGE: International

DEFINITION: Day-night average sound level is energy averaged A-weighted sound level over a 24-hour period with a l0 dB adjustment added to the sound levels between 2200 and 0700. This time weighting is applied in an effort to account for the assumed increased sensitivity to noise intrusions during the nighttime hours.

PURPOSE: Day-night average sound level is a single number descriptor that is used to predict community reaction to noise exposure from aircraft and road traffic. This measure is used for evaluating the total community noise environment. It provides guidelines for assessing compatible land uses and zoning recommendations.

BACKGROUND: Day-night average sound level assesses the physical sound environment by taking into account both the sound levels and the number of noise producing events. The physical characteristics of sound such as the level, frequency components, and duration are measured with A-weighted sound level averaged on an energy basis over a stated period of time. This is referred to as equivalent continuous sound level (abbreviated as QL and symbolized as L_{eq}) and is defined as the constant level of sound during a specified time period that is equivalent to the same amount of sound energy as the actual time-varying sound signal. These two sounds of 'equal energy' both have the same average or equivalent sound levels.

Day-night average sound level is based upon equivalent continuous sound level and enhanced by an adjustment factor for nighttime noise disturbances. Results from community complaint surveys have indicated that the same noise environment may be considered by people as more annoying during the night time than during the day time. It is reasonable to assume that high level noises are more detectable inside the home, and consequently more annoying at night, due to a combination of lower exterior background noise levels, decreased activity inside the home, and raised expectations for rest and relaxation. In order to account for this presumed annoyance generated by intrusive noises, an adjustment factor of 10 decibels is applied (between 10 p.m. and 7 a.m.) to all nighttime noise levels. Essentially, this 10 decibel penalty characterizes the nighttime noise events as being noisier than actually measured. Day-night average sound level is calculated for 24 hours, but it can be computed for a longer time period such as a week or a year. It is recommended that the day-night average sound level be averaged over a yearly period in order to estimate the long term environmental impact. In such a case it is abbreviated as YDENL and symbolized as L_{dny}.

DENL is widely accepted as an effective environmental descriptor by many agencies at both the federal and state government level. It is recommended by the Environmental Protection Agency

as the primary measure for community noise exposure. The National Research Council Committee on Hearing, Bioacoustics and Biomechanics (CHABA) also favors DENL as one of the fundamental measures for assessing a noise environment potentially requiring an Environmental Impact Statement. The Department of Defense uses DENL in describing the noise exposure in the vicinity of military air bases; and it is one of the noise measures used by the Federal Aviation Administration (FAA) in describing the noise environment around airports. The Department of Housing and Urban Development (HUD) revised its noise policy regulations and recommended that DENL be used as the criterion measure to protect people in the community from excessive noise.

TITLE: COMMUNITY NOISE EQUIVALENT LEVEL

ABBREVIATION: CNEL

SYMBOL: L_{den}

UNIT: Decibel (dB)

GEOGRAPHICAL USAGE: State of California

DEFINITION: Community noise equivalent level is a 24-hour noise rating which is based upon A-weighted sound level. Two separate adjustment factors are added to the sound levels measured during the evening and the nighttime periods in an attempt to account for the assumed increased annoyance caused by noise during these hours.

PURPOSE: Community noise equivalent level is used to estimate community reaction to noise exposure resulting from aircraft operations. CNEL ratings for various locations in a community adjacent to an airport provide guidelines for making recommendations or to determine compatible land use development, and zoning regulations.

BACKGROUND: Community noise equivalent level like DENL seems to be an appropriate measure for land use compatibility planning because it takes into consideration the magnitude and the durations of the noise events as well as the frequency of occurrence. Like DENL it weights some time periods in the 24 hour day differently than others in an attempt to estimate peoples' annoyance to noise during the nighttime hours. A 5 decibel adjustment is added to the sound levels measured between the hours of 7 p.m. to 10 p.m. and a 10 decibel adjustment is added to the levels measured between 10 p.m. and 7 a.m.

CNEL can be calculated on a daily, weekly, or yearly basis. It is most often employed as an annual rating for purposes of assessing the impact of aircraft noise exposure. Given the necessary information, such as sound levels and number of events, CNEL contours can be drawn to establish a geographical reference for community noise exposure levels.

CNEL was introduced as one of the regulatory measures incorporated into the California Noise Standards. The regulation imposes a CNEL of 65 dB on noise from new airports and for military airports being converted to civilian use. The 65 CNEL limitation for existing civilian airports took effect on January 1, 1986.

An effort was made to related measured values of CNEL to observed community reactions by adding correction factors to measured CNEL to obtain what one report referred to as 'normalized' CNEL. This normalization procedure with some modifications is similar to the Rosenblith and Stevens method developed for Composite Noise Rating. However, normalized CNEL is rarely used to assess community reactions to certain levels and we recommend that only measured CNEL be used.

TITLE: NOISE AND NUMBER INDEX

ABBREVIATION: NNI

SYMBOL: L_{NNI}

UNIT: Decibel (dB)[28]

GEOGRAPHICAL USAGE: United Kingdom

DEFINITION: Noise and number index is based upon the average maximum perceived noise level for aircraft over-flights occurring within a time period.

PURPOSE: The noise and number index was developed as the appropriate measure to be used in Great Britain for assessing the effects of aircraft noise exposure on community reactions.

BACKGROUND: The Noise and Number Index was one of the outcomes of an extensive study concerning aircraft noise conducted in the vicinity of London's Heathrow Airport. This study combined physical measurements made of the noise exposure
at 85 locations within 10 miles of Heathrow with results from interviews of 2000 people living in this same area. The noise level measurements were reported in terms of a statistical distribution of level and time. The social survey questionnaire focused on peoples' reaction to their immediate living environment taking into consideration the influence of the airport as well as other sociological variables.

NNI was an attempt to describe the total noise exposure at a site, and it used as its basic metric peak perceived noise level. Consequently, there is neither an allowance for the duration of the individual aircraft events nor for pure tones which conceivably could be present in jet aircraft flyovers.

According to Schultz the concept of background noise is implicitly included in NNI by the stipulation that the adjustment for the number of aircraft events be the "number of aircraft flyovers heard" during the specified time period. However, typically only those aircraft with $L_{PN} > 80$ which occur within a time period are considered.

In determining the effect of the number of flyovers, it was estimated that doubling the number of events was equivalent to increasing the noise level by 4.5 dB. Therefore, the factor of 15 was used in the term $15 \log_{10} N$ to adjust for the number of events. The constant 80 is subtracted because it was concluded in the original survey that there was zero annoyance response when the aircraft noise levels were less than 80 dB (PNdB). In fact, in the Heathrow study the lowest aircraft level considered was 84 dB (PNdB).

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[28] It has been suggested that the unit should be PNdB because the primary metric in NNI is perceived noise level. However, like PNL, it was decided that the unit would be the decibel.

The analyses of the social survey resulted in the identification of 58 socio-psychological variables which in turn were used to develop a scale representing
a continuous measure of annoyance. The noise measurements initially defined 14 parameters which were later reduced to two factors: average peak (maximum) noise level and number of aircraft heard in the day or nighttime periods. In a final step, the annoyance scale and the two physical correlates were combined in an attempt to predict the effect of aircraft noise and frequency operations on people's annoyance reactions.

Additional results from the social survey were further analyzed and correlated with the noise and number index to determine people's reactions to aircraft noise in comparison with their reactions to other sources of dissatisfaction in their living environment. These results were analyzed in an attempt to estimate the point at which the noise exposure became unreasonable.

TITLE: WEIGHTED EQUIVALENT CONTINUOUS PERCEIVED NOISE LEVEL

ABBREVIATION: WECPNL

SYMBOL: L_{WECPN}

UNIT: Decibel (dB)

GEOGRAPHICAL USAGE: International

DEFINITION: Weighted equivalent continuous perceived noise level is a cumulative rating scheme which is based upon effective perceived noise level (EPNL). The adjustments incorporated into this measure account for some of the variables associated with aircraft noise such as discrete tonal frequencies, as well as time of day and season of the year.

PURPOSE: Weighted equivalent continuous perceived noise level was developed to assess the total noise exposure from aircraft noise. It is not often used in the United States and is not as widely accepted as the noise exposure forecast (NEF) measure. The principal use is in ICAO analyses.

BACKGROUND: In a 1969 winter meeting of the International Civil Aviation Organization (ICAO), several seminars were held concerning aircraft noise. One of the agreements reached at this meeting was the adoption of ICAO reference units for total noise exposure from aircraft noise. This measure was designed to take into consideration the number of aircraft events, the occurrence of the events during the day or night periods, and the effect of the time of the year.

Like the noise exposure forecast rating (NEF), weighted continuous equivalent perceived noise level (WECPNL) was based upon the effective perceived noise level (EPNL) of each flyover. The EPNL value for each event was summed together on an energy basis and then normalized to l0 sec. to achieve a 'total noise exposure level' (TNEL). The various TNELs could then be converted to 'equivalent continuous perceived noise level' (ECPNL) for different noise exposure time periods. This conversion was necessary to achieve the 'weighted equivalent continuous perceived noise level' which used ECPNL for different periods in a 24-hour day.

The aircraft levels measured in the evening or night hours were 'corrected' or penalized in the sense that 5 or l0 dB was added to the ECPNL. The rational for this adjustment was that aircraft flyovers heard at night are judged more annoying than the same flyovers heard during the day. If WECPNL was calculated on the basis of a two period 24 hour day, there was a 10 dB adjustment for the levels during the night period (2200 to 0700). WECPNL could also be calculated for a three period day. In this case there was a 5 dB correction for the evening hours (1900 to 2200) and a l0 dB correction for the nighttime hours (2200 to 0700).

WECPNL also included what was termed a seasonal correction. This was an adjustment for the noise reduction achieved inside the home assuming the windows were closed during the winter, as opposed to open. (Hopefully this window condition corresponds to the correct season of the

year.) Thus, if WECPNL was computed for the months during the summer, there would be a 5 dB added adjustment.

TITLE: ARTICULATION INDEX

ABBREVIATION: AI

UNIT: None

GEOGRAPHICAL USAGE: United States

DEFINITION: Articulation index is a calculated measure which weights the difference between the speech signal and the background masking noise in an effort to estimate the proportion of normal speech signal that is available to a listener for communication purposes. The results for AI range from 0 to 1.O where 1.0 is equated with lO0-percent speech intelligibility.

PURPOSE: Articulation index can be used to estimate how much the background noise found in an environment or communication system will interfere with speech communication as measured by speech intelligibility tests.

BACKGROUND: The articulation index was initially conceived by French and Steinberg and later modified by K. Kryter. In turn, Kryter's version of AI is the basis of the American National Standard (ANSI) which provides a detailed account of the computational procedures for AI. Conceptually, the AI calculation method is relatively straight forward. However, as a practical matter it is difficult for the ordinary person to interpret in order to evaluate an environment where speech communication would take place.

AI is based upon determining how much of the speech spectrum is masked by the background noise present during normal intercourse between a talker and listener. In order to make this determination the frequency range of the speech spectrum is divided into bands (in the range of approximately 200 to 7000 Hz). Then the difference between the average speech level in these bands and the average noise level in the comparable bands for the background noise is computed. These differences first are weighted and then combined to yield a single index number which can be compared to an estimated amount of speech intelligibility present for a specified environment of interest.

Historically, there are two methods for computing AI. The original procedure advocated by French and Steinberg examines the speech to noise ratio in 20 contiguous frequency bands (frequency range of 200-6100 Hz) which for equal signal to noise ratios contribute equally to intelligibility. The second method analyzes the speech to noise ratio for octave or third octave bands and applies various weighting factors to account for the relative contribution of each band to speech intelligibility.

It is interesting to note several caveats that should be considered when using AI. It is not advisable to use AI as a measure for estimating the effectiveness of a communication system or environment where female talkers or children are involved because AI was based upon, and has been principally validated against, intelligibility tests using male talkers and trained listeners.

This should be a consideration when interpreting AI results for those situations where female talkers or children are present such as typical home or work environments.

Further, while AI is an adequate predictor of speech intelligibility in a steady-state ambient background, it is not effective in predicting the intelligibility of speech in the presence of fluctuating noise levels. However, the Standard does list some provisions for determining the effect of noise having a definite off-on duty cycle. Caution should be exercised in situations where there might be reduced speech intelligibility due to reverberant room acoustics, varying vocal effort of the speaker, or multiple transmission paths.

TITLE: SPEECH INTERFERENCE LEVEL

ABBREVIATION: SIL

SYMBOL: L_{SI}

UNIT: Decibel (dB)

GEOGRAPHICAL USAGE: International

DEFINITION: Speech interference level is the arithmetic average of the sound pressure levels in the four octave bands centered at the frequencies 500, 1000, 2000, and 4000 Hz of the interfering noise in question.

PURPOSE: Speech interference level is a useful measure for determining the necessary vocal effort for face-to face communication. This measure has also been recommended as a means for estimating speech intelligibility in an environment with various background noises by rank ordering the noises according to their speech interference level.

BACKGROUND: Speech interference level appears to be a compromise between simple A-weighted sound level and the more complicated calculation procedure Articulation Index (AI) in predicting the speech masking ability of a large variety of background noises. SIL was initially developed by Beranek in 1947 in an effort to formulate a simplified method of estimating the quality of speech communication for aircraft passengers. This method provided an approximation of the general masking quality of the background noise. However, unlike A-weighted sound level, SIL ignored the contributions of the low and high frequencies in the noise spectrum in terms of their potential speech interference effect.

When SIL was first introduced, it was defined as the arithmetic average of the sound pressure levels in the octave bands identified as 600-1200, 1200-2400, and 2400-4800 Hz. Later new preferred octave band designations, referred to as the preferred speech interference level (PSIL), replaced the old octave band method and was calculated from the average sound pressure level in three preferred octave bands centered at 500, 1000, and 2000 Hz.

The ANSI standard advocates four octave bands (referred to as the 4-Band Method) centered at 500, 1000, 2000, and 4000 Hz as the best method of estimating the masking capability of the background noise.

In order to distinguish among the many different versions for calculating SIL, a precise nomenclature was developed. For example, if the old octave band method is used then the SIL is identified by the abbreviation SIL (0.85, 1.7, 3.4). In turn, the preferred speech interference level method includes the notation SIL (0.5, 1, 2, 4). It is recommended that this type of notation be used if there is an opportunity for confusion as to which octave bands were used to compute SIL.

The ANSI standard ($3.14-1977, refers to two applications of SIL. The obvious situation to apply SIL is in determining the quality of face-to-face communication. The parameters to

consider include speech interference level as well as talker-to-listener distance and voice level required for "Just reliable communication". The ANSI standard defines "Just reliable communication" as a 70-percent speech intelligibility score for monosyllabic words.

Intuitively one can conclude that, for most environmental conditions, as the distance between the speaker and listener increase, the voice level necessary for just reliable communication must also increase. The information summarized here was developed by Webster for voice levels measured outdoors. The four voice levels are identified as normal, raised, very loud, and shout. There is approximately a 6 decibel difference in level between each category of voice level.

It must be noted that the relationships are only approximations of speech efforts. Other variables such as familiarity with speech material, the listener's interest in hearing the talker, visual cues, and the noise characteristics in the environment, among others, all influence the speech levels necessary for just reliable communication. SIL is not an adequate predictor of speech intelligibility if the background noise is not steady state or it contains discrete frequency components.

The ANSI standard also recommended using SIL as a method to rank order potentially interfering noises for the purpose of determining speech intelligibility. The application of this concept is based upon the rationale that noises with the same SIL reduce speech intelligibility by approximately the same amount. Thus two noises with the same SIL result will yield approximately the same speech intelligibility factor.

The ANSI standard formulated a rough guide for deriving which noises are potentially more interfering to speech intelligibility. If the SIL results for one of two noises is 5 dB or greater than the other noise, then it is assumed that the first noise is probably more destructive of speech intelligibility. Conversely, if the two noises differ by less than 5 decibels in their SIL results, then both noises are assumed to be equally disruptive of speech intelligibility.

TITLE: PSYCHACOUSTIC LOUDNESS (TIME VARYING LOUDNESS)

ABBREVIATION: N

SYMBOL: L_N

UNIT: Phon/sone

GEOGRAPHICAL USAGE: International

DEFINITION: The psychoacoustic loudness models the loudness sensation of any sound, which is above hearing threshold. It considers basic human signal processing effects like spectral sensitivity (level dependent frequency weighting), masking (post- and simultaneous), critical bands and nonlinearities.
Loudness calculation begins with the decision for free or diffuse sound field. This is followed by filtering through a bank of band-pass filters, which in turn is followed by rectifying and low-pass filtering (envelope formation). The next two steps consist of a frequency-dependent weighting gk and a nonlinear transform from sound pressure or intensity to specific loudness. For time-variant sounds the non-linear decay of the human hearing system is modeled. Furthermore, effects of the temporal summation and post-masking are taken into account. At the end, the total loudness is calculated by summing the specific loudness values. The low-pass filter at the end simulates that signals with a duration of 10 ms are perceived approximately as half as loud as signals with a duration of about 100 ms. Recent loudness procedures differ mainly in the implementation of the filter bank and in the frequency-dependent weighting . Whereas the DIN 45631 algorithm uses 24 filters with a constant bandwidth on the Bark scale (according to Zwicker's loudness method, approximated by 28 3rd octave filters), the ANSI S3.4-2007 algorithm implements a loudness method based on Moore using approximately 40 filters with a constant band-width on the ERB scale. Additionally, the filter shapes are different. The DIN 45631/A1 algorithm employs very steep 3rd octave filters of 6th order and considers the spread of excitation into the neighboring bands by adding to the specific loudness, in each critical band, a slope towards higher frequencies. The resulting specific loudness is the maximum of the specific loudness calculated from the 3rd octave levels and the value achieved by these slope functions.

PURPOSE: The psychoacoustic loudness was introduced as a measure describing and quantifying loudness sensation in detail.

BACKGROUND: Due to limitations of sound pressure level indicators, which do not include human hearing mechanisms in detail like masking, nonlinearity or temporal effects, the psychoacoustic measure loudness was developed. This measure is based on the knowledge about the human processing of sound gained by psychophysical experiments. Early work from Stevens as well as Zwicker, Fastl or Moore investigations contributed to the development of the

psychoacoustic parameter loudness. First, standards with respect to loudness of stationary sounds were available like DIN 45631(1967, 1991) or ISO 532 (1975). However, in the real world most sounds are time-variant instead of time-invariant. According to the DIN 45631/A1 a sound can be interpreted as stationary when the quotient of the percentile loudness N_5 and the percentile loudness N_{95} does not exceed 1.10. The German Standard DIN 45631/A1 allows for the computation of time varying loudness. The new ISO 532 standard includes the computation of time varying loudness as well. Both standards are applicable to arbitrary sounds and yields the same loudness values for stationary noises as stationary loudness standards. According to these standards, due to the fact that the statistical mean of time-variant loudness over time leads, in general, to results that are too low in comparison to the evaluated loudness, the percentile loudness N_5 should be used when stating the overall loudness perceived.

Frequency and Amplitude Weighted Metrics

TITLE: PSYCHACOUSTIC SHARPNESS

ABBREVIATION: S

SYMBOL: S

UNIT: Acum

GEOGRAPHICAL USAGE: International

DEFINITION: The sharpness calculation is based on loudness calculation. For it, the relationship between the loudness of high frequency components to the total loudness is determined. The sharpness parameter expresses the perceived spectral balance of a sound. More high-frequency content raises the sharpness impression.

PURPOSE: The sharpness parameter describes the perception of the spectral centre of a signal with emphasis on high frequencies. It is usually observed that sensory pleasantness decreases with increasing sharpness.

BACKGROUND:
The calculation of the psychoacoustic parameter sharpness is defined in the German standard DIN 45692. Besides the German standard other methods and procedures for sharpness calculation are available, such as according to Aures or Bismarck. The DIN 45692 standard and Bismarck calculation method produces very similar sharpness results, which are only linked to the spectral shape (specific loudnesses respectively). Unlike these methods the sharpness calculation according to Aures method rises in value for a constant spectral shape as loudness rise. This parameter proved to be helpful in explaining noise annoyance differences for sounds with comparable loudness or sound pressure level values.