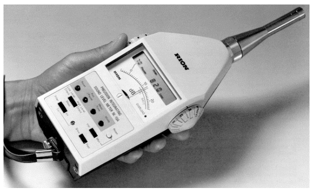

4. NOISE METRICS AND REGULATIONS

4.1 INTRODUCTION

Noise metrics are an attempt to emulate the manner in which humans respond to sound. They enable us to repeatably predict the impact of a given noise on the average person. They are extensively used to predict loudness, annoyance and potential for hear loss. Each government agency seems to have its own motivation and method for quantifying noise. The Federal Highway Administration (FHWA), Federal Aviation Administration (FAA), OSHA and EPA all have different methods for assessing noise. A variety of descriptors and calculation procedures are used. These methods attempt to quantify the complex characteristics of human hearing and human psychology. While they are all based on the decibel scale (dB), there is no agreement on a single best measure. Different procedures have been developed for different applications, such as aircraft, traffic, factory and community noise.

Objectives of this Section:

This section describes the various methods that are commonly employed and will help you to navigate through the alphabet soup of noise metrics. The reader will understand basic noise metrics, their application, calculation and limitations.

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Papers:

8. H. Fletcher and W. Munson, "Loudness, its definition, measurement and calculation", JASA, 5(2), October 1933, pp82-108.
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11. S.S. Stevens, "Procedure for calculating loudness, Mark VI", JASA, 33(11), Nov 1961, pp 1577-1585.
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4.2 WEIGHTING NETWORKS

Weighting networks (implemented with electronic filters) are built into sound level meters to provide a meter response that tries to approximate the way the ear responds to the loudness of pure tones. These weighting curves are directly derived from the Fletcher/Munson equal loudness contours.

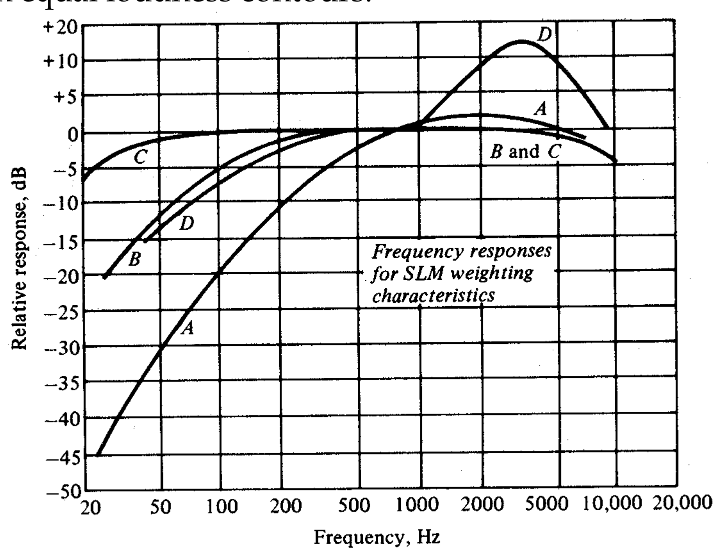

Figure 1.12 Frequency characteristics of the A, B, C, and D weighting networks.

Figure 1 (ref. fig 1.12 lord, gatley and evenson)

The most common weightings are:

A - approximation of 40 phon line (de-emphasizes low frequencies)
B - " 70 phon line
C - " 100 phon line (almost flat)
D - developed for aircraft flyover noise (penalizes high frequencies)

A-weight is the most common:

- it correlates reasonably well with hearing damage
- it is easily implemented in a filter network
- it is a simple measure, overall level is one number
- it is used in most regulations

A-weighted sound levels are obtained by taking the output of a high quality microphone and passing it through an electronic filter that attempts to imitate the sensitivity of the human ear. A good microphone will have a flat frequency response, meaning it will produce the same electrical output level, for any sound frequency input. The human ear however is more sensitive to sounds in the middle frequency region (around 1000 Hz) and much less sensitive to sounds of low frequency as shown in Figure 1. This figure shows equal loudness contours for the human ear, i.e. the relationship between subjective loudness (the solid curves) and the measured sound amplitude (the vertical axis) as a function of frequency. All sounds along a curve sound equally as loud, while the actual amplitude (as would be measured by a sound level meter) varies with frequency. Note how a low frequency sound must have a much higher amplitude to have the same apparent volume. The A-weighted filter approximates the 40 phon line.

Because it is so simple and common, people tend to forget its limitations and they apply A-weighting to situations for which it was never intended. Limitations of A-weighting include:

- Since it is derived from the 40 phon line, it is most valid for low to moderate volume sounds (~ 40-60 dB) and for single, pure tones. For louder noises, B or C weighting is more appropriate, (but are almost never used).
- It is not a good measure of loudness or annoyance for complex sounds consisting of multiple pure tones and/or broad band noise. Two sounds with the same A-weighted level can have quite different levels of annoyance. (ref. 12)
- The A-weighted level provides no indication of the frequency content of a complex noise, so it is almost useless for identifying or separating noise sources or for designing noise control measures.

Table 1. A, C, and D weighting correction values

Center Frequency Hz	A-Weighting Correction dB	C-Weighting Correction - dB	D-Weighting Correction-dB
10	-70.4	-14.3	
12.5	-63.4	-11.2	
16	**-56.7**	**-8.5**	
20	-50.5	-6.2	
25	-44.7	-4.4	
31.5	**-39.4**	**-3.0**	
40	-34.6	-2.0	
50	-30.2	-1.3	-12.8
63	**-26.2**	**-0.8**	**-10.9**
80	-22.5	-0.5	-9.0
100	-19.1	-0.3	-7.2
125	**-16.1**	**-0.2**	**-5.5**
160	-13.4	-0.1	-4.0
200	-10.9	0	-2.6
250	**-8.6**	**0**	**-1.6**
315	-6.6	0	-0.8
400	-4.8	0	-0.4
500	**-3.2**	**0**	**-0.3**
630	-1.9	0	-0.5
800	-0.8	0	-0.6
1000	**0**	**0**	**0**
1250	0.6	0	2.0
1600	1.0	-0.1	4.9
2000	**1.2**	**-0.2**	**7.9**
2500	1.3	-0.3	10.6
3150	1.2	-0.5	11.5
4000	**1.0**	**-0.8**	**11.1**
5000	0.5	-1.3	9.6
6300	-0.1	-2.0	7.6
8000	**-1.1**	**-3.0**	**5.5**
10000	-2.5	-4.4	3.4
12500	-4.3	-6.2	-1.4
16000	**-6.6**	**-8.5**	
20000	-9.3	-11.2	

Quantities which you can read directly from a typical, basic sound level meter include:

L_P = Overall unweighted sound pressure level [designated as dB(lin) or just dB]
L_A = Overall A-weighted SPL (dBA)
L_C = Overall C-weighted SPL (dBC)

4.3. LOUDNESS AND ANNOYANCE RATINGS FOR STEADY NOISES:

Loudness or annoyance measures are not generally available on basic sound level meters, since they require some additional calculations or time averaging. They provide much more information than the overall sound pressure level (with or without frequency weighting).

Loudness level - (Stevens - Mark VI)
This measure provides a quantitative measure of the overall loudness, as well as the relative contribution of each octave band to the overall loudness. It is useful for comparison purposes and gives important 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 Table 2.1. The composite loudness level ***L*** for all the octave bands is then:

$$\text{Composite Loudness Level (sones)} \; L = .7S_{\max} + .3\sum S_i$$

$$S_{\max} = \text{Loudness index of loudest octave band} \qquad \text{Equation 1}$$

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

Example Calculation:

	Octave band center frequency - Hz								
	31	63	125	250	500	1000	2000	4000	8000
Octave band level – dB lin	76	72	70	75	80	74	65	65	66
Band loudness index S_i	3.2	3.7	5.0	8.3	13.5	11.1	7.8	9.3	11.8
Ranking	9	8	7	5	1	3	6	4	2

Using the table that follows:

$$S_{total} = \sum S_i = 73.7$$
$$S_{\max} = 13.5$$
$$L = .7 \times 13.5 + .3 \times 73.7 = 31.56 \text{ sones}$$
$$\text{Loudness Level} \approx 89.8 \text{ phons} \quad \text{(using columns 10 and 11)}$$

Table 2-1 Band-level conversion to loudness index

Band level, dB	Band loudness index									Loudness, sones	Loudness level, phons
	i31.5	63	125	250	500	1000	2000	4000	8000		
20						.18	.30	.45	.61	.25	20
21						.22	.35	.50	.67	.27	21
22					.07	.26	.40	.55	.73	.29	22
23					.12	.30	.45	.61	.80	.31	23
24					.16	.35	.50	.67	.87	.33	24
25					.21	.40	.55	.73	.94	.35	25
26					.26	.45	.61	.80	1.02	.38	26
27					.31	.50	.67	.87	1.10	.41	27
28				.07	.37	.55	.73	.94	1.18	.44	28
29				.12	.43	.61	.80	1.02	1.27	.47	29
30				.16	.49	.67	.87	1.10	1.35	.50	30
31				.21	.55	.73	.94	1.18	1.44	.54	31
32				.26	.61	.80	1.02	1.27	1.54	.57	32
33				.31	.67	.87	1.10	1.35	1.64	.62	33
34			.07	.37	.73	.94	1.18	1.44	1.75	.66	34
35			.12	.43	.80	1.02	1.27	1.54	1.87	.71	35
36			.16	.49	.87	1.10	1.35	1.64	1.99	.76	36
37			.21	.55	.94	1.18	1.44	1.75	2.11	.81	37
38			.26	.62	1.02	1.27	1.54	1.87	2.24	.87	38
39			.31	.69	1.10	1.35	1.64	1.99	2.38	.93	39
40		.07	.37	.77	1.18	1.44	1.75	2.11	2.53	1.00	40
41		.12	.43	.85	1.27	1.54	1.87	2.24	2.68	1.07	41
42		.16	.49	.94	1.35	1.64	1.99	2.38	2.84	1.15	42
43		.21	.55	1.04	1.44	1.75	2.11	2.53	3.0	1.23	43
44		.26	.62	1.13	1.54	1.87	2.24	2.68	3.2	1.32	44
45		.31	.69	1.23	1.64	1.99	2.38	2.84	3.4	1.41	45
46	.07	.37	.77	1.33	1.75	2.11	2.53	3.0	3.6	1.52	46
47	.12	.43	.85	1.44	1.87	2.24	2.68	3.2	3.8	1.62	47
48	.16	.49	.94	1.56	1.99	2.38	2.84	3.4	4.1	1.74	48
49	.21	.55	1.04	1.69	2.11	2.53	3.0	3.6	4.3	1.87	49
50	.26	.62	1.13	1.82	2.24	2.68	3.2	3.8	4.6	2.00	50
51	.31	.69	1.23	1.96	2.38	2.84	3.4	4.1	4.9	2.14	51
52	.37	.77	1.33	2.11	2.53	3.0	3.6	4.3	5.2	2.30	52
53	.43	.85	1.44	2.24	2.68	3.2	3.8	4.6	5.5	2.46	53
54	.49	.94	1.56	2.38	2.84	3.4	4.1	4.9	5.8	2.64	54
55	.55	1.04	1.69	2.53	3.0	3.6	4.3	5.2	6.2	2.83	55
56	.62	1.13	1.82	2.68	3.2	3.8	4.6	5.5	6.6	3.03	56
57	.69	1.23	1.96	2.84	3.4	4.1	4.9	5.8	7.0	3.25	57
58	.77	1.33	2.11	3.0	3.6	4.3	5.2	6.2	7.4	3.48	58
59	.85	1.44	2.27	3.2	3.8	4.6	5.5	6.6	7.8	3.73	59
60	.94	1.56	2.44	3.4	4.1	4.9	5.8	7.0	8.3	4.00	60
61	1.04	1.69	2.62	3.6	4.3	5.2	6.2	7.4	8.8	4.29	61
62	1.13	1.82	2.81	3.8	4.6	5.5	6.6	7.8	9.3	4.59	62
63	1.23	1.96	3.0	4.1	4.9	5.8	7.0	8.3	9.9	4.92	63
64	1.33	2.11	3.2	4.3	5.2	6.2	7.4	8.8	10.5	5.28	64
65	1.44	2.27	3.5	4.6	5.5	6.6	7.8	9.3	11.1	5.66	65
66	1.56	2.44	3.7	4.9	5.8	7.0	8.3	9.9	11.8	6.06	66
67	1.69	2.62	4.0	5.2	6.2	7.4	8.8	10.5	12.6	6.50	67
68	1.82	2.81	4.3	5.5	6.6	7.8	9.3	11.1	13.5	6.96	68
69	1.96	3.0	4.7	5.8	7.0	8.3	9.9	11.8	14.4	7.46	69
70	2.11	3.2	5.0	6.2	7.4	8.8	10.5	12.6	15.3	8.00	70
71	2.27	3.5	5.4	6.6	7.8	9.3	11.1	13.5	16.4	8.6	71
72	2.44	3.7	5.8	7.0	8.3	9.9	11.8	14.4	17.5	9.2	72
73	2.62	4.0	6.2	7.4	8.8	10.5	12.6	15.3	18.7	9.8	73
74	2.81	4.3	6.6	7.8	9.3	11.1	13.5	16.4	20.0	10.6	74

Table 2-1 (Continued)

Band level, dB	Band loudness index									Loudness, sones	Loudness level, phons
	i31.5	63	125	250	500	1000	2000	4000	8000		
75	3.0	4.7	7.0	8.3	9.9	11.8	14.4	17.5	21.4	11.3	75
76	3.2	5.0	7.4	8.8	10.5	12.6	15.3	18.7	23.0	12.1	76
77	3.5	5.4	7.8	9.3	11.1	13.5	16.4	20.0	24.7	13.0	77
78	3.7	5.8	8.3	9.9	11.8	14.4	17.5	21.4	26.5	13.9	78
79	4.0	6.2	8.8	10.5	12.6	15.3	18.7	23.0	28.5	14.9	79
80	4.3	6.7	9.3	11.1	13.5	16.4	20.0	24.7	30.5	16.0	80
81	4.7	7.2	9.9	11.8	14.4	17.5	21.4	26.5	32.9	17.1	81
82	5.0	7.7	10.5	12.6	15.3	18.7	23.0	28.5	35.3	18.4	82
83	5.4	8.2	11.1	13.5	16.4	20.0	24.7	30.5	38.	19.7	83
84	5.8	8.8	11.8	14.4	17.5	21.4	26.5	32.9	41.	21.1	84
85	6.2	9.4	12.6	15.3	18.7	23.0	28.5	35.3	44.	22.6	85
86	6.7	10.1	13.5	16.4	20.0	24.7	30.5	38.	48.	24.3	86
87	7.2	10.9	14.4	17.5	21.4	26.5	32.9	41.	52.	26.0	87
88	7.7	11.7	15.3	18.7	23.0	28.5	35.3	44.	56.	27.9	88
89	8.2	12.6	16.4	20.0	24.7	30.5	38.	48.	61.	29.9	89
90	8.8	13.6	17.5	21.4	26.5	32.9	41.	52.	66.	32.0	90
91	9.4	14.8	18.7	23.0	28.5	35.3	44.	56.	71.	34.3	91
92	10.1	16.0	20.0	24.7	30.5	38.	48.	61.	77.	36.8	92
93	10.9	17.3	21.4	26.5	32.9	41.	52.	66.	83.	39.4	93
94	11.7	18.7	23.0	28.5	35.3	44.	56.	71.	90.	42.2	94
95	12.6	20.0	24.7	30.5	38.	48.	61.	77.	97.	45.3	95
96	13.6	21.4	26.5	32.9	41.	52.	66.	83.	105.	48.5	96
97	14.8	23.0	28.5	35.3	44.	56.	71.	90.	113.	52.0	97
98	16.0	24.7	30.5	38.	48.	61.	77.	97.	121.	55.7	98
99	17.3	26.5	32.9	41.	52.	66.	83.	105.	130.	59.7	99
100	18.7	28.5	35.3	44.	56.	71.	90.	113.	139.	64.0	100
101	20.3	30.5	38.	48.	61.	77.	97.	121.	149.	68.6	101
102	22.1	32.9	41.	52.	66.	83.	105.	130.	160.	73.5	102
103	24.0	35.3	44.	56.	71.	90.	113.	139.	171.	78.8	103
104	26.1	38.	48.	61.	77.	97.	121.	149.	184.	84.4	104
105	28.5	41.	52.	66.	83.	105.	130.	160.	197.	90.5	105
106	31.0	44.	56.	71.	90.	113.	139.	171.	211.	97.	106
107	33.9	48.	61.	77.	97.	121.	149.	184.	226.	104.	107
108	36.9	52.	66.	83.	105.	130.	160.	197.	242.	111.	108
109	40.3	56.	71.	90.	113.	139.	171.	211.	260.	119.	109
110	44.	61.	77.	97.	121.	149.	184.	226.	278.	128.	110
111	49.	66.	83.	105.	130.	160.	197.	242.	298.	137.	111
112	54.	71.	90.	113.	139.	171.	211.	260.	320.	147.	112
113	59.	77.	97.	121.	149.	184.	226.	278.	343.	158.	113
114	65.	83.	105.	130.	160.	197.	242.	298.	367.	169.	114
115	71.	90.	113.	139.	171.	211.	260.	320.		181.	115
116	77.	97.	121.	149.	184.	226.	278.	343.		194.	116
117	83.	105.	130.	160.	197.	242.	298.	367.		208.	117
118	90.	113.	139.	171.	211.	260.	320.			233.	118
119	97.	121.	149.	184.	226.	278.	343.			239.	119
120	105.	130.	160.	197.	242.	298.	367.			256.	120
121	113.	139.	171.	211.	260.	320.				274.	121
122	121.	149.	184.	266.	278.	343.				294.	122
123	130.	160.	197.	242.	298.	367.				315.	123
124	139.	171.	211.	260.	320.					338.	124
125	149.	184.	226.	278.	343.					362.	125

Source: A. P. G. Peterson and E. E. Gross, *Handbook of Noise Measurement*, 7th ed., General Radio Company, Concord, Mass., pp. 25–26. The method used here is that standardized in ANSI S 3.4 - 1968.

Stevens - Mark VII (ref 10)
This is an improvement to Mark VI which uses 1/3 octave data and includes some effects of masking. (see ref. 2, General Radio Handbook for calculation details)

ISO532B – Zwicker Method
This method is similar to the MarkVII method but also accounts for the upward spread of masking and can handle complex sounds with broadband and/or pure tone components. It uses 1/3 octave data and can account for frontal or diffuse sound fields. This seems to be the best method for quantifying annoyance of sound and is now an international standard. (see ISO532B standard for details)

PNL – Perceived Noise Level
This is a similar procedure as Mark VI loudness, but uses equal noisiness contours. It is commonly applied to aircraft noise

EPNL – Effective Perceived Noise Level
This is a refinement of PNL to include a correction for the noise duration and the presence of clearly audible discrete tones. It is used for aircraft noise (FAA) and involves relatively complicated calculations. (See ANSI S6.4-1973 for details)

NC curves – Noise Criterion
Noise levels below 80 dBA are considered safe from a hearing loss perspective. However, they can still be highly annoying and interfere with the effective performance of occupational tasks or other activities. The Noise Criterion method, developed in 1957, rates the background levels in buildings and rooms. It is used to judge the appropriateness of the acoustic environment for various activities. The actual spectrum (octave band levels) is compared to standard NC curves (shown in Figure below). The highest NC level penetrated is the NC rating. This will be discussed further in the section on room acoustics.

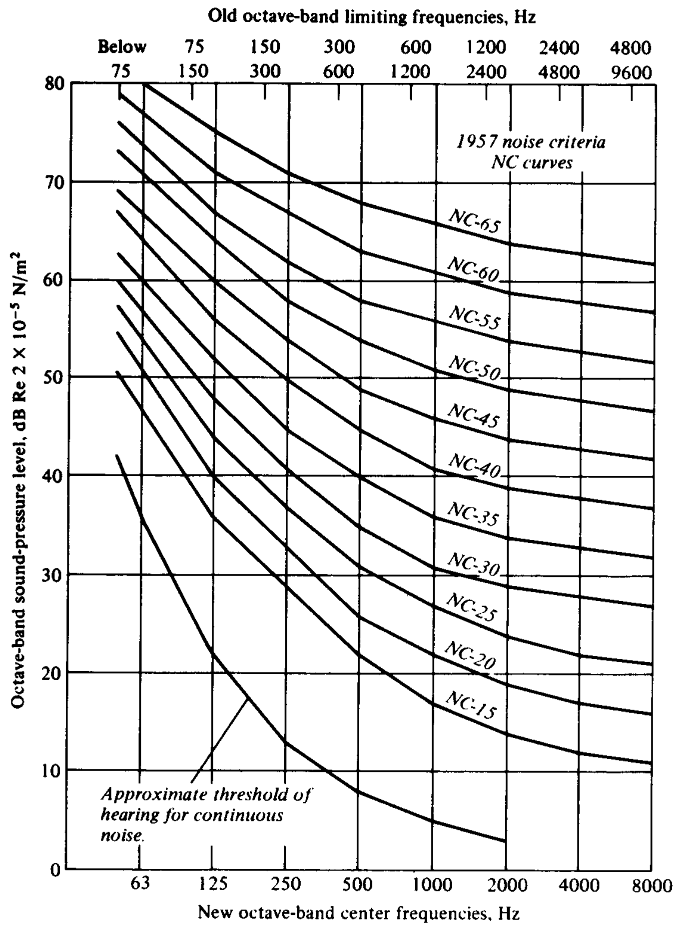

Figure 7.1 Indoor noise criteria (NC) curves (1957) [9].

Figure 2 (source Fig 7.1 lord, gatley and evenson nc.tif)

The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) recommends the following NC levels for various spaces: (ref. ASHRAE Handbook)

Concert Halls	NC 15-20
Executive office	NC 30-40
General open office	NC 35-45
Conference room	NC 25-35
Suburban residence	NC 20-30
Urban residence	NC 25-35
Apartment houses	NC 30-40
Classroom	NC 30-40
Restaurants	NC 35-45

NC is easy to apply, but does not account for low frequency noise (below 63 Hz), which can be very significant in HVAC systems.

RC, NCB :
A potential deficiency of the NC method is that it does not adequately rate the quality of the spectrum. An HVAC system may sound rumbly (low frequency sound) or hissy (high frequency sound), or both if the spectrum matches a particular NC contour. To improve on NC, a number of more recent, and more conservative room measures have been proposed. These include:

RC (ROOM CRITERION), (Blazier, 1981) takes into account lower frequency (down to 16 Hz) and attempts to achieve better balance between low frequency (rumble) and high frequency (hiss) components. It is the preferred method of ASHRAE.

NCB (NOISE CRITERION BALANCED), (Beranek, 1989). NCB also covers the octave bands from 16 through 8000 Hz. It allows significantly higher levels in the 16 and 31.5 Hz bands that does the RC method.

4.4 SPEECH INTERFERENCE

Interference with speech is one of the more negative consequences of excessive noise. Speech intereference causes frustatration, annoyance and irritation. When oral communication is disrupted, worker efficiency can suffer, and the potential for error due to miscommunication is increased. Several methods have been proposed to predict and quantify speech intelligibility including: A-weighted sound level, Speech Interference Level (SIL), Articulation Index (AI) and Speech Transmission Index (STI).

A-weighted sound level is the simplest method for predicting speech intelligibility. The background sound level is measured and a chart such as Figure 16.8 is used. This technique works best if the noise spectrum is flat, the noise levels are steady, and the acoustic environment is non-reverberant (reverberation time less than ~2 seconds).

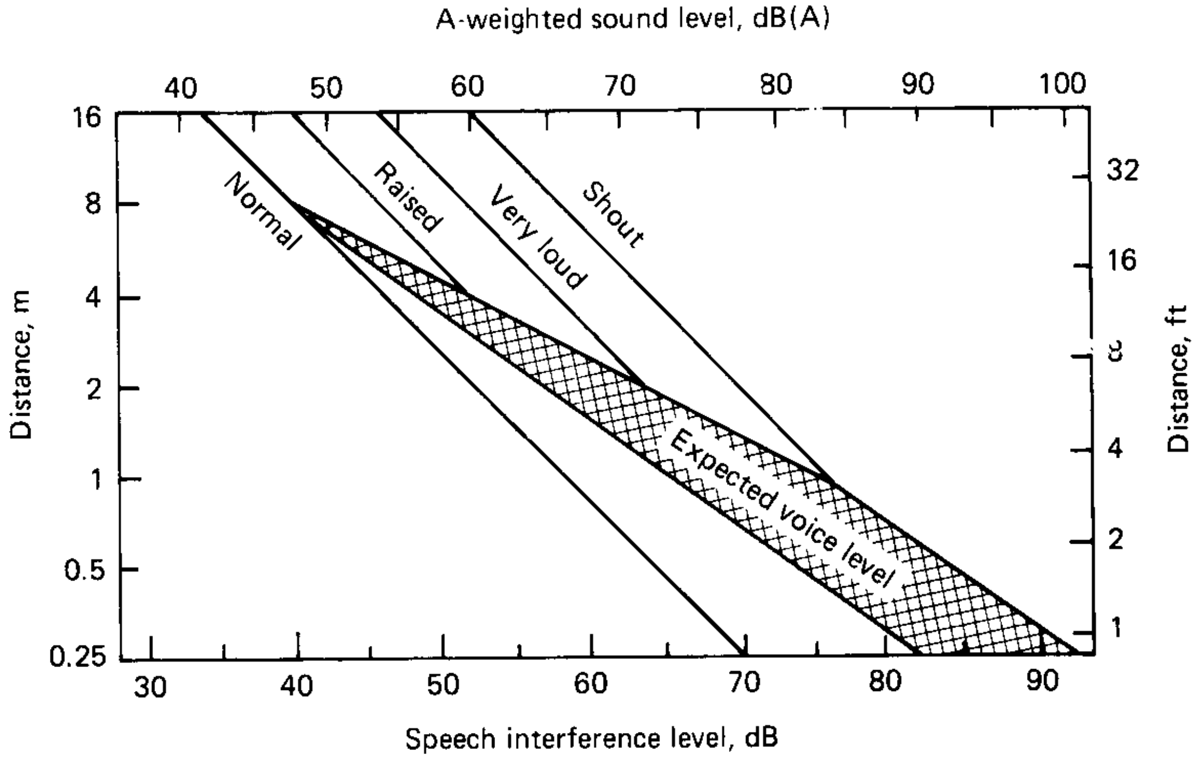

FIG. 16.8 Talker-to-listener distances for just-reliable communication. The curves show maximum permissible talker-to-listener distances for just-reliable speech communication. The parameter on each curve indicates the relative voice level. Since a talker will raise his or her voice in noise, typically at the rate of 3 to 6 dB for every 10-dB increase in noise level above 50 dB(A), the expected voice level will increase with increasing noise level. The cross-hatched area shows the range of permissible talker-to-listener distances under these conditions. The lower bound of the cross-hatched area is for voice level being raised at the rate of 3 dB per 10-dB increase in noise level; the upper bound is for a rate of increase of 6 dB per 10-dB increase in noise level.

Figure 3. (ref. Harris, Handbook of acoustical measurements and noise control)

Speech interference level (SIL, PSIL)
The Speech Interference Level is intended to quantify the effectiveness of speech in the presence of noise. Numerically it is the numerical average of four octave band levels - 500, 1000, 2000 and 4000 Hz. A commonly used, related measure is the Preferred Speech Interference Level (PSIL) which uses three bands (500, 1000, and 2000 Hz).

$$PSIL = \frac{L_{500} + L_{1000} + L_{2000}}{3}$$ Equation #

Some industries, notably in the aircraft industry use the 1K, 2K and 4KHz bands for calculation of SIL.

The Articulation Index (AI) was developed by French and Steinberg [ref JASA, 19(1), Jan 1947, pp 90-119] . 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 rms dB level (plus 12 dB) of the speech signal. 20 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 spread of masking. AI has been adopted as ANSI Standard S3.5-1969. It takes into account background noise, masking and non-flat noise spectra. It is not well suited for highly reverberant environments, or when the speech is distorted, such as by mumbling or poor quality amplification. The calculation of AI is relatively complicated and beyond the scope of this discussion. The interested reader should consult the ANSI standard for calculation details.

4.5 NON-STEADY NOISE, STATISTICAL DESCRIPTORS:

The variation in noise level as a function of time can be very dramatic. A typical time history (as seen below) will show dramatic level fluctuations due to discrete events as well as changing weather conditions. Depending on when a measurement is taken, a reading from a simple sound level meter can be used to prove either side's case in a typical noise dispute. Analysis of these time varying signals can require a statistical descriptor.

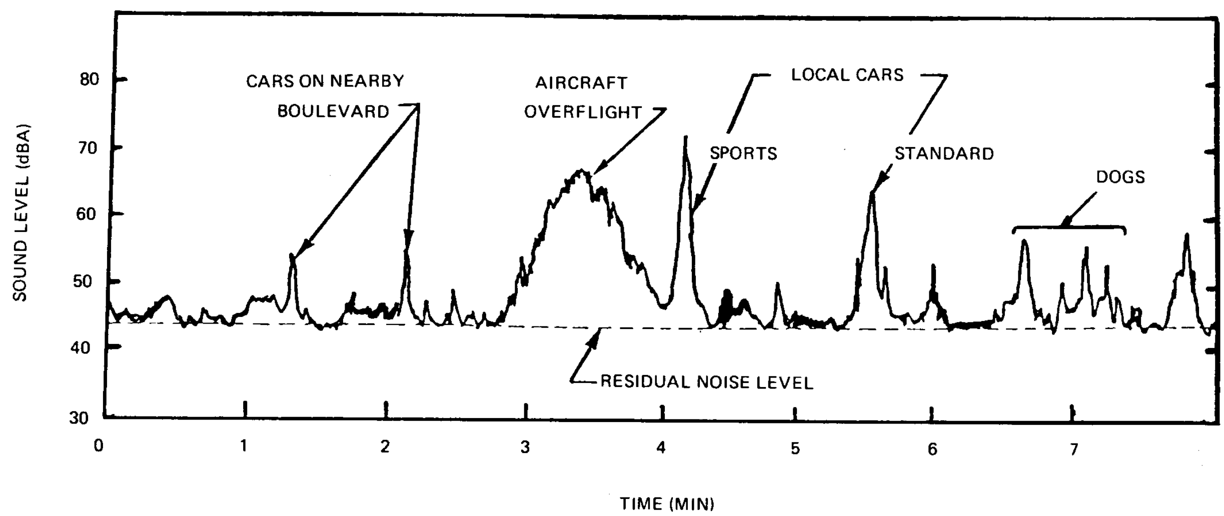

Figure 16.5 Time history of A weighted sound levels of some community noise. (From Ref. 10.)

Figure 4 (source: fig 16.5 Bell and Bell)

Equivalent sound level - L_{eq}

In normal occurrence, sound levels vary during the course of the day. Levels temporarily increase such as when a truck passes, when a dog barks, when an airplane flies over, when an air condition compressor turns on, or when a factory begins its production shift.. *Equivalent Sound Level* (L_{EQ}) is analogous to an average level and is defined as the hypothetical constant sound level over a period of time which results in the same overall sound energy as the actual time varying sound. Since sound energy is proportional to intensity, which is in turn proportional to the square of sound pressure:

$$L_{EQ} = 10\log_{10}\left[\frac{1}{T}\int_0^T \frac{P_A^2(t)}{P_{REF}^2}dt\right] \qquad P_A = \text{rms A - weighted pressure}$$

$$L_{EQ} = 10\log_{10}\left[\frac{1}{T}\int_0^T 10^{L_A/10}dt\right] \qquad L_A = \text{A - weighted level (dBA)} \qquad \text{Equation 2}$$

where $P_{REF} = \text{reference pressure} = 20\mu Pa$

for discrete data samples:

$$L_{EQ} \cong 10\log_{10}\frac{1}{T}\sum_{i=1}^{n}\frac{P_i^2(t)}{P_{REF}^2}\Delta t_i$$

Equation 3

for constant time intervals Δt (one measurement every hour is typical):

$$L_{EQ} \cong 10\log_{10}\frac{1}{n}\sum_{i=1}^{n}\frac{P_A^2(t)}{P_{REF}^2} = L_{EQ} \cong 10\log_{10}\frac{1}{n}\sum_{i=1}^{n}10^{L_A/10}$$

Day-Night Level - L_{DN}

L_{DN} is similar to L_{EQ} but adds a 10 db penalty at night from 10 pm to 7 am. It is widely used in US to compensate for the increased undesirability of noise during sleep periods. EPA recommends a maximum residential level of 55 L_{dn}. For hourly measurements:

$$L_{DN} = 10\log_{10}\frac{1}{24}\left[\underset{(7\text{ am - }10\text{ pm})}{\sum_{i=1}^{15}10^{L_A/10}} + \underset{(10\text{ pm - }7\text{ am})}{\sum_{i=16}^{24}10^{(L_A+10)/10}}\right] \qquad \text{Equation 4}$$

A steady noise of 48.6 dBA equates to 55 L_{DN}

Exceedance Level - L_N

Defined as: the noise level which is exceeded N% of time during a day.

A value of 60 dB L_{10} means that the sound level exceeds 60 dB for 10% of the day. This measure is commonly used for traffic noise measurement. It is also useful for separating fluctuating noise from steady noise.

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.

4.6 HEARING DAMAGE RISK

In order to adequately prevent permanent hearing loss, we need a way to measure the severity of noise and correlate the noise level with risk of hearing damage. There is considerable disagreement over which criteria to use. It is agreed that in general, hearing damage is a function of ***noise level*** and ***exposure time***. Figure 5 shows the percentage risk of developing hearing loss from sustained occupational noise.

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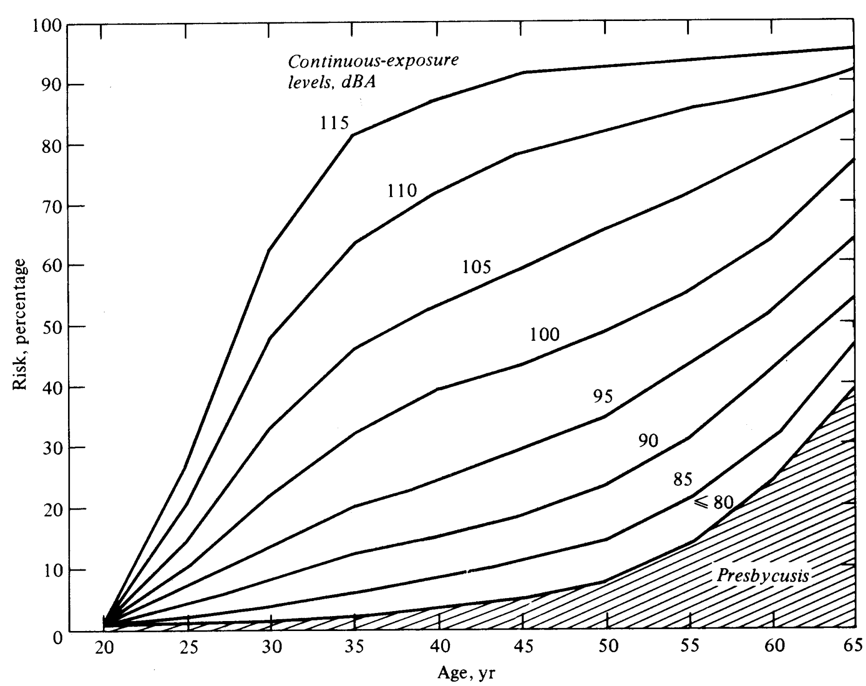

Figure 5 Percentage risk of hearing loss from sustained occupational noise (Fig 2.6 LG&E)

Figure 6a below shows a compilation of published data (Beranek 1971, Burns and Robinson 1970) showing median hearing loss as a function of the percentage risk of incurring that loss for a specified exposure time and level. It is assumed that a person would be exposed to the stated level for about 1,900 hours during each year.

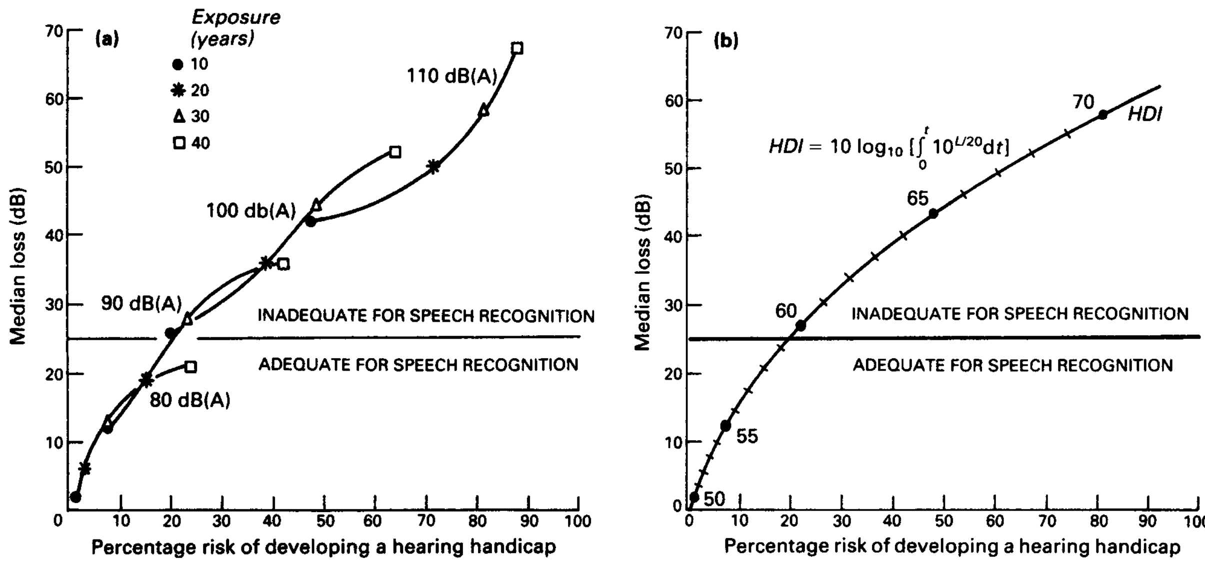

Figure 4.3 Hearing damage as a function of exposure. The percentage risk of developing a hearing handicap and the median loss incurred with exposure are shown as (a) functions of mean sound pressure level in the workplace (dB(A)) and exposure (years); and (b) a function of hearing deterioration index, *HDI*. *L* is the mean exposure level (dB(A)), and *T* is the exposure (years).

Figure 6 Hearing damage as a function of exposure (source, fig 4.3 Bies and Hansen)

Hearing Deterioration Index - HDI

The data of Figure 6a suggests a metric for quantifying hearing damage shown in Figure 5b called HDI (ref. Bies and Hansen text)

$$\mathrm{HDI} = 10\log_{10}\int_0^t 10^{L/20}\,dt \qquad \text{Equation 5}$$

L = mean exposure level (dBA) t = exposure time (years)

This basically says that cumulative damage is proportional to sound pressure.

$$\text{Hearing Loss} \propto p \times T_{\text{exposure}} \qquad \text{Equation 6}$$

With this assumption, a 6 db increase in SPL is equivalent to (causes same hearing loss risk as) doubling the exposure time

A sample calculation of HDI:
A 90 dBA exposure for 20 years (8 hours per day), results in HDI = 58, and a 15% risk of developing 20 dB of hearing loss

Equal Energy Principle

This principle says that hearing loss is proportional to the product of sound energy and exposure time:

$$\text{Hearing Loss} \propto p^2 \times T_{\text{exposure}} \qquad \text{Equation 7}$$

This implies that a 3 db increase in SPL is equivalent to (causes same hearing loss risk as) doubling the exposure time. European and Australian noise exposure standards are based on the equal energy principle (3 dB rule).

There is some justification for either 3 dB or 6 dB exchange rule. However, U.S. standards are based on a 5 dB rule, where a 5 db increase in SPL is assumed equivalent to (causes same hearing loss risk as) doubling the exposure time.

CRITERIA FOR CONTINUOUS NOISE EXPOSURE

Internationally, it has been agreed that **90 dBA** is the maximum acceptable level for an 8 hour work day. This number represents a compromise between health concerns and economic constraints. However, according to Fig 5, this will cause hearing damage in approximately 25% of the population. To minimize the risk of hearing damage, **80 dBA** or less is required. Higher levels are compromises between the cost of noise control and the risk of hearing damage and resulting compensation claims. **70 dBA** exposure over 24 hours will protect 97% of people at all frequencies.

OSHA Noise Standard –Permissible Occupational Noise Levels (1978)

OSHA (Occupational Safety and Health Administration) Act of 1970 and standards developed in response to the Act in 1978 set maximum permissible levels and specify employer remedial action if levels are exceeded.

Table 3 OSHA permissible noise exposure

Level, dBA (slow)	Permissible Exposure (hours)
90	8
92	6
95	4
97	3
100	2
102	1.5
105	1
110	.5
115	.25 or less

If these levels are exceeded:

1. When employees are subjected to sounds exceeding permissible exposure levels (noise dose >1.0), feasible administrative or engineering control shall be utilized.
2. If such controls fail to reduce sound levels to within the permissible limits, personal protective equipment shall be *provided* and the proper use *enforced*.
3. In all cases where the sound levels exceed values specified as permissible limits (>85 dBA or noise dose of 0.5), an *effective hearing conservation program* shall be administered for as long as the noise levels exceed those permitted by law. Hearing conservation programs include the following components:
    a) Exposure monitoring
    b) Employee notification
    c) Audiometric testing (baseline and annual)
    d) Employee training
    e) Hearing protection
    f) Record keeping

Additional action is required if an employee exhibits a "standard threshold shift" i.e. average of 10 dB or more in the 2K, 3K and 4K bands in either ear.

When noise levels vary with time, the total equivalent noise "dose" is either measured with a dosimeter, or calculated. Noise dose **D** for two or more periods at different levels (should never exceed 1) is calculated by:

$$\mathrm{D} = \frac{C_1}{T_1} + \frac{C_2}{T_2} + \ldots + \frac{C_N}{T_N} \leq 1$$

$$C_N = \text{time of exposure at sound pressure level } \mathrm{L_N}$$

$$T_N = \text{total permitted exposure time to } \mathrm{L_N}$$

$$T_N = \frac{8}{2^{(L_{EQ} - 90)/5}}$$

Equation 8

Only levels above 80dBA are considered in the calculation of noise dose. In addition, impulsive noises of greater than 140dB peak sound pressure level are not permitted.

4.7 COMMUNITY NOISE

EPA Guidelines (1974)

Public awareness of noise as a national problem in the United States was dramatically increased in 1970 with the establishment of the Occupational Safety and Health Administration and the extension of noise standards to virtually all American industry in 1971. OSHA's chief concern was to protect against hearing loss due to excessive noise levels in the workplace. Soon thereafter, EPA published its "Report to the

President and Congress on Noise.". This document resulted in widely used guidelines for community noise exposure. While EPA's Office of Noise Abatement and Control was officially closed by the anti-regulation attitude of the early 80's, these guidelines still form the basis for most community noise ordinances throughout the country. They are based on "equivalent sound levels identified as requisite to protect the public health and welfare with an adequate margin of safety". Indoor and outdoor levels are specified which are intended to protect against activity (primarily speech) interference and hearing loss. The most important feature of these guidelines is the recommended limit of 55 L_{DN} for noise in residential areas. Noises which occur at night are recognized to be more objectionable than those which occur during the day. This limit has been widely used as the basis for community noise ordinances across the country as well as internationally.

Table 4. EPA Yearly average* equivalent sound levels identified as requisite to protect the public health and welfare with an adequate margin of safety

		Indoor			Outdoor		
	Measure	Activity interference	Hearing loss consideration	To protect against both effects (b)	Activity interference	Hearing loss consideration	To protect against both effects (b)
Residential with outside space and farm residences	L_{dn}	45		45	55		55
	$L_{eq(24)}$		70			70	
Residential with no outside space	L_{dn}	45		45			
	$L_{eq(24)}$		70				
Commercial	$L_{eq(24)}$	(a)	70	70 (c)	(a)	70	70 (c)
Inside transportation	$L_{eq(24)}$	(a)	70	(a)			
Industrial	$L_{eq(24)}$ (d)	(a)	70	70 (c)	(a)	70	70 (c)
Hospitals	L_{dn}	45		45	55		55
	L_{eq}		70			70	
Educational	L_{eq}	45		45	55		55
	$L_{eq(24)}$ (d)		70			70	
Recreational Areas	$L_{eq(24)}$	(a)	70	70 (c)	(a)	70	70 (c)
Farmland and unpopulated land	$L_{eq(24)}$				(a)	70	70 (c)

Code:

(a) Since different types of activities appear to be associated with different levels, identification of a maximum level for activity interference may be difficult except in those circumstances where speech communication is a critical activity.

(b) Based on lowest level

(c) Based only on hearing loss

(d) An Leq(8h) of 75 dB may be identified in these situations so long as the exposure over the remaining 16 h per day is low enough to result in a negligible contribution to the 24-h average, i.e., no greater than an Leq of 60 dB.

Note: Explanation of identified level for hearing loss: the exposure period which results in hearing loss at the identified level is a period of 40 years.
* Refers to energy rather than arithmetic averages

Reference: *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety*, U.S. Environmental Protection Agency, 550/9-74-004, March 1974.

World Health Organization (1993)

In 1993, the World Health Organization (WHO) published recommended guidelines for protection against noise. These values are primarily oriented towards criteria such as sleep disturbance, annoyance, and speech interference. They are based on results from numerous laboratory and field studies and are very similar to the EPA guidelines. The WHO target values are:

- To protect the majority from being moderately annoyed, the noise level (L_{EQ}) should not exceed 50 dB.
- To protect the majority of people from being seriously annoyed during daytime, the level (L_{EQ}) from steady, continuous noise in outdoor living areas should not exceed 55 dB.
- At night, outdoor levels (L_{EQ}) should not exceed 45 dB, so that the recommended level of 30 dB inside bedrooms for steady state continuous noise can be met with the windows open.

People react differently to the same noise source. What is annoying to one person, may not be noticeable to another. No matter how low the sound level, as long as it is audible, someone will object to it for one reason or another. Numerous studies have been done of the effect of noise from traffic and aircraft sources. A compilation of these studies shown in Figure 7, shows a surprising correlation between the measured noise level (measured in L_{DN}) and the % of people who are highly annoyed by that level. A curve fit of this data results in an equation:

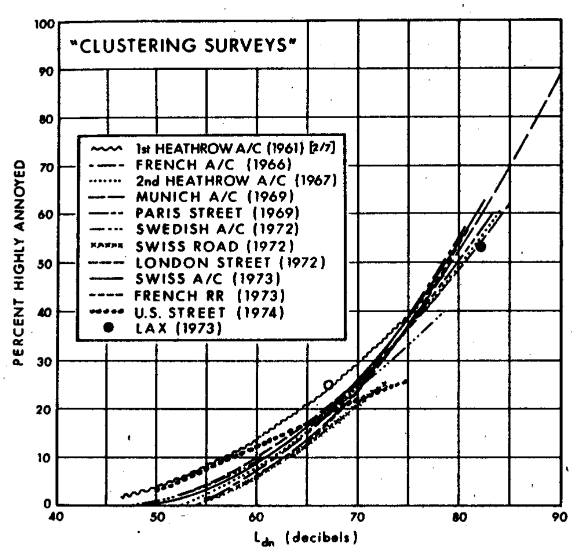

Figure 7. Summary of annoyance data from eleven surveys that show close agreement (ref. T. J. Schultz, Synthesis of social surveys on noise annoyance, Journal of the Acoustical Society of America, Vol. 64(2), August 1978)

$$\%\text{Highly Annoyed} = 0.8553\, L_{DN} - 0.0401 L_{DN}^{2} + 0.00047 L_{DN}^{3} \qquad \text{Equation 9}$$

Using this equation, a L_{DN} value of 55 would result in an estimated 4% of the population being highly annoyed.

Day-nite level (L_{DN})	% Highly Annoyed (by equation 9)
50	1.3
55	3.9
60	8.5

Various State and Local Regulations

State regulations for noise are unusual but one state that has taken a leadership role in this area is Connecticut. Permissible levels are specified for community and environmental noise. The most stringent level is for residential areas at night (45 dBA). Connecticut regulations also define limits for impulse noise, prominent pure tones , ultrasonic and infrasonic noise and the presence of high ambient background levels. The complete text of the Connecticut regulation is included in the Bell and Bell text. Where no state rules are applicable, all municipal governments will generally have at least some sort of "nuisance law" which can be applied to noise which disturbs the peace (i.e. generates a complaint from a citizen). However, these laws are highly subjective in application, and are difficult to enforce and adjudicate. To avoid these problems, many municipalities have well defined, quantified noise ordinances. A representative exmple is the noise standard for New York City. Noise limits are in terms of Leq, measured over a 1 hour period. Consideration is given to the land use zoning, with higher levels permitted in industrial and commercial areas, and during daylight hours (7am-10pm). A relatively simple sound level meter, with A-weighting, and equipped to perform a one hour average, is needed to acquire the data.

The noise regulations for the city of Boston are also shown in Bell and Bell. In this case, maximum levels are specified in octave bands from 31.5 to 8000 Hz. This requires more data to be recorded and a more elaborate (and expensive) sound level meter. The overall limits for Boston (if the individual octave band levels are mathematically combined)of 60 dBA for daytime and 50 dBA for nightime in residential areas, are equivalent to the New York values. Both cities exceed the EPA guidelines by 5 dB, probably due to the traffic and economic realities of big city life. Smaller, more rural communities generally place a higher value on quality of life and may be less tolerant of noise. This attitude is epitomized by the Canadian noise standard which specifies that any noise source which can be heard over the background level of traffic is too loud. One last example is cited, that of Ferguson Township, PA, a mixed rural, light industrial, and residential area which includes part of State College. No daytime noise limits are specified. Nightime limits (from 7 pm - 7 am) are 55 dBA at the boundaries of residential zones and 62 dBA at the boundaries of commercial zones.

8. U.S. NOISE REGULATION SUMMARY

Table 5. Summary of noise regulations from various sources

Agency	Noise Source	Criteria	Level Limit
OSHA, 1978	Any	Protection from hearing loss	90 dBA for 8 hour work day
EPA, 1972	Any	Health and well-being with 5 dB safety margin	55 Ldn
FAA-DOD, 1964	Aircraft	Essentially no complaints Vigorous complaints	< 65 Ldn > 65 Ldn
HUD, 1979-80	Aircraft and ground vehicles	Acceptable Normally Unacceptable	< 65 Ldn > 65 Ldn
Joint Federal Agencies	Aircraft and ground vehicles	Compatible Marginally Compatible Incompatible	55 Ldn 55-65 Ldn > 65 Ldn
Federal Hwy Admin. (FHWA)	Ground vehicles	Compatible for motels, residences, churches, etc	< 67 Leq or $< 70\ L_{10}$
Boston, MA	Any	Daytime residential Nighttime residential	< 60 dBA < 50 dBA
Ferguson Township, PA	Any	Commercial Zones Residential Zones (7pm-7am)	< 62 dBA < 55 dBA