CHAPTER

2

Principles of Environmental Noise

Chapter 1 identified 'environmental noise' as being unwanted sound created by human activities that is considered harmful or detrimental to human health and quality of life, while 'noise' was identified as being sound that is 'out of place'. It was also noted that the characterisation of sound as noise is often subjective and it can vary across individuals. Clearly then, the assessment of environmental noise is a highly complex issue. On the one hand, noise is subjective to the individual experiencing noise exposure – it is an issue of perception; on the other, it is a type of sound and all sounds are governed by the same set of physics. This chapter outlines the core principles behind the definition and measurement of sound and we place particular emphasis on practices related to environmental noise. Some simple definitions and equations are presented; an understanding of these is necessary when considering noise control techniques which are discussed later in the book.

There are many adverse effects associated with exposure to environmental noise. These can range from hearing impairment to sleep disturbance to annoyance and even cardiovascular disorders. These relationships are explored in more detail in Chapter 3. In the case of environmental noise, annoyance refers to the non-specific disturbance from noise and may include the reduced enjoyment of an outdoor space or the necessity of keeping one's windows shut at home as a result of noise immission. The level of annoyance an individual experiences due to noise is a complex issue and is governed by numerous and (often) subjective factors. Intermittent noise, noise that stops and starts, is considered to be more annoying than continuous noise while the presence of audible tones (one frequency being heard above other frequencies, e.g., a high-pitched whine) also increases annoyance. Environmental noise also tends to be more bothersome during summer than winter and research suggests that marital status and gender may also play a part a role in the feeling of annoyance caused by noise exposure (Abo-Qudais and Abu-Qdais, 2005; Miedema et al., 2005).

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BOX 2.1

THE STUDY OF ACOUSTICS

Acoustics is the study of the doctrine of sounds. In 1964 Robert B. Lindsay described the scope of acoustics in the broad fields of Earth Sciences, Engineering, Life Sciences and the Arts. He developed a 'Wheel of Acoustics' to describe how acoustics relates to these fields. This highlighted succinctly the inter-disciplinary nature of the study of acoustics.

The word 'acoustics' is believed to have been introduced to the English language by Archbishop Narcissus Marsh (1638–1713). Archbishop Marsh served as provost of Trinity College Dublin (1679–1683) and was responsible for building the first public library in Ireland in 1701. He also invented the word 'microphone' – almost 200 years before the device was invented (An Introductory Essay to the Doctrine of Sounds, 1683).

2.1 SOUND AS A WAVE

Sound is the result of pressure variations in a medium – typically air. Pressure fluctuations above and below atmospheric pressure are detected by the human ear and this results in the sensation of hearing. Sound can also propagate through solid structures and water. Most will be familiar with SONAR (sound navigation and ranging) systems which use sound to detect objects under the surface of water. A ship using SONAR sends a sound wave into its surrounding liquid environment. When this sound hits an object it reflects back and, by analysing the reflected sound, operators on the ship can locate underwater objects in any direction.

Sound travels in the form of a wave. Figure 2.1 shows the waveform of a simple 'sine' wave (which would sound like a pure tone, e.g., a whistle).

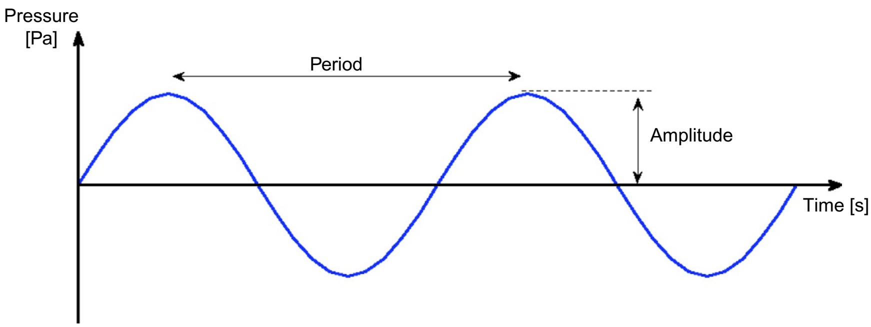

FIGURE 2.1 Simple wave motion – in this diagram the horizontal axis represents time.

The vertical axis corresponds to pressure fluctuations, measured in Pascal, while the horizontal axis represents time.

All sounds have three fundamental characteristics: frequency, amplitude and wavelength.

The frequency of a wave, f, is the number of oscillations per second (or cycles per second). It is expressed in Hertz [Hz] and is named after the German physicist, Heinrich Rudolf Hertz. Sounds with higher frequency are generally heard as sounds with a higher 'pitch' (and variations in pitch create a musical melody); for example, a house alarm has a high pitch.

The time taken to complete one oscillation (repetitive cycle) is called the period, T, measured in seconds. Frequency is related to the period by:

$$f = \frac{1}{T}\,[\mathrm{Hz}] \tag{2.1}$$

The amplitude of a wave is represented by the maximum value of pressure in the vertical direction in Figure 2.1. It corresponds to the amount of energy in the wave. Sounds with higher amplitude have a greater intensity.

The wavelength, λ, is the distance (measured in meters) travelled by a wave during one oscillation. If we plot a wave in the space domain instead of the time domain (Figure 2.2) (i.e. distance is plotted on the horizontal axis instead of time, in order to investigate how the wave changes in space), the wavelength is similar to the period, T, above. The wavelength can be measured between two successive positive peaks in the cycle and corresponds to the physical size of a wave.

2.1.1 Speed of Sound, Wavelength and Frequency

For sound waves in air, the speed of sound generally lies between 330 and 345 m/s. The speed generally depends on air temperature, humidity and atmospheric pressure but 343 m/s is the usual approximation for the

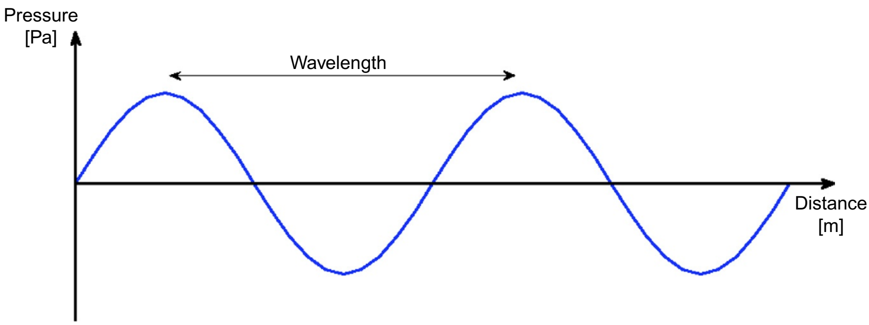

FIGURE 2.2 Simple wave motion – in this example the horizontal axis represents distance.

speed of sound on the surface of the earth (at 20 °C and 1 atmospheric pressure). The speed of sound, denoted by c, allows us to develop a relationship between the period (measured in seconds) and the wavelength (measured in meters).

For a body in motion:

$$\text{Distance} = \text{Speed} \times \text{Time}$$

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}}$$

So, the speed of sound, c, may be calculated from

$$c = \frac{\lambda}{T}$$

But

$$f = \frac{1}{T}$$

Therefore,

$$c = f\lambda \tag{2.2}$$

It follows that a sound wave of frequency 1000 Hz has a wavelength of approximately 0.343 m. The relationship $c = f\lambda$ always holds no matter what the speed of sound.

BOX 2.2

THE SPEED OF SOUND

The speed of sound in water is approximately 1400 m/s (or about four times faster than in air). So the wavelength of a sound wave of frequency 1000 Hz in water is about 1.4 m.

2.1.2 Frequency

Noise is generally made up of a range of different frequencies and not just a single frequency as depicted in Figures 2.1 and 2.2. In fact, the average healthy human ear can detect sounds from about 20 to 20,000 Hz (Table 2.1). When dealing with environmental noise we are rarely interested in sound above 20,000 Hz (ultrasonic frequencies), whereas we are often interested in frequencies below 20 Hz (infrasonic frequencies).

Humans tend to feel infrasound rather than hear it. Sound in this frequency range can also contribute to low-frequency noise issues.

TABLE 2.1 Various Frequency Ranges

Typical Frequency Ranges for Hearing [Hz]	
Human	20–20,000
Dog	40–60,000
Typical Frequency Range of Some Common Sound Sources [Hz]	
Piano	27–4200
Guitar	63–500
Road traffic[a]	50–7000

[a]Note: *For road traffic noise, about 70% of A-weighted sound energy is produced at around 1000 Hz (Sandberg, 2001).*

Low-frequency noise (generally in the range between 20 and 200 Hz) is an issue worthy of some consideration as humans are particularly sensitive to noise in this frequency range (Berglund et al., 1999). The issue of low-frequency noise is addressed throughout the book.

BOX 2.3

SOUND FREQUENCY AND AGEING

It is an unfortunate fact of life that as humans age, our hearing generally begins to deteriorate, both in terms of the frequency and magnitude of the sound we can hear. However, some have recognised the market potential of this issue. For example, high-pitch tones between 10,000 and 20,000 Hz have been played at certain locations (e.g. shopping centres) to deter youths from congregating, whereas adults, with deteriorated hearing, generally cannot hear these higher pitched sounds and are thus unaware of the noise (some questions remain concerning the safety of such devices). Another example includes mobile phone ringtones that claim to be audible to students but are inaudible to the ageing teacher!

Some environmental noise studies may wish to examine the overall noise level across the entire frequency range while other types of studies may wish to examine more closely the frequency content of the noise under observation. This is possible through the use of a frequency spectrum.

Frequency spectrum. Frequency information may be displayed on a graph called the frequency spectrum. Such a graph shows the amplitude of the different frequencies contained in the sound source. For a pure tone

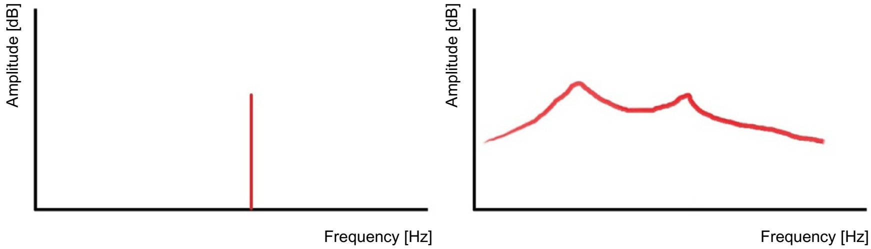

FIGURE 2.3 (a) Spectrum of a single tone (red line); (b) full spectrum across range of frequencies.

the spectrum simply indicates amplitude at a particular frequency (Figure 2.3a). However, in practice, there are frequencies across the entire frequency range of interest and the amplitude of each is shown in the spectrum. In the case of Figure 2.3b, two peaks are observed – these could represent the natural frequency of a system (Box 2.4) and some multiple of this frequency.

BOX 2.4

NATURAL FREQUENCIES AND RESONANCE

All bodies that have a mass and elasticity have a natural frequency (sometimes called the fundamental frequency). The natural frequency of a system is the frequency at which that system will vibrate once it has been set in motion.

The tendency of a system to oscillate with greater amplitude can vary by frequency. Resonance occurs when a system is excited at its natural frequency. When this occurs the amplitude of oscillation of the system can increase significantly. Resonance may be desired or undesired. Some musical instruments rely on resonance to create a favourable timbre. However, undesirable resonance can have devastating consequences. In 1940 the Tacoma Narrows Bridge in Washington (the United States) collapsed due to resonance. The wind that day excited the bridge at one of its natural frequencies and resonance occurred. The bridge began to oscillate and a torsional (twisting) motion developed – ultimately causing the bridge to collapse.

If you tap a wine glass you may hear it ring at its natural frequency. If you sing at this exact frequency you can cause the glass to vibrate through resonance and it might even break!

Certain situations require an analysis of the frequency content of a noise instead of the overall noise level. This requires information expressed across the frequency range. However, if we attempted to analyse each frequency separately, this would result in a huge volume of information. Thus, to make the information more manageable the entire frequency range is usually broken into separate frequency bands.

Octave bands and third octave bands. Octave bands are used to 'group' together different frequencies in a sound, so the frequency information can be analysed easily. Each band covers a specific range of frequencies as identified in Table 2.2. When dealing with octave bands we generally identify each by the 'centre frequency'. Figure 2.4 presents an octave band analysis of a sample noise source. In this example a peak is noted around the 1000 Hz octave band.

BOX 2.5

OCTAVES AND MUSIC

In music, 'Middle C' on a piano is approximately 261 Hz. The C note above this, Tenor C, is an octave above it and has a frequency of approximately 522 Hz – double the frequency of Middle C. Thus an octave corresponds to a frequency ration of 2:1, i.e., a doubling of frequency.

The 1/3rd octave band approach is similar to the octave band analysis, but third octaves are used instead, i.e., there are three bands per octave instead of one. This approach allows for a more detailed analysis and, given the capabilities of today's sound level meters, should be considered the standard approach. Table 2.3 defines the frequency range for each one-third octave band.

TABLE 2.2 The Range of Frequencies Covered by Octave Bands

Lower Band Limit [Hz]	Centre Frequency [Hz]	Upper Band Limit [Hz]
44	63	88
88	125	177
177	250	355
355	500	710
710	1000	1420
1420	2000	2840
2840	4000	5680
5680	8000	11,360

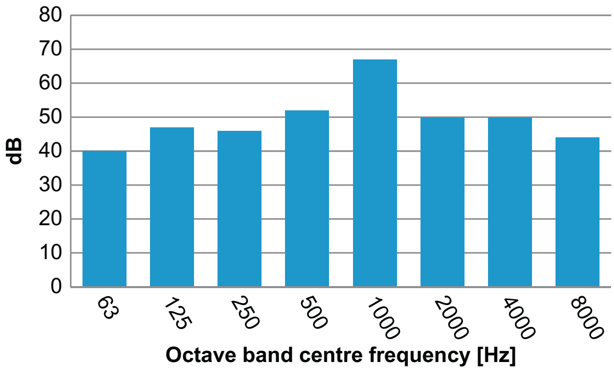

FIGURE 2.4 A noise sample represented in Octave bands.

2.1.3 Broadband vs. Tonal Noise Sources

A noise source is often discussed in terms of its frequency content. A *broadband noise source* has acoustic energy spread out across a wide range of frequencies, whereas a *tonal noise source* has a lot of energy concentrated at certain frequencies – resulting in an audible tone or tones. Examples of broadband sources include gas exhausts or TV static; by way of contrast, a kettle whistling when boiled has a strong tonal content. If a noise source contains an audible tone, it can often be perceived as being much more annoying than a broadband source.

To account for the tonal aspect of some noise sources, some standards describing environmental noise assessment (for example, ISO 1996-2 (ISO 1996-2:2007, 2007) and BS 4142 (BS 4142:1997, 1997)) include a rating level which accounts for the tonal elements in the noise spectrum. This involves adding an adjustment to the measured noise level in order to better describe public response to a more annoying noise source.

In general, the presence of a tone can be determined by comparing the level in one one-third octave band to the level in the two adjacent bands. ISO 1996-2 suggests a simplified method to identify the presence of a tone in this manner. This method tests if the sound pressure level in the one-third octave band of interest exceeds the sound pressure level in both adjacent bands by a constant level difference. This level difference varies with frequency as follows:

- 15 dB in the low-frequency one-third octave bands (25–125 Hz),
- 8 dB in middle-frequency bands (160–400 Hz),
- 5 dB in high-frequency bands (500–10,000 Hz).

TABLE 2.3 The Range of Frequencies Covered by One-Third Octave Bands

Lower Band Limit [Hz]	Centre Frequency [Hz]	Upper Band Limit [Hz]
44.7	50	56.2
56.2	63	70.8
70.8	80	89.1
89.1	100	112
112	125	141
141	160	178
178	200	224
224	250	282
282	315	355
355	400	447
447	500	562
562	630	708
708	800	891
891	1000	1122
1122	1250	1413
1413	1600	1778
1778	2000	2239
2239	2500	2818
2818	3150	3548
3548	4000	4467
4467	5000	5623
5623	6300	7079
7079	8000	8913
8913	10,000	11,220
11,220	12,500	14,130
14,130	16,000	17,780
17,780	20,000	22,390

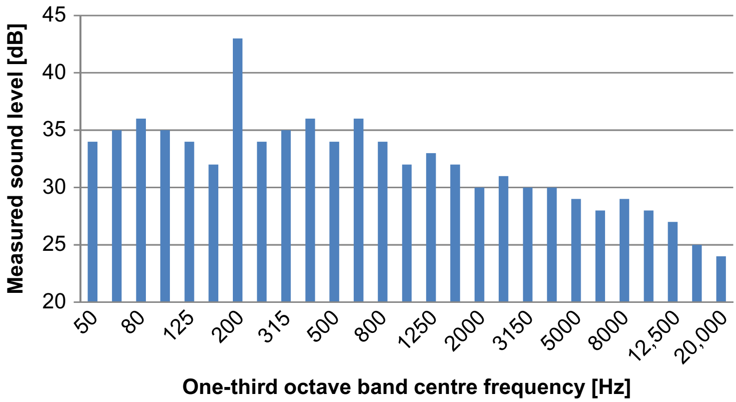

FIGURE 2.5 Investigating the presence of a tone using the ISO 1996-2 simplified method.

In the example in Figure 2.5 there appears to be a tone in the 200 Hz one-third octave band. The level in this band is 43 dB and the levels in the two adjacent bands are 32 and 34 dB. Using the simplified procedure above it may be concluded that a tone is indeed present as the level difference between the 200 Hz one-third octave band and the two adjacent bands is greater than 8 dB for both.

2.2 REPRESENTING SOUND LEVELS WITH THE DECIBEL SCALE

Sound is commonly measured using the decibel [dB] scale. Put simply, the decibel is a ratio of one pressure to another. It uses a logarithmic scale and thus reduces a large range of information down into something more manageable – it enables us to deal with very large and very small numbers with some ease. The Richter scale used to measure earthquake intensity is also a logarithmic scale. In terms of environmental noise the sound pressure level, L_p, in decibels is calculated from:

$$L_p = 10\log_{10}\left(\frac{p}{p_0}\right)^2 [\text{dB}] \qquad (2.3)$$

where p is the sound pressure being measured and p_0 is the reference sound pressure; 2×10^{-5} N/m^2 (or 20 μPa).

The reference sound pressure corresponds to the lowest sound pressure a healthy human ear can detect at 1000 Hz. Thus the decibel is a logarithm of a ratio of one sound against the lowest sound a healthy human ear can hear.

BOX 2.6

THE DECIBEL SCALE AND THE HUMAN EAR

The decibel scale was originally developed to express signal loss along telephone wires. It replaced the concept of a decrease in signal strength along a standard telephone line, measured in 'Miles of Standard Cable'. This unit was termed the 'bel' – named after Alexander Graham Bell. However, the bel was too large a unit to work with, so the decibel (one tenth of a bel) was born.

The human ear truly is a wonderful tool. No microphone can replicate the dynamic range of the human ear. The ear can respond to sounds up to about 120 dB without causing pain. This corresponds to a ratio of intensities of over a billion to 1.

Because the decibel scale is logarithmic, it is quite different to other linear units of measurement (e.g. metres, seconds, etc.). However, the human ear responds to sound pressure in a similar logarithmic fashion. This makes the decibel an ideal measurement unit for working with sound.

BOX 2.7

THE LOGARITHMIC SCALE

Because the decibel is a logarithmic scale, it is worthwhile to summarise some simple mathematical rules for working with logarithmic values:

Multiplication or division inside a logarithm can be represented as addition or subtraction:

$$\log_{10}(a) + \log_{10}(b) = \log_{10}(ab)$$
$$\log_{10}(a) - \log_{10}(b) = \log_{10}\left(\frac{a}{b}\right)$$

When you raise a logarithm to a power you can instead bring that power to the front of the equation:

$$\log_{10}(a^n) = n\log_{10}(a)$$

2.2.1 Sound Power, Sound Pressure and Sound Intensity

At this point it is important to differentiate between sound pressure level (L_p), sound power level (L_W) and sound intensity level (L_I).

Sound pressure. The sound pressure level, as defined above, is the level of sound, expressed in decibels relative to the threshold of hearing.

Sound power. Sound power is the acoustic energy emitted by a sound source over time and is a property of the sound source alone. It is measured in terms of Watts [W] – the standard unit for power.

Sound intensity. Sound intensity is a quantity that describes the rate of flow of acoustic energy per unit area in a certain direction. Because intensity has a direction associated with it, it is a vector quantity (as opposed to sound pressure which is a scalar quantity as it has a magnitude only).

If a sound power W passes through an area S, the sound intensity is given by:

$$I = \frac{W}{S} \tag{2.4}$$

expressed in W/m^2. Consider now a point source propagating in open air. Its energy will be spread out in the shape of a sphere and the size of this sphere will increase the further the sound propagates from the source. The surface area of a sphere is given by $A = 4\pi r^2$, where r is the radius of the sphere (in this case, the distance from the source). So the sound intensity at a distance r from a point source of sound power W is given by:

$$I = \frac{W}{4\pi r^2} \tag{2.5}$$

Sound pressure and *sound power* are often confused in acoustics. Take, for example, a vacuum cleaner switched on and placed on a chair in the centre of a room. This will approximate a relatively constant broadband noise source. If you take a sound level meter and measure the sound level directly in front of the vacuum cleaner, 2 m from the side of the vacuum cleaner and 3 m behind the vacuum cleaner, the measured results will be quite different. This is because what you have just measured is the sound pressure level and it is dependent on a variety of external conditions including, *inter alia*, the orientation of the microphone, its distance from the source, reflections from the room walls, floors and ceilings. Note though that the radiated sound energy from the vacuum cleaner does not change. Every noise has a source and the source of noise (in this case the vacuum cleaner) is described in terms of a sound power level. Sound power is a property of the source alone and as such is often used to compare the sound rating levels of different equipment types. In environmental noise studies the sound source is generally referred to in terms of a *sound power level*; it is the *sound pressure level* that is measured at different distances from the source.

BOX 2.8

EMISSION VERSUS IMMISSION

Noise *emission* and noise *immission*, both measured in terms of decibels, are terms often incorrectly interchanged. Noise emission refers to the noise emitted by the source, in essence the sound power of the source. However, in environmental studies we are often more interested in the noise immission – this is the noise experienced by individuals. Noise emission is dependent on properties of the source, while noise immission is dependent on everything between source and receiver, e.g., multiple sources, the presence of obstacles, the ground cover, etc.

2.2.1.1 Reference Values

Sound pressure, sound power and sound intensity may all be expressed in terms of decibels. Recall that a decibel is simply a ratio between two values. In acoustics, one of these values is always a reference value and in the case of sound pressure level, the reference level corresponds to the threshold of hearing, 20 μPa (recall pressure is measured in Pascal). However, sound power is measured in terms of Watts while sound intensity is measured in terms of Watts/m^2. Thus, different reference levels are used for both.

In the case of sound power the reference value $W_0 = 10^{-12}$ W is used, while in the case of sound intensity the reference value is $I_0 = 10^{-12}$ W/m^2, such that:

$$\text{Sound power, } L_W = 10\log_{10}\left(\frac{W}{W_0}\right) \tag{2.6}$$

$$\text{Sound intensity, } L_I = 10\log_{10}\left(\frac{I}{I_0}\right) \tag{2.7}$$

The reference value for sound intensity, I_0, also represents the intensity at the threshold of hearing and it is for this reason it was chosen as the reference level. Because the sound pressure and sound intensity scales are both referenced to the threshold of hearing, in simple cases the decibel reading can be assumed to be identical for both (Watson and Downey, 2013). Some slight differences may arise because the sound pressure considers sound from all directions but the sound intensity is concerned with one point source over a surface area. However, in general:

$$L_p = 10\log_{10}\left(\frac{p}{p_0}\right)^2 = 10\log_{10}\left(\frac{I}{I_0}\right) = L_I \tag{2.8}$$

2.2.2 Typical Decibel Levels

The decibel may be an unfamiliar scale to some but typically we deal with noise levels between 30 and 100 dB(A)[1] in everyday life. Noise levels below 35–40 dB(A) are usually necessary for a good night's sleep; a busy office may be about 60 dB(A) while the noise level on a footpath beside a busy road might be approximately 75 dB(A) and a departing jumbo jet may result in 120 dB(A) being recorded along the runway. Figure 2.6 displays some typical noise levels and examples of their sources.

The human ear can detect changes in decibel levels, but the level of response is worth noting (Table 2.4). In general, a healthy ear would just about perceive a change in noise level of about 3 dB while a change in noise level of 10 dB would be perceived as an approximate doubling of loudness.

Interestingly, complete silence is rarely experienced by humans. Purpose-built rooms such as anechoic chambers (Figure 2.7) are used to

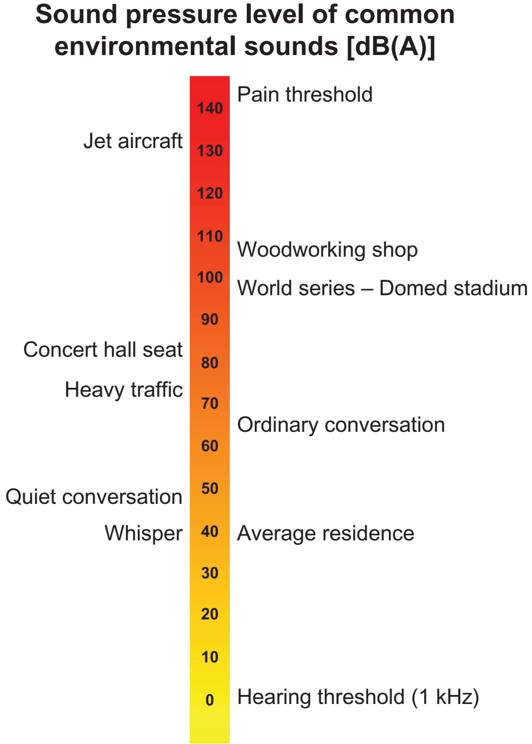

FIGURE 2.6 Typical sound pressure levels of noise sources.

[1]See Section 2.3 for an explanation of A-weighting [dB(A)].

TABLE 2.4 Subjective Effect of Changing Noise Levels

Change in dB Level	Subjective Response
3 dB	Just perceptible
5 dB	Clearly perceptible
10 dB	Twice as loud

FIGURE 2.7 Example of acoustic tests being performed in an anechoic chamber at the University of Hartford, USA (anechoic means non-echoing).

perform acoustic tests and can achieve extremely low noise levels. Sometimes working in such rooms can have a disorientating effect on humans because they have no experience of such low sound levels. In a very quiet environment, the flow of blood in vessels near the eardrum may even be audible as a disquieting shushing sound (Long, 2006).

2.2.3 Working with Decibels

Because the decibel is a logarithmic scale, decibel levels cannot be added or subtracted in the normal arithmetic fashion, but rather decibel levels must be added logarithmically. Thus, two sound levels, L_1 and L_2, are added together in the following way to get a total sound level L_{tot}:

$$L_{tot} = 10 \log_{10}\left(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}}\right) \tag{2.9}$$

BOX 2.9

WORKING WITH DECIBELS – AN EXAMPLE

Example: A sound level meter measures the sound level 1 m away from an idling lawnmower. It records the noise level as 60 dB. Now a second lawnmower, with the exact same sound power as the first, is turned on beside the sound level meter, again at 1 m away. What sound level would the meter now record?

Answer: It is reasonable to assume that the sound level meter is subjected to two noise sources both resulting in 60 dB at its position. So the total noise level that is recorded will be equal to the summation of the two sound levels, 60 dB and 60 dB. This calculation is performed logarithmically as follows:

$$L_{\text{tot}} = 10\log_{10}\left(10^{\frac{60}{10}} + 10^{\frac{60}{10}}\right)$$

$$\rightarrow L_{\text{tot}} = 63\,\text{dB}$$

From the example in Box 2.9 we can deduce that a doubling of the sound source corresponds to a 3 dB increase in the sound pressure level.

There are simple approximations that can be applied to simple situations instead of always reverting to logarithmic addition. In the above example, if the second lawnmower was 65 dB the total level would be 66 dB. This can be obtained using the logarithmic addition above or by using Table 2.5. This simple table can be used to combine sound levels. Depending on the difference between the two sound levels the table outlines a number to be added to the greater sound level in order to arrive at the total value.

From Table 2.5 it is evident that any noise that is 10 dB or greater than a second noise level will require no correction (e.g. 80 dB + 70 dB = 80 dB). In such a case the noise heard at the receiver would be the same sound pressure level whether the second (lower) sound source was present or not.

2.3 A-WEIGHTING

The human ear does not respond equally to sounds at different frequencies; we tend to perceive sounds at a lower frequency as having a lower intensity. In 1933, Fletcher and Munson published a set of equal-loudness curves describing the manner in which the ear responded to sound at different frequencies (Fletcher and Munson, 1933). Fletcher and Munson

TABLE 2.5 Table for Adding Sound Pressure Levels

Difference Between the Two Levels [dB]	Amount Added to the Higher Level [dB]
0	3
1	3
2	2
3	2
4	1
5	1
6	1
7	1
8	1
9	1
10	0

investigated how people reacted to sounds played at different frequencies at the same intensity. For example, they played a tone at 1000 Hz then played another at 500 Hz and a test subject was asked to adjust the second tone until it was perceived as being the same intensity as the first. They then repeated the experiment for a variety of frequencies and intensities and developed equal-loudness contours for each intensity. A-weighting, which is commonly used in environmental noise studies, was developed as a result of this work.

BOX 2.10

LOUDNESS

There is a growing research area called psychoacoustics which examines the psychology behind how people perceive sound. Loudness is a quantity used in psychoacoustics to measure the subjective impression of the intensity of sound. Since it is dependent on the perception of individuals, loudness is an unsuitable quantity for quantitative environmental noise assessments. Also because the term 'loudness' is used in psychoacoustics, it is rarely referred to in studies of environmental noise. For example, one might say that one sound source has a greater intensity than another, but will rarely say that one is 'louder' than another. Loudness is measured in 'phons'.

Building on the initial work of Fletcher and Munson, we now know that the human ear does not perceive a 60 dB sound at 100 Hz to have the same intensity as a 1000 Hz signal played at 60 dB. In fact, the ear perceives sound at 100 Hz as nearly 20 dB lower in magnitude than at 1000 Hz. To account for this we use a weighting system in environmental noise studies to try and replicate the performance of the human ear.

The A-weighting curve follows the general pattern of the 40 phon curve developed by Fletcher and Munson. It is represented in Figure 2.8 along with another weighting curve often used in environmental noise assessments – the C-weighting curve. Numerical values representing these curves are presented in Table 2.6.

The use of A-weighting has become the *de facto* accepted descriptor for environmental noise and numerous studies have shown that A-weighted sound levels provide an acceptable correlation with human response to different noise sources. This will be discussed in more detail in Chapter 3.

2.3.1 Other Weightings

Other weightings have also been developed. While A-weighting follows the 40 phon curve, C-weighting follows the 100 phon curve and provides a much flatter frequency weighting (Figure 2.5). Because of its flatter

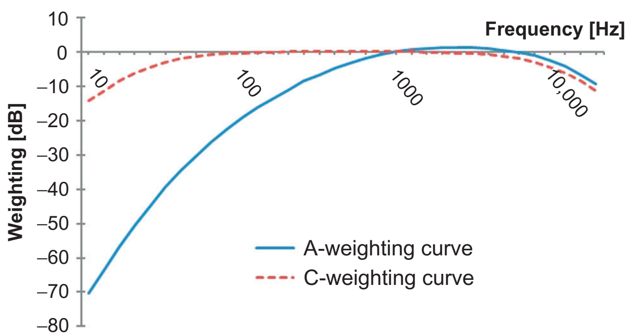

FIGURE 2.8 A-weighting and C-weighting curves.

TABLE 2.6 A-Weighting and C-Weighting Corrections in Octave Bands

Octave Band Centre Frequency [Hz]	63	125	250	500	1000	2000	4000	8000
A-weighting correction [dB]	−26	−16	−9	−3	0	+1	+1	−1
C-weighting correction [dB]	−1	0	0	0	0	0	−1	−3

response, C-weighting is often used when measuring noise peaks. In some situations we may wish to investigate the peak noise level of an impulse (such as a loud bang associated with a sledgehammer blow). C-weighting gives a better representation of the amount of energy contained in an impulse. Noise levels are often reported as dB(A) to indicate A-weighting, dB(C) to indicate C-weighting and dB (or dB(Z)) to indicate no weighting was applied.

BOX 2.11

THE A-WEIGHTING CURVE

The predominant use of A-weighting has been heavily criticised in the past (St Pierre and Maguire, 2004). It has been argued that the equal-loudness contours were developed using single tones and are therefore only applicable to single tone sounds. Furthermore, the relationship between dB(A) measurements and loudness can break down as the sound pressure increases and A-weighting is also a poor descriptor for intermittent noise and for noise with strong low-frequency content.

Given the capabilities of today's instrumentation, it would certainly be worthwhile investigating an alternative to A-weighting – as it stands we are using weighting that is based on work that was conducted nearly 80 years ago. However, how the acoustics community might adapt to any alternative approach remains to be seen.

2.4 NOISE METRICS

A noise indicator or metric is used to reduce a large volume of information about a noise situation into a single number system. It is designed to make the information easy to handle, but still provides accurate information about the noise environment. Environmental noise assessments are generally undertaken to prevent the harmful effects of noise including annoyance and public health problems. In order to assess the extent of these harmful effects, noise is usually assessed in terms of a single indicator (usually this will include A-weighting). Depending on the type of noise, and relevant legislation in a country, the indicator can take many different forms.

BOX 2.12

THE HISTORY OF SOUND LEVEL METERS

In the early days of acoustic measurements, analogue sound meters incorporated a needle which moved over a scale and the time history of the noise was recorded by attaching the meter to a graphic recorder. If the noise level was constantly fluctuating the needle could move rather fast making it difficult to identify the noise level. As such, operators were able to change the 'reaction time' of the sound level meter to fast or slow. The fast setting corresponded to a time constant of 0.125 s while the slow time constant was 1.0 s. These constants were set in standards and are still incorporated in sound level meters today. The subscript 'F' signifies that the fast time constant has been used while 'S' signifies that the slow time constant has been used.

Because the L_{eq} indicator represents the average noise level over time there is no time constant associated with it (the L_{eq} indicator is described in more detail in Section 2.4.1).

There are three broad categories of time-varying noise. They are as follows:

- *Continuous noise*: Noise that is fairly constant over time may be classed as continuous noise. A good example of a source of this type of noise is a continuously operating air conditioning unit.
- *Intermittent noise*: Noise that stops and starts, usually at irregular intervals, is considered to be an intermittent noise. For example, the intermittent use of a saw in a timber plant or the stop-start of a forklift in a warehouse would produce this type of noise.
- *Impulsive noise*: Noise that carries a sudden sharp sound or a sudden bang of short duration such as a gunshot or a sledgehammer blow.

A person is entitled to ask how one measures a value that may be constantly varying. The answer is that nearly all types of noise measurements and indicators describe the noise level over a specified time period. Let us consider different types of metrics used to represent noise.

2.4.1 Continuous Equivalent Noise Level: L_{eq}

Probably the most common type of noise descriptor is the equivalent continuous noise level over a time period T, $L_{eq,T}$. This metric is an energy-based indicator as it represents the total amount of acoustic energy over the specified time period. It is the continuous steady sound level that would have the same total acoustic energy as the fluctuating noise measured over the same period of time. It may be defined as:

$$L_{(\mathrm{eq},\,T)} = 10\log_{10}\frac{1}{T}\int_0^T\left(\frac{p(t)}{p_0}\right)^2 \mathrm{d}t\,[\mathrm{dB}] \tag{2.10}$$

where T is the time period over which measurements occur, $p(t)$ is the instantaneous acoustic pressure and p_0 is the reference sound pressure level (20 μPa).

Graphically it is explained in Figure 2.9. The time-varying noise signal (in blue) is measured over a time T. The amount of energy in this signal is equivalent to the amount of energy contained in a continuous noise level L_{eq} over this same time period (red).

2.4.2 Statistical Indicators: L_{10}, L_{90}, etc.

In some cases, statistical indicators are used to represent noise levels. These indicators report the level of noise exceeded for a certain percentage of the measurement time. Although there are a large variety of statistical indicators, two of the most common are L_{10} and L_{90}. L_{10} represents the noise level exceeded for 10% of the time. For example, an $L_{10,1\mathrm{h}}$ level of 65 dB means that for 6 minutes in that hour (10% of the time) the noise level exceeded 65 dB. L_{90} represents the noise level exceeded for 90% of the time and the L_{90} indicator is often used to describe the background noise level. Figure 2.10 demonstrates in relative terms how the L_{eq}, L_{10} and L_{90} values might look for a sample of varying noise.

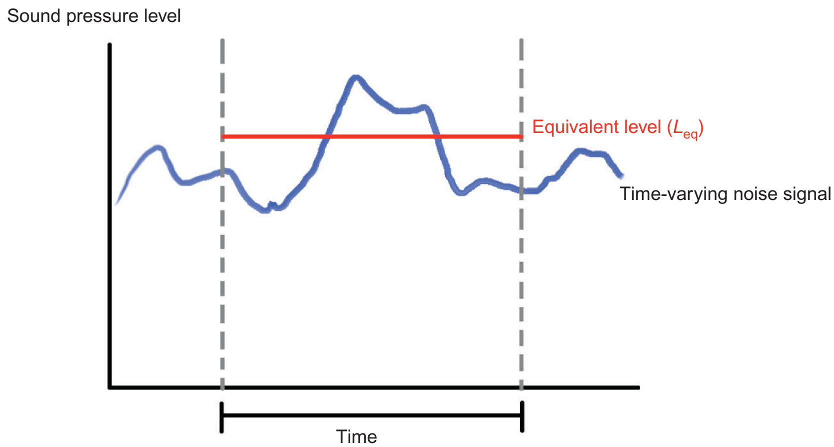

FIGURE 2.9 The L_{eq} level.

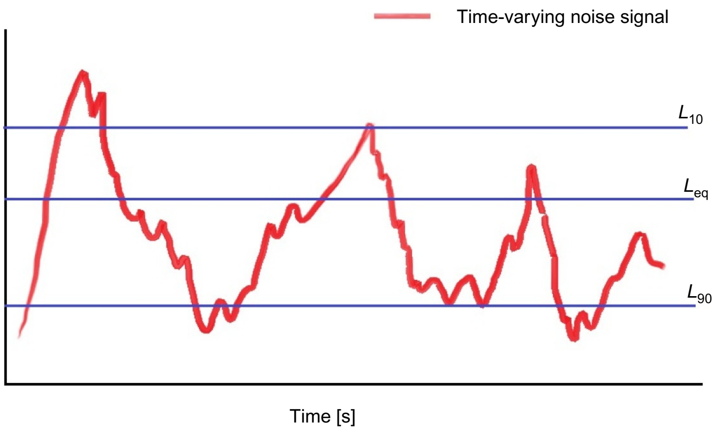

FIGURE 2.10 The L_{eq} level compared with statistical levels.

Although there is no mathematical relationship between L_{eq} and L_{10}, scholars have developed statistical relationships to relate a statistical indicator to an approximate L_{eq} level. For example, for the case of road traffic noise on motorways in the United Kingdom, the following relationship has been developed (Abbot and Nelson, 2002):

$$L_{\mathrm{Aeq,1h}} = 0.94 \times L_{\mathrm{A10,1h}} + 0.77\ [\mathrm{dB(A)}] \tag{2.11}$$

This equation develops a relationship between the standard metric for road traffic noise in the United Kingdom (which is based on the L_{10} index) to the universal European Noise indicators (which are based on the L_{eq} index). This is discussed in more detail in Chapter 5.

2.4.3 Universal EU Noise Indicators L_{den} and L_{night}

EU Directive 2002/49/EC developed two universal noise indicators to be used for the development of strategic noise maps across the EU, L_{den} and L_{night}. These indicators are derivatives of the L_{eq} indicator. L_{den} is the day, evening, night noise indicator and may be calculated from:

$$L_{den} = 10\log_{10}\left(\frac{1}{24}\right)\left(12.10^{\frac{L_{day}}{10}} + 4.10^{\frac{L_{evening}+5}{10}} + 8.10^{\frac{L_{night}+10}{10}}\right)[\mathrm{dB(A)}] \tag{2.12}$$

where L_{day} represents the A-weighted long-term average day-time noise level (between the hours of 07:00 and 19:00 measured) over 1 year, $L_{evening}$ represents the A-weighted long-term average evening-time noise level (between the hours of 19:00 and 23:00) measured over 1 year and L_{night} represents the A-weighted long-term average night-time noise level (between the hours of 23:00 and 07:00) measured over 1 year.

The additional weighting factors (+5 for $L_{evening}$, +10 for L_{night}) are included to account for the fact that noise is generally more annoying and problematic for public health in the evening and night periods. L_{den} is used to represent a value for overall annoyance, while L_{night} represents an indicator for sleep disturbance. The weighting factors for $L_{evening}$ and L_{night} were chosen as it is almost certain that night-time levels are usually about 10 dB lower than day-time levels and evening levels were somewhere in between (European Commission, 2000). As a result of this additional weighting, L_{den} will almost always exceed the individual L_{day}, $L_{evening}$ and L_{night} values (Figure 2.11).

It should be noted that while L_{den} and L_{night} may be useful indicators for planning purposes, they represent long-term average levels and as such may be regarded as unsuitable tools to assess short-term situations, which are often the source of noise complaints to authorities. Thus, in some cases it may be advantageous to use special noise indicators and related limit values. Some examples of when these might be appropriate include when the noise source under consideration operates for only a small proportion of time, the noise contains strong tonal components or the noise has an impulsive character. The possibility of introducing these 'custom-made' noise indicators is important to better represent the problems associated with noise.

2.4.4 Other Common Metrics

Maximum and Minimum Levels, L_{max} *and* L_{min}

L_{max} and L_{min} represent the maximum and minimum sound level measured over the measurement period. They are measured either over the fast or slow time constant (Box 2.12).

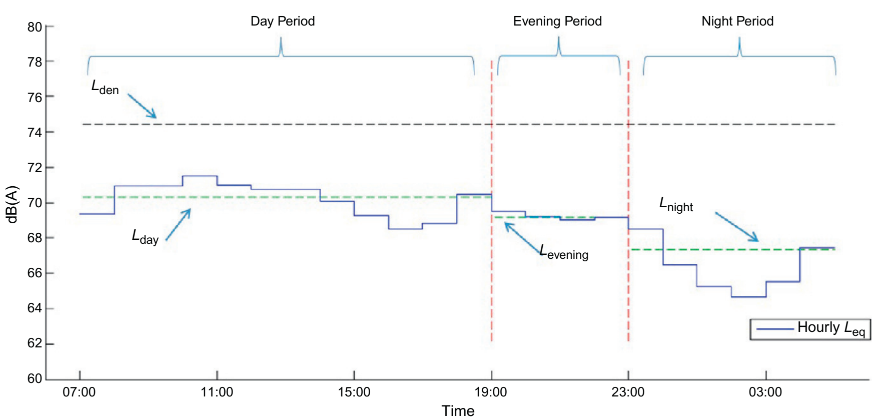

FIGURE 2.11 Typical values for L_{den}, L_{day}, $L_{evening}$ and L_{night}.

Peak, L_{peak}

L_{peak} (or sometimes L_{pk}) is not the same as $L_{\max}$. L_{peak} is the maximum value reached by the sound pressure with no time constant applied. This is the true peak of the sound pressure wave. L_{peak} is usually expressed with C-weighting. This is because C-weighting has a flatter response than A-weighting. L_{peak} is commonly used for the assessment of impulsive noise.

Sound Exposure Level

The Sound Exposure Level (SEL) of a noise event is the constant level which, if maintained for only 1 second, would contain the same A-weighted noise energy as the actual event itself. Essentially, it is an A-weighted L_{eq} level normalised to 1 second. The SEL is often used in railway noise assessments allowing an easy comparison of different train types. Furthermore, the $L_{\mathrm{eq},T}$ level over any time period can be calculated directly from the SEL of an event. If there are several identical events occurring over a time period, the $L_{\mathrm{eq},T}$ level can be calculated from the SEL level for each event. Thus, if we know the SEL for a given event (e.g. a train passage), this can be used to calculate the $L_{\mathrm{eq},T}$ level given the number of identical events, N, that occur during the time period, T, from:

$$L_{\mathrm{eq},T} = \mathrm{SEL} + 10\log_{10}(N) - 10\log_{10}(T)\,[\mathrm{dB(A)}] \tag{2.13}$$

Effective Perceived Noise Level

A common noise metric used when assessing aircraft noise is the effective perceived noise level (EPNL). This metric takes into account the observer's response to the disturbing effect of pure tones such as whines or screeches and the duration of a single noise event. Three basic physical properties of sound pressure must be measured to determine the EPNL: the sound level, frequency and time variation.

Day/Night Average Sound Level (L_{dn})

L_{dn} is the weighted average noise level over 24 h with an additional weighting of 10 dB during the night-time hours (between 22:00 and 07:00). It is widely used in the United States. Miedema and Vos suggest there is a relationship between L_{den} and L_{dn} for different types of transportation sources (Miedema and Vos, 1998); for road traffic noise it is:

$$L_{\mathrm{den}} = L_{\mathrm{dn}} + 0.2\,[\mathrm{dB(A)}] \tag{2.14}$$

2.5 MEASURING NOISE

This section aims to provide an introduction to the standard practices behind environmental noise measurements. In truth the methods can be as varied as the topic itself and an entire book could be devoted to noise measurement methodologies alone. However, whatever method is adopted it should usually follow an international or national standard and most national agencies have guidelines that should be adhered to.

The methodology employed for the measurement task will always depend on the purpose of the measurement and the desired information to be drawn from results. For example, measurements may be taken to provide a general overview of the background noise environment prior to a particular industrial development, to check if a wind farm is in compliance with noise limits, to measure the sound power level of a particular source, or to validate noise predictions. All these situations require different methodologies (and most likely different noise metrics). The spectral content of the noise source may also be required. The objective of the measurement campaign must be clearly defined beforehand and this will dictate the time over which the measurement will take place as well as other factors such as measurement position, height and equipment type.

In the case of strategic noise mapping, the general approach is to calculate a long-term average noise level. This is due to the fact that over the course of a year the source emission and propagation conditions may change due to seasonal effects such as the use of snow tyres, winter temperatures or changing ground surface conditions. As such it is often necessary to conduct measurements over different seasons throughout the year in order to better estimate the long-term average level (Imagine Project Report, 2006). It can be quite cumbersome and expensive to conduct noise measurements over a long time period, so studies will often report short-term measurements, and estimate what the long-term level might be on the basis of the short-term data gathered.

2.5.1 A Competent Person

The assessment of noise requires expertise, experience, independence and objectivity. It is common for guidelines to require measurements to be taken by a 'competent person'. This may require a specific set of educational qualifications (e.g. an engineering degree) but in general a competent person should have:

- A good understanding of acoustics and standard measurement practices;
- A detailed knowledge of national standards and guidelines;

- Familiarity with noise monitoring and meteorological measurement equipment;
- An ability to interpret results and identify anomalies in results that warrant further investigation.

2.5.2 Sound Level Meters and Calibration

A sound level meter is an instrument that records the level of sound as well as performing additional analyses on the sound to present usable information to the operator. Today's sound level meters are capable of continuously logging data over long periods, plotting real-time results, performing octave or one-third octave analyses instantaneously as well as many other features that were previously unavailable. Some meters even come equipped with GSM (Global System for Mobile communication) capabilities and can be remotely monitored. Meters also come in all shapes and sizes, ranging from hand-held meters to long-term installations.

IEC 61672 (2002) gives electro-acoustical performance specifications for three kinds of sound level meters: a conventional sound level meter that measures exponential time-weighted sound level; an integrating-averaging sound level meter that measures time-average sound level; and an integrating sound level meter that measures SEL. A single instrument may make any or all three of these measurements. The standard specifies two performance categories for meters: class 1 and class 2. A class 1 sound level meter will have a better response and must meet tighter tolerances in measurements.

All sound level meters must be subjected to regular calibration. To calibrate a sound level meter means to check its response against a known sound source. This ensures that the meter accurately portrays the real noise level. Sound level meters should be calibrated in a laboratory at least once every 2 years. Users should also have a portable calibrator (this will emit a known sound level at a known frequency and thus allow the user to determine if the meter is working correctly). This should be used before and after each sound measurement to ensure their validity. Portable calibrators must also be calibrated in a laboratory on a regular basis (Figure 2.12).

2.5.3 Measurement Period

The duration of the measurement campaign will depend on the purpose of the measurements, the type of source and the desired accuracy of results. For road traffic noise assessments in Italy a monitoring period

FIGURE 2.12 Picture of a portable calibrator. *Courtesy of Copyright © Brüel & Kjaer.*

of 1 week (logging hourly L_{Aeq} levels) is required, whereas environmental assessments of railway noise require only 24 hours (Brambilla, 2001). In Ireland, road traffic noise assessments involve three 15-min L_{10} measurements, taken over 3 consecutive hours between 10:00 and 17:00, coupled with a 24 hours measurement (National Roads Authority, 2004). Research conducted in Spain found that a random days strategy, where 9 days selected at random throughout the year, yielded a good estimate of the long-term average road traffic noise level (Gaja et al., 2003), while another study recommends that a 2-week measuring period can usually be considered sufficiently representative of longer term variation (Alberola et al., 2005). For the case of wind farm noise, a period of at least 1 week's worth of measurements is normally sufficient to avoid the results being weighted by unrepresentative conditions (The Working Group on Noise from Wind Turbines, 1996). Ultimately, the appropriate monitoring period will be determined by the competent person undertaking the noise monitoring, having due regard to best practice in the area. For strategic noise mapping studies, one might take cognisance of the guidance document on using measurements to determine L_{den} and L_{night} produced during the Imagine project (Imagine Project Report, 2006).

Whatever is decided, it should be acknowledged that L_{den} and L_{night} represent long-term average levels and noise measurements rarely cover this period. Thus, measurements should be seen as a tool to complement predictive studies that use these indicators rather than to 'correct' the result to which the study should be aspiring to.

2.5.4 Microphone Position

In general, measurements should be conducted at a height of either 1.5 or 4 m. Strategic noise maps generally predict noise levels at a height of 4 m. The microphone on the sound level meter should generally be positioned at least 3 m away from hard surfaces to minimise the effect of reflections. Alternatively, ISO 1996-2 suggests flush mounting the microphone on a reflecting surface (the *backing board* method). In this case a correction of −6 dB is applied to represent the incident sound field, i.e., to eliminate the impact of reflections. Another option is to position the microphones 0.5–2 m in front of a reflecting façade. In this case a correction of −3 dB must be applied to determine the incident sound field.

2.5.5 Extraneous and Residual Noise

It is important to take note of the different sources operating in the area. Other extraneous noise sources may be present and these have to be accounted for. For example, the dawn chorus (from birds, etc.) has been noted as a possible significant source of extraneous noise (Abbott and Nelson, 2002a), while in Australia, insect noise has been identified as an extraneous source during the summer months (Caley and Savery, 2007).

One must also take note of the residual sound. The residual sound is the total sound remaining at a given position in a given situation when the specific sounds under consideration are suppressed (ISO 1996-2:2007, 2007). ISO 1996-2 states that if the residual sound pressure level is 10 dB or more below the measured sound pressure level then no correction is required. When the residual sound pressure level is within a range from 3 to 10 dB below the measured sound pressure level, then the following correction may be applied:

$$L_{\mathrm{corr}} = 10\log_{10}\left(10^{\frac{L_{\mathrm{meas}}}{10}} - 10^{\frac{L_{\mathrm{resid}}}{10}}\right) \tag{2.15}$$

where L_{corr} is the corrected sound pressure level, L_{meas} is the measured sound pressure level and L_{resid} is the residual sound pressure level.

2.5.6 Measurements for Strategic Noise Maps

Across Europe, noise maps are generally made using predictive techniques and measurements are only undertaken after calculations are complete. The purpose of these measurements is usually an attempt to validate the modelled results; however, no uniform validation method has yet been developed or agreed upon. An alternative approach was adopted in Madrid where, following a detailed measurement campaign, the strategic noise map was developed primarily using measurement data.

BOX 2.13

STRATEGIC NOISE MAPS

Strategic noise maps, created for the purposes of the EU Environmental Noise Directive, do not require validation through measurement. It would be expensive and time consuming to do so and would require a tremendous amount of noise measurements (in both spatial and temporal resolution). The usefulness of such an arduous task would be questionable especially as the results from strategic noise maps feed directly into noise action plans. It would be most appropriate for action plans to require measurements to be completed at certain locations. Authorities can be strategic in the use of these measurements in that they only need to target the problem areas or 'noise hot-spots'.

In 2002 a noise map for the agglomeration of Madrid was made based on 4395 measuring points. However, this measurement-based noise map was expensive and highly complex to produce. This led to the development of a new measurement system to comply with the Directive in a more effective manner, known as the SADMAM (Sistema Actualizacin Dinmica Mapa Acstico Madrid) (Manvell et al., 2004). The main goal of SADMAM was to produce fast and cheap measured noise maps that combined both long-term and short-term noise levels along with a realistic propagation model. Measurements were taken over short periods at strategic locations in the city by mobile noise monitoring terminals, in the form of a SMART car with a microphone fitted to a telescopic pole. These measurements were used to determine source strengths that were input into a prediction model that created the strategic noise map. The source strengths were determined by measuring noise at receiver positions and using an inverse method approach to determine the noise levels at the source.

BOX 2.14

CALCULATION OF ROAD TRAFFIC NOISE – MEASUREMENT METHOD

Some readers may be familiar with the UK's Calculation of Road Traffic Noise (CRTN) method, which was used in some EU Member States for noise mapping (including Ireland and the United Kingdom). This method also includes a method for measuring road traffic noise. The measurement method was originally intended to be used to validate a measured noise level to a standard sound level at a standard distance (representing the emission level at source). It was to be used when traffic conditions fell outside the scope of the prediction method, e.g., for low traffic volumes. However, it has since become the *de facto* measurement standard to determine the baseline noise environment in Ireland, particularly in the development of Environmental Impact Assessments for road schemes. Thus, the method is being used for a purpose which it was never originally intended.

2.5.7 Observations on a Typical Noise Survey for Road Traffic Noise

Consider the task of measuring the average noise from an operational road. This may be in preparation from a road scheme upgrade or might form the basis of an investigation of complaints from road traffic noise in the area. A typical road traffic noise survey might consist of the following considerations:

- The time interval of measurements should be carefully considered. L_{eq} measurements logged in 15-min intervals for a period of 1 week would provide a useful picture of the noise environment. Some standards may only require a 24 h measurement with 1 h time periods while some may require L_{10} instead of L_{eq}, or even both. Some authors have suggested at least 2 weeks continuous monitoring is required to determine long-term noise levels.
- The microphone should be placed away from all reflective surfaces. Noise can be reflected from hard surfaces, e.g., hard walls, and cause an overall increase in the noise levels. If the microphone is positioned directly beside a reflecting surface, results may be impacted by up to 3 dB.
- The microphone height is also important. A first floor bedroom window might be assessed at a height of 4 m, while a ground floor measurement could take place at 1.5 m. For strategic noise mapping, all calculations are performed at a height of 4 m. Thus, for noise prediction validation a standard height of 4 m is appropriate.

- Measurement should not be made during rain or high wind speeds (>5 m/s). The noise from the wind may impact on the diaphragm of the microphone and often the noise from the wind itself may 'drown out' the noise you are trying to measure. It is good practice to synchronise the sound level meter with a meteorological station and log data at the same time interval. Wind speed, wind direction, temperature and precipitation should all be logged and reported.
- The entire measurement system should be field calibrated both at the start and at the conclusion of the measurement, to ensure valid data were taken.
- The location of the measurement equipment should be clearly stated. All measurements should be repeatable and all measurement reports should provide enough data to ensure the measurement conditions may be replicated at a later date.

2.6 OUTDOOR SOUND PROPAGATION

As sound propagates away from a source outdoors, it is attenuated through a variety of attenuation mechanisms. Many different calculation methods may be used to predict the level of this attenuation. In fact, this issue has been widely recognised as it means different noise studies based on different calculation methodologies may not be reliably compared or combined (these issues are discussed further in Chapter 5). In general, the chosen calculation method will define an approach based on theory and empirical formulae and set out procedures for determining the level of noise produced at the source and the attenuation of the noise as it propagates away from the source. Each calculation methodology will vary slightly but all tend to agree on the general process behind sound propagation. This section presents a summary of the most common types of attenuation mechanisms.

Take a simple industrial source as an example. If the receiver is far enough away, the source may be treated as a point source with sound power L_W. The sound pressure level at the receiver, L_p, due to the industrial source is simply

$$L_p = L_W - A_{tot}\,[\mathrm{dB(A)}] \tag{2.16}$$

where A_{tot} represents the total attenuation (Figure 2.13). This equation often includes corrections for reflections or directivity in the source (some sources may not emit sound equally in all directions), but for general purposes it holds.

The total attenuation represents the sum of all forms of attenuation and may be calculated from:

$$A_{tot} = A_{div} + A_{atm} + A_{ground} + A_{diffraction} + A_{misc}\,[\mathrm{dB}] \tag{2.17}$$

Each of these attenuation mechanisms is described in more detail below.

BOX 2.15

POINT SOURCES AND LINE SOURCES

The sound power represents the level of noise coming from any noise source, e.g., a wind turbine blade, an air condition unit, a factory or a vehicle. In simple cases the source may be modelled as a point source. For sources such as a road, it might be more appropriate to represent the source as a line source. However, some standards break up this line source into a collection of incoherent point sources. The sound power level might then represent the sound power per meter length of the road. This is discussed in more detail in Chapter 5.

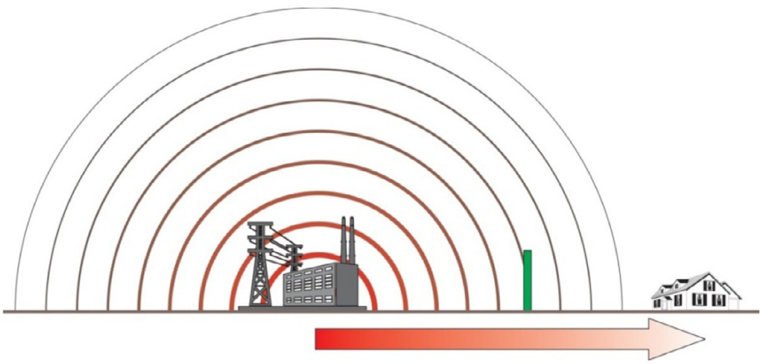

FIGURE 2.13 Different attenuation mechanisms of sound propagating from source to receiver.

2.6.1 Geometric Divergence

As sound propagates away from a source its energy is conserved – but it must be spread out over a wider area. In the case of a simple point source, propagating noise equally in all directions, the energy of the source is spread out over a sphere with surface area $4\pi r^2$. The attenuation due to this geometric divergence, A_{div}, is calculated from

$$A_{div} = 10\log_{10}(4\pi r^2)\,[\mathrm{dB}] \tag{2.18}$$

where r represents the distance from source to receiver. This equation is presented in the French Standard XPS31-133 (AFNOR, 2001).

BOX 2.16

GEOMETRIC DIVERGENCE

Note: In ISO 9613-2 (1996), A_{div} is represented by $20\log_{10}\left(\frac{d}{d_o}\right)+11$. This is equivalent to the above equation when $r=d$ and $d_o=1$ m as demonstrated by the workings below using the rules of logs.

$$\begin{aligned} &A_{div}=10\log_{10}\left(4\pi r^2\right)\\ \rightarrow &A_{div}=10\log_{10}(4\pi)+10\log_{10}\left(r^2\right)\\ \approx &A_{div}=11+10\log_{10}\left(r^2\right)\\ \rightarrow &A_{div}=20\log_{10}(r)+11 \end{aligned}$$

The above equation corresponds to a general rate of 6 dB attenuation per doubling of distance. This rule of thumb is demonstrated by Table 2.7. Attenuation due to geometric divergence at 2.5 m from the source is 19 dB, while the attenuation at 5 m is 25 dB. This attenuation rate is also valid at larger distances (at 200 m $A_{div}=57$ dB; at 400 m $A_{div}=63$ dB). This rule also approximates to a 20 dB reduction for each tenfold increase of distance.

This rule of thumb can be applied when the source of noise may be treated as a point source. Some standards consider a road source as a line source and in this case, sound will propagate from the source in the shape of a cylinder with an ever-increasing radius. As such, the general rule of thumb for a line source changes to a 3 dB reduction per doubling of distance from the

TABLE 2.7 Calculated Values for the Attenuation Due to Geometric Divergence over a Range of Distances

r [m]	A_{div} [dB]
2.5	19
5	25
10	31
20	37
50	45
100	51
200	57
400	63
1000	71

Values have been rounded to the nearest decibel.

source. Attenuation due to geometric divergence is the only form of attenuation that does not depend on the frequency of the sound.

2.6.2 Atmospheric Absorption

As sound propagates through the atmosphere, its energy is gradually converted into heat through a number of molecular processes and this leads to a decrease in the sound level at a receiver point located some distance from the source. At distances close to the source the attenuation due to atmospheric absorption is negligible and only becomes obvious at great distances.

Atmospheric absorption is dependent on four variables: frequency of the sound, atmospheric temperature, humidity and air pressure. ISO 9613-1 provides a range of tables for the attenuation coefficient given certain values of humidity, air pressure, temperature and the frequency of the sound (ISO 9613-2:1996). The general trend is that higher frequencies are attenuated at a higher rate due to atmospheric absorption.

The attenuation may be calculated from:

$$A_{\text{atm}} = \frac{\alpha d}{1000} \, [\text{dB}] \tag{2.19}$$

where α is the attenuation coefficient obtained from tables (Table 2.8 presents some sample values) and d is the distance from source to receiver. For values presented in Table 2.8 it can be seen that atmospheric absorption accounts for approximately only 4 dB at 1000 Hz over a distance of 1 km for the given meteorological conditions compared to approximately 70 dB due to geometric divergence.

2.6.3 Ground Effect

The attenuation due to ground effect is principally dependent on the nature of the ground over which propagation occurs (i.e. whether it is acoustically absorbent or not) and the prevailing atmospheric conditions as some conditions may cause curvature in the propagating sound waves.

The acoustic absorbent properties of a particular ground surface are directly related to its porosity. Compact grounds are generally reflective and porous ground types are generally absorptive. The acoustical properties of different ground surfaces are expressed through the use of a ground factor G, which is assigned a value of between 0 and 1, for which two types of ground surfaces are defined. A value of 0 corresponds to a reflective

TABLE 2.8 Sample Values for α for a Temperature of 15 °C and a Humidity of 70% at One Standard Atmosphere (101,325 kPa)

Centre Frequency [Hz]	125	250	500	1000	2000	4000
α [dB/km]	0.381	1.13	2.36	4.08	8.75	26.4

More detailed tables are presented in ISO 9613-1.

TABLE 2.9 Values of G for Different Ground Types

Surface	Example of Surface	Value
Hard	Concrete, water	$G=0$
Soft	Grass, vegetation	$G=1$
Mixed	Both hard and soft ground	$0<G<1$

ground surface, a hard surface, while a value of 1 represents an absorbent ground surface, a soft surface. Some examples of ground surfaces are displayed in Table 2.9.

In favourable meteorological conditions (downwind), sound rays are curved towards the ground. Consequently, the ground effect is primarily influenced by the nature of the ground close to the source and close to the receiver. Indeed, taking into account the curvature of the rays, the propagation path is predominantly sufficiently high above the terrain in the middle of the propagation path and as such has only a minimal influence on the overall ground effect. However, over large distances, the propagation path can rebound on the terrain between source and receiver and must, therefore, be accounted for. Calculations for ground effect are performed separately for the three different defined regions: the source region, the receiver region and the middle region and each zone will be influenced by the ground factor coefficient, G.

It is worth noting that the ground effect will be subject to a certain amount of variation. Snowfall may change the acoustic properties of a ground surface while the natural cycles in the growth of vegetation can change the acoustic impedance of the ground surface due to, for example, leaves falling on the ground.

2.6.4 Diffraction

One of the most common measures for reducing noise is through the use of a noise barrier. A properly designed barrier will reduce noise propagating from source to receiver through diffraction over the top of the barrier or around its edges. Some noise may also be transmitted through the barrier. For a barrier to be fully effective, the amount of sound passing through it must be significantly less than that diffracting over or around it. To function well a barrier should obscure the direct line of sight between the source and receiver.

An important parameter of diffraction is the path length difference, δ. Path length difference is the difference in length between the diffracted path from the source over the top of the barrier to the receiver, and the direct path from the source to receiver as if the barrier was not present (Figure 2.14). This property governs the effectiveness of all noise barriers; in general, the greater the path length difference, the greater the barrier effectiveness.

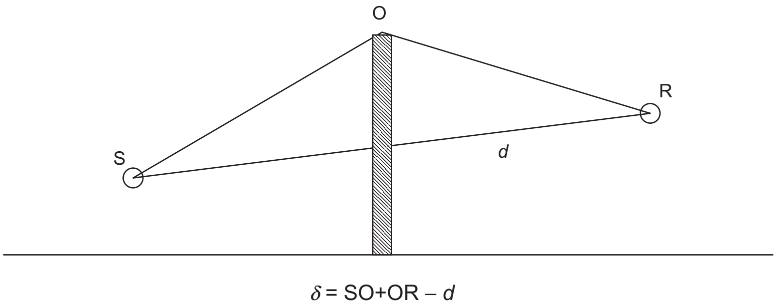

FIGURE 2.14 Calculating the path length difference for a noise barrier.

Noise barriers are most effective when placed close to the source or close to the receiver and, in practice, it should be possible for a noise barrier to result in an insertion loss of 10–12 dB. An insertion loss represents the decrease in noise level due to the presence of the barrier compared with a case where no barrier exists. Higher insertion losses are possible when barriers are placed very close to the source – for example, along railway lines. However, the maximum insertion loss is often limited to about 20 dB.

When calculating attenuation coefficients, the attenuation due to the presence of a barrier will also affect the attenuation arising from ground effects and as such, results obtained for the insertion loss of a barrier will directly impact on the value for ground attenuation.

BOX. 2.17

SIMPLE METHOD FOR CALCULATING BARRIER EFFECTIVENESS

Most calculation methods will provide a very detailed methodology for calculating the attenuation due to a barrier, and for any detailed analysis, readers should always refer to the standard that they are implementing.

A simplified version is presented here. It assumes no sound propagation through the barrier or around the barrier edges (i.e. the barrier is infinitely long).

The attenuation due to a barrier may then be calculated from:

$$A_{\text{diffraction}} = 10\log_{10}\left(3 + \frac{40\delta}{\lambda}\right)\ [\text{dB}] \tag{2.20}$$

where λ represents the wavelength of sound and δ is the path length difference (Figure 2.14).

Noise barriers can be made from many different materials or a combination of materials but must be sufficiently durable and should have low maintenance requirements. The barrier should be solid and the materials chosen should not form cracks or other leaks as a result of wear or weathering. Even small gaps in a noise barrier can significantly reduce the barrier performance. ISO 9613-2 specifies a minimum surface density of 10 kg/m^2 to ensure minimal sound propagation directly through the barrier. In practice, the location of a barrier between a source and a receiver, its height and its length will determine the effectiveness of a barrier.

2.6.5 Miscellaneous Other Effects

2.6.5.1 Temperature Inversion

The speed of sound in air increases with temperature. Normally, the temperature of the air decreases with altitude and this affects the manner in which noise propagates through the air; sound waves tend to be bent away from the ground. However, in special circumstances, perhaps after a storm, a phenomenon known as temperature inversion may occur. In this case the temperature actually increases with altitude and sound waves are refracted towards the earth (Figure 2.15).

2.6.5.2 Wind Effects

Wind can also bend sound waves. Wind speeds close to the ground tends to be slower than wind speeds at altitude. If a receiver is downwind the wind will tend to bend the sound waves back towards the ground. However, when a receiver is located upwind from the source, the opposite occurs, and the sound waves tend to refract upwards (Figure 2.16).

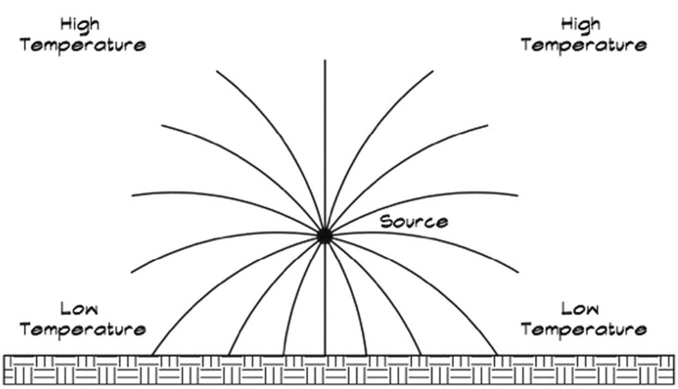

FIGURE 2.15 Wave propagation in thermal inversion. *(Long, 2006).*

BOX 2.18

ACOUSTIC SHADOW/SKIP EFFECT

Some meteorological conditions can lead to an interesting phenomenon called an acoustic shadow. Under special circumstances, sound can become trapped between atmospheric temperature layers and travel great distances before being bent back towards the earth. This can result in sounds being heard at great distances from the source but without being heard at locations in between. There are many examples in history of this interesting phenomenon. In a naval battle between British and Dutch fleets in 1666, battle sounds were heard at many points throughout England but not at other locations closer to the battle (Attenborough, 2007). Several more examples have been recorded by Charles D. Ross in his book *Civil War Acoustic Shadows*, which describes how such atmospheric effects may even have influenced some key battles during the American Civil War (including battles at Gettysburg, Fort Donelson, Seven Pines/Fair Oaks, Iuka, Perryville and Five Forks) (Ross, 2001).

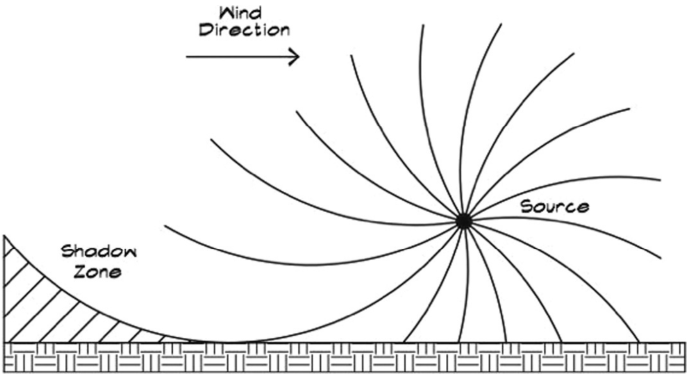

FIGURE 2.16 Wave propagation in a wind gradient. *(Long, 2006).*

2.6.5.3 Foliage

Trees and bushes are very poor noise barriers. Sound can usually propagate directly though a bush or a line of trees with negligible attenuation. However, if foliage is dense enough to block the line of sight completely, some slight attenuation may occur. ISO 9613-2 presents the following values for attenuation due to propagation through foliage (Table 2.10).

TABLE 2.10 Values of Attenuation Due to Foliage as Described in ISO 9613-2

	Nominal Midband Frequency [Hz]					
Propagation Distance, *d*	**125**	**250**	**500**	**1000**	**2000**	**4000**
$10 \leq d \leq 20$	*Attenuation [dB]*					
	0	1	1	1	1	2
$20 \leq d \leq 200$	*Attenuation [dB/m]*					
	0.03	0.04	0.05	0.06	0.08	0.09

It should be noted that one cannot generally plant your way out of a problem. It takes many years for the foliage to become dense enough to be significant. However, foliage may contribute to a subjective 'out of sight, out of mind' effect in terms of noise attenuation. Individuals may perceive the noise level to have been reduced due to the fact that the presence of foliage obstructs the view of the source.

2.7 CONCLUSION

This chapter sets out the basic concepts associated with sound (and noise) and readers should now have an understanding of the scientific study of environmental acoustics. Methodologies for measuring noise (a time-varying quantity) and the different manners in which results can be presented have been discussed. However, this chapter does not represent an exhaustive list of what needs to be known in conducting noise assessments and it is always recommended to consult relevant national and international guidance prior to any noise assessment being undertaken.

The use of the weighted long-term noise indicator, L_{den}, means that noise predictions may not be reflected in short-term measurements, but this does not mean that the accuracy of the measurement or prediction should be called into question. L_{den} should rather be treated as an indicator for annoyance and not an actual noise level experienced by a receiver. The logarithmic nature of the decibel should be well understood and readers should have an idea of likely noise levels for different situations.

The chapter also highlights why it is important to account for frequency and the response of the human ear in environmental noise assessments through the use of A-weighting. Other, more intrusive characteristics of noise, such as noise with strong tonal content and impulsive noise, are dealt with throughout the rest of the book, particularly with regards to industrial noise (Chapter 6).

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