Global Journal of Medical Research: F
Diseases
Volume 20 Issue 12 Version 1.0 Year 2020
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4618 & Print ISSN: 0975-5888

A Critical Review of Global Aircraft Noise Metrics and their Applications

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GJMR-F Classification: NLMC Code: W 84

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Strictly as per the compliance and regulations of:

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OF Orikpete [α], TG Leton [σ] & O.L.Y. Momoh [ρ]

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Keywords: heliport, noise metrics, aircraft noise, equivalent continuous sound level.

I. Introduction

Noise is any sound perceived to be loud or unpleasant by the ear through any medium. It is a health hazard that causes discomfort, stress, lack of concentration, reduction in performance, and in extreme cases, loss of hearing. People get exposed to harmful noise levels through the use of machines, equipment at workplaces, and social gatherings, hence the need to evaluate noise and identify areas where people are prone to be exposed to harmful levels of noise to protect their health and safety.

An aircraft noise metric refers to the unit or quantity that quantitatively measures the effect of aircraft noise on the environment. Various aircraft noise metrics that are used to measure aircraft noise have evolved globally. These noise metrics were developed to capture different aspects of aircraft noise over time, and to understand the effects of aircraft noise on community residents living close to airports or heliports. Some of these noise metrics are simple but do not include subjective factors in their analysis; others that capture both the objective and subjective aspects of aircraft noise effects are complex and difficult to interpret. In selecting a noise metric to use for the measurement of aircraft noise, it is necessary to strike a balance between precision and simplicity. Selecting a metric for assessing aircraft noise is no simple task because it must reflect the impact on people and must be easy to understand. There is no single aircraft noise metric that can describe all responses in all situations. However, nowadays, the most used noise exposure measure for all sources is the L_{eq} and, for aircraft noise, this is in widespread use around the world. It is the aim of this paper to provide a critical review of the various noise metrics that are currently in use globally in the evaluation of aircraft noise and the associated effects.

II. Theoretical Framework

a) Noise Metrics: what are they?

Noise metrics are an attempt to emulate the way humans respond to sound (Lamancusa, 2000). Most sounds that occur in the environment are not constant, but their sound level varies over time. To characterize the magnitude of such sounds, various descriptors, or metrics, have been developed. In other words, noise metrics are the units or quantities that measure the effect of noise on the environment, and they fall into two groups (Plotkin et al., 2011). (Murphy and King, 2014)further, expatiate that noise metrics are used to reduce large volumes of information about a noise situation into a single number system. They further explained that noise metrics were designed to make acoustic information easier to handle while still providing accurate results about the noise environment. All noise metrics are used to help quantify various aspects of noise and depending on the type of noise and relevant legislation in a country, noise metrics can take many different forms. While they are all based on the decibel scale, there is no agreement on a single best measure (Lamancusa, 2000).Some noise metrics are used to describe a single flight phase, such as take-off or landing, while others describe the combined effect of the various phases of flight within a specified time. Both types of noise metrics help in understanding how people tend to respond to a given noise condition.

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Noise metrics are basically of two types: single event metrics and cumulative noise metrics.

Single event metrics describe the noise impact of a single aircraft movement or over-flight in terms of its intrusiveness, loudness, or noisiness. They quantify the impact of an event, and the duration and time are also considered. There are four single event metrics, which include: maximum sound level (L_{max}), Sound Exposure Level (*SEL*), Single Event Noise Equivalent Level (*SENEL*), and Effective Perceived Noise Level (*EPNL*).

Cumulative noise metrics refer to metrics that quantify the noise impact from multiple aircraft movements during a given time frame. They quantify noise over an extended period and cover several events. There are nineteen cumulative event metrics. Examples include Equivalent Sound Level (L_{eq}), Percentile Noise Levels or Statistical metrics (L_{10}, L_{50}, L_{90}), Time-Above a Specified Level (*TA*), Day-Night Average Sound Level (L_{dn}), Day-Evening-Night Average Sound Level (L_{den}), Noise and Number Index (*NNI*), Weighted Equivalent Continuous Perceived Noise Level (*WECPNL*), Community Equivalent Sound Level (*CNEL*), Composite Noise Rating (*CNR*), etc.

To adequately describe noise on a broadband spectrum, several metrics have been used. These metrics or descriptors have various areas of application. Some of the metrics mentioned below were adapted from (Page et al., 2015) and (Plotkin et al., 2011); however, it is important to state categorically that from a scientific point of view, the best noise metric to employ is the one that performs best in predicting the effect of interest (WHO, 2018). A single global noise metric that would capture all the factors influencing people's perception of aircraft noise and produce a definitive measure of annoyance is highly desirable, but such does not exist.

i. *Equivalent Sound level (L_{eq})*

Equivalent Sound Level (L_{eq}) is a measure of the exposure resulting from the accumulation of A-weighted sound levels over a period of interest, which could be an hour, 8-hour, night-time, or 24 hours. It is defined as the hypothetical steady sound, which contains the same energy as the actual variable sound, over a defined measurement period, T (Figure 1). It is important to state the applicable period because the length of the period can be different depending on the time frame of interest. L_{eq} is the most used noise metric for all types of noise sources, and for aircraft noise, its use is widespread across the world. It is the metric used in Germany, the United Kingdom, Nigeria, and the International Organization for Standardization (ISO) for measuring aircraft noise (Airbus, 2003). Conceptually, L_{eq} may be thought of as a constant sound level throughout the period of interest that contains as much sound energy as the actual time-varying sound level with its normal crests and troughs. It is an energy-based indicator as it represents the total amount of acoustic energy over the specified period. The equation for computing L_{eq} is presented as shown in Eq1 as:

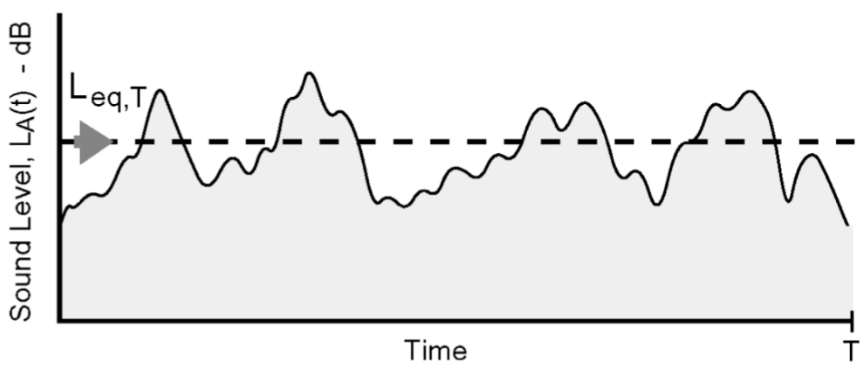
$$L_{eq} = 10\log_{10}\left[\frac{1}{T}\sum_{i=1}^{n}10^{(0.1L_i)}\right] \quad (1)$$

Assuming the reference pressure = 20 μPa

Where:

L_i = A - weighted pressure (dB)

T = time (seconds)



Source: (Jones and Cadoux, 2009)

Figure 1: Graphical illustration of L_{eq}

Note that the average sound level suggested by L_{eq} is not an arithmetic mean but a logarithmic or energy-averaged sound level. L_{eq} can be measured or calculated in a variety of ways. The total noise exposure is determined if the meter runs continuously during the measurement period. If we want to monitor only the contribution of aircraft noise to the total, as aircraft events are discontinuous, the meter can be programmed to read only when aircraft noise is controlling the overall sound level. When individual aircraft noise levels are higher than those due to other sources, this is often readily accomplished with automatic noise monitoring systems by choosing a suitable threshold level to trigger the integration (Jones and Cadoux, 2009).

ii. *Maximum Noise Level (L_{max})*

The most basic measure of a noise event, such as the over-flight of an aircraft is the maximum sound level recorded (Jones and Cadoux, 2009). L_{max} represents the highest noise level measured during a single event in which the sound changes with time (Murphy and King, 2014). For instance, during an aircraft over flight, the noise level starts at the ambient or background noise level, rises to the maximum level as the aircraft flies closest to the observer, and returns to the background level as the aircraft recedes into the distance (Wyle, 2008). So, L_{max} depicts the highest noise level reached during a flyover. L_{max} is important in judging if a noise event will affect the conversation, watching television or listening to the radio and other routine activities. L_{max} is frequently used in noise disturbance research as it has been found to correlate well with levels of both sleep disturbance and reading and speech interference for school children. However, L_{max} is not able to reflect the number of or frequency with which very noisy events occur. The disadvantage of L_{max} is that it describes only one dimension of an event and provides no information on the cumulative noise exposure generated by a noise source. Although it gives some measure of the intrusiveness of the event, it does not entirely describe the total event because it does not take into consideration the period that the sound is heard (Wyle, 2008). To further emphasize, two events with identical L_{max} may produce very different total exposures with one having a very short duration and the other may be much longer.

iii. *Peak Noise Level (L_{peak})*

The peak sound pressure level is the highest instantaneous level obtained by a sound level measurement device. The peak sound pressure level usually measured using 20 microseconds or faster sampling rate and is usually based on unweighted or linear response of the meter (Wyle, 2008). It is the highest C-weighted sound level measured during a single event with no time constant applied. It is used for the assessment of impulsive noise (Murphy and King, 2014).

iv. *Single Exposure Level(SEL)*

The most common measure of noise exposure for a single aircraft flyover is the *SEL*. *SEL* is a normalized value of L_{eq}; the period considered being one second. This *SEL* value represents the A-weighted sound level, which, when produced during one second, would result in the same L_{eq}. This allows us to get rid of the influence of the measurement period and compare events of different durations. It is also expressed in dB(A) (Airbus, 2003). (Murphy and King, 2014)further clarified that the *SEL* of a noise event is the constant level, which if maintained for only one second, would contain the same A-weighted noise energy as the actual event itself. In other words, *SEL* is essentially an A-weighted L_{eq} level normalized to one second. Since SEL is normalized to one second, it will almost always be bigger in magnitude than the L_{max} for the same event. For most aircraft events, the SEL is about 7 to 12 dB higher than the L_{max}. *SEL* is used in aircraft noise assessments allowing for an easy comparison of different types of aircraft(Murphy and King, 2014).Since SEL combines an event's overall sound level along with its duration, SEL provides a comprehensive way to describe noise events for use in modelling and comparing noise environments. Although the SEL noise metric attempts to capture the total noise energy, it is difficult to accurately account for differences in background noise. It is also complex and difficult for communities to understand. The main disadvantage of SEL is that, for events lasting more than one second, it provides a measure of the net impact of the entire acoustic event. Still, it does not directly represent the sound level heard at any given time.

v. *Single Event Noise Exposure Level (SENEL)*

SENEL is a very slight variation on *SEL*. Just like *SEL*, it is the one-second-long steady-state level that contains the same amount of energy as the actual time-varying level. However, unlike *SEL*, it is calculated only over the period when the level exceeds a selected threshold. *SENEL* is derived from *SEL* in the way that only transient sounds exceeding a certain level are accounted for [typically 65 dB(A)] (Airbus, 2003).

vi. *Percentile Noise Levels or Statistical Sound Levels (L_{10}, L_{50}, L_{90})*

Sometimes, it may be preferable to represent noise levels with statistical indicators, and these give the noise level exceeded for a certain percentage of the measurement time. This metric is commonly used for traffic noise measurement. The most common are L_{10} (which represents the noise level exceeded for 10% of the time, L_{50}(which stands for the noise level exceeded 50% of the time, and L_{90} (which stands for the noise level exceeded 90% of the time) (Murphy and King, 2014). L_{90} is a good measure of background noise; L_{50} is the median noise, which is not necessarily the same thing as L_{eq}(the mean); L_{10} is a good measure of intermittent or intrusive noises, such as traffic, aircraft flyovers, barking dogs, etc. (Lamancusa, 2000).

vii. *Noise Pollution Level (NPL)*

Noise pollution level can be determined using Eq. 2 found in (Peirce, Weiner, and Vesilind, 1998), and also cited in (Nwaogozie and Owate, 2000)

$$NPL\ [dB(A)] = L_{50} + (L_{10} - L_{90}) + \frac{(L_{10} - L_{90})^2}{60} \quad (2)$$

Where:
L_{10} = Noise level at 10% time exceeded
L_{50} = Noise level exceeded 50% of the time
L_{90} = Noise level exceeded 90% of the time

The NPL may also be determined using Eq. 3 as:

$$NPL = L_{eq} + K\sigma \quad (3)$$

Where:
K = Constant with a value of 2.56
σ = the standard deviation of the computed L_{eq} values

viii. *Noise Criteria (NC) Curves*

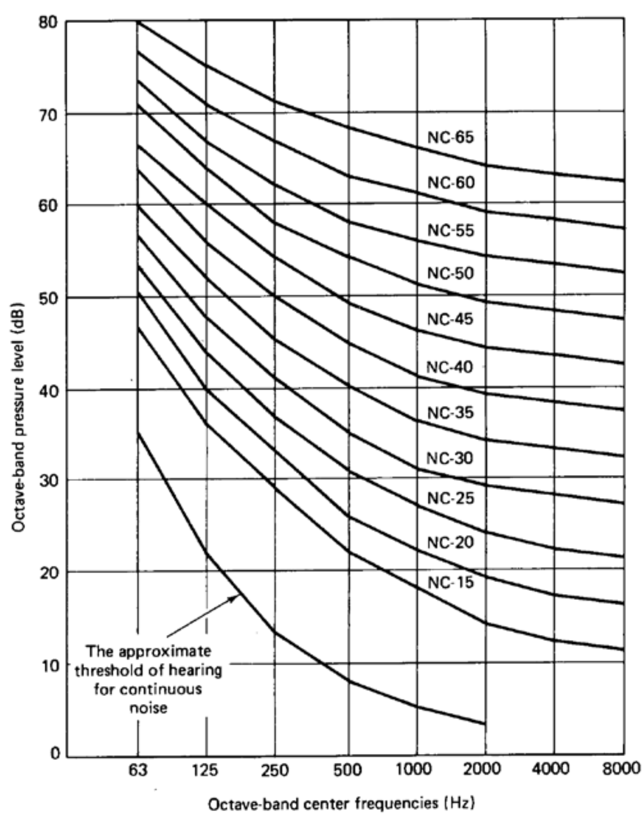
Noise levels below 80 dB are considered safe from a hearing loss perspective. However, they can still be highly annoying and interfere with the smooth performance of occupational tasks or other activities. Noise criterion curves were established in 1957 in the USA and are used to rate the background levels in buildings and rooms, for example, noise from air-conditioning equipment. For a given noise spectrum, the *NC* rating may be obtained by plotting its octave band levels on the set of *NC* curves (shown in Figure 2 below). The noise spectrum is specified as having an *NC*rating the same as the lowest *NC* curve, which is not exceeded by the spectrum(Lamancusa, 2000).

Table 1

Centre Frequency (Hz)	62.5	125	250	500	1000	2000	4000	8000
Band Pressure Level (dB)	41	45	48	50	46	42	40	38

Source: (Eargle, 1994)

For example, a sound having the following octave-band noise (Table 1) is rated as NC-46 since when plotted in Figure 2, it exceeds the NC-45 curve by 1 dB at 500 Hz. The recommended Noise Criteria range for urban residence is 25-35 NC (ASHRAE, 1996).

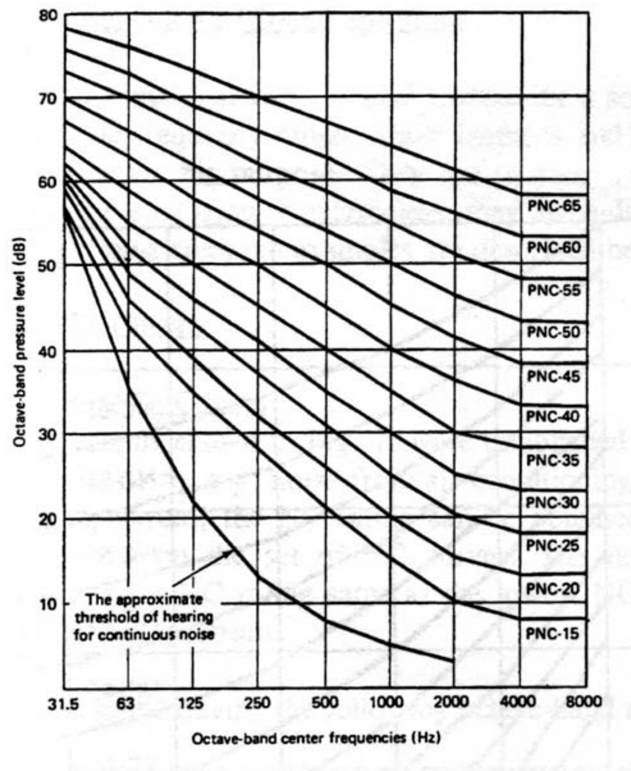


Source: (Robinson and Dadson, 1956)

Figure 2: Noise Criterion (*NC*) curves

ix. *Preferred Noise Criteria (PNC) Curves*

The *PNC* curves were introduced in 1971 as a modification on the *NC* curves in response to criticism that in offices designed to *NC* curves, the air-conditioning noise was too rumbly (low-frequency sound) and hissy (high-frequency sound). The curves are shown in Figure 3 below. In the previous example given earlier, the noise spectrum will have a rating of PNC-47 as it exceeds the PNC-45 curve by about 2 dB at 4 kHz. The recommended Preferred Noise Criteria (PNC) range for living quarters is 20-30 PNC (ASHRAE, 1996).

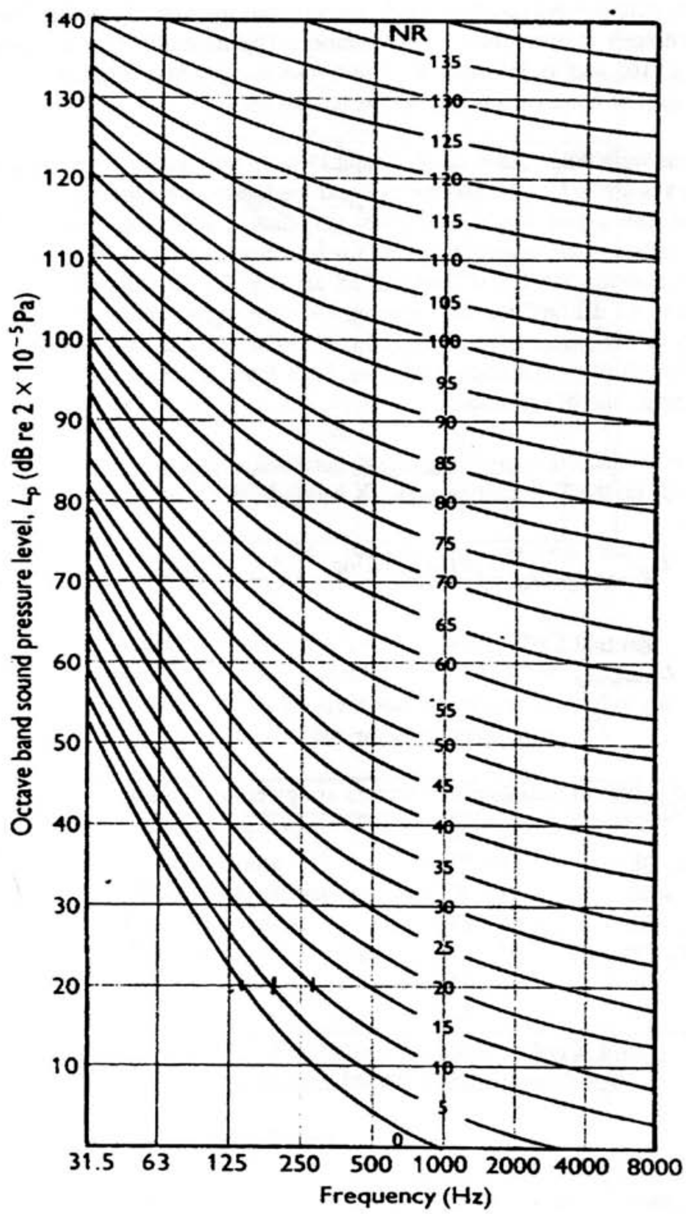


Source: (Beranek, Blazier, and Figwer, 1971)

Figure 3: Preferred Noise Criterion (PNC) curves

x. *Noise Rating (NR) Curves*

These curves were developed in Europe to assess community noise complaints. They are shown in Figure 4. Their use is like that for the *NC* and *PNC* curves.



Source: *(Schultz, 1982)*

Figure 4: Noise Rating (NR) Curves

xi. *The Articulation Index (AI)*

(French and Steinberg, 1947) developed the Articulation Index (AI) noise metric. The basic concept of AI is that speed intelligibility is proportional to the average difference in dB between the masking level of noise and the long-term root mean squared dB level (plus 12 dB) of the speech signal. Twenty relatively narrow frequency bands are used, corresponding to the critical bandwidth of the ear. This method determines a masking spectrum of a noise that may be different from the noise spectrum due to the spread of masking. It considers background noise, masking, and non-flat noise spectra. The disadvantage of the AI noise metric is that the calculation of AI is relatively complicated. It is not well suited for highly reverberant environments or when the speech is distorted, such as by mumbling or poor-quality amplification.

xii. *Speech Interference Level (SIL)*

Speech interference level (*SIL*) is a metric that estimate show much a given noise spectrum will disrupt, or interfere with, effective speech communication. *SIL* is evaluated using different formulae depending on the industry. All the various forms of *SIL* are computed by taking the arithmetic mean of un-weighted, full-octave band sound pressure levels, as expressed in decibels (dB). The only difference between the various forms of *SIL* is the octave bands included in the calculation. The various forms are: Preferred Speech Interference Level

(*PSIL*) used by the Acoustical Society of America, *SIL* used by the aviation industry, and *ANSI SIL* used by the American National Standards Institute (ANSI). According to (Lamancusa, 2000), some industries, especially the aviation industry, prefer to use the 1 000, 2 000, and 4 000 Hz bands to calculate *SIL*.

$$PSIL = \frac{L_{500} + L_{1000} + L_{2000}}{3} \tag{4}$$

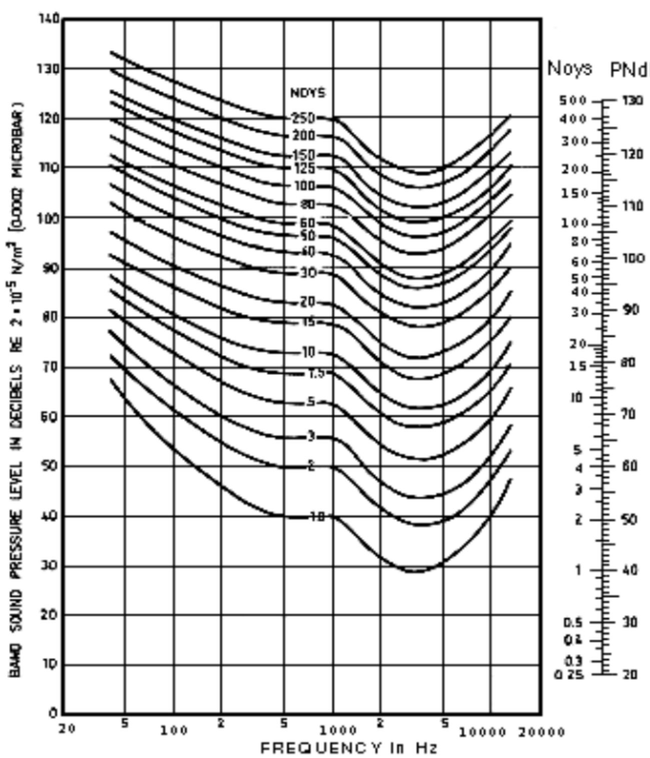
$$SIL = \frac{L_{1000} + L_{2000} + L_{4000}}{3} \tag{5}$$

$$ANSI\ SIL = \frac{L_{500} + L_{1000} + L_{2000} + L_{4000}}{4} \tag{6}$$

xiii. *Perceived Noise level (PNL)*

Different types of aircraft, such as jets, propeller-driven aircraft, and helicopters, all have distinctive noise characteristics due to combinations of sound from various sources having different frequency ranges, intensities, and time histories. The annoyance perceived by an observer as an aircraft type flies over is described by its noisiness. Perceived noisiness may be defined as a measure of how unwanted, objectionable, disturbing, or unpleasant the sound is. The PNL scale allows for different human sensitivity to different frequencies, but it is more complicated (Jones and Cadoux, 2009). *PNL* has been adopted as the best descriptor of aircraft noise nuisance, according to (Airbus, 2003). *PNL* is determined by a combination of measurement and mathematical calculation, involving spectra analysis. To determine *PNL*, it is measured with a sound level meter equipped with electronic one-third octave filters. Each frequency band level in the spectrum is converted to a noisiness value, and these are summed specially to obtain the total noisiness of the sound (Jones and Cadoux, 2009). It is used in rating the noisiness of sounds, and it is evaluated in three steps.

Step 1: The measured one-third octave band sound pressure level in the range 50 - 1 000 Hz that occurs in each instant of time is converted to perceived noisiness (noy) using the noy chart in Figure 5.



Source: (Sincero and Sincero, 1996)

Figure 5: Chart showing the noy scale

Step 2: The perceived noisiness values gotten from step I is then combined using Eq. 7

$$N_t = 0.15 \sum N_i + 0.85 N_{max} \tag{7}$$

Where:

N_i = the noy value corresponding to each frequency band and sound pressure level.

N_{max} = the maximum noy value obtained in the conversion of the octave band data to noy.

Step 3: The effective noy value (N_t) is finally converted to Perceived Noise Level (*PNL*) using the Eq 8

$$PNL = 40 + \frac{10\log_{10} N_t}{\log_{10} 2} \quad (8)$$

The unit of *PNL* is PNdB (Perceived Noise Decibel).

xiv. *Noise and Number Index (NNI)*

The noise and number index attempt to measure the subjective noisiness of an aircraft. It uses the PNdB as a basis and considers the number of aircraft per day (or night) as a primary annoyance factor. NNI represents a composite level measure of exposure to aircraft noise, considering the average event noise level and the number of aircraft in a specific period (0700-1900 hours).Mathematically, it is expressed as:

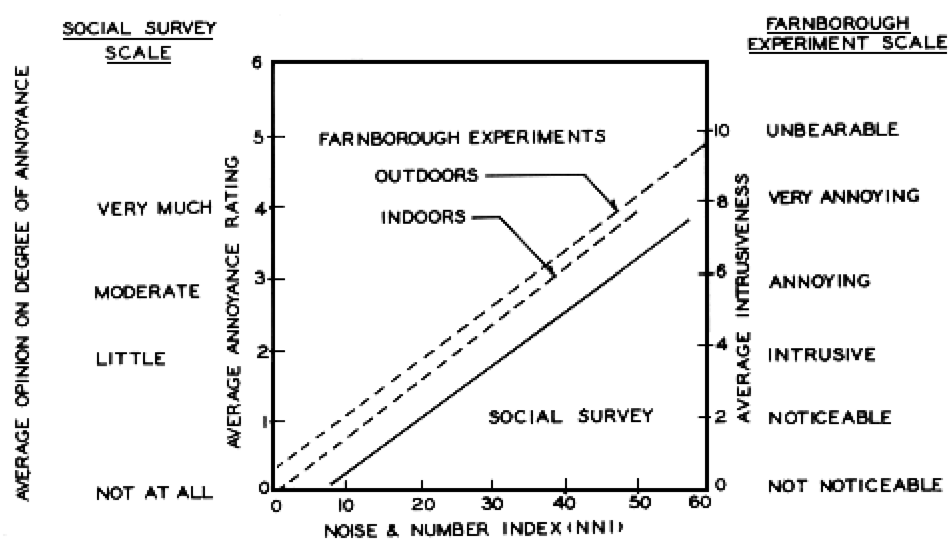
$$\mathrm{NNI} = (\text{Average Peak PNdB}) + 15\log_{10}\mathrm{N} - 80 \quad (9)$$

Where:
N = Number of flights
PNdB = Average peak PNdB is the logarithmic average of the highest levels of all over-flights.
80 = Normalized constant.

This considers the results of social surveys that showed that the annoyance factor was zero at 80 PNdB.

NNI was propounded using social surveys and noise measurements. Social surveys measured, amongst other things, the annoyance from aircraft noise expressed by a sample of individuals living at different places around Heathrow airport. Noise data were then matched to this reported disturbance, measured by scales constructed from the social survey data (Jones and Cadoux, 2009). According to (Airbus, 2003), the *NNI* scale (Fig 6) was first proposed by the Wilson Committee on noise in Britain. It spans from 0 – 60, and based on social surveys, the Wilson committee assigned values of annoyance to the index with the committee agreeing that an unreasonably high level of aircraft noise is attained between 50 - 60. An NNI of 55 was used to indicate a high annoyance area, and NNI = 35 was used to indicate the threshold of community annoyance(Jones and Cadoux, 2009).

The main criticisms of NNI were that it was out of date; that people's reactions and the change in attitudes to aircraft traffic and noise invalidated its use. It was also considered to be out of line with the metrics used by other countries and therefore was not standardized. The weighting was not considered to be sufficient for the number of aircraft. The noise level and number are not the arithmetic mean from all aircraft, including all aircraft in this count would constitute a better match with annoyance. A final disadvantage of the *NNI* was that the exclusion of night movements led to an under-estimation of disturbance, which eventually led to a change from *NNI* to L_{eq} as the metric for monitoring aircraft noise exposure for airports in the United Kingdom in 1990 (Jones and Cadoux, 2009).



Source:(Airbus, 2003)

Figure 6: Chart showing the *NNI*

xv. *Tone-Corrected Perceived Noise Level (PNLT)*

When some pure sounds are in the frequency spectra, the annoyance appears to be higher. The sound pressure level obtained by adding a tone correction to the perceived noise level is the *PNLT* and was developed for aircraft noise. It is evaluated from octave or one-third octave spectra. Each individual spectrum is examined using a specified process for the presence of tones, identified by spikes, for which a tone-correction is evaluated. This is a penalty added to the PNL calculated for that individual spectrum to give the so-called tone-corrected perceived noise level or PNLT (Jones and Cadoux, 2009). Mathematically, it may be represented as:

$$PNLT = PNL + C \quad (10)$$

C is a tone correction factor calculated for each spectrum to account for the subjective response to the maximum tone (Airbus, 2003).

xvi. *Effective Perceived Noise level (EPNL)*

The noise made by an aircraft flying over is complicated by its motion, which causes its intensity and frequency composition to change with time. Much research into human perception of aircraft noise led to the conclusion that *PNL* did not adequately reflect the true noisiness of a complete aircraft event unless the effects of both tones and duration are considered (Jones and Cadoux, 2009). *EPNL* is commonly used when assessing aircraft noise, and it is vital to note that this metric is used for noise certification of all commercial subsonic jet aircraft and also propeller-driven airplanes (Airbus, 2003; Murphy and King, 2014). It is a metric that considers the duration of the noise event based on a tone corrected perceived noise level time history. In order to determine *EPNL*, the complete set of ½-second *PNLT* values is integrated to determine the level of the 10-second long steady sound, which would have the same perceived noisiness. Mathematically, it is defined as:

$$EPNL = PNL_{max} + 10 \log\left(\frac{t_{10}}{20}\right) + F\ (dB) \quad (11)$$

where

PNL_{max} is the maximum perceived noise level during a flyover in PNdB,

t_{10} is the duration (in seconds) of the noise level within 10 dB of the peak PNL,

and *F* is a correction (generally found to be more annoying than broadband noise without perceived tones). For many practical applications, *F* is about +3 dB.

The unit of *EPNL* is EPNdB (Effective Perceived Noise Decibel).

The reason for normalizing EPNLs to 10 seconds is to penalize those aircraft that make a lot of noise for a relatively long time. EPNL tends to be more accurate at high noisier events than quieter events. EPNL is usually larger than the certified values, which is particularly noticeable for departure noise levels. This means EPNL is unlikely to represent the noise experienced by communities surrounding an airport or heliport. Coupled with the tone corrections that are thought to be subjective, EPNL, and related noise metrics are less powerful and complex to communicate.

xvii. *Weighted Equivalent Continuous Perceived Noise Level (WECPNL)*

WECPNL may be considered as a hybrid of *EPNL*, since it incorporates *EPNL* which is tone and duration corrected, but also includes a time-of-day energy average and a seasonal correction based on temperature (Jones and Cadoux, 2009). It characterizes flyover and run-up noise events with *EPNL* and *PNLT,* respectively. *WECPNL*, like *CNEL*, averages sound levels at a location over a 24-hour period, with penalties of 5 and 10 dB representing the evening and night-time, because of increased sensitivity to noise during those hours. It is the metric used for aircraft noise measurement in Japan, although there is now a move towards the L_{eq} metric (Airbus, 2003).

xviii. *Day Equivalent Sound Level (L_{day})*

Day Equivalent Sound Level (L_{day}) represents the noise exposure level over the day-time period, typically 0700-1900 hours.

xix. *Night Equivalent Sound Level (L_{night})*

According to (Jones and Cadoux, 2009), L_{night} represents the noise exposure level over the night-time period, typically 2300-0700 hours. Measures of L_{night} have been used to assess night flying restrictions, but this metric is not widely used.

xx. *Day-Night Average Sound Level (DNL or L_{dn})*

For the evaluation of community noise effects, and particularly aircraft noise effects, the Day-Night Average Sound Level (*DNL* or L_{dn}) is used. It is a cumulative metric that accounts for all noise events in 24 hours with a night-time penalty of 10 dB for events during the night. It considers a night time (2200-0700 hrs) event ten times more disturbing than a daytime (0700-2200 hrs). It is widely used in Belgium, New Zealand, and the United States of America, especially the Environmental Protection Agency (EPA) (Murphy and King, 2014). Mathematically, it is expressed as:

$$L_{dn} = 10.\log\left[\frac{1}{86400} * \left[\sum_{i=1}^{n} 10^{\frac{L_{AE\,(i)day\,[0700-2200]}}{10}}\right] + 10\sum_{j=1}^{n} 10^{\frac{L_{AE\,(j)day\,[2200-0700]}}{10}}\right] \quad (12)$$

Where:

n is the number of events

$L_{AE(i)day[0700-2200]}$ is the *SEL* produced by a trajectory during the [0700-2200] period.

$L_{AE(j)day[2200-0700]}$ is the *SEL* produced by a trajectory during the [2200-0700] period.

86400 is the day duration in seconds. That is, $24 \times 60 \times 60 = 86400$

The values of *DNL* or L_{dn} can be measured with standard monitoring equipment or predicted with computer models. Due to the *DNL* or L_{dn} metric's close correlation with the degree of community annoyance from aircraft noise, it has been formally adopted by most federal agencies in the United States for measuring and evaluating aircraft noise for land use planning and noise impact assessment. Countries currently using this metric include Denmark and Finland (SI, 2005). EPA recommends a maximum residential level of 55 L_{dn}, which is equivalent to a steady noise of 48.6 dB(A) (Lamancusa, 2000).

Several issues have arisen from the use of *DNL* or L_{dn} and the percentage of persons highly annoyed: no one actually "hears" a DNL; there is a high variability from study to study around a nominal Schultz curve, and in many situations "highly annoyed" is not an appropriate measure of human response. Although the percent highly annoyed and DNL approach has been widely accepted, variability around a nominal Schultz curve is troubling. There are reports that this approach is not enough to predict community response (Fidell, 2002).

xxi. *Community Noise Equivalent Level (CNEL)*

CNEL was developed in the early 1970s by the State of California in the United States of America for community noise exposure, with particular emphasis on airport noise. It is similar to L_{dn} but considers three time periods, namely day (0700-1900 hours) for which there is no weighting or penalty; evening (1900-2200 hours) for which there is a three times weighting corresponding to approximately 4.8 dB penalty; and night (2200-0700 hours) with ten times weighting equal to 10 dB penalty. It is used in comparing the noise impact of communities and for regulating airport noise impact. Mathematically, it is expressed as:

$$CNEL = 10.\log\left[\frac{1}{86400}\left[\sum_{i=1}^{ni} 10^{\frac{L_{AE(i)day\,[0700-1900]}}{10}}\right] + 3\sum_{j=1}^{nj} 10^{\frac{L_{AE(j)evening\,[1900-2200]}}{10}} + 10\sum_{k=1}^{nk} 10^{\frac{L_{AE(k)night[2200-0700]}}{10}}\right] \quad (13)$$

Where:

n is the number of events

$L_{AE(i)day[0700-1900]}$ is the *SEL* produced by a trajectory during the [0700-1900] period.

$L_{AE(j)evening[1900-2200]}$ is the *SEL* produced by a trajectory during the [1900-2200] period.

$L_{AE(k)evening[2200-0700]}$ is the *SEL* produced by a trajectory during the [2200-0700] period.

86400 is the day duration in seconds. That is, $24 \times 60 \times 60 = 86\,400$

The use of CNEL has been criticized as not accurately representing community annoyance and land-use compatibility with aircraft noise (Wyle, 2008).

xxii. *Day-Evening-Night Average Sound Level (L_{den})*

For long-term noise exposure, L_{den} has a proven relationship with the degree of community noise annoyance and particularly with the percentage of highly annoyed respondents. It has been a noise metric in use in the Netherlands since 2003.

L_{den}, in combination with special dose-effect relations, is also applicable in the following cases: annoyance due to noise with strong tonal components, annoyance due to noise with an impulsive character, and adverse effects on learning by children.

The definition of the L_{den} is like the *CNEL*. The only difference is that the weighting factor for the evening for L_{den} is 5 and 3 for *CNEL* respectively. This is the metric adopted for use for aircraft noise measurement by the World Health Organization (WHO, 2018). Mathematically, it is expressed as:

$$L_{den} = 10.\log\left[\frac{1}{86400}\left[\sum_{i=1}^{ni} 10^{\frac{L_{AE(i)day\,[0700-1900]}}{10}}\right] + 5\sum_{j=1}^{nj} 10^{\frac{L_{AE(j)evening\,[1900-2200]}}{10}} + 10\sum_{k=1}^{nk} 10^{\frac{L_{AE(k)night[2200-0700]}}{10}}\right] \quad (14)$$

Where:

n is the number of events

$L_{AE(i)day[0700-1900]}$ is the *SEL* produced by a trajectory during the [0700-1900] period.

$L_{AE(j)evening[1900-2200]}$ is the *SEL* produced by a trajectory during the [1900-2200] period.

$L_{AE(k)evening[2200-0700]}$ is the *SEL* produced by a trajectory during the [2200-0700] period.

86400 is the day duration in seconds. That is, $24 \times 60 \times 60 = 86400$

Note that in France, the day-time period is 0600-1800 hrs, the evening is 1800-2200 hrs, and the night-time period is 2200-0600 hrs (Jones and Cadoux, 2009).

xxiii. *Störindex (Q)*

The German Störindex (Q) is like L_{dn} but gives a greater emphasis to the number factor (trade-off factor ≈ 13.3) and less to the night-time weighting (5 dB penalty only). Luxembourg has also adopted this noise metric (Jones and Cadoux, 2009).

xxiv. *Airport Noise Level (L_{VA})*

This metric is used in Italy as an equivalent continuous sound level. A 10 dB weighting factor is applied to the night movements (Jones and Cadoux, 2009).

According to (Cotana and Nicolini, 2003), an airport noise level (L_{VA}) is defined as:

$$L_{VA} = 10 \log \frac{1}{N} \sum_{j=1}^{N} 10^{\frac{L_j}{10}} \quad dB(A) \qquad (15)$$

Where:

N is the observation time (days), which must be equal to 21 days.

L_j is the airport noise level referred to as a one-day observation time.

The one-day airport noise level is defined mathematically as:

$$L_j = 10 \log \left[\left(\frac{17}{24}\right) 10^{\frac{L_d}{10}} + \left(\frac{7}{24}\right) 10^{\frac{L_n}{10}} \right] dB(A) \qquad (16)$$

Where:

L_d and $L_n$is the airport noise levels referred respectively to a daytime period (0600-2300 hours) and a night-time period (2300-0600 hours)

xxv. *Flygbuller (FBN)*

The Swedish equivalent of L_{eq}, this metric includes a 9-hour night period (2200-0700 hours), with a weighting of 10 dB, and a 3-hour evening period (1900-2200 hours) with a weighting of 4.78 dB. Using 4.78 dB gives a numerical weighting on the number of flights of exactly 3, whereas the 5 dB weighting in L_{den} effectively makes one evening flight count as 3.162-day flights (Jones and Cadoux, 2009).

xxvi. *Equivalent Aircraft Noise (EFN)*

Equivalent Aircraft Noise (EFN) is Norway's L_{eq} based metric. It is a composite index based on the equivalent continuous A-weighted sound level comparable to L_{den} but including a continuous-time weighting factor. This applies the commonly used night weighting factor of 10 but avoids discontinuities at the beginning and end of the night period. Also, a Sunday day-time penalty is introduced. These functions are based on considerations of both sleep disturbance and annoyance (Jones and Cadoux, 2009).

xxvii. *Hourly L_{eq} around the shoulder hours*

In civil airports in Switzerland, the 16-hour L_{eq} is used (0600-2200 hours) for the daytime, whereas for the night-time, three 1-hour L_{eq} values apply, for 2200-2300, 2300-2400, and 0500-0600 hours. The 1-hour L_{eq} at night has a twofold function: they impose a limitation of the maximum allowable noise from a single event to minimize sleep disturbance, while on the other hand, they are also sensitive to the number of movements (Jones and Cadoux, 2009).

xxviii. *Kosten Index (Ke)*

Kosten Index (Ke) is a noise metric based on L_{max} and has been in use in the Netherlands since 2003. However, in February 2003, the Kosten Index was replaced by L_{den}, after a new Aviation Act came into effect for Schiphol Airport. Metrics based on L_{max} do not consider the duration of the noise, and hence are possibly less representative of the disturbance due to the noise event. However, they are easier to measure and often much simpler for the public to understand (Jones and Cadoux, 2009).

xxix. *Psophic Index (IP)*

The Psophic Index (IP) is based on the PNL scale, with night-time movements weighted by a 10 dB factor, and with a trade-off of 10, and has been in use in France until April 2002. It was also used in French-speaking areas of Belgium. However, the Psophic Index (IP) has been replaced with L_{den} since 2002 (Jones and Cadoux, 2009).

xxx. *Noise Exposure Forecast (NEF)*

The NEF noise metric was first developed by the United States in the 1960s to predict noise levels in commercial airports. It combines the sound level expressed in EPNL with the number of events. A trade-off factor of 16.7 is applied to night-time operations only (10 for day-time movements). It is like NNI in that only events above a certain EPNL are considered. NEF is used in Canada, Hong Kong, Spain, and Greece. A practical disadvantage of NEF is the difficulty of routine noise monitoring in EPNL. Australia uses a modified version of NEF, the Australian Noise Exposure Forecast (ANEF), which incorporates a weighting for1900-0700 hours.

xxxi. *Number of Events Above a Specified Level (NA)*

The Number of events Above (NA) is a noise metric that reflects the average number of times noise equals or exceeds a chosen threshold level during a specified period. NA contours can be depicted at any noise threshold level (x) and any user-defined number of events (z), using the notation 'NAx(z),' meaning 'z' events at or above noise level 'x.' These analysis parameters (x and z) may differ in each affected community, based on specific circumstances. No guidelines have yet been established for NA analyses, but individual jurisdictions may apply national guidelines in such a way as to reflect unique conditions at each airport or heliport. So, each jurisdiction has some latitude in establishing local noise standards. The NA metric provides for much flexibility and can be applied to any noise environment, such as daytime, night-time, or any user-defined number of hours.

xxxii. *N_{70}*

To provide an easier way to relate the effects of aircraft noise to the Australian public, a new metric called the N_{70} noise metric was developed (Southgate et al., 2000).The N_{70} is useful because it can easily be understood by a novice. Also, the N_{70} noise metrics are more sensitive to changes in noise levels than the ANEF. The N_{70} also has the advantage of permitting measured noise levels to be very neatly summarized for any given period. This type of information is useful as a supplement to L_{eq}-based noise metrics and as a communication tool. A strong drawback of this noise metric is that it treats a noise event at 70 dB(A) the same as one at 90 dB(A) (Jones and Cadoux, 2009).

xxxiii. *Time-Above a Specified Level (TA)*

The Time-Above a Specified Level (TA) metric describes the total number of minutes that instantaneous sound level (usually from an airplane or helicopter) is above a given threshold. For instance, if 90 dB is the specified threshold, the metric would be referred to as "TA90." Any threshold may be chosen for the TA calculation. The metric can be sensitive to the type of aircraft that creates the noise, as different aircraft models will have different noise signatures.

Time above threshold TA is determined from:

$$TA\ (in\ minutes) = Time\ (L_A \geq L_T) \tag{17}$$

Where:

L_A = A-weighted sound level

L_T = Threshold of reference in dB(A)

The *TA* metric is typically associated with 24-hour annual average daily conditions but can represent any period.

xxxiv. *Person Events Index (PEI)*

According to (Jones and Cadoux, 2009), the PEI allows the total noise load generated by an airport to be evaluated by summing, over the exposed population, the total number of instances where an individual is exposed to an aircraft noise event above a specified noise level over a given period. For example, if a departure off a specific runway at an airport by an aircraft type leads to 20 000 people being exposed to a single event noise level greater than 70 dB(A) then the PEI(70) for that event would be 20 000. If there were a further similar event, the PEI(70) would double to 40 000 since there would have been that number of instances where a person was exposed to a noise level louder than 70 dB(A). The PEI is expressed mathematically as:

$$PEI(x) = \sum P_N\, N \tag{18}$$

where,

x = the single event threshold noise level expressed in dB(A)

P_N = the number of persons exposed to N events $> x$ dB(A)

xxxv. *The Average Individual Exposure (AIE)*

(Jones and Cadoux, 2009) argued that the PEI does not indicate the extent to which aircraft noise is distributed throughout a community. For instance, an annual PEI(70) of 2 million for an airport could mean that one person has been exposed to two million events over70 dB(A) (if we imagine it were possible), or that two million people have each received one event or it could be arrived at by any other combination of the two factors. The AIE is mathematically expressed as:

$$\mathrm{AIE} = \frac{\mathrm{PEI}}{\mathrm{Total\ exposed\ population}} \tag{19}$$

xxxvi. *Composite Loudness level (L)*

This measure provides a quantitative measure of the overall loudness, and the relative contribution of each octave band to the overall loudness. It is useful for comparison purposes and gives vital information for the cost-effective application of noise control treatments. It was derived from empirical data with relatively flat spectra (no pure tones) and diffuse sound fields.

Loudness levels in each octave band are determined from Tables. The composite loudness level L for all the octave bands is then:

$$L\ (sones) = 0.7S_{max} + 0.3\sum S_i \tag{20}$$

where

S_{max} = Loudness index of loudest octave band

S_i = Loudness index of the i^{th} octave band

xxxvii. *Noise Gap Index (NGI)*

The *NGI* is defined as the difference between aircraft noise and background noise. The *NGI* assumes that people living in areas of different background environmental noise levels may have different reactions to the same aircraft noise level. Mathematically, it is given as prescribed by (Issarayangyun, Samuels, and Black, 2004) as:

$$NGI = {L_{eq}}^A - {L_{eq}}^B \tag{21}$$

where

${L_{eq}}^A$ = Aircraft flyover noise determined from 0700 to 1700 hours

$L_{eq}{}^{B}$ = Background noise determined from 0700 to 1700 hours

xxxviii. *Low-frequency noise level (LFNL)*

It was developed in response to airport low-frequency noise issues. It rates the community annoyance from low-frequency noise. It is derived from the composite maximum of levels in one-third octave bands.

III. Review of Previous Studies

In the quest to determine the best and efficient method to evaluate noise, studies have been conducted on the different methods used in noise evaluation. One study is research by (Lamancusa, 2000), where he shed more light on the basic noise metrics, their application, computation, and drawbacks. Another study by (Miedema and Oudshoorn, 2001) produced a modelled noise annoyance distribution system with the mean varying as a function of noise where day–night level (L_{dn}) and day–evening–night level (L_{den}) were used as noise metrics. (Revoredo and Slama, 2008)went further to present the Integrated Noise Model (INM) generated noise footprints method for establishing relationships between L_{dn} used in airport noise zoning and L_{eq} used in urban areas for evaluating annoyance. Also, (You and Jeon, 2008) investigated just noticeable differences (JND) of sound quality metrics using refrigerator sounds. A substantial amount of improvement for each sound quality metric, which affects subjective responses to refrigerator noise, was noticed.

In a review by (Hooper et al., 2009), the authors concluded that there was no best method to demonstrate aircraft noise exhibition, and any attempt to improve noise management should be engaged with the physiological, psychological, and sociological determinants of disturbance. From another survey on metrics, (Jones and Cadoux, 2009) stated that the L_{eq} indicator constitutes the basis for aircraft noise computation, it can quantify the number of noise occurrence, the noise energy, and the period in which the event occurred. Sound metrics for the description of environmental noise were reviewed by (Fiebig and Genuit, 2010).In apsychoacoustic test (More et al., 2010)showed that loudness has a higher annoyance magnitude than toughness, while roughness varies slightly in annoyance due to aircraft noise. These noise characteristics hurt humans living around airports as calculated and measured by (Osueke and Ofondu, 2011) using NNI, CNR, NEF, and CNEL noise metrics. (Mertre et.al., 2011) developed a method for rating noises of diverse spectra character called perceived noise level (PNL) to rate annoyance effect of aircraft flyover noise. It was computed from sound pressure magnitudes quantified in octave. (Wang, Xia, and Xu, 2012) analyzed the foundational principles, computational method, and control standard of noise metrics of major countries of the world. He observed that existing airport noise metrics are not complete and needs improvement.

In another development by (Helenoand Slama, 2013), a fuzzy logic system was used to evaluate the relationship between annoyance percentage, L_{day}, and L_{night} metrics for noise effects on aircraft inhabitants. Similarly, (Heleno, Slama, and Bentes, 2014)used L_{eq}-based noise metrics to lessen aircraft noise since L_{day} and L_{night} metrics report the effect generated by aircraft movement better. (McMullen, 2014) concluded in a psychoacoustic test to examine the effect of rotorcraft sound characteristics on annoyance that *EPNL* and *SEL* were better forecasters of annoyance. (Cho et al., 2014) proposed a conversion based on noise annoyance (CBA) method regarding interoperable use between aircraft noise metrics, noise measurements, and socio-acoustic surveys in converting Korean WECPNL into L_{den}.

Furthermore, (Loubeau et al., 2015) recommended eight metrics (PL, ASEL, BSEL, ESEL, LASmax, LAFmax, PNL, and a hybrid metric ISBAP) for their ability to predict human response to sonic boom out of twenty-five evaluated metrics. Also, (Torija, Self, and Flindell, 2016) estimated the 57dB(A) L_{eq} contour area for the UK for several projected aviation growth rates and noise reduction rates due to new technologies. (Johansen, Horney, and Tien, 2017) reviewed the strength, limitations, and classified the existing community resilience metrics that apply across hazard and geographic areas.

Out of the different noise metrics analyzed by (Spilski et al., 2019), L_{eq} predicts annoyance better compared to L_{den}, L_{max}, Emergence, and NAT. Sound quality metrics, loudness, roughness, tonality, sharpness, and fluctuation strength analyzed in (Vieira et al., 2019) showed that sound quality metrics for aircraft landing and taking off were different, and the two metrics *EPNL* and PA_{mod} were not in agreement for all aircraft types. (Taufner et al., 2020) compared metrics for environmental noise identification in schools in the airport area. The L_{dn} and *TA* were investigated using acoustic simulation and noise mapping. Results showed that the criteria adopted by municipal and airport officials were unsatisfactory and do not reflect the intermittent behavior of this type of noise.

Recently, (Asensio, Pavón, and de Arcas, 2020)proposed a minimum set of basic energetic indicators that allows communication and reporting, as the COVID-19 pandemic lockdown has affected environmental noise and modified urban soundscapes. In a review by (Rob, 2020) he emphasized the need to keep up with the use of the L_{eq}-based metrics presently used for noise tracking and statutory description and also suggested that additional single event metrics be regularly issued by airports to better illustrate how noise is encountered on the ground.(Ma, Mak, and Wong,

2020) studied the impact of spatial factors on physical sound metrics and psychoacoustic metrics; the role and statistical parameters of the metric in characterizing acoustical properties. The study showed that that the sound intensity metrics L_Z or L_A, as well as the subjective loudness metric *N* are distance-dependent.

Research by (Issarayangyun, Samuels, and Black, 2004) dealt with the development of a new noise metric for reporting and evaluating aircraft noise. The noise metric, which was termed the Noise Gap Index (NGI) was formed on the presumption that people living in places of dissimilar surrounding noise react dissimilarly to the same aircraft noise magnitude.

Despite the detailed analysis done in all the reviewed literature, none of these studies captured all the important aircraft noise metrics in a single volume. This review paper has been able to itemize all the important aircraft noise metrics used internationally in a single volume. This will be a very useful reference for future researchers in environmental noise.

IV. Conclusion

A descriptive account of all the global aircraft noise metrics was given, emphasizing that L_{eq} is the best for aircraft noise measurement because it is easy to measure and easy to understand by laypersons. The equivalent sound level (L_{eq}) gives the steady-state noise level over a specified period. It is the most widely used global aircraft noise metric since it considers the number of noise events, the noise energy, and duration of events. The L_{eq} metric provides a more accurate evaluation of aircraft noise exposure for a specific period, particularly for day-time periods when the night-time penalty under the *DNL* or L_{dn} metric is not suitable. Just as *SEL* has proven to be a good measure of the noise impact of a single event, L_{eq} has been established to be a good measure of the impact of a series of events during a given period. L_{eq} can be adapted to account for different time sensitivities and have different weightings applied. This means that it has the potential to be adjusted to suit the preferences or characteristics of a community or noise source. L_{eq} provides the basis for which other secondary aircraft noise metrics such as *DNL* or L_{dn} and *CNEL* are developed. The multiple advantages of L_{eq} as an aircraft noise metric makes it the preferred choice for airport and heliport noise impact assessments, especially in Nigeria. This has resulted in a substantial volume of consistent aircraft noise data over the years, which can be easily compared to make a more informed judgment on the effects of aircraft noise on host communities.

Acknowledgements
None.

Conflicts of Interest
The authors declare that there is no conflict of interest.

Funding
None.

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