ENVIRONMENTAL NOISE POLLUTION

Noise Mapping, Public Health, and Policy

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Dublin and Hartford
December 2013

Preface

Noise – The chief product and authenticating sign of civilization
Ambrose Bierce, The Devils Dictionary, 1907

Environmental noise has traditionally been dismissed as an inevitable fact of life and has not been targeted and controlled to the same extent as other health risks. A growing body of research linking noise to adverse health effects coupled with proactive legislation, primarily in the EU, is now driving change. Environmental noise has often been referred to as the 'forgotten pollutant' but is now recognised as an environmental and public health issue which needs to be addressed in modern society. For some people, noise is nothing more than a minor inconvenience, but for others noise exposure can lead to negative health effects varying from annoyance and sleep deprivation to more serious issues such as hearing impairment and cardiovascular diseases. Indeed, excessive exposure to environmental noise has been linked to a series of negative health effects in children including their cognitive impairment. For the first time, clear links between these adverse health effects and noise exposure have been identified, and estimates of their proliferation across the population have been established. The World Health Organization recently estimated that at least 1 million healthy life years are lost every year from traffic-related noise alone in Western Europe while the social cost of noise from road and rail across the EU has been valued at approximately €40 billion per year. Given that dose–response investigations are still relatively under investigated, it is likely we have not yet fully grasped the true extent of the noise pollution problem.

Despite this increase in awareness and the rapidly accumulating evidence pointing to the health issues associated with excessive noise pollution, environmental noise continues to be poorly understood by practitioners, policymakers and the general public. Although environmental noise issues now feature on the policy agenda, there is no adequate reference guide available that is relevant to specialists while also being accessible to policymakers, students and non-specialists. The core aim of this book is to provide such a reference guide. This text is thus intended to serve as a guideline for all stakeholders, ranging from professionals working in the field to members of the general public wishing to learn more about environmental noise. It is also meant as a reference guide for students studying acoustics, civil and environmental engineering, urban planning as well as public health professionals.

The key to driving effective change in environmental noise pollution is to clearly define the problem and then identify appropriate control strategies and actions. In discussions with the general public, it seems that most people can easily relate to the problem of noise pollution – everyone knows someone who is annoyed either by aircraft noise or noise from a busy road or factory. Addressing noise issues requires a deeper understanding of various control strategies and must be sensitive to a range of technical and contextual issues. This book endeavours to provide the material necessary to develop this understanding irrespective of whether the reader is a planner, politician, acoustician, student or member of the general public.

We begin by introducing the fundamentals of acoustics and focus specifically on how they relate to the assessment and management of environmental noise. The aim here is to provide readers who may not have scientific background with technical information that is needed to understand subsequent chapters and to do so in a manner that is accessible to a wide-ranging audience. This is followed by a state-of-the-art review of existing studies linking long-term environmental noise exposure with various adverse health effects. We also detail the chief source mechanisms for the key categories of environmental noise: road, rail, aircraft and industrial sources. Noise prediction/calculation methods for different noise sources used across the world are also outlined and discussed in detail, and this information provides the reader with an appreciation of the technical detail involved in noise prediction modelling. The book concludes with examples of best practice in noise mitigation strategies. The most effective noise mitigation approaches generally take a holistic approach to noise abatement and rarely focus on only one technical initiative. To highlight this, we identify specific initiatives that best emphasis how mitigation measures should form part of an overall noise control policy.

In general terms, this book is aimed at an international audience, and it is intended to act as a robust reference guide for stakeholders globally. After all, environmental noise is a global issue and does not recognise national borders. Europe is undoubtedly the world leader in planning for the management and control of noise pollution. Accordingly, the European Union's Environmental Noise Directive is considered in detail along with an assessment of how various Member States set about achieving the ambitious requirements set down by that seminal piece of legislation. The Directive has probably been the single most progressive step in the battle to control the proliferation of environmental noise. The results from the first round of noise mapping under the Directive (completed in 2007) show that lessons learned from this phase have directly improved the approach towards noise mapping in the most recent second phase (completed in 2012). These lessons may serve to guide all stakeholders on best practice in the assessment of noise. The European experience can be used to highlight not only best practice but also potential pitfalls that should be should be avoided for noise assessment and management. Throughout the text, we identify both the strengths and weaknesses of the Environmental Noise Directive and the approach to its implementation by Member States.

The successful management and control of environmental noise involves interdisciplinary considerations. When environmental noise is considered at an early stage, for example, by vehicle manufacturers, it can frequently be eliminated at source. This is always the preferred solution because noise control as a retrograde step is usually much less effective and sometimes wholly ineffective. Noise should be a detailed consideration in national planning systems which could be strengthened with appropriate legislative instruments. Indeed, it is considerably easier and cheaper to redesign a road on paper then to subsequently erect noise barriers across hundreds of kilometres of road. Of course, environmental noise considerations should not be limited to planners and engineers. Automobile and tyre manufacturers should consider noise in the design process of vehicles and tyres. Industrial operators should consider noise levels in all site operations and should favour quieter machines and processes where possible. If real change is to be realised, perhaps the most logical, albeit controversial, step is to introduce statutory environmental noise limits that are rigorously enforced. Moreover, there is potential for a psychoacoustic approach towards noise control which might help maximise the impact of mitigation measures. This approach has many attractive aspects but is not yet sufficiently developed to make a real difference in current noise mitigation strategies. However, it is our hope that this book will spark debate and interest in these and related emerging concepts and ideas.

For the first time, this book brings together academic expertise, real-world experience and international computational methods and guidelines for understanding environmental noise. We provide a comprehensive overview of the issue, how it can be assessed according to a number of different methodologies and, most importantly, how it can be mitigated. Our aim is to inform the reader in such a way so that the best solution(s) available on a case-by-case basis might be more effectively understood and identified. We do not intend to offer definitive overage of all problems – the breadth and scale of the topic renders this impossible. Instead, we attempt to educate the reader on the principles of environmental noise in order to provide a sound basis upon which noise issues can be considered. In some ways, the aspiration of the book is similar to the overall objective of the Environmental Noise Directive: to reduce exposure to environmental noise by raising understanding and awareness of its impact. While this has not yet been realised, the tide of understanding and awareness is slowly turning and thus this book represents one more in a series of small steps towards a healthier, quieter society.

CHAPTER

1

Environmental Noise Pollution

1.1 DEBATES AND CHALLENGES

A recent article in the *New York Times* came with an intriguing headline: 'Behind city's painful din, culprits high and low' (Buckley, 2013). The painful din that is described is the seemingly inescapable background and impulsive noise embedded within major world cites such as New York. As for the culprits – they are the producers of noise being emitted from the very depths below the ground to the skies overhead and seemingly everywhere in between. In the article, the author describes the everyday subjugation of New Yorkers to various sources of environmental noise – road and rail traffic noise, nightly construction activity (underground and over ground), helicopters and airplanes, bars and nightclubs, police and emergency sirens, among others. But more importantly, the piece describes the human experiences of excessive noise – how it actually affects people's everyday lives. Because very often the human impact of environmental noise gets lost in the technical detail: the noise indicators, the decibel scale, the modelling and measurement procedures. The detail is, of course, very important. In fact, it is crucial for understanding and assessing noise pollution as a public health problem. But emphasising only the technical nature of the problem risks normalising noise pollution as an abstract, stoical and somewhat inaccessible experience even though we know it is often viewed as a personnel affront to the people being subjected to it. Rather than noise being an abstract notion then, almost everyone has an intuitive understanding of what it is because we all experience it on a daily basis. In fact, the manifestation of noise exposure as emotion in humans is incredibly subjective even though the physiological impacts are broadly similar. We know from scholarship that human sensitivity to noise is variable – two people exposed to the same sound pressure level can have quite different subjective reactions in terms of their annoyance levels and associated psychological effects. Therefore, understanding the variable ways in which noise affects its human recipients is a vital accompaniment to technical understanding and problem solving for noise pollution problems.

New York is not exclusive in having a noise problem; rather, it is quite a typical example of the sound environment of modern cities. While European cities are perceived as being somewhat quieter than North American cities, rapid urbanisation and the increased concentration of human settlement and associated activity across relatively small areas typically lends itself to nosier environments. And it is a problem that has plagued cities, in particular, for centuries. Often cited in the literature is the fact that Julius Caesar banned chariots from the streets of Rome during the night because citizens could not sleep. However, it is the Greeks who are credited with the first noise abatement ordinance: in the first century B.C., they banned potters and tinsmiths, as well as roosters, from residential areas of their cities (Goldsmith, 2012). Even in New York, a relatively young city, the fight against noise has been ongoing for over a hundred years. During the Constitutional Convention in Philadelphia (1787) which resulted in the U.S. Constitution, dirt and straw were used to cover the cobblestone streets in front of Pennsylvania State House in an effort to reduce noise levels. In New York (1905), the *New York Times* decried the 'Trolley cars, boiler making, elevated roads, subway trains, harbor sirens, and various steam whistles, riveting machines, trucks laden with slabs of iron and rails of steel, milk wagons banging over the pavements in the small morning hours, hand organs, phonographs with megaphone attachment, fish horns, knife-grinding serenades, yelling junkmen, hucksters and peddlers with cowbell distractions, cracked bells ringing day and night in churches and chapels'.[1] In response to the problem, Julia Barnett Rice founded the Society for the Suppression of Unnecessary Noise in 1906 and this body was largely responsible for the signing into law of New York's first piece of noise abatement legislation prohibiting steamboat captains from unnecessarily sounding their whistles.

In today's cities, the characteristics of the noise have changed with changes in the structure of the economy together with technological change that has been both a force for quieter and nosier cities simultaneously. No longer have we steam whistles or boiler making but these have been replaced by alternative sources of noise such as cars and motorcycles with wider tyres and high-powered engines. The history of noise is not simply a case of being quieter in the past and louder in the present – that is far too simplistic. Noise has always been a problem, particularly for cities. But there is certainly some truth to the suggestion that noise is the forgotten environmental problem. Given its history, there is little doubt

[1]'The noisiest city on Earth', *New York Times*, 2 July 1905.

that it has not been tackled with the same vigour as other environmental pollutants (e.g. air pollution) but the reasons for this are not entirely obvious.

So we can clearly see that noise pollution is an age-old problem that has a tendency to come full circle. In other words, we are still discussing many of the same issues and problems today in relation to its prevalence that were discussed hundreds and even thousands of years ago. So while the character of the noise problem has altered with changing technological and cultural norms, its essence remains largely the same. The crucial difference between modern societies and those of the past is that noise pollution now affects a greater proportion of the population primarily because more people now live in cities than at any time in our previous history and cities are notorious noise hotspots. The challenge then for acousticians, environmental scientists, epidemiologists, planners and policymakers is to collectively understand the impacts of environmental noise on humans and simultaneously figure out ways to control its excess. Indeed, unless steps are taken to curb noise pollution, there is little doubt that its impact will increase at least at the rate of urbanisation. But it would be wrong to think that noise is an environmental problem that is exclusive to cities. It is one that reaches out beyond urban limits and into the countryside affecting rural dwellers also. Thus, the need to assuage the impact of noise pollution should not be confined to urban areas; rather, strategies that aim towards noise mitigation must also encompass noise hotspots beyond core city-regions.

1.2 ENVIRONMENTAL NOISE

Definitions can sometimes be uncomfortable for scholars. In many respects, this is because scientists do not always like to set definitional boundaries on a concept or phenomenon that does not necessarily fit with definitional rigidity. Environmental noise is one of those concepts, largely due to the fact that the characterisation of sound as noise is quite subjective depending on the individual being exposed. Nevertheless, it is important for the reader to have a working definition that acts as a reference point for the focus upon which this book is based. It is also important for governments, national and supranational organisations who strive to reduce noise; definitions determine how noise is assessed, regulated and mitigated as an environmental problem. In other words, how it is defined places boundaries around how to control noise as a pollutant. In this sense, it gives people and policymakers a target to agree on, debate and attempt to control. And definitions of environmental noise do vary somewhat in the literature. While the differences are not extreme, it is important to note that they do exist. Certainly, there are some quite distinct variations in how *noise* and *environmental noise* are defined.

Noise is generally referred to as unwanted sound that can negatively disrupt human or animal life. Goldsmith (2012) has recently taken issue with that definition arguing that such a definition leaves open the possibility that some sounds could be unwanted simply for what they signify rather than the sound being unwanted in itself (e.g. the voice of an enemy). This demonstrates the contested nature of how noise is defined. And we can never completely agree on what noise is: a rock concert can be a musical nirvana to some ears but an unbearable racket to others. He suggests an alternative based on the physicist George William Clarkson Kaye's 1931 definition of noise as 'sound out of place'. It is sound that is unwanted, inappropriate, interfering, distracting and irritating (Henry, 2013).

Environmental noise, on the other hand, has been defined as any unwanted sound created by human activities that is considered harmful or detrimental to human health and quality of life (Murphy et al., 2009). Specifically, environmental noise refers only to noise affecting humans and is concerned exclusively with outdoor sound caused generally by transport, industry and recreational activities. Thus, environmental noise is a form of pollution. And this classification is quite useful because it means that confronting noise becomes quite intuitive. By way of definition, pollution is something that is to be avoided, controlled, regulated or eliminated because of its negative impact on humans and human–environment relations.

1.3 THE BOOK'S FOCUS AND *RAISON D'ÊTRE*

The foregoing discussion leads to an obvious question about the nature of the contribution of this book. There have been many contributions to the noise literature over the last decade. These contributions have ranged from more technical aspects of noise and the prevailing sound environment (Kang, 2007) to more recent contributions on the sensory history of noise (Goldsmith, 2012), and its social history and usage (Henry, 2013). The focus of this book is not on sound *per se* but on a subset of sound – environmental noise. And there have been surprisingly few titles that explore issues around environmental noise. This is somewhat unexpected given that there seems to be more awareness and attention not only among policymakers about noise pollution issues but also among the general public who are much more educated and indeed exercised to action about noise pollution issues in their local communities than in the recent past.

This book then offers something different from previous contributions in that it is focussed exclusively on environmental noise pollution. That is, noise in the environment that is considered out of place which affects humans negatively and is classified as a pollutant. Having said this, we are conscious of the rich and varying history of sound and its interpretation as noise. We acknowledge that a Harley Davidson motorcycle might be a frightful noise for some people but an exhilarating sound to those who drive them.[2] And while we recognise that, as in the previous example, the characterisation of sound as noise is often subjective, we take the view that the subjective views of a single individual or a small minority are acceptable only insofar as the emission of that sound does not infringe on the rights of others to an environment that is relatively free from noise-induced annoyance and disturbance.

Thus, this book is concerned in the first instance about the nature of the relationship between environmental noise and humans, specifically within the context of the health effects of environmental noise. That is the issue of crucial import for this book – environmental noise has been found to negatively affect human health. And these health effects are highly concentrated spatially with cities being the hotspots for noise-induced health effects. Therein, the primary sources are noise from the use of transportation infrastructure such as roads, railways, airports as well as from industrial sources. While we acknowledge that there are indeed other sources of environmental noise in cities and beyond, this book has the aforementioned sources as its fundamental focus. And there are good reasons for this; in the EU alone, somewhere in the region of 50 million people are exposed to night-time noise above 50 dB(A) from these sources within city-regions with a further 28 million exposed beyond these areas. While these figures are EU specific, they generalise for the vast majority of nations around the world. In fact, they are likely to be significantly worse in developing world cities where noise pollution is often not even considered to be an environmental problem. Given that the World Health Organization (WHO) sets 40 dB(A) night-time as the value above which health effects are noticeable in humans, the exposure figures point to the seriousness of excessive exposure to environmental noise as a major problem throughout the world.

Understanding the relationship between noise and human health confers a responsibility on scholars, acoustics/environmental practitioners and students to understand not only its sources but ultimately how it is transmitted to the receiver, i.e., a human subject. In this regard, the book focuses on how noise sources can be understood and assessed through a range of modelling and measurement procedures which are often source and indeed nation specific. While the book is principle-based and offers a geographically diverse view of environmental noise issues from around the world, it does

[2] In fact, Harley Davidson filed a sound trademark application for its distinctive V-twin engine sound in 1994, indicating the extent to which sound can be used to brand consumer products.

place emphasis on developments in the European Union. The reasons for this are quite logical: the EU leads the world in terms of its approach to understanding, modelling, assessing and mitigating environmental noise. It has, by some way, the most progressive and large-scale noise assessment policy in the world. Moreover, it is a policy which has a basis in environmental law though Directive 2002/49/EC, also known as the Environmental Noise Directive. For that reason, we focus on the principles employed by the EU's mandatory strategic noise mapping and action planning process as a way of illustrating best practice that can be adopted and translated across jurisdictions beyond Europe. We also focus on how noise can be mitigated at its source and through propagation-based abatement measures but also by focussing on holistic strategies which include raising education and awareness about environmental noise as an environmental and public health problem. So while a good portion of the discussion has a European focus, the principles outlined and the issues faced are, in our view, universal; they can be applied to almost anywhere in the world. After all, noise is, and always has been, a worldwide issue.

The book then is structured in such a way as to outline the fundamental principles and concepts of environmental noise – its technical characteristics and properties, how it is measured and modelled and how it propagates outdoors in Chapter 2. This acts as the starting point for further discussion and exploration of environmental noise as a pollutant and provides the technical background that is essential for the accessibility and understanding of subsequent chapters. Chapter 3 offers a state-of-the-art review of the existing evidence base for the health effects of environmental noise on humans. Essentially, this is the most fundamental reason why environmental noise is considered a pollutant that needs to be avoided, controlled and mitigated against. Chapter 4 provides an outline of the strategic noise mapping process concentrating on its key principles and processes. This is provided as essential context for the discussion of noise sources in the following two chapters. Chapter 5 is somewhat more technical in nature and deals with sources of transportation noise and how the source and propagation characteristics are modelled. In Chapter 6, similar attention is given to sources of industrial noise while the modelling and measurement of other sources such as wind farm noise is considered. Chapter 7 concentrates on technical and pragmatic approaches for noise mitigation. This includes a detailed account of measures for noise mitigation at the source and measures to limit noise propagation at the point of the receiver. The principles associated with noise action planning as an approach to noise mitigation are also discussed in detail. The final chapter – Chapter 8 – offers some broad ranging reflections on existing and future approaches for environmental noise mitigation. It also focuses on emerging technical developments in noise modelling and measurement as well as some suggestions for improving environmental noise policy and legislation.

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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).

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).

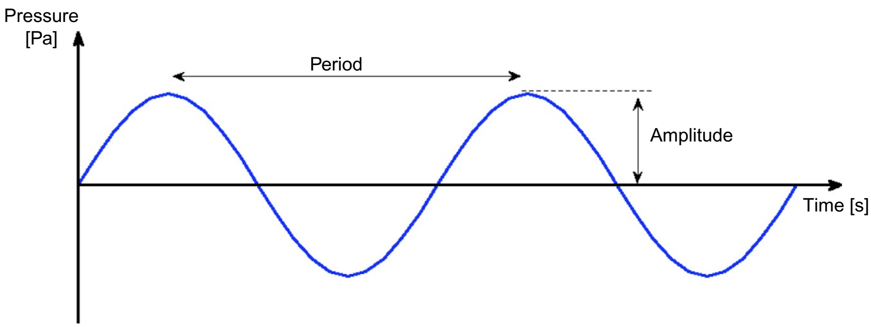

FIGURE 2.1 Simple wave motion – in this diagram the horizontal axis represents time.

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:

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

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

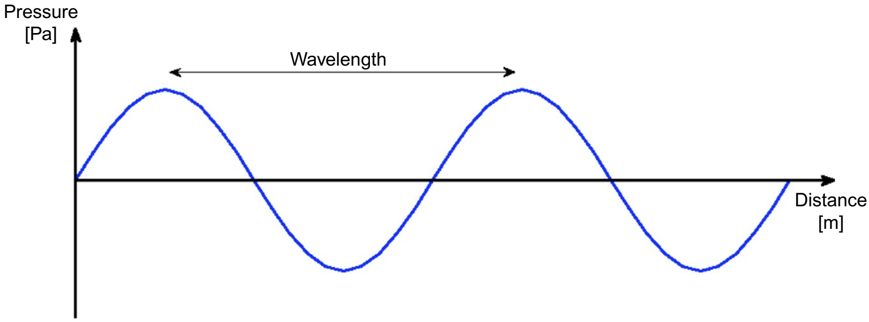

FIGURE 2.2 Simple wave motion – in this example the horizontal axis represents distance.

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

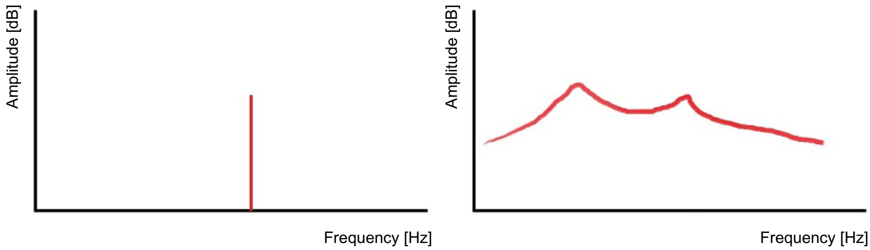

FIGURE 2.3 (a) Spectrum of a single tone (red line); (b) full spectrum across range of frequencies.

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

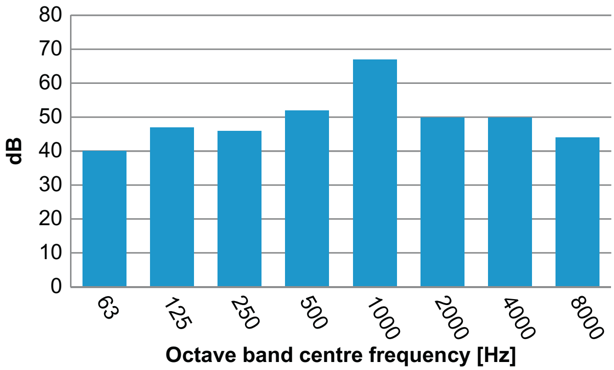

FIGURE 2.4 A noise sample represented in Octave bands.

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

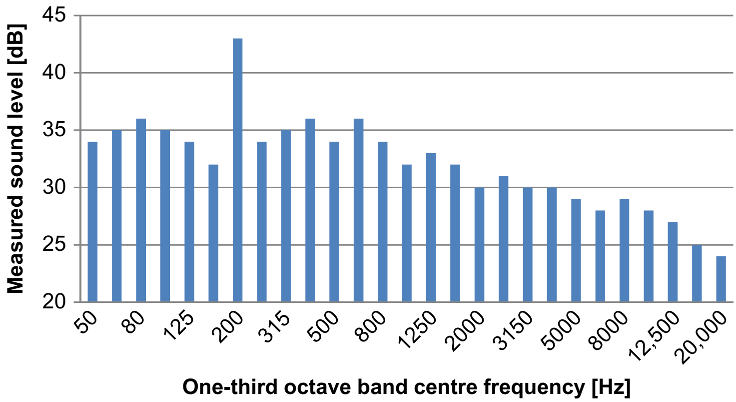

FIGURE 2.5 Investigating the presence of a tone using the ISO 1996-2 simplified method.

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:

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

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

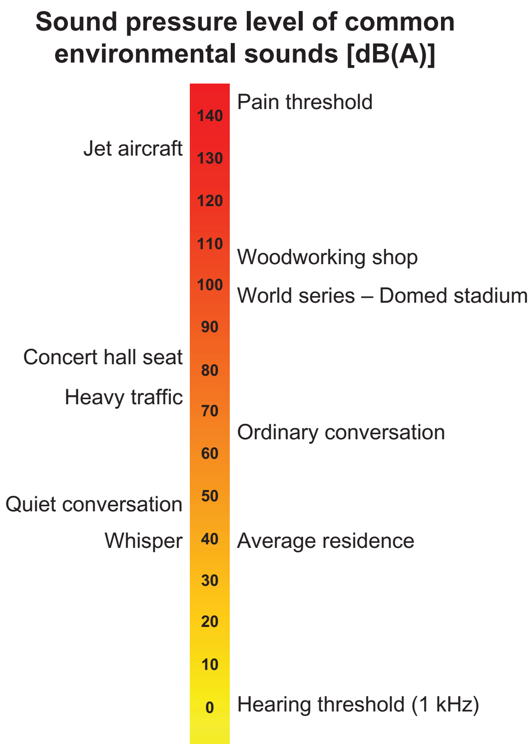

FIGURE 2.6 Typical sound pressure levels of noise sources.

[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:

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

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

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

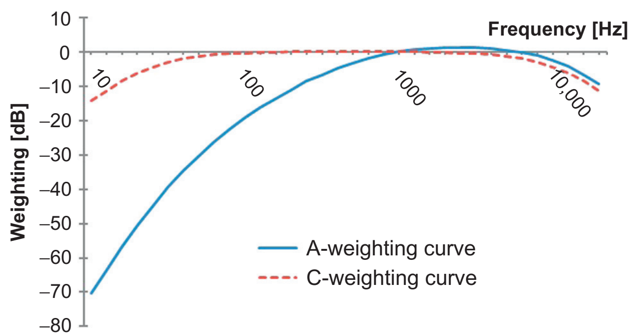

FIGURE 2.8 A-weighting and C-weighting curves.

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 $L_{10,1h}$ 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.

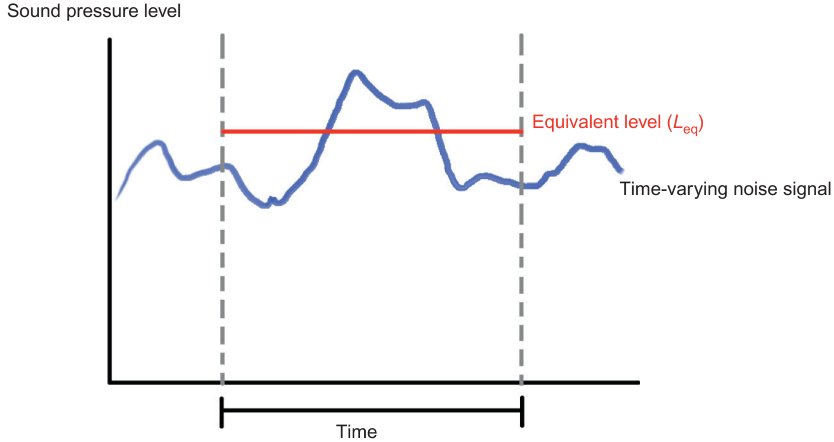

FIGURE 2.9 The L_{eq} level.

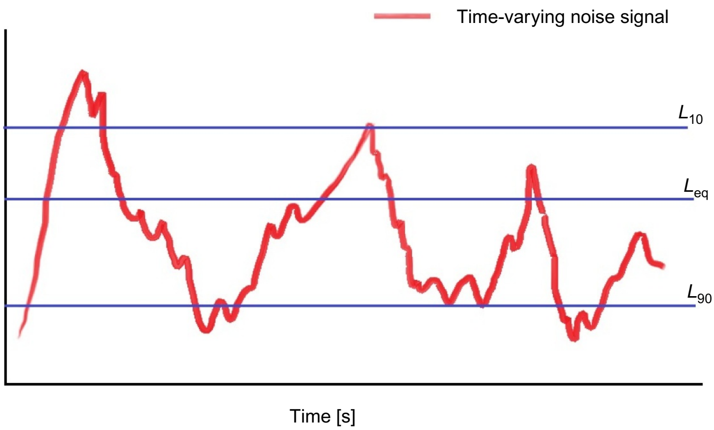

FIGURE 2.10 The L_{eq} level compared with statistical levels.

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):

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

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:

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

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).

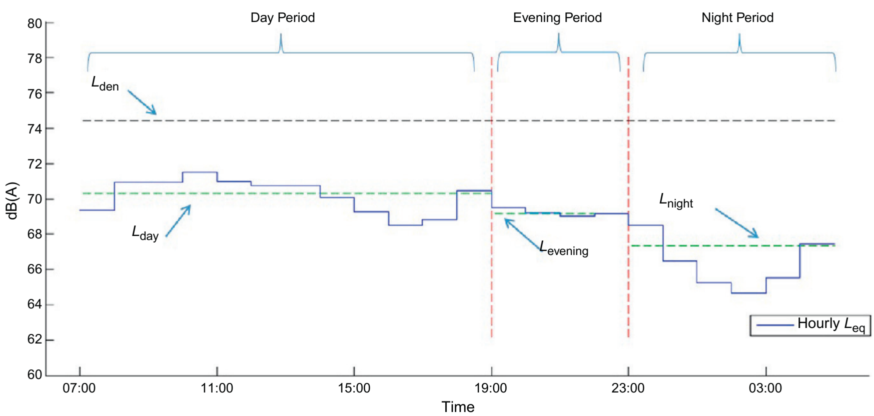

FIGURE 2.11 Typical values for L_{den}, L_{day}, $L_{evening}$ and L_{night}.

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 $L_{eq,T}$ 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 $L_{eq,T}$ 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 $L_{eq,T}$ level given the number of identical events, N, that occur during the time period, T, from:

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

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:

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

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

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

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:

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

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.

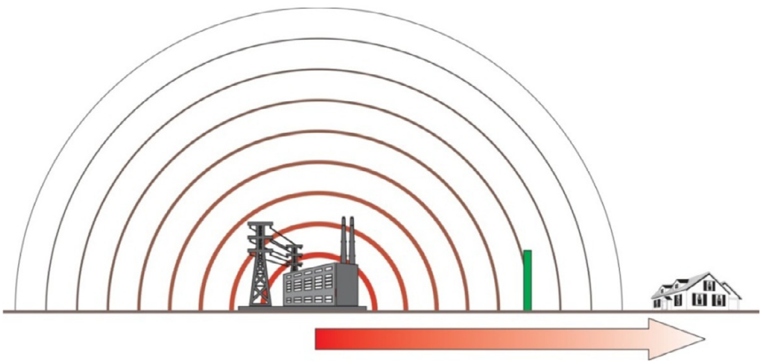

FIGURE 2.13 Different attenuation mechanisms of sound propagating from source to receiver.

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:

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

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.

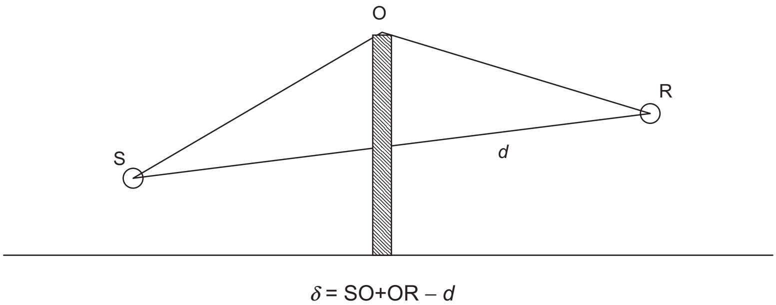

FIGURE 2.14 Calculating the path length difference for a noise barrier.

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:

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

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).

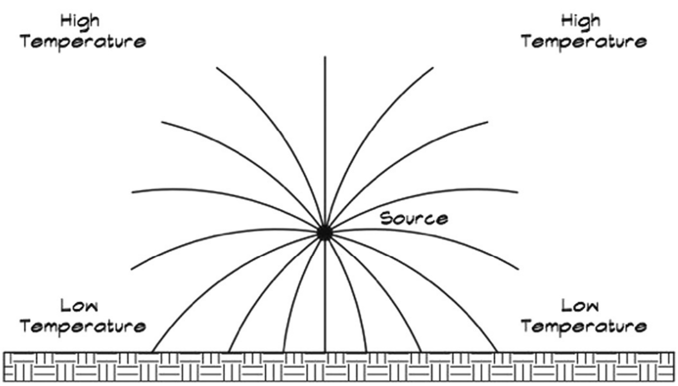

FIGURE 2.15 Wave propagation in thermal inversion. *(Long, 2006).*

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).

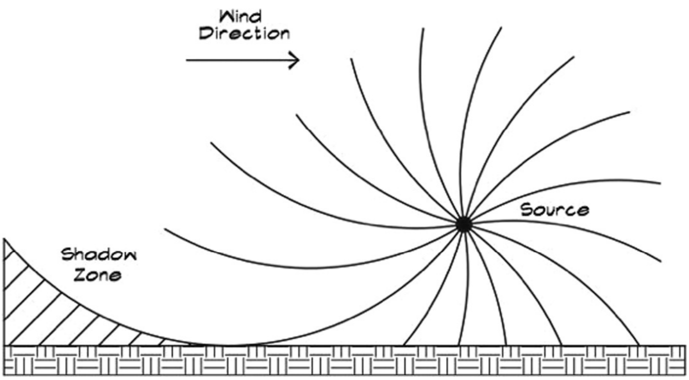

FIGURE 2.16 Wave propagation in a wind gradient. *(Long, 2006).*

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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CHAPTER

3

Environmental Noise and Health

3.1 INTRODUCTION

In urban areas, unwanted sounds (environmental noise) come overwhelmingly from road-based transportation but rail-based, airport transportation and industrial noise are also important sources. In the European Union (EU), problems with noise pollution have often been given similar concern ratings as those for global warming (CALM, 2007). In fact, results from the environmental burden of disease in Europe project show that traffic noise was ranked second among the selected environmental stressors evaluated in terms of their public health impact in six European countries (WHO, 2011), indicating the heightened awareness among the general public about noise pollution as an environmental issue. Moreover, a recent Eurobarometer survey showed that 44% of Europeans believe that noise affects human health to a 'large extent', an increase of 3% since 2006 (European Commission, 2010). The range of results for individual nations is shown in Figure 3.1 and indicates that the largest percentage of the population believing noise affects human health to a 'large extent' is in Italy (74%), while the lowest percentage is in Ireland (16%). In fact, Ireland is something of an oddity with 39% of the population of the opinion that noise has no impact on human health.

Very often, discourse concerning noise pollution implies and perhaps indeed overemphasises the negative aspects of the sound environment (Papadimitriou et al., 2009). But we are all aware, and indeed have direct experience, of sounds not only associated with negative feelings and emotions but also associated with positive ones, e.g., birds, music, etc. In this context, recent research around the sonic dimension of the landscape more generally has started to receive more attention in the academic literature (Mazaris et al., 2009). Here, this research is often referred to within the context of the concept of 'soundscape', a term coined by Schafer (1994) to describe perceptions of the acoustic environment in a landscape setting. Thus, while there are other more positive aspects of the sound

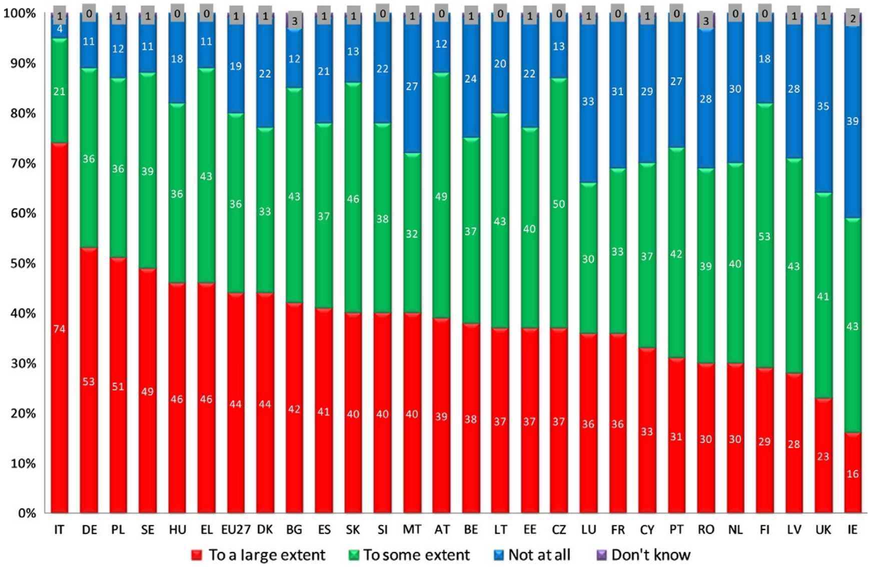

FIGURE 3.1 EU attitudes to the question of whether noise affects human health. *Source: EC (2010).*

environment being researched, it is clear that it is the negative aspects that have the greatest need for attention given their ability to impact public health and quality of life issues negatively. In this regard, the recent publication by the WHO (2011) of its seminal *Burden of Disease from Environmental Noise* document not only sets out the evidence base on the health effects of environmental noise in Europe but also attempts to quantify the extent of the problem. The document elucidates the extent to which noise pollution is a serious public health problem and that, contrary to the trend for other environmental stressors (e.g. second hand smoke, dioxins and benzene), which are declining, noise exposure is actually increasing in Europe and worldwide. Moreover, as further evidence of the growing recognition of noise as a health problem, the evidence emerging from the WHO document informed the recently established WHO European health policy – Health 2020.

3.2 THE NOISE–HEALTH PROBLEM

Table 3.1 shows a summary of the results from the WHO (2011) *Burden of Disease from Environmental Noise* study. The results are the first comprehensive effort at identifying the impact of excessive environmental noise on public health. The study concludes that one in three individuals in

TABLE 3.1 Burden of Disease from Environmental Noise in Europe

Noise-Induced Exposure	Public Health Impact
Annoyance	587,000 DALYs[a] lost for inhabitants in towns >50,000 population
Sleep disturbance	90,3000 DALYs for EUR-A[b] inhabitants in towns >50,000 population
Cardiovascular diseases	61,000 years for ischaemic heart disease in high-income European countries
Tinnitus[c]	22,000 DALYs for the EUR-A adult population
Cognitive impairment in children	45,000 DALYs for EUR-A countries for children aged 7–19 years

[a]*DALYs are the sum of the potential years of life lost due to premature death and the equivalent years of 'healthy' life lost by virtue of being in states of poor health or disability (WHO, 2011).*
[b]*EUR-A is a WHO epidemiological subregion in Europe comprising Andora, Austria, Belgium, Croatia, Cyprus, the Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Luxembourg, Malta, Monaco, the Netherlands, Norway, Portugal, San Marino, Slovenia, Spain, Sweden, Switzerland and the United Kingdom.*
[c]*Tinnitus is defined as the sensation of sound in the absence of an external sound source (WHO, 2011).*
Source: Adapted from WHO (2011).

Europe is annoyed during the daytime and one in five has disturbed sleep at night purely from traffic noise alone. The methodology devised in the WHO document to assess the burden of disease due to environmental noise represents the state of the art in risk assessment and quantification of the health effects of noise exposure. Much of the calculations are based on data taken from environmental noise maps constructed as part of EU member state requirements under the terms of the EU Environmental Noise Directive (END) detailed in the next chapter. This quantification of the scale of the public health problem associated with excessive environmental noise exposure is badly needed so that decision makers can gauge the nature and extent of the problem and determine the allocation of resources for mitigation.

The WHO (2011) methodology consists of calculating the burden of disease on the basis of the exposure–response relationship, exposure distribution, population-attributable fraction, background prevalence of disease and disability weights (DWs) of the outcome. The exposure–response relationship was derived from existing epidemiological studies or meta-analysis of published results. The incidence or prevalence of the health outcome in a population (e.g. for cardiovascular diseases) can be obtained by the national health statistics or surveys of the population. The *attributable fraction* is the proportion of disease in the population that is estimated to be caused by environmental noise. DW factors were used to reflect the severity of the disease on a scale from 0 (representing perfect health) to 1 (representing most imperfect health, i.e., death). The burden of disease is expressed in

FIGURE 3.2 Graphic description of the DALY. *Source: CC-by-sa Planemad/Wikipedia.*

terms of disability-adjusted life years (DALYs), which is the sum of potential years of life lost due to ill-health, disability or early death and the equivalent years of healthy life lost by virtue of being in states of poor health or disability. It is represented by the following equation:

$$\text{DALYs} = \text{YLD} + \text{YLL} \tag{3.1}$$

where YLD is years lived with disability and YLL is years of life lost.

One DALY is equivalent to 1 year of healthy life lost and is described graphically in Figure 3.2. Using this methodology, the report estimates that anywhere between 1 and 1.6 million healthy life years are lost every year from traffic-related noise in western European countries and this does not include estimates of the impact of daytime noise on shift workers.

BOX 3.1

THE DISABILITY-ADJUSTED LIFE YEAR

The DALY was originally developed by Harvard University for the World Bank and first used as input to the *World Bank's World Development Report 1993*: *Investing in Health*. Since then, it has been adopted by the World Health Organisation as a core metric for measuring the burden of disease in populations throughout the world. However, the metric has not been without its critics with Anand and Hanson (1997) describing it as '. . .flawed, and its assumptions and value judgements are open to serious question'.

We can see then that the impacts of noise pollution are highly significant and demonstrate the detrimental impacts of excessive environmental noise exposure on public health and overall quality of life. It is important to note that the burden of disease referred to in Table 3.1 relates to the non-auditory effects of environmental noise exposure. This is due to the fact that it has been well established for many decades that prolonged exposure to noise levels of relatively high degrees can lead to direct hearing loss and/or hearing impairment and the vast majority of this is related to occupational noise exposure (see Prasher, 2003). There is general agreement that exposure to sound levels less than 70 dB does not produce hearing damage, regardless of the duration of exposure (Goines and Hagler, 2007). At the same time, there is also agreement that exposure for more than 8 h to sound levels in excess of 85 dB(A) is potentially hazardous. However, environmental noise is not associated with any significant auditory effects because it is generally not associated with noise levels above 70 dB(A) for significant periods of time. As a result, noise pollution research over the last three decades has focussed on the relationship between noise exposure and related non-auditory health effects.

3.3 THE NOISE–STRESS RELATIONSHIP AND EFFECTS OVERVIEW

The noise–stress relationship is fairly well understood in principle. Noise activates the sympathetic and endocrine system. Specifically, it activates the pituitary–adrenal–cortical axis and the sympathetic–adrenal–medullary axis (Babisch, 2002). Changes in stress hormones are frequently found in acute and chronic noise experiments. Indeed, the results from laboratory studies have found changes in blood flow, blood pressure (BP) and heart rate in reaction to noise stimuli; they have also found increases in the release of stress hormones including catecholamines[1] adrenaline and noradrenaline, and the corticosteroid cortisol (Babisch, 2003).

In the medical literature, two principal pathways are relevant for the development of negative and adverse health effects resulting from noise exposure (Babisch, 2002): 'direct' and 'indirect' arousal and activation of the human organism (Figure 3.3). 'Direct' arousal is determined by the instantaneous interaction of the acoustic nerve with the various structures of the central nervous system. The 'indirect' pathway refers to the cognitive perception of sound (as noise), its cortical activation and related emotional responses whereby not only the noise level itself but subjective effects of noise annoyance has an association with negative health effects (Babisch et al., 2013). The 'indirect' pathway starts with noise-induced disturbances of activities such as communication and sleep. More pragmatically, noise tends to induce stress by disturbing sleep and interfering with relaxation and concentration as well as other cognitive effects that activate the sympathetic nervous system and the endocrine system (Babisch et al., 2001). As a result, both 'direct' and 'indirect' pathways can initiate physiological stress reactions which may result in a number of negative health effects especially as a result of long-term exposure.

[1]Catecholamines are hormones produced by the adrenal glands, which are found on top of the kidneys. They are released into the blood during times of physical or emotional stress.

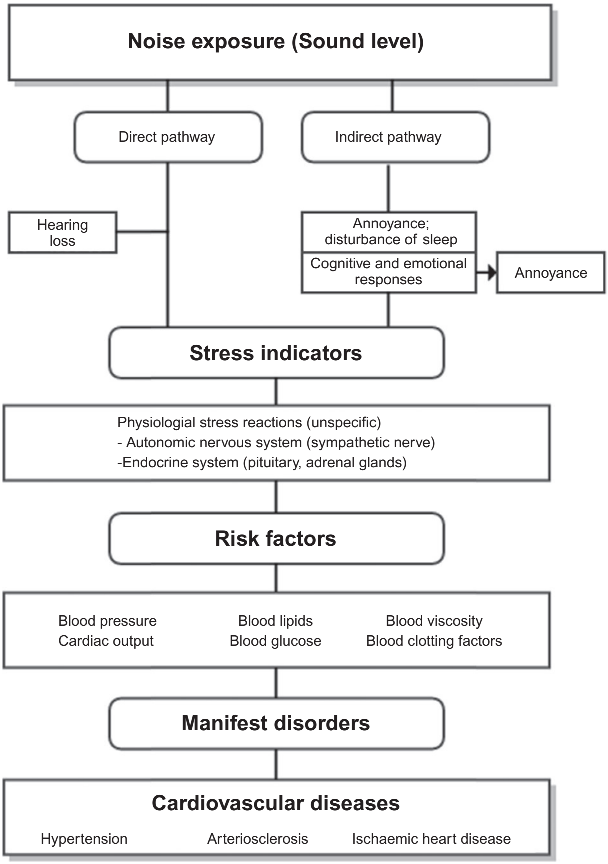

FIGURE 3.3 Noise effects reaction scheme. *Source: After Babisch (2002).*

Physiological experiments on humans have shown that noise exposure even at a moderate level acts via an indirect pathway and has health outcomes similar to those caused by high noise exposures on the direct pathway (WHO, 2009). Thus, acute noise effects occur not only at high sound levels but also at relatively low environmental sound levels when, rather importantly, physical recuperation might be taking place and when activities such as concentration, relaxation and sleep are disturbed (WHO, 2009). It is because of this relationship that the EU END recommends evaluating environmental noise exposure on the basis of estimates of noise annoyance (WHO, 2011).

The most significant effects of environmental noise on health come in the form of annoyance and sleep disturbance. Both are potential health stressors which can lead to and/or trigger more serious health problems. Figure 3.4 describes a pyramid of health effects which shows the graduation of severity of health-related impacts associated with chronic

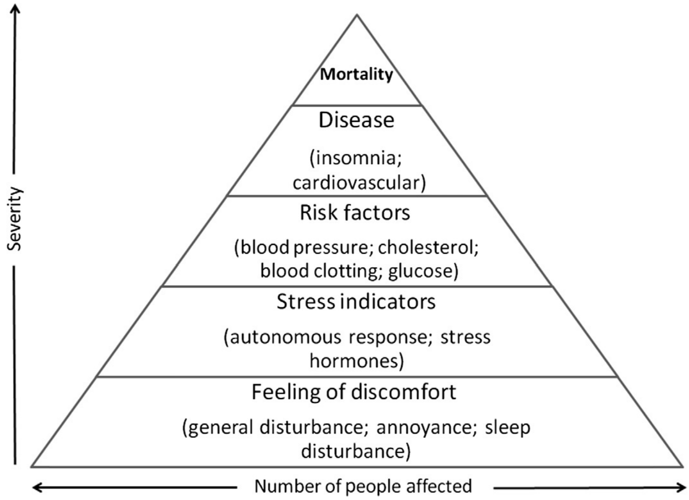

FIGURE 3.4 Pyramid of health effects of noise. *Source: Redrawn from Babisch (2002).*

long-term exposure to environmental noise; they range from feelings of discomfort through to enhanced risk of cardiovascular disease and ultimately mortality. Table 3.2 shows a summary of the main health effects of environmental noise exposure, the noise indicator used and the level above which health effects are considered detrimental for specific effects.

3.4 ENVIRONMENTAL NOISE AND ANNOYANCE

Annoyance response to transportation noise is considered to be quite a complex phenomenon. However, it is generally accepted to be the subjective discomfort associated with environmental noise exposure in humans and can be induced by individual perceptions of noisiness, disturbance to daily activities or a broadly negative feeling about the surrounding acoustic environment. One of the main characteristics affecting an individual's perception of sound as noise is its loudness or perceived intensity (Stansfeld and Matheson, 2003). As seen in Chapter 2, loudness comprises the intensity and tonal distribution of sound. In the scholarly literature, the evidence is mixed as to the importance of the duration and frequency components of sound as well as the number of sound events involved in determining annoyance.

It can be seen then that noise annoyance is subjective and this is primarily because, physiologically, individuals vary in their sensitivity to noise. For example, Raw and Griffiths (1988) found that self-reported sensitivity to noise is the most important variable for predicting ratings of annoyance. Put another way, different people may be more or less

TABLE 3.2 Summary of Effects and Threshold Levels for Effects of Nocturnal Noise Where There Is Sufficient[a] Evidence Available

Effect		Indicator	Threshold [dB]
Biological effects	Change in cardiovascular activity	–[b]	–[b]
	EEG awakening	$L_{Amax,inside}$	35
	Motility, onset of motility	$L_{Amax,inside}$	32
	Changes in duration of various stages of sleep, in sleep structure and fragmentation of sleep	$L_{Amax,inside}$	35
Sleep quality	Waking up in the night and/or too early in the morning	$L_{Amax,inside}$	42
	Prolongation of the sleep inception period, difficulty in getting to sleep	–[b]	–[b]
	Sleep fragmentation, reduced sleeping time	–[b]	–[b]
	Increased average motility when sleeping	$L_{night,outside}$	42
Well-being	Self-reported sleep disturbance	$L_{night,outside}$	42
	Use of somnifacient drugs and sedatives	$L_{night,outside}$	40
Medical conditions	Environmental insomnia[c]	$L_{night,outside}$	42

[a] *This means that a causal relation has been established between exposure to night noise and a health effect.*
[b] *Although the effect has been shown to occur or a plausible biological pathway could be constructed, indicators or threshold levels could not be determined.*
[c] *Environmental insomnia is the result of diagnosis by a medical professional while self-reported sleep disturbance is essentially the same, but reported in the context of a social survey.*
Source: WHO (2009).

annoyed by the same sound intensity. Thus, non-acoustic factors such as age, socio-economic characteristics and fear of noise have been found to play a major role in determining individual reactions to noise in the form of annoyance scores (Miedema and Vos, 1999, 2003; van Kamp et al., 2004). For example, after controlling for noise level, Fields (1992) found that noise annoyance increases with fear of danger from the noise source, sensitivity to noise, the belief that the authorities can control the noise, awareness of the non-noise impacts of the source and the belief that the noise source is not important. Indeed, it is estimated that only 33% of individual noise annoyance is accounted for by acoustic parameters (Guarinoni et al., 2012). The WHO report on the *Burden of Disease from Environmental Noise* concludes that one in three individuals in Europe is annoyed during the daytime. It is estimated that around 57 million people (12% of the population) in 25 EU countries are annoyed by road traffic noise with approximately 24 million (42%) of those being severely annoyed. In addition, rail traffic noise is estimated to cause annoyance in about 5.5 million people (1% of the European population), 2 million of who are severely annoyed (den Boer and Schroten, 2007).

As indicated earlier, noise annoyance is generally associated with the 'indirect' reaction chain in the human organism which is closely related to the initiation of emotional stress (i.e. cortical perception). Indeed, research studies have shown that individuals annoyed by noise tend to experience a series of negative emotions including anger, disappointment, unhappiness, withdrawal, distraction, anxiety, exhaustion and even depression (Fidell et al., 1991; Fields, 1998; Miedema, 2002; WHO, 2011). Thus, environmental noise has negative impacts on a person's quality of life and often forces unwanted alterations in the everyday behaviour of individuals. Examples include preventing residents from using residential areas such as balconies and common areas due to excessive noise levels as well as the shutting of windows in homes to prevent noise immission (Berglund et al., 1999). According to Stansfeld and Matheson (2003), conversation, watching television and listening to the radio are the activities most disturbed by aircraft noise, while traffic noise is often most disturbing for sleep but similarly affects everyday behaviour negatively.

Overall, road traffic noise is responsible for causing the greatest levels of annoyance. Figure 3.5 shows results from a longitudinal study from the Netherlands where residents reported road traffic noise as being responsible for the greatest volume of people highly annoyed while noise from

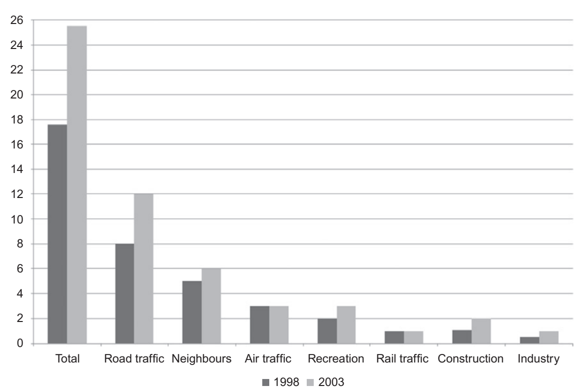

FIGURE 3.5 Percentage of the population highly annoyed by noise during sleep in the Netherlands. *Source: Adapted from WHO (2009).*

industry is the least. It is interesting to note also that the general trend is for a significant increase in annoyance from 1998 to 2003 and this trend holds for nearly all noise sources. These results generalise across Europe and imply that the problem of environmental noise is disimproving considerably over time. Of the various transport modes, rail is responsible for the least volume of annoyance in the general population; road-based modes account for the most. Indeed, it has been shown repeatedly in attitudinal studies that the degree of noise annoyance depends on the mode of transport being considered. At the same average noise level, the percentage of individuals highly annoyed increases from least to most in the following order: rail traffic noise, road traffic noise and aircraft noise. This relationship has been shown in studies by Miedema (2004) among others and has led to the introduction of a rail bonus in legislation in some countries (e.g. Germany) where the average rail traffic noise level may be 5 dB(A) higher than other traffic modes because of its lesser impact on annoyance (Basner et al., 2011). Indeed, a recent study of annoyance due to mixed transportation noise in Hong Kong found that when both road and rail noise are present, road traffic noise induces annoyance, while rail noise has the opposite effect (Lam et al., 2009). Rather interestingly, the same study found that perceived noisiness is a better predictor of noise annoyance than the actual noise exposure level.

The standard approach by which noise annoyance is assessed at the population level is through an attitudinal questionnaire. The International Commission on Biological Effects of Noise (ICBEN) and International Organisation for Standardisation (ISO) have made significant efforts to standardise the use of questions in noise annoyance surveys. They introduced a standard 11-point numerical scale as well as a 5-point semantic scale (see Figure 3.6). As well as this, Fields et al. (2001) have provided additional clarification for the conduct of noise reaction questionnaire surveys for

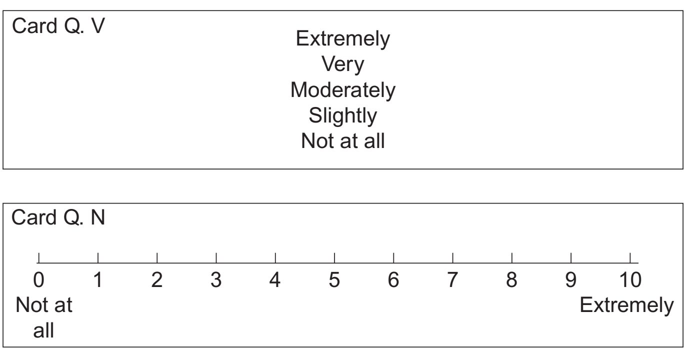

FIGURE 3.6 Answer cards for verbal (V) and numeric scale (N) noise annoyance questions. *Source: Fields et al. (2001).*

research purposes to ensure standardisation and comparison across studies. They recommend that noise reaction questions consist of one verbal answer scale question (V) and one numeric answer scale question (N) as follows:

> Q.V: Thinking about the last (..12 months or so..), when you are here at home, how much does noise from (..noise source..) bother, disturb, or annoy you; Extremely, Very, Moderately, Slightly or Not at all?
>
> Q.N: Next is a zero to ten opinion scale for how much (..source..) noise bothers, disturbs or annoys you when you are here at home. If you are not at all annoyed choose zero, if you are extremely annoyed choose ten, if you are somewhere in between choose a number between zero and ten. Thinking about the last (..12 months or so..), what number from zero to ten best shows how much you are bothered, disturbed, or annoyed by (..source..) noise?

If the questions are interviewer-administered, then respondents choose their answers from show cards provided to them based on the previously mentioned standardised scale (Figure 3.6).

Generally, studies that attempt to calculate noise annoyance do so on the basis of the proportion of the population that cite being 'annoyed' or 'highly annoyed' by environmental noise. Recently, the WHO has endorsed the use of 'highly annoyed' as the key reference condition for assessing potential health effects in the general population. Given that a number of noise reaction surveys have assessed response to noise using a range of different categories, it is often necessary to standardise various studies on a 0–100 scale to ensure comparability between studies (WHO, 2011).

The WHO (2011) have recently presented a methodology for estimating the prevalence of noise annoyance by combining existing noise exposure data with exposure–response relationships for noise annoyance that were determined in previous studies. Using evidence relating to burden of disease from other studies, they calculated the DW across the population of people 'highly annoyed' by noise at 0.02 (2%) albeit they acknowledge a potential DW range of anything from 1% to 12%. Although the methodology used is fairly crude, it is a pragmatic starting point for assessing the disease burden of environmental noise as a result of annoyance.

3.5 ENVIRONMENTAL NOISE AND SLEEP DISTURBANCE

It is now well established in the literature that excessive environmental noise disturbs sleep. If the disturbance is at a level that is severe enough, it can lead to sleep deprivation which can seriously affect the physical and mental health of an individual. The WHO (2009) estimate that 90,300 DALYs in populations greater than 50,000 are lost to sleep disturbance as a result of environmental noise exposure in the EU. No similar quantification has been applied in other jurisdictions throughout the world although localised (often city-specific) research investigating the link between noise exposure and sleep disturbance has indeed been completed beyond the EU.

Sleep disturbance is considered to be part of the extra-auditory effect of noise. The processing of auditory information involves a complex network of brain structures. The organ of Corti, which is located in the cochlea, is the receptive organ for audition (Pirrera et al., 2010). It is responsible for sending auditory information to the brain via the cochlear nerve. Input into the auditory area of the brain through the auditory pathways is prolonged by inputs reaching the brain as well as the cortical area and the descending pathways of the autonomic functions. Indeed, it has been established that individuals can experience autonomic responses to noise at low levels that do not lead to wakefulness (Muzet, 2007). As a result, an individual who is sleeping will still respond physiologically to noise stimuli from the surrounding environment even though the exact extent of the noise sensitivity of each individual is often dependent on several factors and can vary considerably.

Sleep disturbance can be quantified objectively by the number and duration of nocturnal awakenings, the number of sleep stage changes and modifications in their amounts. Subjectively, it can also be measured through questionnaires distributed to subjects on the morning after a night's sleep. Physiologically, sleep can be monitored using a sleep polygraph which records electroencephalography (EEG) and eye movements, while muscle tone is measured by means of electrodes (Carter, 1996). This method yields overnight measures of total sleep time, sleep efficiency and per cent of total time in the various sleep stages. Arousals and awakenings, whether they occur naturally or as a response to a noise event, can also be derived from a sleep polygraph. Indeed, it is also possible to detect whole-body movements and arm movements from accelerometers as an indicator of sleep disturbance (see Ohrstrom et al., 1988), while wrist movements have also been used in similar studies (Horne et al., 1994). From this, it is possible to deduce that excessive environmental noise exposure can significantly disturb sleep in the form of arousals, awakenings and in reducing the amount of time an individual spends in the deep sleep stages. These deep sleep stages – slow wave sleep (SWS) and rapid eye movement (REM) – are considered to be particularly important for physical recuperation in humans with SWS, in particular, acting as an energy restoration state for the sleeping body (Muzet, 2007). Carter's (1996) detailed review has shown that excessive exposure to noise during the night tends to reduce the amount of SWS. Indeed, a series of more recent studies focusing on the effects of aircraft-noise events on sleep structure showed that an increase in aircraft-noise events was associated with a decrease in SWS and increased awakening frequency in study subjects (Basner and Samel, 2005; Basner et al., 2006). Even earlier research has reported that REM sleep rhythmicity may also be affected by environmental noise (Naitoh et al., 1975). Research conducted by Ohrstrom and Skanberg (2004) has shown that sleep quality at home is reduced after exposure to traffic noise when compared to a quiet reference night. In terms of prevention and abatement, research has shown that if the indoor noise level is reduced, the amount of REM sleep and SWS can be increased considerably (Vallet et al., 1983).

In the early 1970s and 1980s, much of the research investigating the relationship between noise and sleep was at an early stage. There is now a significant body of work with consistent results, demonstrating the negative impacts of environmental noise on sleep structure. To take only one example, a recent study analysed the effects of train noise and vibration on human heart rate during sleep in Gothenburg, Sweden (Croy et al., 2013). The study had 24 participants each of whom spent six consecutive nights in a sleep laboratory – one habituation, one control and four experimental nights. For the experimental nights, 20 or 36 trains with low-vibration or high-vibration characteristics were presented to the subjects. The results found that exposure led to a statistically significant change of heart rate within 1 min of exposure to train noise and cardiac responses tended to be higher in the high-vibration than in the low-vibration condition. The results show that the human physiology reacts almost instantly to noise exposure during sleep. The authors concluded that train noise provokes heart rate accelerations during sleep which may affect the cardiovascular functioning of persons living close to railways in the long term. Similar results have been found in related studies. A recent review of the available evidence found a clear association between aircraft-noise events and sleep disturbance (Perron et al., 2012). The disturbances varied across studies but generally included awakenings, decreased SWS time and the increased use of sleep medication for noise-exposed subjects.

While environmental noise is an acute problem during the night-time period, it is also disturbing to sleep during the daytime period. Given that a significant proportion of the total workforce may be involved in shift work during the night and tend to sleep during the day, especially in the vicinity of airports and hospitals, noise-induced sleep disturbance can also be a daytime phenomenon. Indeed, this is an issue which is often neglected by environmental and public health officials. For example, the recent WHO report (2009) somewhat underestimates the extent of sleep disturbance from environmental noise because it only considers healthy life years lost to night-time sleep disturbance. The report does indeed recognise this as a problem, but further research is needed in the future assessing the extent of daytime sleep disturbance among populations.

Noise-induced sleep disturbance can vary for different modes of transport (road, rail, air) or modes in combination. In a recent laboratory-based study in Germany, 72 subjects (32 males) were studied for 11 consecutive nights with 0, 40, 80 and 120 noise events employed in a balanced design in terms of number of noise events, maximum sound pressure level and equivalent noise load (Basner et al., 2011). The results revealed that road traffic noise was responsible for the most significant changes in sleep structure and continuity despite the fact that subjects considered air and rail more disturbing subjectively; cortical and cardiac responses during sleep were lower for air compared to road and rail traffic. The difference between subjective attitudinal and objective physiological results associated with the various modes was attributed to road traffic noise events being too short to be consciously perceived by the subjects that had awoken in response to the noise events. An interesting aspect of the study was that the authors asked subjects to complete morning questionnaires to subjectively assess their previous night's sleep. They found that despite subjects being in an unconscious state for most of the night, they were able to distinguish not only between nights with and without noise but also between nights with low and high degrees of traffic noise exposure, indicating that morning questionnaires might be a more robust method of assessing traffic noise effects on sleep than previously thought.

One of the major issues related to environmental noise and sleep disturbance concerns how the noise might be characterised, specifically, whether the noise is considered to be continuous or intermittent. Laboratory studies using recorded intermittent and continuous traffic noise have demonstrated beyond any reasonable doubt that human subjects are disturbed more by intermittent noise than by continuous noise (Ohrstrom and Rylander, 1982). This is discussed further in Chapter 6. In Ohrstrom and Rylander's study, subjective sleep quality, mood and performance on reaction time (RT) tasks were all impaired by exposure to intermittent environmental noise at night, while continuous noise had a considerably less impact on sleep quality and no impact at all on mood or task performance. In another study, it was found that intermittent noises with peak noise levels above 45 dB(A) can increase the time taken to fall asleep by up to 20 min (Ohrstrom, 1993). And yet, for public health purposes noise continues to be evaluated during the night-time with continuous equivalent noise level indicators such as L_{eq}, L_{den} and L_{night} which, despite adding a night-time penalty (in the case of L_{night}), tend to smooth out intermittent noise events, thereby underestimating the magnitude of the health impact in terms of disturbance. Indeed, even as far back as the 1970s, Vernet (1979) found a low correlation between L_{eq} and the number of sleep disturbances for people exposed to road and rail traffic noise; by way of comparison, the study found a strong correlation between the number of disturbances and sleep stage changes with the peak noise level (L_{peak}) and number of noise events. This implies that it would be useful for relevant public authorities to use a noise disturbance indicator that accounts for intermittent noise in its equation if appropriate assessment of the sleep disturbance associated with night-time environmental noise exposure is to be achieved.

The reason why sleep disturbance is such an important issue in environmental noise studies relates to the fact that a reduction in sleep quality is associated with an array of secondary impacts – 'after-effects' – which are generally felt the day after disturbance has occurred. They encompass a broad range of psychological and physiological changes that may be evident in an individual including fatigue, low work capacity, reduced cognitive performance, changes in daytime behaviour as well as mood changes and associated negative emotions (Murphy et al., 2009). Tiredness is perhaps the most obvious impact of night-time exposure to noise and sleep disturbance. A number of studies have highlighted that individuals report increased feelings of fatigue after excessive night-time environmental noise exposure (Ohrstrom, 1995). Change in mood is another frequently reported after-effect. For example, in a laboratory-based study, Skanberg and Ohrstom (2006) found that subjects tended to have a better mood during quiet reference nights when compared with noisy nights. Moreover, Pirrera et al. (2010) have pointed out that there seems to be decent evidence to suggest that while sleep disturbance generally has negative effects on mood, intermittent traffic noise causes larger mood effects than continuous noise. Aside from mood, Stansfeld and Matheson (2003) point out that community surveys have found high percentages of people reporting 'headaches', 'restless nights' and 'being tense and edgy' in high noise areas.

Performance tasks have also been linked to the after-effects of sleep disturbance from environmental noise. Studies assessing the link between environmental noise, disturbed sleep and performance are usually examined through tests of RTs. A number of studies have shown that when RT tasks from the evening before a noisy night are compared with those from the morning after, longer RTs and a decrease in performance were found (Ohrstrom, 1995; Ohrstrom and Rylander, 1990). Marks and Griefahn's (2007) study demonstrated that subjects tended to have longer RTs after noisy nights when compared to quiet nights, while Griefahn and Gros (1986) found higher RTs together with more errors (for men and older subjects) following noisy rather than quiet nights.

BOX 3.2

ENVIRONMENTAL NOISE AND SLEEP IN RATS

In a 2005 study, 29 male rats were exposed to environmental noise for 9 consecutive days in a laboratory setting (Rabat et al., 2005). The study sought to determine the effect of chronic noise exposure on sleep and to evaluate inter-individual vulnerability of sleep to environmental noise. The researchers monitored the sleep states of the rats by EEG recording and chronically implanted cortical electrodes. Audio software was used to translate all the noise frequencies from the human to the rat audiogram. Environmental noise exposure comprised background noise of 70 dB(A) as well as several unpredictable noise events. The results showed that following 9 days of exposure, there was an increase in wakefulness amounting to 16 h when compared to a controlled environment of 40 dB(A). In addition, the results showed that environmental noise exposure disturbs both SWS and paradoxical sleep (PS); after 9 days exposure rats lost about 1.1 and 0.75 h/day of SWS and PS, respectively. Rather interestingly, the study also revealed that rats do not habituate to the situation even after exposure ends and that chronic exposure to an environmental noise permanently disturbs sleep parameters in rats. The research has potential insights for the relationship between environmental noise and sleep in humans.

3.6 ENVIRONMENTAL NOISE AND CARDIOVASCULAR DISEASE

3.6.1 Hypertension

It is now well known that short-tem exposure to environmental noise is a stressor that activates the sympathetic and endocrine system. This may lead to acute changes in BP and heart rate as well as elevated levels of stress hormones in the body. Over the last two decades, a series of studies have produced results which suggest that transportation noise is associated with negative cardiovascular effects (Babisch, 2002). In particular, the evidence demonstrating a link between transportation noise and ischaemic heart disease (IHD) has increased considerably (Babisch, 2011). This is related to evidence which has emerged, suggesting that noise exposure increases the risk of hypertension and arteriosclerosis (a thickening or hardening of the arteries).

Studies investigating the relationship between environmental noise and hypertension have tended to focus on either aircraft or road noise exposure relationships, and the results emerging have not generally been consistent. According to Babisch (2006), this is most likely due to problems associated with how individual studies have been designed. However, since 2006, a considerable volume of additional evidence has emerged, suggesting a more definitive link between noise and hypertension (Davies and Kamp, 2012). Barregard et al. (2009) have recently examined physician-diagnosed hypertension in a cohort of 1953 adults. When road traffic noise, age, sex, heredity and body mass index were controlled for in logistic regression models as well as allowing for >10 years of latency, the odds ratio for hypertension was 1.9 (95% CI 1.1–3.5) in the highest noise category (56–70 dBA) and 3.8 (95% CI 1.6–9.0) in men. The study showed a positive association between residential road traffic noise and hypertension, indicating that individuals exposed to high levels of environmental noise are 1.9 times more likely to suffer from hypertension than non-exposed subjects (with males 3.8 times more likely). Similar results overall were found by Bluhm et al. (2007) among a sample of 667 adults in a municipality north of Stockholm although, conversely, their results found that women were more likely to suffer from hypertension due to higher noise exposure than men, indicating an inconsistency in results from different studies. The HYENA (hypertension and exposure to noise near airports) study provided interesting data (4861 respondents) on the effects of aircraft and/or road traffic noise in a study around six major European airports. It uncovered statistically significant exposure–response relationships between night-time aircraft as well as average daily road traffic noise exposure and risk of hypertension when adjustment was made for major confounders (Jarup et al., 2008). The study found a significant increase in risk of hypertension per 10 dB increase (adjusted) in road traffic noise; a more pronounced dose–response relationship was evident for men.

Babisch and van Kamp (2009) have recently summarised the evidence linking aircraft noise and hypertension. They conclude that there is indeed sufficient evidence for a positive relationship between aircraft noise and high BP but that the exact magnitude of the effect is still uncertain at present. Interestingly, they found that the effects were more pronounced when subjective measurements of high BP were considered, indicating the possibility of over reporting when subjective indicators are being utilised. Selander et al. (2009), using a subset of the HYENA data (439 subjects), found elevated morning cortisol levels in relation to aircraft noise at night, but only for women, and notably only those who were employed. Niemann et al.'s (2006) study of eight European cities found a statistically significant relationship between road traffic noise and hypertension. Rather importantly, their results show that the effect of severe noise exposure was evident in the respiratory system as well as the cardiovascular system. This was particularly the case for children where a close relationship emerged between traffic noise exposure and disorders of the respiratory system in children.

In the literature, the evidence base is considerably stronger for aircraft noise than for road traffic noise which continues to be somewhat variable. For example, a recent study in Sweden using 25,851 subjects found no association between environmental noise from roadways (assessed as traffic volume) and self-reported hypertension (Eriksson et al., 2012). However, the study found an increased risk for subjects exposed to railway noise greater than 50 dB(A) with a prevalence odds ratio of 1.55. This is quite a surprising result given that railways have traditionally been seen as less of an environmental noise risk especially in Europe. Overall, the body of evidence suggests an association between noise exposure and risk of hypertension although a direct causal link is yet to be fully established.

3.6.2 Ischaemic Heart Disease

As mentioned already, exposure to noise affects the sympathetic and endocrine system resulting in acute physiological responses such as heart rate, BP, stress hormones and electrocardiogram (ECG) changes (Babisch, 2011). In fact, the long-term effects of chronic noise exposure at high noise levels have been studied in animals with results showing permanent vascular changes and alterations of the heart muscle indicating a greater risk of cardiovascular mortality (Ising et al., 1979). In research studies, the relationship between noise and prevalence of IHD for cross-sectional studies is generally assessed by cyclical symptoms of angina pectoris, myocardial infarction (MI) or ECG abnormalities or from self-reported questionnaires regarding doctor-diagnosed heart attack (Babisch, 2006). For longitudinal studies, IHD incidence is assessed using hospital records, ECG measurements or clinical interviews (WHO, 2009).

The WHO (2009) has recently concluded that there is sufficient evidence to suggest a relationship between excessive daytime noise exposure and increased cardiovascular risk. However, the increase in risk is only evident in areas with a daytime average sound pressure level above 60 dB(A). Moreover, the evidence linking road traffic noise with IHD is stronger than that for aircraft noise due to a lack of research investigating the association between aircraft noise and cardiovascular health (WHO, 2011). However, the same document – *Night Noise Guidelines for Europe* – has also concluded that, with respect to night noise, only limited evidence of increased risk of cardiovascular disease is evident for night noise levels above 55 dB(A). As Babisch (2011) has pointed out, this does not mean that a link does not exist but that the available evidence base is limited because there are an insufficient number of studies completed where the exposure of the bedroom is explicitly related to the night noise level. The vast majority of studies that have been completed have been on the link between daytime noise and cardiovascular health and have simply inferred relations for night noise from daytime studies which is obviously not ideal in terms of determining a definitive relationship during night-time. As a result, additional research is needed explicitly investigating night noise levels and bedroom exposure.

Despite these caveats, Babisch et al. (2005) found evidence of a link between traffic noise exposure (using noise maps) greater than 60 dB(A) and increased risk of MI – commonly known as heart attack – for subjects in Berlin. Their research revealed that men were susceptible to greater risk than women who demonstrated no increased risk from chronic traffic noise exposure. Additional research by Babisch et al. (2013) suggests that noise is an effect modifier in that it may be an environmental stressor which increases the risk of cardiovascular outcomes in exposed subjects. A similar and more recent study in Switzerland analysing 15,532 deaths from MI found that mortality increased with increasing level and duration of aircraft-noise exposure with individuals living in the same location for more than 15 years at greater risk (Huss et al., 2010).

In addition, a recent study was conducted investigating in the relationship between traffic noise and incidence of stroke in Denmark (Sørensen et al., 2011). In total, 1881 cases of Danish adults aged between 50 and 64 living in the Copenhagen or Arhus area were analysed. The results revealed a relationship which suggested that the incidence of stroke increased by 14% for every 10 dB(A) increase of traffic noise (L_{den}). More specifically, they showed that residential traffic noise was particularly associated with a higher risk of stroke among people older than 64.5 years old.

Occupational noise is also associated with increased cardiovascular risk. A recent study of 6307 workers in the United States concluded that self-reported occupational noise is strongly associated with prevalence of coronary heart disease (CHD) including being associated with a two- to threefold increased prevalence of angina pectoris, MI, CHD and hypertension (Gan et al., 2011).

3.7 ENVIRONMENTAL NOISE AND COGNITIVE IMPAIRMENT IN CHILDREN

Over the last two decades, there has been a major increase in the number of studies investigating the effect of environmental noise on children. This is largely related to the fact that early evidence indicated that children might be particularly susceptible to the risks associated with excessive environmental noise exposure. According to the WHO (2009), risk groups are people who may be either sensitive to or more exposed to environmental noise exposure or both. Children are considered to be one of those groups where environmental noise has more significant health impacts relative to the rest of the general population. While the WHO (2009, p. 75) have stated that children do not appear to be at any additional risk than the rest of the population with respect to cardiovascular outcomes, the long-term impacts of exposure at a young age have yet to be studied and it may well be that there are longer term impacts of chronic exposure during childhood particularly within the context of cognitive development.

The most consistent impact on children exposed to excessive noise levels is in terms of cognitive impairments, motivation and annoyance. Studies that have considered the effect of noise on children have tended to focus on noise in schools rather than at home. As such, there is now a useful body of literature highlighting the impacts of noise exposure on child cognition and learning. Studies have found that tasks involving central processing and language comprehension, such as reading, attention span, problem solving and memory, appear to be most affected by exposure to noise (Evans and Maxwell, 1997; Stansfeld and Matheson, 2003). In other words, the effects of environmental noise have been shown fairly uniformly across the entire range of cognitive functions.

Hygge et al. (2002) found that aircraft noise had a significant and negative impact on the reading ability of schoolchildren. In a different study of 1358 children aged between 12 and 14 years old, 10 experiments were used to test for recall and recognition of a text in quiet and noisy conditions for various transportation noise sources including road, rail, aircraft and combinations of these with one or other source dominating (Hygge, 2003). Overall, the results found a strong and negative noise effect on recall and a smaller but still significant effect on recognition. Similarly, a study examining teacher's reports of their students showed that noise-exposed children have greater difficulty concentrating than children from quieter schools (Ko, 1981), while research in the United States found a link between environmental noise exposure and reduced visual attention in children (Hambrick-Dixon, 1988). In a recent study of London primary schoolchildren (7–12 years old), external noise was found to have a significant negative impact on performance with the effect being somewhat greater for the older children included in the study (Shield and Dockrell, 2008).

Somewhat worrying is the emerging link between transportation noise exposure and children's mental health. It is notable that only a small number of studies have attempted to examine the link between environmental noise and psychological disorders in children. As a result, the present nature of the relationship is tentative and in need of further confirmation. However, a recent study – the UK RANCH[2] project – examined the link by conducting a cross-national, cross-sectional study assessing 2844 pupils (aged 9–10) from 89 schools around three major airports in the Netherlands, Spain and the United Kingdom (Stansfeld et al., 2009). Mental health issues explored included emotional problems, conduct disorder, hyperactivity, peer problems and prosocial behaviour.[3] The results revealed that aircraft-noise exposure was significantly associated with high levels of hyperactivity, while road traffic noise was significantly associated with higher levels of misconduct after adjusting for socioeconomic factors. Indeed, similar results for hyperactivity were confirmed in a more recent study in Germany (Tiesler et al., 2013). In the first longitudinal study of the effects aircraft-noise exposure on children, a 6-year follow-up of the RANCH study confirmed many of the results of the original study including that aircraft-noise exposure at school might impair reading comprehension and lead to an increase in noise annoyance in children.

A number of studies have also identified an association between chronic exposure to aircraft noise and reduced motivation in children (Evans et al., 2001). However, the results are certainly not conclusive and demonstrate some inconsistency which means that further research is needed in the area. For example, in a Los Angeles study of the effects of aircraft noise on children's cognition and motivation, the authors found that children exposed to chronic aircraft noise were more likely to give up on a difficult puzzle than children not suffering from chronic noise exposure (Cohen et al., 1980). In a 1-year follow-up to the Los Angeles study, which included the same students, the finding that noise-exposed children were more likely to give up on a difficult puzzle was not replicated demonstrating inconsistency in the results (Cohen et al., 1981). Similarly in a Munich study, children from noisy communities were found to give up more easily on an insoluble puzzle than children from quiet communities (Evans et al., 1995). Rather interestingly, that study also found an association between noise-exposed children and reduced quality of life scores on a standardised index.

[2]Road traffic noise and Aircraft Noise exposure and children's Cognition and Health (RANCH).

[3]Prosocial behaviour refers to voluntary behaviour intended to benefit another such as helping, sharing, donating, co-operating and volunteering, generally demonstrating altruism and solidarity to others.

BOX 3.3

AIRCRAFT NOISE AND COGNITIVE PERFORMANCE IN SCHOOLCHILDREN

A 2002 study in Munich, Germany assessed how children's reading was affected by changes in ambient noise levels caused by modified airport operations (Hygge et al., 2002). At that time, the simultaneous opening and closing of the new and old airports at separate locations provided a unique opportunity to conduct a study on the effects of aircraft noise on children. Children near both sites were recruited into aircraft-noise groups and control groups with no aircraft noise (controlling for economic status). A total of 326 children took part in data collection experiments before and after the switchover of airports. After the switchover, the study found that long-term memory and reading were impaired in the noise group at the new airport but it improved significantly in the group that was formerly exposed to noise at the old airport. Not only that but short-term memory also improved for the group formerly exposed to noise at the old airport. Meanwhile, at the new airport speech perception was impaired in the group newly exposed to environmental noise. The study concluded that aircraft noise has clear cognitive impacts on children.

3.8 ENVIRONMENTAL NOISE AND TINNITUS

Tinnitus is defined as the sensation of sound in the absence of an external sound source and is often associated with partial hearing loss. It can cause sleep disturbance, cognitive effects, anxiety, psychological distress, depression communication problems, frustration, irritability, tension, inability to work, reduced efficiency and restricted participation in social life (WHO, 2011). Excessive exposure to noise is generally what causes tinnitus. Environmental noise from social/leisure noise such as personal music players, gun shooting events, music concerts, sporting events and events using firecrackers is associated with tinnitus (WHO, 2011). Somewhere between 50% and 70% of patients with chronic noise trauma and 12–50% of patients with noise-induced hearing loss report having tinnitus (Sindhusake et al., 2004). Population-based research investigating the relationship between environmental noise exposure and tinnitus is rare in the academic literature, but it is generally accepted that it is a risk when noise exposure is high.

3.9 THE SPECIAL CASE OF LOW-FREQUENCY NOISE

The relationship between low-frequency environmental noise exposure and health-related problems has been less of a focus in the academic literature than noise in the traditional A-weighted bands. Although exact definitions are somewhat difficult to pinpoint, low-frequency noise (LFN) is generally taken to be noise from 20 to 200 Hz with noise below 20 Hz being referred to as infrasound (Leventhall, 2004). Most walls in buildings tend to be deficient in attenuating noise in the low-frequency region (Leventhall, 2003), meaning that residential exposure to LFN can pose an even greater problem than noise in the normal frequency range.

The WHO recognise the special place of LFN as an environmental problem suggesting that 'low-frequency components in noise may increase the adverse effects considerably' (Berglund et al., 1999, p. 61). Persson and Bjorkman (1988) and Persson et al. (1990) found that dB(A) underestimates the level of annoyance for LFN. This, along with other related work, implies that noise at low frequencies is considered more annoying by individuals (Berglund et al., 1996; Broner, 1978; Pawlaczyk-Luszczynska et al., 2010). Moreover, related research has also found that LFN has a greater degree of 'unpleasantness' than noise in the A-weighted frequency bands (Inukai et al., 2000; Nakamura and Inukai, 1998). Exposure to LFN also causes sleep disturbance (Leventhall, 2003) and its associated secondary effects with the WHO (Berglund et al., 1999) noting that it 'can disturb rest and sleep even at low-sound levels'. Indeed, the work of Ising and Ising (2002) has demonstrated that LFN seriously impacts on the sleep quality of children. Moreover, Persson-Waye et al. (2002) have shown that adult exposure to low-frequency traffic noise is associated with greater degrees of fatigue and a negative mood.

Other research on LFN and health has indicated that it has an impact on peripheral task performance (Kyriakides and Leventhall, 1977), while more recent research has shown that it negatively affects demanding verbal tasks in the work environment (Persson-Waye et al., 2001). Ising and Ising (2002) demonstrated that compared to a control group, children exposed to LFN have significantly more problems with concentration and memory. In public surveys conducted to assess subjective well-being for individuals exposed to LFN, Møller and Lydolf (2002) found multiple self-reported health effects including disturbance when falling asleep, awakenings, frequent awareness of the noise, irritation and disturbance when reading. Other effects reported were insomnia, lack of concentration, headaches and palpitations. A laboratory study by Persson-Waye et al. (1997) showed that subjects exposed to LFN were less happy and had a poorer social

TABLE 3.3 Criteria for the Control of Annoyance due to Low-Frequency Noise

Sensitive Receiver		Range	Criteria L_{eq} [dB(C)]
Residential	Night-time or plant operation 24/7	Desirable	60
		Maximum	65
	Daytime or intermittent (1–2 h)	Desirable	65
		Maximum	70

Source: *Broner and Knight-Merz (2011).*

orientation. Moreover, Persson-Waye and Bengtsson's (2002) work suggests that LFN represents 44% of all noise complaints in Sweden.

To account for the additional annoyance likely to be experienced due to the presence of LFN, the overall A-weighted noise level (usually expressed in terms of L_{Aeq}) may be adjusted by a correction factor. For annoyance due to LFN, Broner and Knight-Merz (2011) propose simple criteria (Table 3.3): if the noise level is fluctuating by 5 dB(C), then a penalty of 5 dB(C) should be added, i.e., the criteria should be reduced. This is because annoyance is exacerbated due to the significant change in perceived loudness with change in sound pressure levels. A further procedure for the assessment of LFN is presented by Newman and McEwan (1980) who reference a British Gas Corporation criterion for specifying noise control for gas turbines. This involves a 60 dB limit in the 31.5 Hz octave band at the nearest dwelling. If there are distinguishable tonal or impulsive elements present in the noise source BS 4142 suggests applying a 5 dB correction factor to the L_{eq} value. However, ISO 1996-1 offers a more stringent and detailed approach: for tonal elements in the noise source, the correction should be 3–6 dB.

3.10 CONCLUSION

The broad conclusion that can be drawn from the evidence presented in this chapter is that environmental noise is quite a serious public health issue throughout the world. Much of the research that has been conducted on the health effects of noise in the last two decades has had Europe or the United States as its main geographic focus. However, the implications of the emerging body of evidence for public health policy throughout the world are significant. While the EU, in particular, is leading the way in terms of assessment and mitigation of excessive environmental noise exposure, it is important that other nations follow that lead in order to prevent noise pollution becoming an even more prominent public health issue.

Overall, the evidence suggests that environmental noise should be placed at the forefront of national and international health policies in order to prevent unnecessary adverse health impacts on the general population. This involves attempting to mitigate against the harmful effects of environmental noise on citizens. In this regard, the WHO (2009) have recently suggested that night-time noise levels above 40 dB(A) should be mitigated against to protect public health. This implies that policymakers should strive towards achieving levels below this figure. Indeed, Table 3.4 demonstrates that noise exposure even above 30 dB (A) is associated with a range of adverse health effects (see Table 3.4). If citizens are to be protected, it will require a long-term strategy that will need to incorporate the adoption of night-time noise limit values through legislation.

TABLE 3.4 Health Effects of Various Noise Levels in the General Population

Average Night Noise Level over a Year $L_{night,outside}$ [dB]	**Health Effects Observed in the Population**
Up to 30	Although individual sensitivities and circumstances may differ, it appears that up to this level no substantial biological effects are observed. $L_{night,outside}$ of 30 dB is equivalent to the no observed effect level (NOEL) for night noise.
30–40	A number of effects on sleep are observed from this range: body movements, awakening, self-reported sleep disturbance and arousals. The intensity of the effect depends on the nature of the source and the number of events. Vulnerable groups (for example, children, the chronically ill and the elderly) are more susceptible. However, even in the worst cases the effects seem modest. $L_{night,outside}$ of 40 dB is equivalent to the lowest observed adverse effect level (LOAEL) for night noise.
40–55	Adverse health effects are observed among the exposed population. Many people have to adapt their lives to cope with the noise at night. Vulnerable groups are more severely affected.
Above 55	The situation is considered increasingly dangerous for public health. Adverse health effects occur frequently, and a sizeable proportion of the population is highly annoyed and sleep disturbed. There is evidence that the risk of cardiovascular disease increases.

Source: WHO (2009, XVII)

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CHAPTER

4

Strategic Noise Mapping

4.1 INTRODUCTION

For environmental noise research, mapping is an extremely important part of the process of quantifying and visualising noise pollution levels (De Kluijver and Stoter, 2003). Indeed, environmental noise pollution is an inherently spatial phenomenon. It varies across geographic space depending on the location of the noise source, the receiver and the intervening obstacles (e.g. the terrain, buildings, barriers). Understanding how it varies across space, how many people it affects and how it can be mitigated is all part of the process of strategic noise mapping. The process of digitally mapping environmental noise across geographic space allows researchers and policymakers to identify locations that are subject to excessive noise levels and if there are individuals residing in those areas affected by excessive pollution. Thereafter, steps can be taken to reduce noise levels so that public health is protected. The mapping process also allows for the identification of areas of good sound quality – often referred to as quiet areas – so that these can be protected into the future as amenity areas for rest or recreation that are free from noise disturbance.

Accordingly, this chapter provides an outline of the strategic noise mapping approach developed and utilised across Member States of the EU. Focus is placed on the EU precisely because it is the world leader in terms of environmental noise policy and related legislation. However, related noise mapping studies and associated research in other jurisdictions are also presented to demonstrate the wide adoption of the EU approach to assessment and mitigation of environmental noise across the globe. In outlining the strategic noise mapping process, emphasis is placed on the principles of the noise mapping process in terms of mapping, modelling, estimating exposure and action planning. However, a critical view of the process is also undertaken in that the chapter provides suggestions throughout for best practice improvements as well as improvements that could be made in related policy and legislation at the EU level.

4.2 EU NOISE POLICY AND LEGISLATION

Legislation attempting to regulate environmental noise is not a recent phenomenon at the EU level. It is a process that has been evolving since the establishment of the economic union back in the 1970s. Table 4.1 presents the extent of legislative instruments in relation to the various sources of environmental noise and demonstrates that the EU has been heavily involved in using these instruments to regulate noise at the point of manufacture through the establishment of permissible noise limits. While that continues to be the case, the important change in direction in relation to environmental noise legislation in recent years is that it has moved from being almost entirely focussed on regulating noise at *source* to attempting to mitigate environmental noise at the point of the *receiver* through the establishment of the Environmental Noise Directive (END).

Within the context of an emerging evidence base suggesting links between exposure to environmental noise and public health concerns, noise policy gained greater prominence in EU environmental policy throughout the 1990s. In 1993, the *Fifth Environmental Action Programme of the European Community* established as a basic objective that individuals should not be exposed to noise levels which may endanger their health and quality of life (European Community, 1993) and established a number of targets for mitigating exposure by the year 2000. Later, the EU *Green Paper on Future Noise Policy* was published (European Commission, 1996) which focussed on stimulating public discussion on a future approach for EU environmental noise policy. The document examined the various environmental impacts of noise, the noise situation in the EU and existing policies to reduce noise exposure. With regard to the latter, it focussed on reducing noise at source and limiting the transmission of noise between the source and receiver (i.e. people affected). It also outlined a framework for the assessment and reduction of noise exposure and future actions for noise mitigation. In this sense, it indicated the importance of shared responsibility across the EU for effective noise policy and reaffirmed that the management and reduction of noise from different sources should be prioritised.

The key document linking noise exposure to public health concerns was produced by the World Health Organisation (WHO) – *Guidelines for Community Noise* (Berglund et al., 1999). This document was seminal in that it established noise pollution as a serious public health issue worldwide. According to the document, 40% of the population of EU countries was exposed to road traffic noise with an equivalent sound pressure level exceeding 55 dB(A) during daytime; the corresponding figure for night-time was 30%. Taking all exposure to transportation together, the WHO estimated that approximately 50% of EU citizens lived in zones of

TABLE 4.1 Legislation Regulating Noise at Source in the EU

Noise Source	Related EU Legislation
Automobile	• Directive 70/157/EEC on the approximation of the laws of the Member States relating to the permissible sound level and the exhaust system of motor vehicle; • Directive 97/24/EC on certain components and characteristics of two- or three-wheel motor vehicles; • Directive 92/23/EEC relating to tyres for motor vehicles and their trailers and to their fitting; • Regulation No. 661/2009 concerning type-approval requirements for the general safety of motor vehicles, their trailers and systems, components and separate technical units intended therefore; • Regulation No. 1222/2009 on the labelling of tyres with respect to fuel efficiency and other essential parameters
Aircraft	• Directive 89/629/EEC on the limitation of noise emission from civil subsonic jet aeroplanes; • Directive 2006/93/EC on the regulation of the operation of aeroplanes covered by Part II, Chapter 3, Volume 1 of Annex 16 to the Convention on International Civil Aviation, second edition (1988); • Regulation 216/2008/EC on common rules in the field of civil aviation and establishing a European Aviation Safety Agency; • Directive 2002/30/EC on the establishment of rules and procedures with regard to the introduction of noise-related operating restrictions at Community airports
Railway	• Directive 2008/57/EC on the interoperability of the rail system within the Community; • Commission Decision 2002/735/EC concerning the technical specification for interoperability relating to the rolling stock subsystem of the trans-European high-speed rail system; • Commission Decision 2002/732/EC concerning the technical specification for interoperability relating to the infrastructure subsystem of the trans-European high-speed rail system; • Commission Decision 2011/229/EU of concerning the technical specifications of interoperability relating to the subsystem 'rolling stock – noise' of the trans-European conventional rail system
Outdoor equipment	• Directive 2000/14/EC on the approximation of the laws of the Member States relating to the noise emission in the environment by equipment for use outdoors
Recreational craft	• Directive 2003/44/EC amending Directive 94/25/EC on the approximation of the laws, regulations and administrative provisions of the Member States relating to recreational craft
Household appliances	• Directive 2009/125/EC establishing a framework for the setting of ecodesign requirements for energy-related products; • Commission Regulation No. 206/2012/EU implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for air conditioners and comfort fans;

Continued

TABLE 4.1 Legislation Regulating Noise at Source in the EU—cont'd

Noise Source	Related EU Legislation
	• Commission Regulation No. 1016/2010/EU implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for household dishwashers; • Commission Regulation 643/2009/EC implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for household refrigerating appliances; • Commission Regulation 1015/2010/EU of 10 November 2010 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for household washing machines

acoustical discomfort. Just a few years later, the *6th Environmental Action Programme of the European Community* was adopted by the Council and the European Parliament specifically targeted the problem of environmental noise. The Programme stipulated that future environmental noise policy should aim at 'substantially reducing the number of people regularly affected by long-term average levels of noise, in particular from traffic...' as well as 'developing and implementing instruments to mitigate traffic noise' (European Commission, 2002, 10, 12).

At the EU level, these policy documents together with academic research on noise and health relationships have been instrumental in the development of a legislative framework for the management of environmental noise in Europe. In response to a rising evidence base suggesting health effects associated with excessive noise pollution, the EU passed Directive 2002/49/EC, also known as the END (EU, 2002). Recognising the potential public health concerns, it sought to develop a common approach towards the avoidance, prevention and reduction of the harmful effects of exposure to environmental noise using a strategic noise mapping process. This will be discussed in detail in the next section.

Since the END, there have been some policy documents specifically focussing on environmental noise and its reduction. Of particular note is the recent WHO *Night Noise Guidelines for Europe* (2009) which effectively updated *Guidelines for Community Noise* (1999). It not only sets out the health effects of night-time noise exposure but also offers guidance on how to reduce the harmful effects of night noise in the EU. As mentioned previously (Chapter 3), that document recommended a non-binding limit value of 40 dB(A) $L_{\text{night,outside}}$ if authorities are to prevent their citizens from being exposed to harmful effects of environmental noise pollution. But it also recognised that some authorities might not be able to adopt that limit value initially and suggested an interim value of 55 dB(A) $L_{\mathrm{night,outside}}$ until it becomes more feasible for individual authorities to adopt the recommended limit value. This was followed up by the *Burden of Disease from Environmental Noise* document in 2011 which quantified for the first time the nature and extent of the disease burden from environmental noise exposure across the EU.

The most recent policy document focusing on environmental noise is *Towards a Comprehensive Noise Strategy* (Guarinoni et al., 2012). It attempts to expand the discussion beyond the relationship between noise and health in a more pragmatic manner. It critically assesses existing noise policy and legislation at the EU level by focusing on specific complementarities and disparities. In particular, it points toward the urgent need for more stringent source-based noise legislation than exists at present by reducing permissible noise levels for the manufacture of transport vehicles. The document points out that for the END to be successful into the future, there must be a complementary focus on reducing permissible noise levels at the source if serious noise reductions are to be achieved at the point of the receiver. In the absence of such reduction, the document concludes that the END is likely to only have a limited effect in terms of reducing noise levels across the EU and the cost of doing so will likely fall on the public purse rather than on private manufacturers. One worrying trend over the last decade is that permissible noise levels for road traffic vehicles have not been reduced nearly as aggressively as in previous decades. In fact, rather than decreasing permissible noise levels for vehicle manufacturers, there have actually been some regressive steps in this area including the introduction of special permissible noise limits for 'super cars' which, counter intuitively, are now higher than those for regular automobiles. It is hard to believe that this change, in particular, is anything other than a legislative response to lobbying from high-end European car manufacturers. It ultimately implies that those able to afford highly expensive motor cars are also permitted to produce more negative environmental externalities in terms of environmental noise. Despite this, the general trend has been for the European authorities to be proactive in terms of tackling the problem of environmental noise across Europe with a series of policy and legislative innovations that are beyond compare in other jurisdictions.

4.3 THE ENVIRONMENTAL NOISE DIRECTIVE

The overall objective of the END is to identify a common EU approach aimed at avoiding, preventing or reducing the negative and harmful effects caused by environmental noise. Environmental noise is defined as unwanted or harmful outdoor sound created by human activity, such as noise emitted by means of transport, road traffic, rail traffic, air traffic and industrial activity. The END indicates a series of actions that need to be implemented progressively by Member States in order to achieve the objectives of the END. These are (Guarinoni et al., 2012):

- Monitoring of environmental noise – Member States must develop strategic noise maps in order to estimate the level of population and/or building exposure to environmental noise in priority areas in their jurisdictions;
- Managing environmental noise issues – on the basis of the developed strategic noise maps, Member States must adopt action plans containing measures designed to address noise issues, including noise prevention/reduction and preserving sound quality where it is deemed to be good;
- Public information and consultation – strategic noise maps, action plans and relevant information about noise exposure, its effects and measures considered to address environmental noise issues should be made available to the public or developed in consultation with the public;
- Development of a long-term EU strategy – with a view to reduce noise emitted by the major sources (in particular road and rail vehicles and infrastructure, aircraft, outdoor and industrial equipment and mobile machinery), the EU and Member States should cooperate in order to provide a framework for EU policies addressing environmental noise issues.

In terms of scope, the END applies to environmental noise affecting humans particularly in residential or industrial areas as well as public parks and other quiet areas in agglomerations and the open countryside. However, the END does not apply to noise caused by the exposed person, noise created by domestic activities or neighbours, noise at the work place or inside means of transportation. Member States are obliged to designate competent national authorities responsible for the implementation of the END which is many cases tends to be the national Environmental Protection Agency. Overall, the END is concerned with four core areas that are considered vital for the assessment and management of environmental noise across the EU. These include (1) strategic noise mapping, (2) population exposure estimation, (3) noise action planning and (4) dissemination of results. Each of these areas is now discussed in more detail.

4.4 STRATEGIC NOISE MAPPING

Although there had been some modest efforts to produce noise maps in the mid-1990s (de Vos and Licitra, 2013), the practice of strategic noise mapping became a standard approach used across EU states as a result of the passing of the END. Defined broadly, noise mapping is simply a means of presenting calculated and/or measured noise levels in a representative manner over a particular geographic area (Murphy and King, 2010). In the END, noise mapping is defined as 'the presentation of data on an existing or predicted noise situation in terms of a noise indicator, indicating breaches of any relevant limit value in force, the number of people affected in a certain area, or the number of dwellings exposed to certain values of a noise indicator'. From this, it can be seen that under the END, noise maps are considered to be multi-dimensional because they incorporate not only measured/calculated noise levels for a geographic area but also include information about potential breaches of national statutory limits as well as the number of people and number of dwellings exposed to environmental noise.

Within the END, 'strategic noise mapping' is defined somewhat differently than 'noise mapping'. A strategic noise map is defined as 'a map designed for the global assessment of noise exposure in a given area due to different noise sources or for overall predictions for such an area'. In other words, while 'noise mapping' is focussed primarily on the presentation of noise data, 'strategic noise mapping' is primarily concerned with the assessment of noise exposure under the terms of the END. Indeed, the mapping requirements of the END are concerned primarily with 'strategic noise mapping'. Assessment of exposure to environmental noise is to be achieved using 'strategic noise maps' for major roads, railways, airports and agglomerations using the harmonised noise indicators L_{den} and L_{night} that were developed specifically for the END. L_{den} is an annual noise indicator which describes the average day-evening-night-time A-weighted equivalent sound pressure level over a complete year, while L_{night} describes the night-time A-weighted equivalent sound pressure level over a complete year. L_{den} is given by the following equation:

$$L_{den} = 10 \log\frac{1}{24}\left(12^{*}10^{L_{day}/10} + 4^{*}10^{L_{evening}+5/10} + 8^{*}10^{L_{night}+10/10}\right) \tag{4.1}$$

The day period is generally taken to be from 07.00 to 19.00 while evening and night-time periods are taken to be from 19.00 to 23.00 and 23.00 to 07.00, respectively. The weighting factors in the above equation are designed to account for the increase in annoyance at different periods throughout the entire day, hence the addition of 10 to the value for L_{night} and 5 to the value of $L_{evening}$ meaning that escalations in night-time noise are more punitive with respect to limit values. However, the END also allows for additional supplementary indicators to L_{den} and L_{night}. During the first phase of noise mapping, the use of supplementary indicators was rare; in cases where they were used, L_{max} or L_{eq} were the supplementary indicators of choice. However, many different indicators exist and their use may maximise the value of strategic noise mapping. Possible additional examples include perceived noise level, sound exposure level (SEL) or even % highly annoyed (%HA) and % highly sleep disturbed (%SD).

On the basis of L_{den} and L_{night}, Article 7(1) of the END requires Member States to produce strategic noise maps for all major roads, railways, airports and agglomerations on a 5-year basis, starting from 30 June 2007. In the first phase (June 2007), strategic noise maps were compiled for: all agglomerations with more than 250,000 inhabitants; all major roads with more than 6 million vehicle passages a year; railways with more than 60,000 train passages a year; and major airports with more than 50,000 movements a year within the territories. The results of this process have recently been made available via a noise observation and information service for Europe (NOISE) which is maintained by the European Environment Agency (EEA),[1] while a preliminary European-wide analysis of the results has already been attempted (van den Berg and Licitra, 2009). The second phase (June 2012) requires that strategic noise maps are produced for all agglomerations with a population in excess of 100,000 individuals and also sees a reduction in the thresholds for major roads (to 3 million vehicle passages) and railways (to 30,000 vehicle passages). The strategic maps must satisfy minimum requirements as listed in Annex IV of the END and should be reviewed every 5 years.

Figure 4.1 presents a standardised schematic of best practice steps involved in the strategic noise mapping process. During the first phase of the END, these steps were applied in a rather variable way by each nation and, therefore, the results of the process were also variable. The standardised approach has a series of components: data collection; noise calculation; validation and mapping; estimation of population exposed; noise action planning; and public dissemination. This process is elaborated upon in the following section.

4.4.1 Data Collection/Input Data

Perhaps the most important part of the process is data collection; it is crucial that accurate data are available in order to acquire accurate calculation levels at noise receiver points. Generally, the main data required for noise mapping are information relating to traffic flows on the links/routes to be assessed which are representative of traffic flow for individual sources (road, rail, air and industry) for a full year for the area under consideration. Building height and geometry information is also needed as this affects the path of sound waves in the built environment. In addition, depending on the calculation method being utilised, local meteorological and topographical information may also be required including relative

[1]See http://noise.eionet.europa.eu/ for more information.

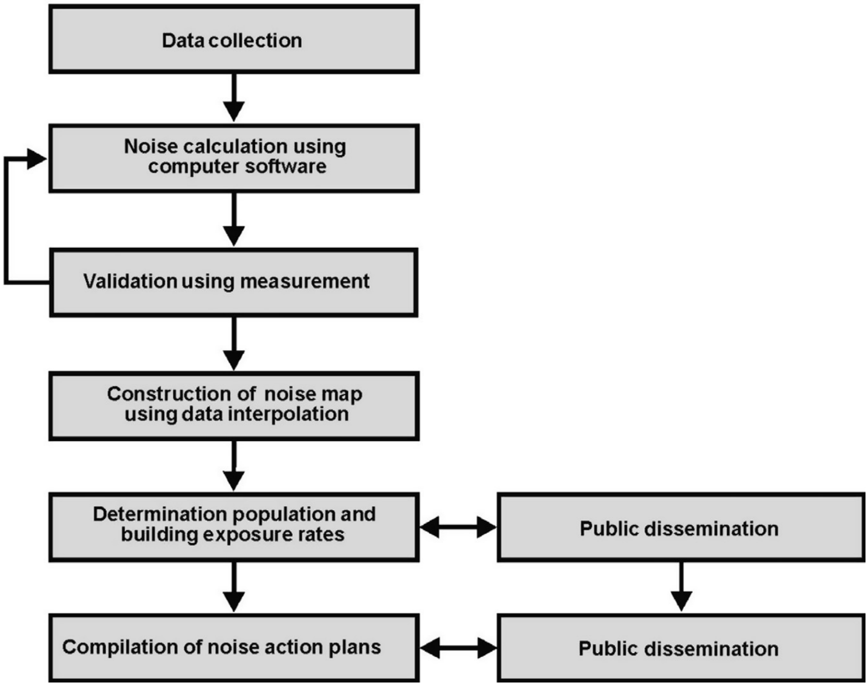

FIGURE 4.1 Schematic of the noise mapping process.

humidity, wind speed and temperature. For road traffic noise, for example, data related to the sound power characteristics of vehicles are generally standardised within calculation software on the basis of typical characteristics of light and heavy vehicles. An outline of the main data needed for noise modelling calculations is provided in Table 4.2.

4.4.2 Calculation Methods for Noise Mapping

Numerous calculation methods exist for predicting noise levels at specific receiver points. Similarly, the results obtained from calculations may be expressed using a variety of noise indicators. For noise studies, both issues are problematic because these difficulties make comparison between studies extremely difficult. One objective of the END was to establish a uniform approach to the assessment and management of environmental noise. In this regard, the END has addressed the latter issue relating to noise indicators through the introduction of the L_{den} noise indicator. However, in relation to the former issue, a standardised noise calculation model has yet to be fully developed but is currently in the process of being completed (see Box 4.1).

TABLE 4.2 Overview of Main Data Sources for Noise Calculations

	Parameters				
Data	**Road Traffic**	**Railway Traffic**	**Aircraft Traffic**	**Industry**	**Acoustical Data**
Sources and Emissions	Road geometry Gradient Curvatures Surface cover Speed Volume of traffic Heavy vehicle percentage Type of traffic flow Traffic lights	Number and types of trains Average speed Sirens Railway structure (in cuttings, level or elevated) Type of rails, ballasts and ties Bridge structures	Airport plan Runway configuration Flight operations (daily, yearly, etc.) Types of aircrafts	Layout plan for open air activities Factory buildings Manufacturing process Indoor–outdoor equipment Operation modes (hourly, daily, weekly)	Sound power levels in L_W, dBA and the spectral values Source directivity Reference sound pressure levels with temporal and spectral variations For complex sources: contributions from individual parts

	Parameters				
Data	**Ground Cover and Woodland**	**Buildings**	**Obstacles**	**Meteorological Factors**	**Acoustical Data**
Physical Environment	Type of surface (sound absorption coefficient) Width of surface under sound path Surface area configuration of different surface types Type of plants Configuration of trees (deciduous, evergreen, etc.)	Location Geometry Façade shape (ba lconies, etc.) Number of floors (or total height) Function Façade cover (sound reflection properties)	Natural (topography) or built barriers Location (distance from source) Thickness Length Height Surface type Top profile of screens Surface cover Constructional material	Wind gradient Temperature gradient Humidity (air absorption) (Short-, mid- and long-term average values) Favourable conditions increasing noise levels	Effects of physical factors on immission values caused by wave divergence absorption, diffraction, refraction, scattering of sound Total sound attenuation

	Parameters				
Data	**Land Use Information and Applicable Noise Limits**	**Population Structure**	**Building and Usage**	**Future Plans About Area**	**Acoustical Data**
Demographic	Urban residential Suburban and rural Health care buildings Educational buildings Administrative area Shopping centres Industrial and mixed zones Touristic area (hotels, motels) Recreational and entertainment area Parks and cemeteries	Total population Number of residents for each building Social, educational and economical characteristics of community Seasonal activities (in touristic areas)	Sensitivity to noise Indoor noise limite Times of occupation (daily, yearly) Open/closed windows Existence of AC equipment Indoor noise sources (background noises) Layout of rooms Building construction	On-going and future constructions Extension or modification of noise sources. Existing noise action plans	Noise – dose and response relationships for various types of land uses Noise levels and performance effects Outputs from noise maps: Number of people and buildings exposed to various noise levels Number of buildings having quiet façades

Source: *Kurra and Dahl (2012).*

For the first round of noise mapping, the END recommended several standards to be used by countries with no national standard or by those who wished to change computation methods. These standards were envisioned to be interim standards for use until a standardised European method was developed by the EU, although Member States were free to use alternative methods in the development of strategic noise maps. For road traffic noise, the chosen standards were the French national computation method 'NMPB-Routes-96 (SETRA-CERTU-LCPCCSTB)', referred to in 'Arrêté du 5 mai 1995 relatif au bruit des infrastructures routières, Journal Officiel du 10 mai 1995, Article 6' and in the French standard 'XPS 31–133'. For input data concerning emission, these documents refer to the 'Guide du bruit des transports terrestres, fascicule prévision des niveaux sonores, CETUR 1980'. For railway noise, the Netherlands national computation method published in 'Reken- en Meetvoorschrift Railverkeerslawaai '96, Ministerie Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, 20 November 1996' was selected as the recommended interim method while for aircraft noise ECAC.CEAC Doc. 29 'Report on Standard Method of Computing Noise Contours around Civil Airports', 1997 was selected. Of the different approaches to the modelling of flight paths, the segmentation technique referred to in Section 7.5 of ECAC.CEAC Doc. 29 was to be used. For industrial noise ISO 9613-2: 'Acoustics - Abatement of sound propagation outdoors, Part 2: General method of calculation' was to be used. Each of these methods is discussed in more detail in Chapters 5 and 6.

While the interim methods have been widely implemented in their country of origin, it was deemed appropriate to publish additional guidance on the implementation of the standard for noise mapping under the END. Indeed, Annex II of the END commits the Commission to publish guidelines on the interim methods along with providing emission data for aircraft noise, railway noise and road traffic noise, on the basis of existing data. In August 2003, the Commission issued recommendations concerning the emission data of the interim computation methods, taking cognisance of the universal noise indicators L_{den} and L_{night} (European Commission, 2003). Additionally, in 2002, European Commission DG Environment engaged the service of Wölfel to develop adaptations and revisions of the interim methods for the purpose of strategic noise mapping in Europe (Wölfel Group, 2003).

In situations where a Member State chose to use a calculation method other than the recommended interim method, that Member State was required to demonstrate that the adopted method produced equivalent results. This requirement was designed to ensure comparability of results across member states. Yet, the manner by which to determine equivalence was not described in the END which led to considerable confusion among competent authorities in Member States. In order to assist Member States in determining equivalence in their mapping methods, a number of technical protocols were developed by the Joint Research Centre (JRC) of the European Commission (JRC, 2008). These protocols were made available to each Member State who was asked to report back about the results of the equivalency exercise. However, only a few Member States participated in this exercise. It was noted that this could be 'eventually attributed to the fact that Member States were reluctant in facing discussions concerning equivalency' (JRC, 2008, 6). In the responses received by the JRC, one communication noted 'As the EU Directive does not call for identical results it should not become necessary to demonstrate equivalence by means of a parallel computation of specific cases' (JRC, 2008, 13), while another observed that applying the equivalence protocol could 'prove a costly and time-consuming task just at the stage when Member States are working hard to meet the very challenging timetable for action planning', stating that 'it will be difficult to determine what deviation from the interim method will be acceptable' (JRC, 2008, 32). The result of this was that despite interim methods being recommended, most nations used their national calculation methods where one was available. This has had a significant impact of the efficacy of comparing noise mapping results across Europe.

Each national calculation method was originally developed to the specific conditions or legislation as applied in each nation (long before the END was conceived). Thus, the Dutch prediction method for railway noise is tailored for Dutch trains travelling on typical Dutch railway tracks. The UK CRTN method for road traffic noise predicts noise levels over 18 h of the day because this time period was enshrined in the legislation which preceded CRTN. One must also consider the time period in which these calculation methods were developed; CRTN (UK) was developed in 1988, the French Guide du Bruit was developed in 1980; the US Federal Highway Authority's Traffic Noise Model (TNM) Version 1.0 was released 1996; in 1990, the German RLS 90 calculation method revised a 1981 version; and in 1993, the Acoustical Society of Japan developed the ASJ Method for road traffic noise. While most methods have been revised in recent years (or accompanied by good practice documents), they are all based on methods that were developed prior to the advent of the personal computer and data-logging sound level meters. Furthermore, no calculation method was ever developed with the intention of producing strategic noise maps on a national scale. In fact, calculation methods (of the 1970s, 1980s and 1990s) were developed for implemention via hand calculation (Hepworth, 2006).

Table 4.3 shows the wide range of calculation methods used for each type of noise source in the first phase of the END; more or less identical approaches were also used for the second round. This highlights the variety of acoustical standards currently in use across the EU. The only way to ensure that a consistent approach is adopted across Europe is for every Member State to implement the same calculation method which is why the EU are now on the brink of establishing a common standardised prediction methodology for noise mapping in the EU – referred to as CNOSSOS-EU (Kephalopoulos et al., 2012).

BOX 4.1

COMMON NOISE ASSESSMENT METHODS IN EUROPE (CNOSSOS-EU)

Article 6(2) of the Directive states that '. . .Common assessment methods for the determination of L_{den} and L_{night} shall be established by the Commission. . .'. CNOSSOS-EU is a common noise calculation method for road, railway, aircraft and industrial noise across the EU (Kephalopoulos et al., 2012). Indeed, CNOSSOS-EU also develops a methodology for assigning receiver points to the façades of buildings and assigning population data to the receiver points at the façades of buildings. The methodological framework underpinning CNOSSOS-EU is based on noise assessment methods that are in existing use in some Member States (e.g. Austria, Denmark, Finland, France, Germany and Sweden). Following its adoption, CNOSSOS-EU is to be used by the Member States for the purpose of strategic noise mapping as required by Article 7 of the END. The introduction of the new methodology is a welcome development because it offers a solution to the inconsistent noise mapping undertaken in the past. For the first time it will allow a direct comparison of noise exposure at the EU level. Indeed, historical comparability of noise maps may be maintained by undertaking back calculation for the first two rounds of noise mapping if Member States choose to do so.

The development of CNOSSOS-EU was co-ordinated by the Directorate-General for the JRC on behalf of the Directorate-General for the Environment. It involved collaboration between the European Commission, European Environment Agency, European Aviation Safety Agency, the WHO and nearly 150 noise experts from across Europe. Following the development phase (Phase A) of CNOSSOS-EU, the Commission will amend Annex II of the END during the implementation phase (Phase B) of the project from 2012 to 2015. The ultimate objective is to have the common noise assessment methodology implemented and operational for the third round of strategic noise mapping in 2017.

However, it remains to be seen how European Member States will interpret the CNOSSOS-EU method. Aspects of the method have already been questioned and some experts appear reluctant to embrace it. The method

TABLE 4.3 Noise Calculation Methods Utilised Across the EU During the First Round of Strategic Noise Mapping

Road	Rail
RVS 3.02	RMR (SRM 11)
NMPB/XPS 31–133	NBT85
Temanord 525	Temanord 524
RLS90	NMPB/XPS 31–133
CRTN	Schal03
RMW 2002 (SRM I+II)	CRN
StL 86	SEMIBEL
Industry	**Air**
OAL 28	OAL 24
ISO9613	ECAC DOC 29
Nordforsk 32	AzB
Handleiding Industrielawaai	INM
BS5228	RLD/BV-01 and RLD/BV-02
	FLULA

is still in preliminary format, but the current release gives some indication of the proposed detail. If it is to be a successful endeavour, it will have to be finalised in an open, clear and logical manner with input from all relevant stakeholders. To date, this has been achieved with the establishment of the CNOSSOS-EU Technical Forum of Experts. This technical forum has brought CNOSSOS-EU to its current stage, but it is not yet complete. The final step requires validation of the methods, and it is likely that this will have to be completed in each Member State in order to ensure widespread adoption.

As well as the inherent differences associated with the use of different calculation methods, different commercial software packages (Box 4.2) are being used for fulfilment of the terms of the END together with unknown spatial interpolation techniques and different colouring display methods. As well as this, the END contains a number of unclear phrases and missing provisions. For example, noise maps have to be developed near major roads but what constitutes 'near' is not explicitly defined (McManus, 2009). Taken together, all of these issues produce results which make comparison of strategic noise mapping results across EU states extremely difficult. The recent *Good Practice Guide for Strategic Noise*

Mapping and the Prediction of Associated Data on Noise Exposure (WGAEN, 2006) has attempted to provide a toolkit of practical workaround solutions for the various obstacles encountered during the noise mapping process as well as offering a uniform interpretation of the Directive itself. Indeed, it is envisaged that CNOSSOS-EU will iron out many of these difficulties.

BOX 4.2

SOFTWARE PACKAGES AND NOISE MODELLING

Research has uncovered that different commercial software packages may yield different results while applying the same national computational method. A study conducted in the United Kingdom outlined the extent of variation between several commercial packages implementing the CRTN standard (Hepworth, 2006). Results obtained from the commercial software were compared over a 1-km^2 calculation area. The greatest mean difference was 2 dB(A), and the greatest individual difference at a single calculation point was 11 dB(A). These results indicate that the use of different software packages implementing the same standard, with the same input data, will have a significant effect on the resulting noise map. Other research has reported variances of up to 6 dB(A) due to different interpretations of the Dutch national calculation method RMV2 (Nijland and Van Wee, 2005), while similar problems have been highlighted by Arana et al. (2010). Indeed, King and Rice (2009) argue that to truly achieve standardisation in noise studies, competent authorities should be required not only to apply the same calculation procedures but also to employ the same calculation software. In this context, Guarinoni et al. (2012) have recently recommended that an open source noise calculation software package is produced by the EU to be utilised by all nations for the CNOSSOS-EU method.

4.4.3 Producing a Noise Map

In order to produce a strategic noise map, the process proceeds by calculating noise levels at receiver points on uniform grids placed over the study area using the input data and noise modelling approaches described in the previous sections. All calculations are performed at the standard receiver height of 4 m above the ground according to the terms of the

END. These calculations are normally undertaken using commercial software programs which have embedded algorithms for national noise source and propagation standards for nations across the EU. After calculations have been undertaken in commercial software, it is best practice to validate modelling results using sound level meter measurements to ensure that the model provides an accurate representation of the true sound environment. Validation measurement should be performed according to ISO 1996-1 (ISO, 2003) and should adhere to international best practice for undertaking noise measurement described in Section 2.5, Chapter 2.

In terms of representation, grid sizes for noise calculations can range from 5 to 20 m^2 resolutions. In open areas outside agglomerations, larger grid resolutions may be adequate whereas in urban areas a grid spacing of less than 10 m is desirable. Indeed, it is also possible to use a variable grid spacing which declines in resolution away from the noise source (see De Kluijver and Stoter, 2003; see Figure 4.2) in order to reduce the overall number of receivers and speed up calculation time. Normally, noise maps are then produced using a process of spatial interpolation within a Geographic Information System (GIS) as presented in the noise map of Dublin, Ireland (Figure 4.3). Spatial interpolation is a mathematical method of constructing new data points within the range of a discrete set of known data points across a geographic area. The main interpolation methods available within a GIS framework are nearest neighbour, kriging, spline and inverse distance weighting. Murphy et al. (2006) have pointed out that the choice of interpolation method in noise mapping studies can be important due to different spatial interpolation methods producing slightly different mapping results both in a quantitative and in a qualitative sense. While most commercial noise mapping programs have an embedded mapping component allowing users to produce maps without the need for a GIS system, they are extremely limited in terms of their functionality. For example, the mapping component in commercial software does not usually provide the user with a choice of spatial interpolation method. In fact, many of them do not specify the method being utilised in the mapping process at all (Murphy and King, 2013). Overall, commercial packages do not compare positively with the mapping techniques available in commercial GIS packages. In particular, the ability of GIS packages to deal with numerous types of spatial data far outweighs that available within commercial noise mapping packages. As a reflection of this, some commercial software packages offer import/export functionality in an attempt to take advantage of the greater ability of GIS to manipulate spatial data in a more sophisticated and customised manner.

The absence of a standardised colour scheme makes it difficult to compare maps from different EU states. Very often, noise maps are produced with different colour codings despite the fact that an ISO standard exists for the presentation of acoustics graphics (ISO 1996-2). However, this

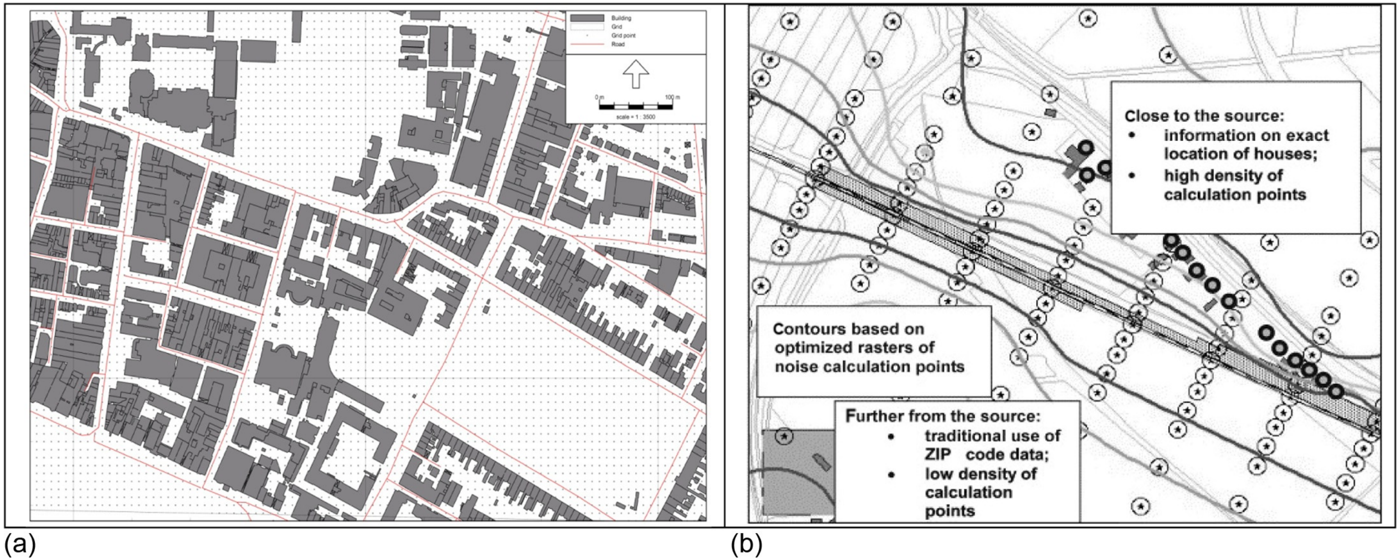

FIGURE 4.2 Uniform (a) and irregular (b) receiver grids for noise calculation purposes. *Source: Panel (b): De Kluijver and Stoter (2003).*

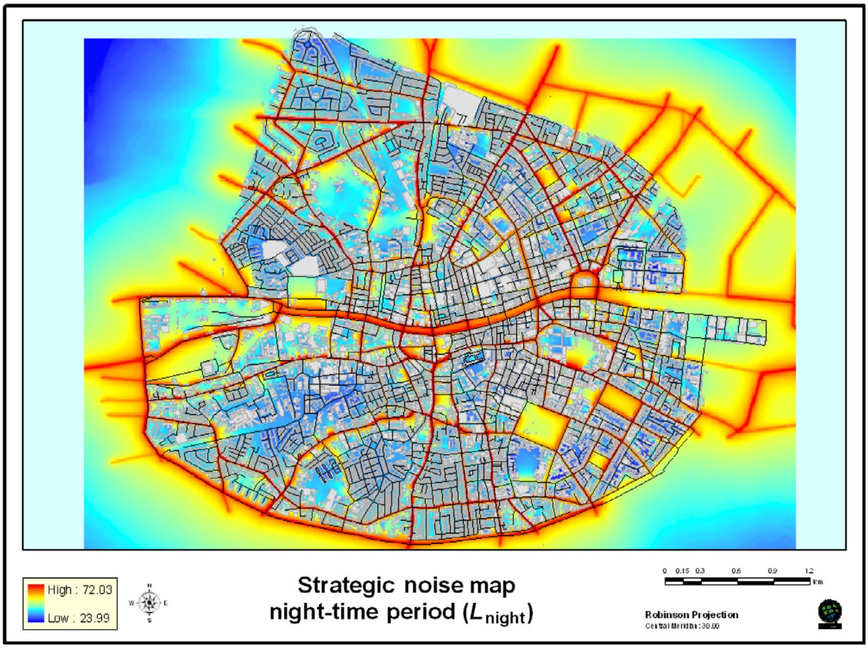

FIGURE 4.3 Noise map of Dublin, Ireland. *Source: Murphy and King (2011).*

standard has since been revised and includes no specifics on colour coding. Indeed, the recent best practice document from the WGAEN (2008) does attempt to deal with the issue of colour coding by providing more specific guidelines for relevant authorities. Moreover, the question of whether results should be presented using graduated colouring techniques or specifically delineated colour contours remains unclear. In comparative terms, this could prove to be problematic given that different methods affect the visual impact of noise mapping results when they are presented to the general public.

4.4.4 Estimating Population Exposure

The second key element of the END is the determination of levels of exposure to environmental noise using the common indicators L_{den} and L_{night}. The END requires competent authorities in each Member State to provide estimates of the number of people living in dwellings that are exposed to values of L_{den} and L_{night} in various categories[2] at the most

[2]The categories stated in the Directive are 55-59, 60-64, 65-69, 70-74 and >75 for L_{den} and 50-54, 55-59, 60-64, 65-69 and >70 for L_{night}.

exposed building façade and separately for road, rail, air traffic and industrial noise (EU, 2002, 24). In addition, where it is deemed appropriate and where the information is available, people living in dwellings that have special insulation against environmental noise or have a quiet façade[3] should also be reported. Thus, strategic noise maps must be accompanied by relevant assessment data detailing the level of exposure for each area under consideration. However, the END does stipulate that strategic noise maps can take the form of graphical plots or numerical data in table or electronic form.

In procedural terms, approaches aimed at estimating the exposure of people to environmental noise must consider three issues (Brambilla, 2013):

1. Assignment of receiver points to the building façade
2. Assignment of population to buildings
3. Assignment of population data to the receiver points at building façades

In the first instance, in order to estimate population exposure to noise separate calculations must be undertaken placing receiver points at the building façade – these are often referred to as 'façade calculations'. This is highlighted in Annex VI of the END. It is important also to point out that when noise levels are calculated at receiver points at façades, the noise level refers to the incident sound level – also known as the 'free field' sound. This means that reflections from the façade under observation are excluded from the calculation of noise levels. However, if external façade levels are required, a suitable correction factor can be applied. As demonstrated in Figure 4.4, façade calculations involve using separate receiver points from those used for the development of strategic noise maps. It is good practice to place receiver points at 0.1 m in front of the façade with spacing of 3 m between individual calculation points and at a height of 4 m (as for strategic noise mapping grids). While a height of 4 m is stipulated in the END, it is unlikely to be representative of the actual exposed population, particularly in urban areas. Specifically, a 4-m height is adequate in suburban of low-density areas where buildings are a few stories high, but is likely to be inaccurate in central city areas where building heights run to many stories. For example, Law et al.'s (2011) noise mapping study of Hong Kong demonstrates the inadequacy of 4 m receivers points for the high rise nature of buildings in that city.

The recently published CNOSSOS-EU report suggests a common approach for assigning receiver points to buildings based largely on the

[3]A quiet façade refers to the façade of a dwelling at which the value of L_{den} is more than 20 dB(A) lower than at the façade having the highest value of L_{den}.

FIGURE 4.4 Example receiver placing for calculating noise at building façades.

German method. Using that method, the following approach is used to calculate exposure (Kephalopoulos et al., 2012, 115):

- façades are split up every 5 m from the start position onwards, with a receiver position placed at the half-way distance;
- the remaining section has its receiver point in its mid-point;
- for buildings with floor sizes that indicate a single dwelling per floor level, the most exposed façade noise level is used directly for calculating exposure statistics and related to the number of inhabitants;
- for other buildings, exposure statistics use all receiver points in a weighted manner so that the sum of all receiver points represents the total number of inhabitants.

Once noise levels are known at the receiver points for each building façade, it is a rather straightforward process in a GIS to assign individual buildings with the noise level associated with the receiver point at the most exposed façade. This is normally undertaken using a procedure known as spatial joining in a GIS. Typically, population exposure is estimated by first determining the number of residential units for each building in the study area. Once determined, each residential unit is assigned an average household size value. For example, if there are 80 people residing in a building and the building has 32 residences (i.e. apartments), the average household size is 2.5. Given the number of residential units for each building in the study area and the average household size associated with each building location and the building noise level, it is possible to compute estimates of the residential population for each building exposed to environmental noise within a specific noise category. This is generally the approach that has been adopted thus far under the END although different procedures have been adopted depending on the availability of data (see Murphy and King, 2011; Murphy et al., 2009). However, if more detailed data are available in specific circumstances, then estimates of the residential population in individual units can be substituted with more precise data.

The foregoing approach is not without its flaws. In particular, it fails to account for the design of individual buildings and specifically whether the bedroom is located at the most exposed façade for individual residences within buildings. By counting individuals living in a particular household, the assessment method assumes, particularly during the night-time period, that all individuals living in a particular household are exposed to the noise level at the most exposed building façade. Thus, estimates of population exposure are likely to be overestimated to a significant degree if assessment is based at the individual level. Moreover, assessment of exposure to noise is based on the assumption that individuals reside in their dwelling and sleep there all year around, whereas in many EU cities, workers and students leave the city at the weekend to return to rural areas. Thus, the assessment method fails to account for transient populations when providing estimates of population exposure.

There are other methods of estimating population exposure to noise that have been used in specific national contexts. One of these is the German method – VBEB (Vorläufige Berechnungsmethode zur Ermittlung der Belastetenzahlen durch Umgebungslärm/Preliminary Calculation Method for Determination of the Number of Persons Exposed to Environmental Noise). The method assumes that the position, size, floor plan and number of residential units of a building are not generally known. Thus, the approach assumes that the total number of building inhabitants is distributed equally across receiver points located at the building façade. In this way, an 'inhabitant per assessment point' is determined (German Federal Gazette, 2007). The method generally produces much more conservative estimates of the population exposed to noise than the approach described previously. Other methods include the average-level exceedance (ALE) method and the 'nearest grid method' (NEAR). Licitra et al. (2009) applied the END, VBEB and ALE methods to the same area in Pisa, Italy. Their results showed that the END method was significantly more precautionary (in that it had higher estimates) than either the

ALE or VBEB method. In fact, their results found that at the exposure level of 60 dB(A) L_{den}, the END method estimated a population exposure rate of 47%, whereas the corresponding figures for the VBEB and ALE methods were 20% and 37%, respectively. This highlights the extent to which different estimation approaches can produce drastically different estimates of population exposure to environmental noise. Moreover, the results imply a potentially alarming overestimation of population exposure arising from the results of population exposure estimation across the EU as part of the END.

Very often, estimating population exposure can be a complex process for a number of reasons but mainly due to the fact that population data in individual buildings are not often known and therefore estimating the population associated with individual buildings can be difficult. Moreover, it is often not possible to know the orientation of the bedroom (i.e. whether it is at the most exposed façade or not) for large-scale noise mapping studies and this can often produce overestimates of exposure. In addition, in the first round of noise mapping in the EU, some nations (e.g. Ireland among others) produced estimates of population exposure based solely on strategic noise maps without undertaking façade calculations. When these issues are taken together, it can be seen that the results of exposure studies across the EU are likely to have a significant degree of error. Indeed, they are also difficult to compare across the EU because of the variation in the nature of the data and estimation procedure used across the continent.

For the first and second round of noise mapping, there has been no standardised method for estimating population exposure. It is likely that that will also be the case for the third round in 2017. In the END, emphasis is placed on providing information about the number of people living in dwellings that are exposed to various noise categories at the most exposed façade. The *Good Practice Guide* (WGAEN, 2008) makes a number of recommendations regarding the assessment of population exposure based on the type of data available within each Member State. However, the approaches suggested fall far short of a standardised methodological approach. Given these criticisms, standardised approaches have recently been developed for estimating population exposure under the CNOSSOS-EU methodology. The approach provides for estimating exposure both in cases where population information is available and unavailable for buildings in specific areas (see Kephalopoulos et al., 2012, pp. 111–115).

It is notable also that the END does not stipulate any guideline limit values for population exposure to L_{den} and L_{night}. The EU did not set common European-wide noise limit values. It was felt that this would be impossible given the large differences in scale and comprehensiveness of implemented noise measures throughout the different Member States (European Commission, 2000). Yet, as mentioned already, guideline limit values for environmental noise already exist in WHO policy documents (Berglund et al., 1999; WHO, 2009) which provides a framework for the establishment of dose–effect relations for environmental noise exposure. Looking to the future, and assuming that the more pressing methodological problems have been dealt with adequately, it would appear important that guideline limit values are set by the EU for both L_{den} and L_{night}. In its absence, it is extremely difficult to assess the extent of dose–effect relationships within and between Member States adequately. Indeed, a recent EU policy document recommends that while limit values should not be established immediately, their establishment as part of END revisions should be a key medium-term target for EU policymakers (Guarinoni et al., 2012).

4.4.5 Noise Action Planning

Chapter 7 provides a detailed account of existing noise mitigation approaches, including action planning measures and best practice case studies that assist with reducing noise exposure. As a result, the following discussion focuses only on the emergence of action planning under the terms of the END and subsequent implementation of action plans by Member States.

The END recognises that the development of strategic noise maps is simply a means to an end for improving public health across the EU. In this sense, noise maps are seen to be a precursor to implementing effective and sustainable noise reduction measures so that exposure to excessive noise can be reduced in agglomerations and within the vicinity of noise sources beyond city regions. Thus, based upon noise mapping results, Member States must prepare action plans containing measures addressing noise issues and their effects for major roads, railways, airports and large agglomerations (>100,000 people). According to Article 8.1(b), the plans should also aim to protect quiet areas against an increase in noise. However, the ENDs rather vague definition left ample discretion for Member States to subjectively interpret the concept of quiet areas. This subsequently led to a great deal of confusion surrounding how quiet areas should be defined for each nation and a considerable divergence in the approaches used for noise mitigation and sound quality preservation.

According to the END, action plans refer to ‘plans designed to manage noise issues and effects, including noise reduction if necessary’. The END also requires that action plans are reviewed, if deemed necessary by the competent authority, when a major development occurs that may affect the existing noise situation including residential, commercial, retail or major infrastructure developments. In addition, action plans are to be reviewed every 5 years after the initial date of approval. Thus, noise action planning is process-oriented in the sense that it is constantly evolving and regularly taking account of major changes that are likely to affect the sound quality of a local area.

The END also introduces the notion of 'acoustical planning' which has direct relevance to the development of action plans for noise. 'Acoustical planning' refers to 'controlling future noise by planned measures, such as land-use planning, systems engineering for traffic, traffic planning, abatement by sound-insulation measures and noise control of sources'. In other words, the END points directly to the role that can be played by national planning systems in the future mitigation of environmental noise and recent research has demonstrated the impact that land use and traffic management measures can have on reducing noise pollution in cities (King et al., 2009, 2011a,b).

As outlined already, noise action planning is envisioned as a method for the management of noise issues and effects. In this regard, the END requires that noise mitigation measures are put in place to deal with areas considered to be of poor sound quality and suggestions have been made within the END about measures that could perhaps be utilised by the relevant authorities (Table 4.4). The difficulty with noise mitigation measures is trying to connect the correct mitigation measure with the appropriate problem. For example, a noise barrier may not be an

TABLE 4.4 Minimum Required Elements for Actions Plans and Potential Noise Mitigation Measures in the END

Minimum Required Elements for Action Plans	Potential Mitigation Measures
• Description of agglomeration, major roads, major railways or airports • The authority responsible • The legal context (national legislative compliance) • Limits values (if applicable) • Summary noise mapping results • Evaluation of human exposure; identification of problems potential improvements • Record of public consultation • Noise reduction measures in force or in preparation • Actions to be taken in next 5 years • Estimates of the reduction of the people affected • A long-term strategy • Financial information (cost-effectiveness assessments, etc.) • Provision for evaluation of action plan implementation and results	• Traffic planning • Land-use planning • Technical measures at noise sources • Selection of quieter sources • Reduction of sound transmission • Regulatory or economic measure or incentives

appropriate measure to be adopted within cities given the potential aesthetic consequences, but it may be appropriate for areas that are less visually sensitive. Similarly, reducing the speed limit on motorways may be less suitable than the erection of a noise barrier. Thus, the key to implementing noise mitigation measures is for decision makers to take account of the severity of the noise situation as well as the local context for implementing such measures.

Policymakers must also be careful not to lose sight of the need to preserve quiet areas of good sound quality under the terms of the END. There is a danger that areas of good sound quality will be neglected or simply ignored if they are considered to be 'unproblematic'. In this sense, action plans should be careful to clearly identify 'quiet areas' within the strategic noise mapping process which would allow for the ongoing monitoring of these areas and the evolution of the sound quality within them. Moreover, quiet areas are poorly defined in the END which fails to set a guideline decibel value below which quiet areas could be appropriately categorised. This is a further area for clarification in future legislative amendments which has been aided considerably by a recent UK policy document which assists in the definition of quiet areas (DEFRA, 2006).

A further element of this strand of the END relates to public consultation. Competent authorities are required to 'ensure that the public is consulted about proposals for action plans' and that they are 'given early and effective opportunities to participate in the preparation and review of the action plans'. Authorities are also required to ensure that 'the results of participation are taken into account and that the public is informed on the decisions taken'. To date, public consultation has been limited in many states. For example, public consultation has generally been limited to placing strategic noise maps on the internet while little attempt appears to have been made to inform the public of actions to be taken as a result of noise action planning. As it stands currently, public consultation is seen very much as an afterthought of the strategic noise mapping process where public communication and information dissemination is occurring in a rather *ad hoc* and tokenistic fashion.

4.4.6 Dissemination of Results to the General Public

The final major element of the END centres on the dissemination of information derived from the strategic noise mapping process to the general public. Indeed, one of the central objectives of the END is to ensure that 'information on environmental noise and its effects is made available to the public'. The END requires that strategic noise maps and action plans are not only made available to the public but also disseminated in accordance with Directive 90/13/EEC on the freedom of access of information to the environment. The availability of the information must also conform to the minimum requirements for strategic noise mapping and action plans laid down in Annexes IV and V of the END. Information presented to the general public is required to be 'clear, comprehensible and accessible'.

Member States are obliged to provide the Commission with information from their strategic noise maps, summaries of the action plan details and noise control programmes at regular intervals, as well as to update the Commission on competent bodies, noise limit values and designated roads, railways, airports and agglomerations. On the basis of this information, every 5 years the Commission publishes a summary report and sets up a database of strategic noise maps in order to facilitate the compilation of a report on the implementation of the END. The first implementation report was published by the Commission on 1 June 2011. The full reporting obligations set out under the END are contained in a number of provisions and are summarised in Table 4.5.

The core issue surrounding the dissemination of information to the public relates primarily to the method of dissemination of strategic noise mapping information to the public. At present, the methods used are primarily the online availability of strategic noise maps and associated noise actions plans. In addition to this, a recent European Environment Agency (EEA) document – *Presenting Noise Mapping Information to the Public* – highlights the need for the public to be informed about the use and limitations of the results of noise mapping so that their expectations for the action planning stage remain realistic (WGAEN, 2008). Indeed, numerous additional suggestions are offered for improving the presentation of noise mapping information to the public through the establishment of a central government website for national data, press releases, public forums and school education.

Most strategic noise maps are available only in two dimensions and are often difficult for a relatively uninformed public to understand clearly. Some scholars have attempted to present noise mapping results as a 3D representation of 2D information (Law et al., 2011; Murphy et al., 2006; Stoter et al., 2008). Such approaches offer better visualisation of noise mapping results than the more conventional approaches currently being adopted and have the potential to enhance public engagement with noise mapping and action planning exercises. More recent approaches have advocated the incorporation of strategic noise mapping results into virtual urban simulations (Law et al., 2011; Murphy et al., 2007). Such an approach would enable end users to experience strategic noise mapping results in a manner akin to that of an online gaming experience (see Drettakis et al., 2007; Tsingos et al., 2003). In this way, the end user is able to negotiate the surrounding environment and experience changes in environmental noise in a more realistic fashion. These changes would also

TABLE 4.5 Reporting Requirements of Member States Arising from the END

Implementation Deadline	Summary Description of Data Sets to Be Reported	END Provision	Updates by Member States
30 June 2005	Major roads, major railways, major airports and agglomeration designated by MS and concerned by first implementation step	Art. 7-1	Mandatory every 5 years
18 July 2005	Establishment of competent bodies for strategic noise maps, action plans and data collection	Art. 4-2	Possible at any time
18 July 2005	Noise limit values in force or planned and associated information	Art. 5-4	Possible at any time
30 December 2007	Strategic noise maps related data as listed in annex VI for major roads, railways, airports and agglomerations concerned by first implementation step • Per agglomeration ≥250,000 inhab. • Per major civil airport ≥50,000 movts/year • For overall major roads ≥6 million veh/year • For overall major railways ≥60,000 trains/year	Art. 10-2 Annex VI	Mandatory every 5 years
31 December 2008	Major roads, railways, airports and agglomerations designated by Member States and concerned by second implementation step	Art. 7-2	Possible at any time
18 January 2009	Noise control programmes that have been carried out in the past and noise measures in place • Per agglomeration ≥250,000 inhab. • Per major civil airport ≥50,000 movts/year • For overall major roads ≥6 million veh/year • For overall major railways ≥60,000 trains/year	Art. 10-2 Annex VI 1.3 and 2.3	No update
18 January 2009	Action plans-related data as listed in annex VI for major roads, railways, airports and agglomerations concerned by first implementation step + any criteria used in drawing up action plans	Art. 10-2 Annex VI + Art. 8-3	Mandatory every 5 years

TABLE 4.5 Reporting Requirements of Member States Arising from the END—cont'd

Implementation Deadline	Summary Description of Data Sets to Be Reported	END Provision	Updates by Member States
	• Per agglomeration $\geq$250,000 inhab. • Per major airport $\geq$50,000 movts/year • For overall major roads $\geq$6 million veh/year • For overall major railways $\geq$60,000 trains/year		
30 December 2012	Strategic noise maps related data as listed in annex VI for major roads, railways, airports and agglomerations concerned by second implementation step • Per agglomeration $\geq$100,000 and $<$250,000 inhab. • For overall major roads $\geq$3 million and $<$6 million veh/year • For overall major railways $\geq$30,000 and $<$60,000 trains/year	Art. 10-2 Annex IV	Mandatory every 5 years
18 January 2014	Noise control programmes that have been carried out in the past and noise measures in place • Per agglomeration $\geq$100,000 and $<$250,000 inhab. • For overall major roads $\geq$3 million and $<$6 million veh/year • For overall major railways $\geq$30,000 and $<$60,000 trains/year	Art. 10-2 Annex IV 1.3 and 2.3	No update
18 January 2014	Action plans-related data as listed in annex VI for major roads, railways, airports and agglomerations concerned by second implementation step + any criteria used in drawing up action plans • Per agglomeration $\geq$100,000 and $<$250,000 inhab. • For overall major roads $\geq$3 million and $<$6 million veh/year • For overall major railways $\geq$30,000 and $<$60,000 trains/year	Art. 10-2 Annex VI + Art. 8-3	Mandatory every 5 years

correspond to those incorporated within strategic noise mapping results. Certainly, such innovative approaches would assist in raising awareness about environmental noise in the future although they are likely to be the exception rather than the rule.

4.5 STRATEGIC NOISE MAPPING IN THE EU: RESULTS FROM THE FIRST PHASE (2007)

Under the terms of the END, the first phase of noise mapping was to be concluded by Member States by June 2007. However, only a handful of countries submitted the required data by the deadline. Almost all nations have since completed the first round. Because the first phase was in some respects experimental, there was some leeway in relation to the submission of results. At the time of this book going to press, submitted data for the second round, due for submission in October 2012, were not yet available to the general public.

From the data submitted under the END's 2007 reporting round, estimates have been generated of the number of EU citizens within each Member State that are exposed to noise levels above 55 dB(A) L_{den} and 50 dB(A) L_{night}.[4] Overall, 164 agglomerations were involved across the EU with 82,575 km of major roads (>6 million vehicle passages a year), 12,315 km of major railways (>60,000 train passages a year) and 76 major civil airports (>50,000 movements a year) mapped under the process (de Vos and Licitra, 2013). Although there are clearly problems with a lack of consistency in calculation, mapping method and approaches to estimating exposure, the data collected from the first round and made publicly available through the Noise Observation and Information Service for Europe database (NOISE),[5] provides an initial, albeit tentative, indication of existing levels of population exposure to environmental noise in the EU. Indeed, it is the largest noise exposure database ever assembled worldwide.

Table 4.6 summarises the main results arising from the estimation of population exposure for the first round of noise mapping within and outside agglomerations. The results suggest that approximately 56 million people across the EU are exposed to environmental noise above 55 dB (A) during daytime from road traffic within agglomerations, while 33 million are exposed to noise from major roads outside agglomerations.

[4]Strategic noise maps pursuant to annex VI were provided in the first round for: agglomerations ≥250,000 inhab., major civil airports ≥50,000 movts/year, major roads ≥6 million veh/year and major railways ≥60,000 trains/year.

[5]Noise Observation and Information Service for Europe database—N.O.I.S.E.: http://noise.eionet.europa.eu/.

TABLE 4.6 Population Exposure to Environmental Noise in the EU

Scope	Number of People Exposed to Noise Above $L_{den} > 55$ dB (Million)	Number of People Exposed to Noise Above $L_{night} > 50$ dB (Million)
WITHIN AGGLOMERATIONS		
All roads	56	40.2
All railways	7.8	6.2
All airports	3.4	1.9
Industrial sites	0.8	0.5
MAJOR INFRASTRUCTURE (OUTSIDE AGGLOMERATIONS)		
Major roads	33.4	22.7
Major railways	5.8	4.8
Major airports	1.3	0.4

Note: Based on data submitted from the first phase of strategic noise mapping (2007) by the Member States up to 30 June 2011.
Source: Noise Observation and Information Service for Europe (http://noise.eionet.europa.eu/)

Additionally, and more worrying from a public health perspective, is that approximately 40 million people across the EU are exposed to noise above 50 dB(A) from roads within agglomerations during the night with a further 22 million exposed outside agglomerations. Given that the WHO sets 40 dB (A) night-time as the value above which health effects are noticeable (see Chapter 3), the results highlight the scale of potential health impacts across the EU. These figures are expected to be revised upwards as more noise mapping data are received and/or assessed and with further EU enlargement. Also, further increases in noise emissions and therefore exposure is also likely as road traffic volumes are expected to intensify in the future.

According to recent Eurostat data,[6] road-based passenger transport (measured as passenger kilometres travelled) accounts for 92.9% of overall ground travel in the EU-27, while railways (including trams, metro, etc.) accounts for only 7.1%. Despite this, the railway accounts for 14.9% of the number of people exposed to environmental noise from ground-based transportation sources during night-time and 13.2% during the

[6] http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Passenger_transport_statistics.

day–evening–night period. So while road transport is overwhelmingly the main source of acoustical discomfort, the railway system plays an important role in this regard also.

The results from the process also show that there is significant variability in terms of exposure across the EU. Figure 4.5 shows that the proportion of the population within agglomerations exposed to road-based environmental noise above 50 dB(A) during night-time ranges from highs of 85% and 83% in Slovakia and Ireland, respectively, to lows of 9% and 21% in Estonia and the Netherlands, respectively. The average for the EU-27 is 40%. Turning to night-time noise from railways, Figure 4.6 shows that the average proportional exposure to noise above 50 dB(A) from rail sources is 6%. Once again there is significant variation across nations and the results are quite obviously biased in favour of those nations with little railway infrastructure. The results for exposure from rail-based sources range from highs of 35% and 16% in Slovakia and Austria, respectively, to lows of 1% in counties such as Bulgaria, Denmark, Ireland and Lithuania. The results for aircraft are displayed in Figure 4.7. They show that countries with the greatest proportional levels of exposure above 50 dB(A) are Portugal (14%), Belgium (4%) and Bulgaria (3%) with the EU-27 average lying at 1%. Overall, the results demonstrate a considerable pollution problem across Member States. However, they also highlight the significant degree of variability of exposure across nations, which is likely

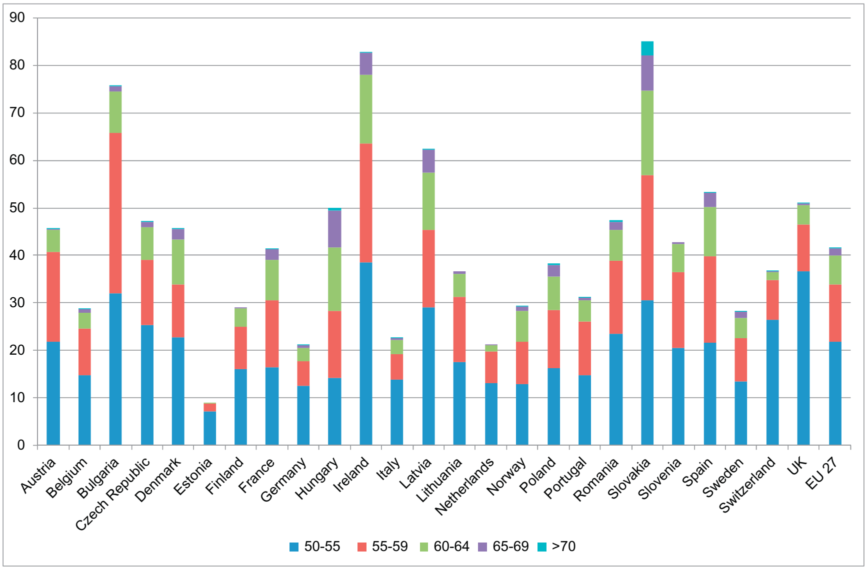

FIGURE 4.5 Proportion of inhabitants within agglomerations exposed to various categories of road-based environmental noise using the L_{night} indicator.

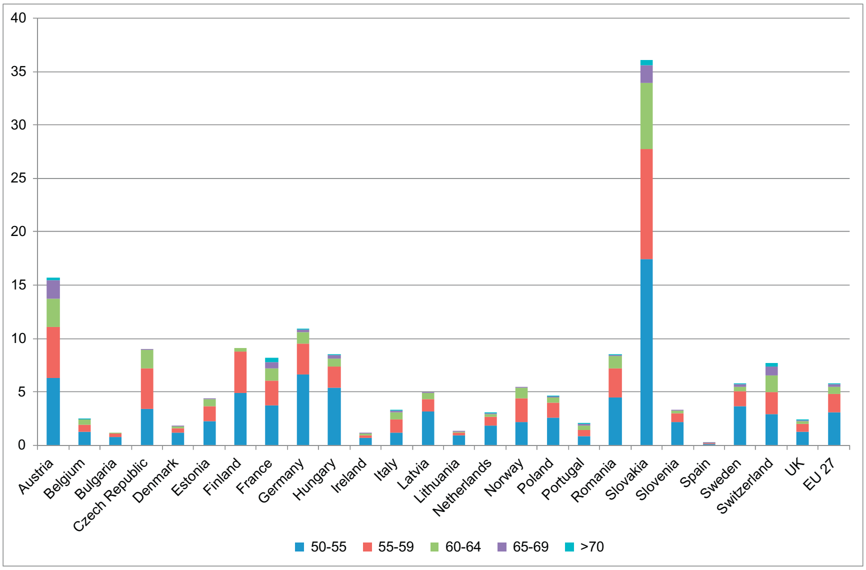

FIGURE 4.6 Proportion of inhabitants within agglomerations exposed to various categories of rail-based environmental noise using the L_{night} indicator.

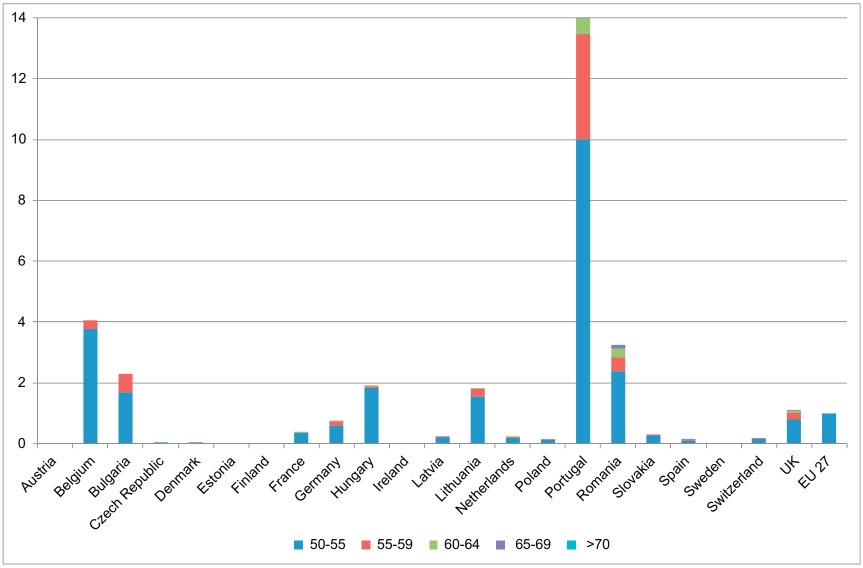

FIGURE 4.7 Proportion of inhabitants within agglomerations exposed to various categories of aircraft-based environmental noise using the L_{night} indicator.

to be linked to the imposition and adoption of different policies in relation to noise management and control.

While being highly innovative in policy and legislative terms, the strategic noise mapping process has not been without its challenges. Guarinoni et al. (2012) have highlighted some of the specific obstacles towards full implementation of the END. These include delays to implementation by Member States, non-enforcement of national noise limit values after the noise mapping process has been completed, the generally poor and highly variable quality of strategic noise maps, inconsistencies in calculation approaches, poor quality action plans, divergent approaches to identifying quiet areas and general administrative confusion among responsible bodies.

4.6 STRATEGIC NOISE MAPPING BEYOND THE EU

The signing into European law of the END has had a significant policy impact around the world. More than 10 years on from its signing into EU law, it has also been important for stimulating noise pollution exposure research which had been fairly scarce up until the beginning of the new millennium. Particular areas of research focus have included noise calculation and mapping approaches, methods of assessing population exposure as well as different approaches for noise mitigation through noise action planning. More broadly, however, the END has had a significant impact in terms of policy transfer throughout the world with not only scholars but also administrative authorities in countries beyond the EU applying strategic noise mapping approaches to their territories.

While not mandated in the United States (US), some academic studies have applied the EU strategic noise mapping process to locations in US states. A number of European-based commercial noise mapping software vendors offer the option to implement the Federal Highway Administration's (FHWA) TNM even though it has not been officially 'approved' by the FWHA; others have simply applied the EU calculation approaches to locations in the United States which has allowed a number of strategic noise mapping studies to be undertaken. To take some examples, researchers recently created strategic noise maps for roadways in Chittenden County, Vermont (Kaliski et al., 2007). Their research found that 30% of residents were exposed to road traffic noise levels above 45 dB(A) L_{eq} despite Chittenden being considered a rural county in US terms. More recently, Seong et al. (2011) undertook road noise mapping for Fulton County, Georgia, including noise mapping of downtown Atlanta. Their estimates of population exposure after constructing noise maps found that 48% of the resident population was exposed to noise levels of 55 dB(A) or higher during daytime with 32% exposed to 50 dB(A) or higher during night-time. Noise mapping approaches have also been applied in a

Canadian context albeit in a limited manner. Novak et al. (2009) created a noise map of the Huron Church Road (with approximately 32,000 vehicle crossings per day), the main transportation route leading to the Ambassador Bridge which the Windsor–Detroit border crossing relies heavily upon.

Beyond North America, a considerable volume of strategic noise mapping has been undertaken in Asia. In fact, beyond Europe, the vast majority of noise mapping research has been conducted in Asian countries. To take one example, Box 4.3 shows the recent development of innovative state-of-the-art 3D noise maps for Hong Kong. However, other noise mapping research has also been conducted there. Lam and Ma (2012) have conducted one of only a few longitudinal studies of the acoustic environment over time. They determined the noise environment of residential complexes built at different time periods using noise mapping at three spatial scales: the dwelling, the neighbourhood and the community. They provided evidence that overall noise levels in newly built developments are lower than those in older developments, suggesting slight improvements in the noise environment associated with newly constructed residential environments. There has also been noise mapping research undertaken comparing the high- and low-density cities of Wuhan, China and Manchester, UK, respectively, and the noise levels therein (Wang and Kang, 2011). Their results show the considerable effect that urban morphology has on the distribution of traffic noise in those cities. Additionally in a Chinese context, Sheng and Tang (2011) have undertaken noise mapping research in the Macao Peninsula. The authors found that 60% of traffic noise levels along the major pedestrian sidewalks in the evening peak hour exceed the National Standard of 70 dB(A) in China.

Furthermore, Ko et al. (2011a) created strategic noise maps of Youngdeungpo-gu, an administrative district of Seoul, South Korea. They found that 35% of the resident population was exposed to noise levels greater than 55 dB(A) during daytime, while approximately 80% was exposed to levels above 40 dB(A) during night-time as a result of combined exposure to road and rail noise. In a separate study, Ko et al. (2011b) also developed strategic noise maps for the city of Chungju, Korea. They developed an excess noise map by comparing road traffic noise maps with a standard noise map. As a result of the assessment, the exposed population was more accurately estimated, showing that 20% of the population is exposed to daytime noise above 55 dB(A), while 68% is exposed to noise levels above 40 dB(A) during night-time. Lee et al. (2008) also undertook noise mapping research in Seoul by utilising noise mapping for environmental impact assessment of a development site in the downtown area, while Cho et al. (2007) created a noise map of Pusan National University, Busan (South Korea's second largest city) using noise measurement and GPS data.

Also within an Asian context, Mehdia et al. (2011) produced noise maps of the entire city of Karachi, Pakistan. While they did not explicitly estimate population exposure for the city, by comparing population density maps with strategic noise maps, they concluded that a large number of people were at risk of excessive environmental noise exposure. Tsai et al. (2009) undertook strategic noise mapping and estimation of the exposed population in Tainan City, Taiwan. They found that more than 90% of the population is exposed to unacceptable noise levels and that the exposed population is greater in summer (ca. 97%) than in winter (ca. 90%).

In South America, the noise mapping process has been used in Brazil, Chile and Argentina. In a Brazilian context, Zannin and de Sant'Ana (2011) used measurement-based noise mapping to assess the evolving acoustic characteristics of a road-restructuring project at various stages of implementation in the outskirts of the city of Curitiba. In a more recent study, Zannin et al. (2013) once again undertook measurement-based noise mapping but this time for the educational campus of the Polytechnic Center of the Federal University of Parana (UFPR) also in the city of Curitiba. Their results found that 90% of the 58 measurement points recorded noise levels above 55 dB(A). Pinto and Mardones (2009) completed a noise mapping study of the Copacabana neighbourhood in Rio de Janeiro and found that noise levels exceed recommended limit values in the city. Dintrans and Préndez (2013) have recently utilised noise mapping techniques to model the impact of various noise control measures in Santiago, Chile, while Suárez and Barros (2014) recently produced a noise map for the same city using a simplified low-cost modelling technique. Their research was in line with previous similar research (Murphy and King, 2011) which suggests that it is possible to reduce environmental noise exposure through appropriate traffic management and mitigation measures in cities. Similar scenario analysis was also conducted in the city of Aracaju, Brazil (Guedes et al., 2011). Using a strategic noise mapping approach, the authors found that the physical characteristics of cities including building density, geometry and location and the existence of open spaces exert a significant influence on environmental noise. In Argentina, Ausejo et al. (2010) have also studied the uncertainty associated with strategic noise mapping in the Macrocenter of the Independent City of Buenos Aires.

Noise maps have also been utilised in the Middle East. Kurra and Dal (2012) used noise maps to determine the required façade insulation in Beşiktaş, a municipality of Istanbul, Turkey. The approach allows for the transformation of façade noise levels into insulation contours and proposes a categorisation scheme to facilitate the task of both acousticians and architects when designing building façades. Moreover, a recent Iranian study used the noise mapping concept to analyse environmental noise pollution from traffic noise in the city of Yazd (Nejadkoorki et al., 2010).

Overall then, it can be seen quite clearly that the scope of the impact of the EU's strategic noise mapping approach is significant. It has been successful at stimulating similar noise mapping studies and estimates of exposed populations in jurisdictions beyond the EU and on almost every continent. Indeed, the foregoing discussion highlights the innovative ways in which the strategic noise mapping process has been applied many of which were never the original intention of the END but have been made possible because of the development of commercial noise mapping software as a result of the adoption of the noise mapping process into legislation.

BOX 4.3

3D NOISE MAPPING IN HONG KONG

The Government of Hong Kong recently developed state-of-the-art 3D noise maps for the municipality of Hong Kong (see Law et al., 2011). Given the unique nature of the topography of the city and its density, traditional 2D noise mapping approaches were deemed to be unsuitable for accurately describing the noise environment. In Hong Kong, there are ca. 110,000 buildings within an area of around 1100 km^2. The approach utilised a combination of modelling, GIS and computer graphics technology to develop 3D noise maps. Users can visualise the results by flying through the city which makes it much easier for the general public to understand and experience the noise environment of the city, thereby enhancing public dissemination and engagement with the problem and potential solutions to environmental noise (Figure 4.8).

FIGURE 4.8 3D noise mapping in Hong Kong. *Source: Law et al. (2011).*

4.7 CONCLUSION

The emergence of strategic noise mapping as an approach to reduce the harmful effects associated with environmental noise has proven to be a highly innovative piece of environmental policy within the EU. The EU is one of the few jurisdictions around the world who are taking the problem of environmental noise seriously both as an environmental policy issue and as a public health problem. The introduction of the END has allowed for a quantification of the burden of disease resulting from excessive environmental noise exposure, and while such data are to be viewed somewhat tentatively, it has served to demonstrate the scale of environmental noise pollution as a major public health policy concern into the future. Indeed, the END has also served to stimulate awareness of environmental noise across the world with numerous researchers applying the principles of the strategic noise mapping process to other jurisdictions. Even more importantly is that EU noise policy and associated noise mitigation approaches are gaining interest from other nations who see environmental pollution as a serious concern for their citizens that needs to be addressed.

It should also be clear from the chapter that the strategic noise mapping process is not without its problems. There are some considerable methodological hurdles that need to be overcome in the process so that estimates of exposure are more robust and also that results of the process can be realistically compared across Member States. The key issues of developing a standardised noise calculation method across the EU as well as developing a common approach for estimating population exposure are currently being dealt with under CNOSSOS-EU which should help eliminate methodological problems for future strategic noise mapping rounds.

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CHAPTER

5

Transportation Noise

Transportation systems provide the infrastructure required to satisfy the mobility needs of society. Ultimately, the role of the transportation system is to overcome the friction associated with the physical separation between land uses, goods, services and people. The growth in travel demand over the last decades has led to a range of significant transport-related policy problems (Murphy, 2012). Chief among these are environmental externalities produced by transportation systems. Within that context, noise pollution is one of the most pressing environmental problems associated with transportation. It poses key challenges for policymakers not least in relation to how noise from transportation sources should be assessed, controlled and reduced into the future.

Noise from transportation is the world's most prevalent form of environmental noise and road traffic is the most common source. European authorities have estimated that, within Europe, 89.8 million people are exposed to noise in excess of 55 dB L_{den} due to road traffic, while the number exposed to the same level from railway is 11.7 million and that for aircraft is 4.3 million (European Commission, 2011). Considering these results are based on the first phase of mapping (2007), and the thresholds for mapping were twice those for the second phase[1] (except for aircraft noise), these estimates are likely to significantly underestimate the extent of exposure to transportation noise in Europe.

Chapter 4 discussed the Environmental Noise Directive (END) and how it led to the development of strategic noise maps across Europe. This chapter explores the mathematical models that may be used to model

[1]For the second phase of noise mapping (2012), the thresholds defining major roads, rails and agglomerations were reduced by 50%, e.g., for the case of major roads only those roads carrying in excess of 6 million vehicles were mapped in the first phase, whereas this threshold was reduced to 3 million vehicles for the second phase. This meant the length of major roads to be mapped significantly increased. In Ireland, for example, it increased from approximately 600 to more than 4000 km.

noise sources in the development of strategic noise maps, with particular focus on emission calculations for the three main modes of transportation: road traffic, rail traffic and aircraft. The main source mechanisms of each are discussed, and the details of some key emission models are presented. The description of the source emission across several national calculation methods is presented throughout this chapter.[2]

Noise maps may be based on noise measurements or noise predictions. Intuitively, it might be considered preferable to measure environmental noise instead of developing noise maps through predictive techniques; measurements would provide a real representation of noise levels experienced onsite and predictions are limited by the accuracy of the input data (as well as the fidelity of the prediction method itself). It is often difficult to obtain these data, and in many cases, default values, averages or simple assumptions are used to fill data gaps. However, it would be unfeasible to perform noise measurements over the temporal and spatial resolution required to develop an accurate noise map which is why prediction is most frequently utilised. Moreover, noise prediction models have the additional advantage of being able to predict future noise levels. As such, the vast majority of strategic noise maps in Europe have been developed through predictive techniques. One notable exception is the case of Madrid, Spain (Manvell et al., 2004), where measurement data were used to make their strategic noise maps (see Section 2.5.6).

Calculation methods for noise prediction generally consist of two parts: a method to calculate the level of noise at the source (the source model) and a method to describe how noise will propagate away from the source (the propagation model). Most methods that are used in practice are either empirical or semi-empirical and contain many simplifying assumptions including a very basic definition of the source characteristics (Wolde, 2003). These models are generally based on empirical observations (measurements) and, therefore, are only accurate for source and receiver conditions which are similar to those associated with the original dataset (Wolde, 2003). This is the main limitation of empirical models and is one of the main reasons behind the development of a new more holistic calculation method for noise mapping in Europe (CNOSSOS-EU).

[2]Details presented in this chapter are informative and should not be treated as a full transcription of a national standard. For full details, the reader should always consult the original standard. Readers should also note that the computational method should be viewed as just one aspect of noise prediction method and much more importance should be placed on the acousticians input. It is often the case that the expertise of the user and how different scenarios are specified will have a greater impact on results than the model used (Butikofer, 2012).

Most noise prediction methods, irrespective of whether they are dealing with road, rail, air or industrial sources, implement some form of the following basic equation:

$$L_p = E - A_{tot} + C \tag{5.1}$$

where L_p represents the sound pressure level at a receiver. Different calculation methods will use different indicators to describe this quantity, for example, $L_{10,18\mathrm{h}}$, L_{Aeq}, L_{den}, EPNL, among others.

E represents the emission of the source. This is essentially a representation of the sound power of the source, L_w. We use E instead of L_w because the description of the source varies so much from standard to standard. It can be represented as the sound power of a single point source, the sound power per unit length of a simple line source, or even a sound pressure level at a certain reference distance from the source (which could then be used to estimate the sound power if required). The French method for road traffic noise represents E as a sound power per metre length of road, whereas the UK method considers a 'basic noise level', in terms of L_{10} at a reference distance of 10 m away from the nearside carriageway edge. The Dutch method for railway noise considers E only as an input value to enable the prediction of a sound pressure level at a receiver and not specifically as a sound power level (de Vos, 2012).

A_{tot} represents the total amount of sound attenuation occurring between source and receiver and generally includes ground attenuation, atmospheric attenuation, attenuation through geometric divergence and attenuation by diffraction around noise barriers. The manner in which each attenuation mechanism is accounted for varies considerably between national standards.

C represents a collection of different correction factors that may arise due to reflections from a facade, different road surfaces or train track types, or more detailed corrections to the emission term, E (which might be introduced before attenuation is accounted for).

5.1 ROAD TRAFFIC NOISE

Since the 1970s, acoustics has played an important role in vehicle design. In particular, interior vehicle noise has declined significantly over the last few decades in response to consumer preferences for quieter interiors. However, similar improvements have not been achieved for exterior noise levels largely because eternal noise from vehicles is an environmental externality not experienced by vehicle occupants (Guarinoni et al., 2012).

The extent of population exposed to noise from road traffic far exceeds that of rail and aircraft sources combined. This is not surprising when one considers that there are estimated to be approximately 587 vehicles for every 1000 people in Western Europe. In the United States and Canada, the corresponding figures are 812 and 626, respectively, while the figure for Central and South America is 150 (The Vehicles Technologies Office, 2012).

Road traffic noise is a combination of noise resulting from the propulsion system of a vehicle (*engine noise*) and noise due to the interaction between the tyres of the vehicle and the road surface (*tyre/road noise* or *rolling noise*). The level of noise a vehicle produces is largely dependent on the speed it is travelling at and speed influences the contribution of each source mechanism; at low speeds, engine noise dominates, while at higher speeds, tyre/road noise dominates. The speed at which rolling noise begins to dominate over engine noise is called the crossover speed. It varies for different vehicle types; heavy vehicles have a higher crossover speed compared to light vehicles, while electric vehicles (with minimal engine noise) have a very low crossover speed. Knowledge of this crossover speed can help determine the most appropriate type of noise mitigation measure for a particular scenario. For example, a low-noise road surface (which reduces rolling noise) would have little impact in an area where engine noise is dominant.

In the past, road traffic noise prediction methods did not have separate calculation approaches for the different source mechanisms of a vehicle; rolling noise and engine noise were calculated together, and it was assumed that a vehicle could be represented as a simple moving point sound source. This single moving point source could then be represented by a line source by integration over time (DGMR, 2002). This line source was then used to describe a road, or alternatively, the line source could be divided into a number of incoherent stationary point sources. The height of the source varies across different calculation standards but is generally a short distance above the centre of the road lane. The Harmonoise method (a predecessor to CNOSSOS-EU) for road traffic noise actually proposed two separate sources positioned at different heights to model rolling noise and engine noise separately.

5.1.1 Rolling Noise

At high speeds, rolling noise is the most dominant source of noise from a moving vehicle. Noise is generated due to the interaction between the vehicle's tyres and the road surface. A number of factors influence the level of noise emission:

- an impact occurs when the tyre hits the road surface. This can be compared to a small rubber hammer hitting the road surface at an oblique angle (Bernhard and Sandberg, 2005);

- aerodynamic noise is generated as air is squeezed out between the thread patterns as the tyre compresses when it rolls over the surface. This is typically most important in the frequency range between 1000 and 3000 Hz;
- vibrations of the tyre tread and belt due to irregularities in the road surface result in noise generation. These vibrations generate noise that is typically in the frequency range between 200 and 300 Hz. Smooth pavement structures can reduce the generation of noise from vibrations;
- friction between the tyre and the road surface will also cause 'stick–slip' type vibrations (the rubber of the tyre sticks to the road surface at the contact area and then slips away).

The noise is enhanced further through a phenomenon known as the 'horn effect'. The geometry at the tyre/road interaction forms the shape of a horn which causes large radiation of noise emitted at this point. Tyre width, tread pattern and vehicle load all influence the level of rolling noise generated.

The type of road surface also plays an important role in noise emission because different road surfaces have different absorption characteristics. Noise is reflected off impervious road surfaces, whereas porous road surfaces absorb noise and reduce reflections. In the case of a porous surface, with a high built-in air void, air can be pumped down into the pavement structure, thereby reducing the noise generated from air pumping. Porous surfaces are generally referred to as low-noise surfaces. They not only reduce the reflection of sound but also reduce noise due to vibrations and the contribution of the horn effect. Low-noise surfaces are often utilised as a noise mitigation measure and may form part of a noise action plan. They are discussed in greater detail in Chapter 7.

5.1.2 Engine Noise

Most road vehicles are (currently) powered by internal combustion engines. In an internal combustion engine, a sudden increase in the fuel/air mixture pressure occurs when fuel is burned. The pressure rise excites the engine structure causing sound and vibration (Wilson, 2006). There are many subsources of engine noise including the engine exhaust, air intake, fans and auxiliary equipment, among others. The term 'engine noise' usually refers to all contributory mechanisms.

There is one exception – the sounding of a horn (or warning signal). Even though many people might consider the horn to be the most annoying aspect of vehicle noise, it is not considered as a noise source for calculation models or indeed for strategic noise mapping.

BOX 5.1

ELECTRIC VEHICLES

Electric vehicles are being heralded as a real alternative to the internal combustion engine (Figure 5.1). They are often reported as silent vehicles and have been successfully used in the past to significantly improve the soundscape. The long serving electric milk vehicle fleet across the United Kingdom proved to be very suitable for delivering in the early hours of the morning. However, the acoustic benefits of electric vehicles are only realised at low speeds because at higher speeds rolling noise dominates. There are some potential acoustic savings at higher speeds if the vehicle is lighter with thinner, smaller tyres, but the vehicle will certainly not be silent. Furthermore, there are proposals to add artificial noise to electric vehicles in an effort to help visually impaired pedestrians identify the presence of an electric vehicle. Careful consideration of the type of artificial noise to be introduced is required. After all, an excessive increase of warning sounds on the streets might even have a disorientating effect on pedestrians, thus defeating its original purpose as well as increasing overall environmental noise levels.

FIGURE 5.1 Acoustic tests involving an electric vehicle in Ireland.

5.1.3 Road Traffic Noise Calculation Methods

There are many different prediction methods for road traffic noise. In the first phase of noise mapping, a total of seven different road traffic noise calculation methods were used across all EU Member States. Some common methods for road traffic noise prediction are presented in this section.

NMPB96 (France)

The END recommended interim method (to be used while CNOSSOS-EU is being developed) for road traffic noise is the French national computation method 'NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB)', referred to in 'Arrêté du 5 mai 1995 relatif au bruit des infrastructures routières, Journal Officiel du 10 mai 1995, Article 6' and in the French standard 'XPS 31-133'. This method describes the manner in which sound propagates from source to receiver. For input data describing noise emission, reference is made to 'Guide du Bruit' (CETUR, 1980). The emission data presented in this document are based on several thousand measurements recorded between 1973 and 1977 (Besnard et al., 1999). The emission model is thus described in Guide du Bruit, whereas NMPB 96 describes the propagation model.

One of the main criticisms of this method is that it relies on source data that is more than 30 years old. However, in preparation for the first phase of noise mapping, road traffic noise emission data contained in Guide du Bruit, the German RLS 90 method and the Austrian RVS 3.02 method were all compared. It was found that the emission data in Guide du Bruit were as good as these methods, both of which are still in regular use today (Wolfel, 2003a).

BOX 5.2

NMPB 2008

Following an in-depth revision of the standard, the French method was updated in 2008 (NMPB 2008). Probably, the most important change between NMPB 2008 and NMPB 96 is that the new method separates rolling noise and engine noise in calculations (Dutilleux, 2013). For more information on the revised method, the reader is referred to Service d'étudessur les transports (2009).

CALCULATION DETAILS

In NMPB 96, a flow of cars along a road is modelled as a line source (or a number of line sources) which is divided into a set of incoherent point sources. Three segmentation techniques may be used to divide the road into these point sources: equiangular decomposition, decomposition by uniform step or a combination of the two. Each point source then represents a line segment of length l_i (Figure 5.2). Because this length may vary depending on the segmentation adopted, it must be considered in equations for sound power to ensure a uniform emission at source. This is accounted for by using the correction $10\log_{10}(l_i)$; for a 1 metre segment length, the correction is 0 dB, while for a 2 metre segment, the correction is approximately 3 dB.

The sound power of a single point source, $L_{A,W,i}$, for each octave band, j, is calculated from

$$L_{A,W,i} = L_{A,W/m} + 10\log_{10}(l_i) + R_j + C \tag{5.2}$$

where $L_{A,W/m}$ is the sound power per metre along the road for each octave band, l_i is the length of the line section of the source, R_j is the spectral correction for each octave band and C is the correction for the type of road surface. The length of the line section may be calculated from Equation (5.3) and Figure 5.2:

$$l_i = \frac{|S_{i-1}S_i| + |S_iS_{i+1}|}{2} \tag{5.3}$$

$L_{A,W/m}$ may be calculated from:

$$L_{A,W/m} = 10\log_{10}\left(10^{\frac{E_{lv}+10\log(Q_{lv})}{10}} + 10^{\frac{E_{hv}+10\log(Q_{hv})}{10}}\right) + 20 \tag{5.4}$$

where E_{lv} and E_{hv} are the sound emission levels for light and heavy vehicles, respectively, determined from nomograms contained in Guide du Bruit; Q_{lv} and Q_{hv} are the volumes of light and heavy vehicles during the reference time interval. The sound emission levels E_{lv} and E_{hv} are caused by the movement of a vehicle at a speed, v, in one of four traffic flow types (fluid continuous flow, pulsed continuous flow, pulsed accelerated flow or pulsed decelerated flow). The noise emission is determined from the nomogram figure for the case under consideration and represents the sound level for a single light or heavy vehicle travelling at a given speed over a given road type.

The nomograms presented in Guide du Bruit are essentially charts representing numerical relationships between the noise level and the

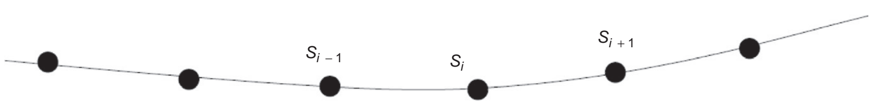

FIGURE 5.2 Segmentation of a road source into a collection of point sources.

conditions under which the vehicle is travelling. Alternatives to these nomograms have been developed with a view to making them more practical to implement in software (see Box 4.1) (Wolfel, 2003a). Through this alternative method, the emission level may be calculated from:

$$E = E_0 + a \log_{10}\left(\frac{v}{v_0}\right) \tag{5.5}$$

where values of E_0 and a are presented in tables. Table 5.1 reproduces these data for the case of light vehicles travelling in fluid continuous flow.

Values for the spectral correction, R_j, are presented in Table 5.2 (AFNOR, 2001). This term corrects results to an A-weighted traffic spectrum.

The original NMPB-96 method does not include corrections for different types of road surface. However, the European Commission recommended the different road surface corrections presented in Table 5.3

TABLE 5.1 Values for E_0 and a for Light Vehicles Travelling in a Fluid Continuous Flow (Wolfel, 2003a)

Fluid Continuous Flow			
Slope	**Speed (v) [km/h]**	**E_0 [dB]**	**a**
Flat	$v < 44$	29.4	0
	$v > 44$	22.0	21.6
Down	$v < 44$	29.4	0
	$v > 44$	22.0	21.6
Up	$v < 43$	37.0	−10.0
	$43 \leq v \leq 44$	32.1	4.8
	$v > 80$	22.0	21.6

TABLE 5.2 Values for the Spectral Correction, R_j

j	**Octave Band Centre Frequency [Hz]**	R_j
1	125	−14.5
2	250	−10.2
3	500	−7.2
4	1000	−3.9
5	2000	−6.4
6	4000	−11.4

TABLE 5.3 Recommended Corrections for Different Road Surfaces. The speed differentiations are only relevant to porous surfaces (European Commission, 2003).

Road Surface Category	Noise Level Correction		
Porous surface	0–60 km/h	61–80 km/h	81–130 km/h
	−1 dB	−2 dB	−3 dB
Smooth asphalt	0 dB		
Cement concrete and corrugated asphalt	+2 dB		
Smooth texture paving stones	+3 dB		
Rough texture paving stones	+6 dB		

(see also Box 4.1), for the development of strategic noise maps under the END.

CRTN (United Kingdom)

CRTN is the road traffic noise prediction method used across the United Kingdom. It is also used extensively in Ireland, Australia, New Zealand and Hong Kong. The method was released in 1988 and replaced a previous method developed in 1975. The Transport and Road Research Laboratory and the Department of Transport in the United Kingdom carried out the revision. The method includes separate emission and propagation models. It differs from NMPB 96 in that it treats roads as line

BOX 5.3

THE ORIGIN OF CRTN

The original purpose of CRTN was to assess whether or not a property would qualify for additional sound insulation under the 1975 UK Noise Insulation Regulations. Under the legislation, a residence was entitled to additional insulation if the facade noise level was greater than or equal to 68 dB(A) $L_{A,10,18\text{h}}$, among other conditions. This explains why CRTN predicts noise in terms of the L_{10} index, for the 18 hours between the hours of 06:00 and 24:00. The method was developed long before noise mapping became a tool for environmental assessment.

The 18-hour time basis is probably drawn from results of social surveys conducted in the United Kingdom in the 1960s. At that time, a data-logging sound meter was an expensive piece of equipment and required constant logging by an operator. This constant logging, coupled with the view that noise was not a major issue during the night time, may be the reason the United Kingdom opted for an 18-hour indicator instead of an indicator covering the full 24 hours.

sources and not a collection of point sources. Predicted noise levels are expressed in terms of the L_{10} index.

In a 2001 review of some of the most common traffic noise prediction models, it is noted that CRTN is distinguished by its extensive use of curve fitting between empirical data even when it was known that this approach did not conform to theory (Steele, 2001). The review concludes that the CRTN L_{10} index is in fact a pseudo-L_{10}, which greatly simplifies calculations but concomitantly includes a related loss of validity with the author of the study concluding that the CRTN method is now obsolete (Steele, 2001). However, the method is still widely used in practice and was used for noise mapping in the United Kingdom and Ireland for the first two phases of the END. It had to be adapted to meet the requirements of the END, most notably to convert L_{10}-based results to the universal noise indicators L_{den} and L_{night}. Additionally, in August 2008, the UK Highways Agency published additional advice to CRTN procedures (Highways Agency (UK), 2008). This included advice on how to deal with issues outside the scope of the initial model such as dual source lines, median noise barriers and corrections for thin surfacing systems. In light of these amendments, it is probably too hasty to label the method as obsolete; however, in the case of strategic noise mapping, the method does have considerable limitations.

CALCULATION DETAILS

The method proceeds by dividing a road into a number of separate segments so that the noise level variation is less than 2 dB(A) in any one segment. Each segment is then treated as a separate noise source, and calculations are performed separately for each. The method predicts a *basic noise level* which is essentially a representation of the source emission. The basic noise level may be calculated from:

$$L_{10,1\mathrm{h}} = 42.2 + 10\,\log_{10}(q) \tag{5.6}$$

or

$$L_{10,18\mathrm{h}} = 29.1 + 10\,\log_{10}(Q) \tag{5.7}$$

where q and Q are the hourly and 18-h flows, respectively, of all vehicles (both heavy and light). This basic noise level is then corrected to account for various aspects of the traffic flow such as the mean traffic speed, V, and the percentage of heavy goods vehicles (HGVs), p:

$$\mathrm{Correction}_{V\&p} = 33\,\log_{10}\left(V + 40 + \frac{500}{V}\right) + 10\,\log_{10}\left(1 + \frac{5p}{V}\right) - 68.8 \tag{5.8}$$

A correction for the gradient of the road, G, expressed as a percentage, is calculated from:

$$\mathrm{Correction}_G = 0.3G \tag{5.9}$$

The influence of the road surface is also considered. There are two equations for impervious road surfaces: one for concrete surfaces and the other for bituminous surfaces. In both cases, the input variable is the texture depth (TD) of the road surface, expressed in millimeters. The TD may be determined using a sand-patch test. Equations are valid when the traffic speed is greater than or equal to 75 km/h. If the traffic speed is less, then a fixed correction of −1 dB(A) should be applied.

For concrete, the correction is:

$$\text{Correction}_{\text{TD}} = 10 \log_{10}(90\text{TD} + 30) - 20 \tag{5.10}$$

For bituminous surfaces, it is:

$$\text{Correction}_{\text{TD}} = 10 \log_{10}(20\text{TD} + 60) - 20 \tag{5.11}$$

BOX 5.4

COMPARING XPS31-33 AND CRTN EMISSION MODELS

In preparation for the second phase of noise mapping, the Irish National Roads Authority performed a comparison between CRTN, which is commonly used in Ireland, and the END recommended interim method for road traffic (King et al., 2009). The comparison focused on the emission component of both models.

The study found that both models predicted similar changes in emission for variations in the total vehicle flow and traffic composition. Significant differences were noted across different traffic flow types (which CRTN does not consider) and vehicle speeds. Assessing the change in the average speed of vehicles in a flow also highlights a potential limitation associated with the use of CRTN. Some countries impose an upper speed restriction on HGVs, typically 80 km/h on all roads. Hence, HGVs and light vehicles have a separate speed limit on major roads. In the CRTN method, the speeds for light and heavy vehicles cannot be input as separate variables (Equation 5.8) and, as such, the impact that changes in the HGV speed limit might have on noise levels cannot be assessed directly.

CONVERTING $L_{A10,18h}$ TO L_{den} AND L_{night}

CRTN predicts noise levels in terms of the $L_{A10,18h}$ indicator, whereas noise maps developed under the END must be presented using the L_{den} and L_{night} indicators. Thus, a conversion procedure is required to present CRTN results using these uniform indicators. In 2002, the

Transport Research Laboratory (TRL) published a paper describing a number of mathematical procedures that could be used to convert values of $L_{A10,1h}$ and $L_{A10,18h}$ to values of L_{den}, L_{day}, $L_{evening}$ and L_{night} (Abbott and Nelson, 2002). This enabled CRTN to be used to estimate the necessary EU indices by applying an end correction to calculated L_{A10} values. However, because CRTN was designed to predict an 18 hour noise level, significant issues arise in calculations of hourly night-time noise levels between the hours of 24:00 and 06:00 (i.e. hours outside the scope of the original method), particularly in the case of roads with low traffic volumes. For example, the TRL conversion procedures were subsequently evaluated for use in Ireland and were found to be unreliable. The research found that under conditions where traffic volumes are low (e.g. during the night-time period), the correlation between L_{10} and L_{eq} deteriorated (O'Malley et al., 2009). This implies that the L_{night} conversion procedure is less reliable during periods where traffic flows fall to low volumes as often experienced during the night.

Traffic Noise Model (United States)

In the United States, the Federal Highway Administration (FHWA) developed a computer programme to predict noise levels in the vicinity of highways called the FHWA Traffic Noise Model (TNM). Since its release, TNM has been used to test compliance with policies and procedures under FHWA regulations. The Code of Federal Regulations, in particular section 772.9 'Traffic Noise Prediction', requires all official analyses (for federally funded highway projects) to use the TNM (Federal Highway Authority, 2012). Other (computer) models may be used provided the FHWA have determined that the alternative model is consistent with the methodology of the FHWA TNM.

TNM Version 1 was released in 1998 and replaced the '108 model', FHWA Highway Traffic Noise Prediction Model (FHWA-RD-77-108), which was developed in the 1970s. TNM was based primarily on extensive measurement data taken between 1993 and 1995 (Fleming et al., 1995a). Since 1998, the FHWA has updated TNM on a number of occasions, the most recent being in April 2004 which resulted in TNM Version 2.5. The FHWA is currently in the process of finalising the development of TNM Version 3.0 which will include GIS functionality (e.g. the capacity to incorporate a digital terrain model) and 2D graphics.

The main difference between TNM and other prediction models discussed in this book is that TNM is packaged in the form of an approved computer programme and only this programme is validated for use in the Unites States by the FHWA. While some European software developers offer the option to implement the TNM algorithm, these implementations have not been tested, evaluated or approved by the US FHWA.

CALCULATION DETAILS

The model starts by calculating the noise level resulting from a single lane of single traffic type (i.e. vehicle category) at a receiver. This calculation is then repeated for all combinations of lanes and traffic types. The sound pressure level at a receiver is calculated through a number of adjustments to a reference sound level, identified as a Reference Energy Mean Emission Level (REMEL) in TNM. These reference levels describe the maximum sound level emitted by a vehicle pass-by at a distance of 15 m.

The REMEL database is a database of noise emission levels derived from measurements of over 6000 vehicle pass-by events, taken across nine states in the United States, encompassing both constant traffic flow and interrupted traffic flow and including subsource height data (Federal Highway Administration, 1998). The reference emission levels are contained within a database in TNM for a number of different vehicle types, road surfaces and driving conditions (cruising, accelerating and idling). Data are available in 1/3 octave bands for five standard categories of vehicles:

- automobiles (light vehicles) – generally with gross vehicle weight less than 4500 kg;
- medium duty trucks – generally with gross vehicle weight between 4500 and 12,000 kg;
- heavy duty trucks – generally with gross vehicle weight more than 12,000 kg;
- buses – representing all vehicles designed to carry more than nine passengers; and
- motorcycles – defined as vehicles with two or three tyres and an open-air driver/passenger compartment.

These data were used to develop a regression relationship between the sound level and speed for the five vehicle types in TNM (see Figure 5.3). All results are representative of the baseline condition. This refers to constant traffic flow (cruise throttle), on a level graded roadway and on an ‘average’ pavement (dense-graded asphalt concrete and portland cements concrete combined).

In addition, TNM includes full-throttle noise emission levels for vehicles on upgrades and vehicles accelerating away from traffic-control devices such as stop signs, toll booths, traffic signals and on-ramp start points. The model combines these full-throttle noise emission levels with internal speed computations to account for the full effect of roadway grades and traffic-control devices.

Two source heights, one at road height (0 m) and the other at 1.5 m height (except in the case of heavy trucks which have an upper height

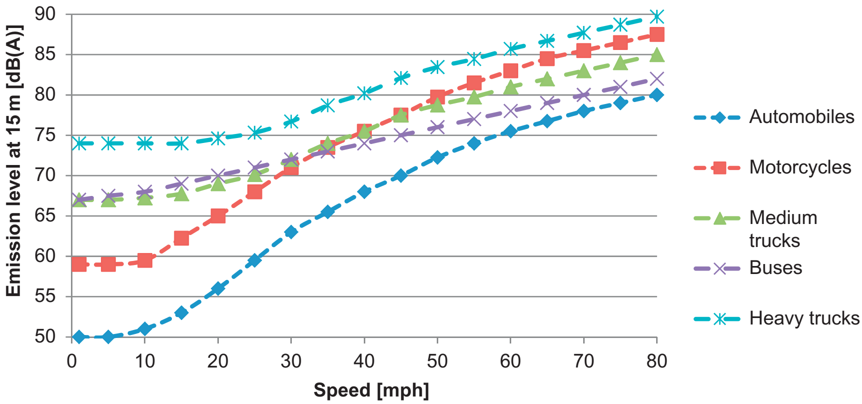

FIGURE 5.3 A-weighted noise emissions for separate vehicle categories under cruise conditions. *Adapted from Federal Highway Administration (1998).*

of 3.66 m) are used. The sound energy is then distributed between these source heights. TNM also has the ability to accept limited REMEL data for user-defined vehicle types. The model can be applied to the following surface types:

- dense-graded asphaltic concrete (DGAC);
- portland cement concrete (PCC);
- open-graded asphaltic concrete; and
- a composite pavement type consisting of data for DGAC and PCC combined.

To calculate the noise at a receiver, adjustments are made to the reference vehicle noise emission level for each vehicle class accounting for the various acoustic effects associated with traffic flow, distance and shielding:

$$L_{Aeq,1\mathrm{h}} = \mathrm{EL}_i + A_{traffic,i} + A_d + A_s \tag{5.12}$$

where EL_i is the vehicle noise emission for each vehicle type i; $A_{traffic,i}$ is an adjustment for the quantity and speed of each vehicle type i; A_d and A_s are adjustments made in the propagation model and account for the distance between road and receiver and the shielding and ground effect between road and receiver. The adjustment for traffic flow is a function of the quantity of vehicles in the flow, v, and their speed, s, and is presented in Equation (5.13). The adjustment is applied separately for each vehicle type, i, and performed over 1/3 octave bands.

$$A_{traffic,i} = 10\log_{10}\left(\frac{V_i}{S_i}\right) - 13.2 \tag{5.13}$$

Under most situations, FHWA TNM uses vehicle speeds that are input by the user. However, there are two situations where TNM computes the vehicle speed separately: (1) when traffic speeds are reduced by upgrades and (2) when they are reduced by traffic-control devices.

CNOSSOS-EU (The Proposed Common European Method)

CNOSSOS-EU Working Group 2 was charged with the development of a source model for road traffic noise. The emission model for road traffic was released in preliminary form in 2012 (Kephalopoulos et al., 2012). It is not expected to change significantly in future revisions of the model. It defines five different categories of vehicle (m):

- light vehicles [$m=1$];
- medium heavy vehicle [$m=2$];
- heavy vehicles [$m=3$];
- powered two wheelers (e.g. motorcycles) [$m=4$a for powered two wheelers $\leq$50 cc and $m=4$b for powered two wheelers $>$50 cc];
- an open category to be defined accounting for future needs (e.g. electric vehicles) [$m=5$].

CALCULATION DETAILS

The CNOSSOS-EU model describes the noise emission of an average European road vehicle in terms of its sound power level. Each vehicle type is represented by a single point source positioned at a height of 0.05 m above the road surface. The noise emission of traffic is represented by a source line characterised by its directional sound power per metre per frequency. CNOSSOS-EU separates calculations for rolling noise and engine (propulsion) noise.

For rolling noise, the sound power level, $L_{WR,i,m}$, for each vehicle category m, and frequency band, i, is given by:

$$L_{WR,i,m} = A_{R,i,m} + B_{R,i,m}\log_{10}\left(\frac{v_m}{v_{ref}}\right) + \Delta L_{WR,i,m}(v_m) \tag{5.14}$$

where v_m is the average speed of the traffic flow and values for A_R and B_R are given in tables in the standard across octave bands for each vehicle category and for a reference speed of $v_{ref}=70$ km/h. $\Delta L_{WR,i,m}$ is the sum of all corrections to be applied to rolling noise including corrections for road surface, studded tyres, speed variation and temperature. Figure 5.4 plots the variation of $L_{WR,i,m}$ with changes in speed.

For propulsion noise, the sound power level L_{WP} is given by:

$$L_{WP,i,m} = A_{P,i,m} + B_{P,i,m}\left(\frac{v_m - v_{ref}}{v_{ref}}\right) + \Delta L_{WP,i,m} \tag{5.15}$$

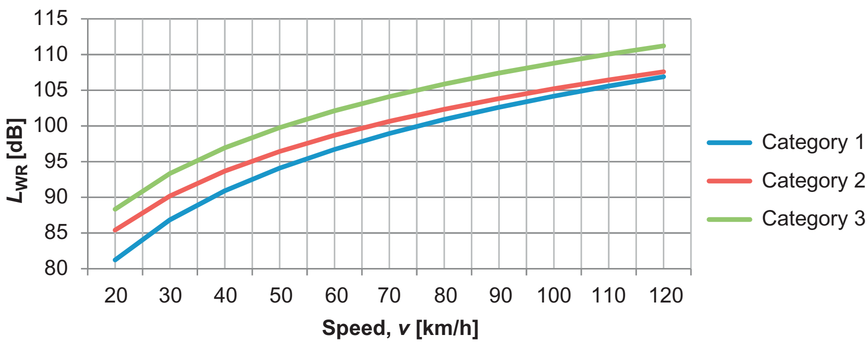

FIGURE 5.4 The variation of rolling noise with speed for the first three categories. Note that the CNOSSOS-EU method does not calculate rolling noise for powered two wheelers.

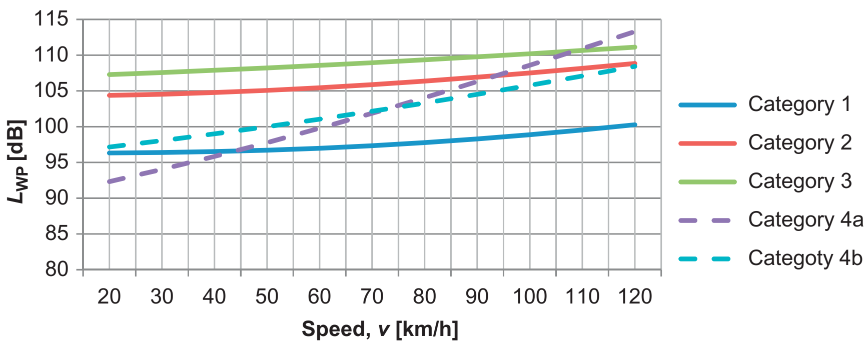

FIGURE 5.5 The variation of propulsion noise with speed for each vehicle category.

Again the coefficient A_P and B_P are given in tables in the standard for octave bands for each vehicle category and for a reference speed of $v_{ref}=70$ km/h. $\Delta L_{WP,i,m}$ is the sum of all corrections to be applied to the propulsion noise source including the effect of the road surface on propulsion noise, road gradients and varying driving conditions. Figure 5.5 plots the variation of $L_{WP,i,m}$ with changes in speed.

Having established values for rolling noise and propulsion noise for a vehicle driving under specific conditions, the overall sound power for that vehicle, $L_{W,i,m}$, is the energetic sum of the rolling and propulsion noise:

$$L_{W,i,m} = 10\log_{10}\left(10^{\frac{L_{WR,i,m}}{10}} + 10^{\frac{L_{WP,i,m}}{10}}\right) \tag{5.16}$$

An exception is the case of powered two wheelers where only the propulsion noise is considered and thus $L_{W,i,m}$ is equal to $L_{WP,i,m}$ when $m=4$.

In a steady traffic flow Q (vehicle per hour) with an average speed v (km/h), the directional sound power per metre, per frequency band of the source line, $L_{W,eq,i,m}$ is defined by:

$$L_{W,eq,i,m} = L_{W,i,m} + 10\log_{10}\left(\frac{Q_m}{1000v_m}\right) \tag{5.17}$$

These sound powers should be calculated for each octave band, i, between 125 Hz and 4 kHz and for all vehicle categories in the flow.

OTHER CONSIDERATIONS

The CNOSSO-EU road traffic noise model also considers several conditions beyond the scope of traditional models. For example, we know from research that the acceleration and deceleration of vehicles (i.e. driver engine behaviour) can affect vehicle noise emissions. However, in practice, acceleration is generally neglected for the purpose of strategic noise mapping; yet in cases where Member States wish to evaluate this effect, CNOSSOS-EU will have the ability to provide such a correction. The method must also be valid when used across a wide range of European meteorological conditions. As such, the effect of air temperature on rolling noise is considered along with possible corrections for studded tyres (i.e. winter tyres). The age of a road surface may also influence the noise emission. A future publication, provisionally titled 'Guidelines for the competent use of CNOSSOS-EU', will provide information on how this and other factors may be taken into account during the modelling procedure. The publication will also provide further details on how to model multi-lane roads, the measurement method for deriving sound power levels from roadside sound pressure measurements, default values for missing data, among other items.

5.2 RAILWAY NOISE

Rail is generally perceived as one of the most environmentally friendly modes of transport. The European Rail Research Advisory Council report that a train journey from London to Brussels produces only around 10% of the emissions per passenger of a plane journey on the same route, while the energy consumption of rail passenger transport (1.27 terra watt-hour (TWh)) is minimal compared to that of road transport (51 TWh) (Travaini and Schut, 2012). However, rail transport is not pollution free and the EU Future Noise Policy Green Paper noted that the public's main criticism of rail transport is the excessive noise that it produces (European Commission, 1996). Railway noise is the second most dominant source of environmental noise in Europe with approximately 9 million people exposed to levels above 50 dB(A) during the night-time (European Commission, 2011). Contrary to road traffic, where permissible noise limits at the source have existed in the EU since the 1970s, noise standards for trains only came into force at the beginning of the twenty-first century (Guarinoni et al., 2012).

Railway transport, encompassing both passenger and freight trains, is increasing. The capacity of the European railway network must be enlarged to help enable an effective modal shift towards rail, thereby helping to support a low carbon economy (Travaini and Schut, 2012). However, the combination of greater volumes of railway traffic and faster and heavier trains will likely lead to more railway noise disturbance in the future (Gidlöf-Gunnarsson et al., 2012).

Railway noise is generally considered to be less annoying than both road traffic noise and aircraft noise. In Germany, a bonus of 5 dB(A) has been set by German noise regulations, i.e., it is assumed that railway traffic noise must be 5 dB(A) louder than road traffic noise to achieve the same level of annoyance (Schreckenberg et al., 1999). Similarly, ISO 1996-1 (2003) recommends a railway noise bonus of between 3 and 6 dB(A) in railway noise assessments.

Discussions on railway noise tend to focus on line operation. Line operations refer to the movement of railroad locomotives and freight or passenger trains over a main line or branch line of tracks (Long, 2006). Railway noise is produced from a combination of three main source mechanisms: rolling noise, engine noise and aerodynamic noise. Like road traffic noise, each source mechanism is dependent on the speed of the train. Figure 5.6 shows how the contribution of each source mechanism varies with vehicle speed. There are other sources associated with the operation of a railway including noise from depots, PA systems, vending machines, chimes/horns, among others. However, these sources tend to be considered as industrial noise and are discussed in greater detail in Chapter 6.

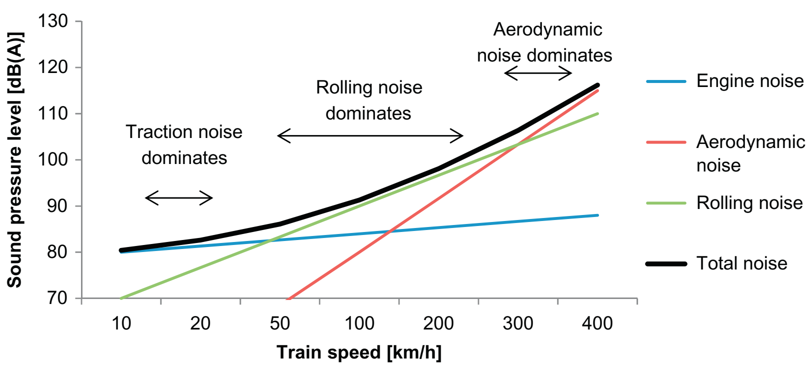

FIGURE 5.6 Approximate Relationship of different railway noise source mechanisms with speed. *Adapted from de Vos (2012).*

Noise emission varies significantly across different train types and freight trains are typically the main source of railway noise problems. Many freight trains are still equipped with cast iron tread brakes and employ the same technology (and resulting noise performance) as rail vehicles operating 50–100 years ago (de Vos, 2003). Freight trains in Europe consume most of the environmental capacity[3] of existing lines because the noise emission from freight trains is about 10 dB(A) higher than passenger trains and freight trains frequently operate during the night-time period when people are more susceptible to noise-induced sleep disturbance (de Vos, 2003).

5.2.1 Rolling Noise

Rolling noise is the main source mechanism affecting rail vehicles, and it dominates at speeds between 30 and 200 km/h (Clausen et al., 2012). Rolling noise (or *rail/wheel* noise) is produced by the interaction between the train wheels and the track surface. Within this context, there are a number of mechanisms whereby noise is generated. When a train is in motion, both the wheel and the track vibrate, thereby creating noise. This is caused by vertical dynamic forces due to minor surface irregularities in the rail and wheel contact area (de Vos, 2012). Vibrations are induced in both the wheel and the track, and rolling noise results from both (Figure 5.7). The impact of the wheel on a rail joint will also generate noise – this will occur when rails are not continuously welded. Flange squeal can also be generated as a result of sliding contact between wheel flanges with steel rails. The roughness of the wheels, track roughness and the track support structure all play an important role in the noise generation and radiation process.

BOX 5.5

ROUGHNESS

Rolling noise results from the vibration–excitation between the wheels and the track. Because the entire wheel and track system is excited by the combined roughness at the interface, the combined roughness value determines the level of rolling noise. This is why combined roughness is considered in noise emission models instead of considering wheel and track roughness separately (Hardy and Jones, 2004). Wheel roughness is a function of the braking system used on the train. Trains

[3] Environmental capacity typically refers to the ability of an environment to accommodate a particular activity or rate of an activity without unacceptable impacts.

BOX 5.5 *(cont'd)*

employing brake block technology or a combination of brake blocks and disc brakes tend to produce markedly more noise than trains with disc brakes alone (Jabben and Potma, 2004). Trains equipped with only disc brakes are generally about 8–10 dB(A) quieter than cast-iron tread-braked vehicles operating along good quality track. Moreover, where train wheels are comparatively smooth, the difference between rolling noise on a smooth track and a badly corrugated track can be more than 20 dB(A) (Hardy and Jones, 2004).

The roughness level, L_r, is usually expressed in dB, and may be calculated from:

$$L_r = 20\log_{10}\left(\frac{r}{r_o}\right)$$

where r represents the root mean square of the roughness amplitude and r_o is the reference roughness level of 1 μm.

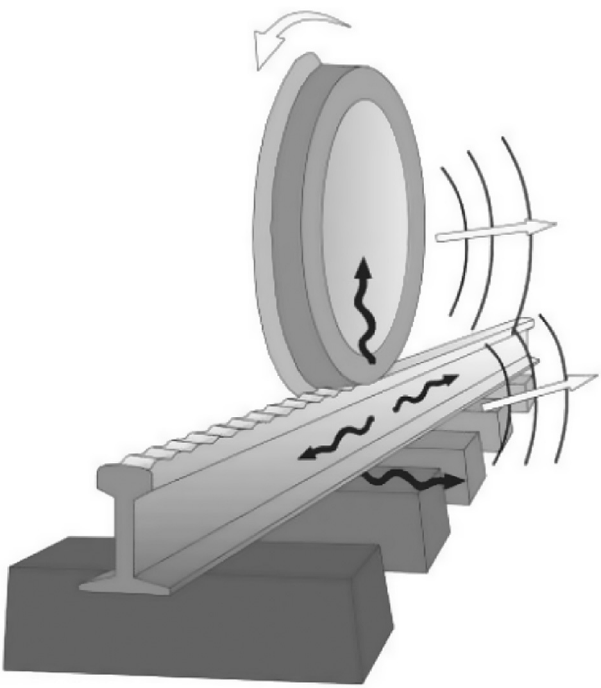

FIGURE 5.7 The mechanisms behind the generation of rolling noise.

5.2.2 Engine Noise

The mechanical processes required to power a train and propel it forward result in significant engine noise. Examples include exhaust noise, noise from fans and cooling systems, engine and transmission vibrations among others. In the literature, it is often referred to as *engine noise*, *power unit noise* or *traction noise*. When nonelectrified trains are idling, accelerating, and when operating at speeds below 60 km/h, engine noise is generally the dominant source mechanism (Dittrich and Zhang, 2006).

Electric trains are significantly quieter than their diesel counterparts. They generally draw power from overhead (or underground) power lines and thus do not have the same range of noise sources as those associated with diesel locomotives. However, in the case of light rail vehicles and trams, power units are sometimes located on the roof of the train. Power unit noise emitted at this height is virtually unscreened and will propagate directly to first and second storey buildings in cities (Federal Ministry of Transport, 2000).

5.2.3 Aerodynamic Noise

Modern high-speed trains travel at such high speeds that their movement through the air causes significant aerodynamic noise. Irregularities in the body of the main train (e.g. protruding objects, cavities, wakes) cause air turbulence as the train pushes the air aside. This turbulence creates pressure disturbances that result in noise (similar to the effect produced by an aircraft fuselage; see Section 5.3.1). It becomes a significant noise source at very high speeds, normally in excess of 200 km/h.

5.2.4 Other Sources

Other sources such as curve squeal (caused by a stick–slip type effect on tight curved tracks), brake squeal, ground vibrations, bridge noise and impact noise caused by crossings, switches and rail joints can also occur and sometimes dominate other sources. At times, where a catenary system is used, overhead cables can also generate a ‘whip’ noise. Different noise prediction methods consider these sources in different levels of detail, and there is little uniformity in how each factor is considered. For example, the Dutch and German calculation methods for railway noise differentiate between wooden and concrete sleepers. The Dutch method considers concrete sleepers to be 2 dB(A) quieter than wooden ones, whereas, in the German method, it is the other way around (Nijland and van Wee, 2005).

5.2.5 Railway Noise Calculation Methods

Railway noise calculation methods are slightly different to the methods used for road traffic noise. Generally, emission levels are divided across different train types which are divided into a number of classifications (more than for road traffic). However, while the emission models vary significantly, the associated propagation model follows the same principles described for road traffic models.

Reken-en Meetvoorschrift Railverkeerslawaai (The Netherlands)

This section is based on the Wolfel translated version (Wolfel, 2003b) of the Dutch 'Reken-en Meetvoorschrift Railverkeerslawaai' (RMR) standard for railway noise which is the END recommended interim method for strategic noise mapping. This method provides two different calculation methodologies: a simplified methodology (SRM-I) and a detailed methodology (SRM-II). Because it is the Dutch national computational method for railway noise, it was developed for typical trains and track surfaces in the Netherlands.

CALCULATION DETAILS

The RMR emission model splits trains into 10 different railway vehicle categories which are generally differentiated by the wheel brake system and drive unit (see Table 5.4). These categories are used to predict an emission value, E, for each rail vehicle category. Note that the emission value is not a sound power per unit length or a sound pressure level at a certain

TABLE 5.4 Different Train Categories

Category, c	Train Description
1	Block braked passenger trains
2	Disc braked and block braked passenger trains
3	Disc raked passenger trains
4	Block braked freight trains
5	Block brakes diesel trains
6	Diesel trains with disc brakes
7	Disc braked urban subway and rapid tram trains
8	Disc braked InterCity and slow trains
9	Disc braked and block braked high-speed trains
10	Provisionally reserved for high-speed trains of the ICE-3(m) (HST East) Type

distance; rather, it is a number (representing the emission of the source) to serve as an input into the model to allow for the prediction of a long-term average noise level at a receiver (de Vos, 2012).

For the simplified method (SRM-I), the emission values, in dB(A), may be determined by combining the noise from braking and non-braking trains:

$$E = 10\log_{10}\left(\sum_{c=1}^{y} 10^{\frac{E_{nr,c}}{10}} + \sum_{c=1}^{y} 10^{\frac{E_{r,c}}{10}}\right) \tag{5.18}$$

where $E_{nr,c}$ is the emission per rail vehicle category for non-braking trains, $E_{r,c}$ is the emission term for braking trains, c is the train category and y is the total number of categories present. Trains are considered 'braking' when the brake system is active. The emission values are calculated from:

$$E_{nr,c} = a_c + b_c\log_{10}v_c + 10\log_{10}Q_c + C_{b,c} \tag{5.19}$$

$$E_{r,c} = a_{r,c} + b_{r,c}\log_{10}v_c + 10\log_{10}Q_{r,c} + C_{b,c} \tag{5.20}$$

where the standard emission values, a_c, b_c, $a_{r,c}$ and $b_{r,c}$, are provided in tables in the standard (reproduced in Table 5.5), Q_c is the average number of non-braking trains of the considered rail category during the time period of interest, $Q_{r,c}$ is the average number of braking trains of the considered category and v_c is the average speed of the train [km/h]. C_{bc} is a correction factor, determined as a function of train category and track

TABLE 5.5 Emission Values as Functions of Railway Category, c

	Non-Braking		Braking	
Category, c	a_c	b_c	$a_{r,c}$	$b_{r,c}$
1	14.9	23.6	16.4	25.3
2	18.8	22.3	19.6	23.9
3	20.5	19.6	20.5	19.6
4	24.3	20.0	23.8	22.4
5	46.0	10.0	47.0	10.0
6	20.5	19.6	20.5	19.6
7	18.0	22.0	18.0	22.0
8	25.7	16.1	25.7	16.1
9	22.0	18.3	22.0	18.3
10	n/a	n/a	n/a	n/a

These emission values are derived from multiple regression curves, based on measurements conducted in the late 1980s (de Vos, 2012).

TABLE 5.6 Description of Different Track Types

Number	Description
1	Railway tracks with single block or double block (concrete) sleepers, in ballast bed
2	Railway tracks with wooden or zigzag concrete sleepers, in ballast bed
3	Railway tracks in ballast with non-welded tracks, tracks with joints or switches
4	Railway tracks with blocks
5	Railway tracks with blocks and ballast bed
6	Railway tracks with adjustable rail fixation
7	Railway tracks with adjustable rail fixation and ballast
8	Railway tracks with poured in railway lines
9	Railway tracks with level crossing

type, and is presented in a table in the standard. Several different track types are considered in the method (Table 5.6). C_{bc} is zero for all vehicles travelling on type 1 tracks; thus, this track type can be considered as the standard reference track.

The emission values for train categories 1–8 are determined for two different source heights, one at the level of the railhead (the top surface of the rail on which the wheels of the rolling stock run) and the other located 0.5 m above the railhead. For high-speed trains (category 9), there are four different source heights: 0.5 m above the railhead, 2.0 m above the railhead, 4.0 m above the railhead and 5.0 m above the railhead.

The standard also includes procedures to model emission from concrete and steel bridge structures. For concrete structures, rolling noise emission and the noise radiation of the structure itself are contained in the track correction table. For steel structures, the rolling noise emission is contained in the correction factor for tracks, while the additional noise from the structure itself is accounted for by raising the initial emission factor by an extra factor, $\Delta L_{E,bridge}$, to account for the bridge. The more detailed method SRM-II allows for up to five different source heights, and emission values are determined in octave bands instead of an overall A-weighted sound pressure level.

The RMR prediction method has been revised twice since 1996 (2006 and 2009), and both revisions were subsequent to the publication of the END. The 2006 revision includes a measurement method that may be used to assign a train of unknown category into an existing category or to develop a new category, while the 2009 revision includes more vehicle categories (de Vos, 2012).

Calculation of Railway Noise (United Kingdom)

In the United Kingdom, the Calculation of Railway Noise (CRN) is the standard method for predicting railway noise. It was developed in 1995. CRN was developed under similar noise insulation legislation as CRTN. Authorities in the United Kingdom have since recognised that the nature of the rolling stock fleet has changed considerably since the original development of the method and that the 1995 method is no longer representative of the current fleet (Hardy et al., 2007). As such, a study was commissioned by the Department for Environment, Food and Rural Affairs (DEFRA) to investigate the potential for using back-end corrections with CRN to account for real levels of rail head roughness in the United Kingdom and to allow for the effects of rail grinding strategies to be catered for in modelling (Hardy and Jones, 2004). The CRN standard predicts results in terms of the overall A-weighted noise level but does not provide equations across octave bands. Final results are presented in terms of an L_{Aeq} based index.

CALCULATION DETAILS

The rail track is first divided into segments such that the variation of noise within each track segment is less than 2 dB(A). Then, the reference sound exposure level (SEL) at a reference distance of 25 m from the near-side edge of the track is calculated. This approximates a single vehicle running on a flat and continuously welded track on concrete sleepers laid in ballast. This is calculated from:

$$\mathrm{SEL} = 31.2 + 20\ \log_{10}(V) \tag{5.21}$$

or for diesel engines under full power:

$$\mathrm{SEL} = 112.6 - 10\ \log_{10}(V) \tag{5.22}$$

where V is the train speed in km/h. SEL is then corrected to account for vehicle type, the number of vehicles and the track/support structure. These corrections are presented in a detailed table in the CRN standard (in Table A1.1 of CRN), but a selection of corrections is reproduced in Table 5.7. Corrections are also required for the track support structure and are given in Table 5.8.

Following adjustments to account for the attenuation of noise, the corrected SEL may be converted to an L_{Aeq} value taking into account the time

TABLE 5.7 Selection of Sound Exposure Level Corrections for Individual Railway Vehicles

Category	Description	Correction [dB(A)]
1: Tread braked passenger coach	British Rail MKI	+14.8
	Gatwick Express	+16.7
2: Disc braked passenger coaches	British Rail MKIII	+6.0
	Class 319 EMU	+11.3
3: Tread braked freight vehicles	2-axle tank wagons	+12.0
5: Disc braked freight vehicles	Merry Go Round Coal Hopper HA	+8.0
7: Diesel locomotive	Class 20,33	+14.8
7: Electric locomotive	Class 73,86,87,90,91	+14.8
8: Diesel locomotives under full power	Class 20,31,33,37	0.0

Adapted from Department of Transport (1995).

TABLE 5.8 Correction to Rolling Noise for Different Track and Track Support Structures

Category	Correction [dB(A)]
Continuously Welded Rail (CWR) concrete or timber sleepers plus ballast	+0
Jointed track (18.3 m lengths). Points and crossings	+2
Slab track	+2
Concrete bridges and viaducts	+1
Steel bridges	+4
Box girder	+9

Adapted from Department of Transport (1995)

period over which the assessment is concerned and the number of train passages within this time period, Q:

$$L_{Aeq,18\,\mathrm{h}} = \mathrm{SEL} - 48.1 + 10\log_{10} Q_{day} \tag{5.23}$$

$$L_{Aeq,6\mathrm{h}} = \mathrm{SEL} - 43.3 + 10\log_{10} Q_{night} \tag{5.24}$$

Two quantities are predicted, $L_{Aeq,18\mathrm{h}}$ for the day time and $L_{Aeq,6\mathrm{h}}$ for the night-time.

BOX 5.6

CRN AND THE END

One of the major limitations of CRN is that it assumes that the rail head is comparatively smooth and this leads to a consistent underprediction of noise levels in the field. The reasoning behind this is that CRN was originally developed for application under the UK's Noise Insulation Regulations which was only supposed to be applied to new railways (and thus new and smooth rails) (Hardy and Jones, 2004). It was not developed with the intention of preparing strategic noise maps for existing and new rail systems.

In order to allow applicability under the END, speed-dependent back-end corrections were derived so reliable noise maps could be determined using CRN. A large proportion of the current fleet is outside the scope of the original CRN method. As such, source correction terms for rolling noise were also determined for these railway vehicles to enable strategic noise maps to take account of these vehicles (Hardy et al., 2007).

CNOSSOS-EU (The Proposed Common European Method)

CNOSSOS-EU Working Group 3 was charged with the development of the railway traffic noise emission source model. At the time of writing, it is not yet complete. Parameters associated with different track section types are not yet available but will be developed during phase B of the CNOSSOS-EU process (2012–2015). Nevertheless, this section provides a summary of the proposed method and provides an indication of the level of detail that will be contained in the method.

The CNOSSOS-EU method defines a *vehicle* as a subunit of a train that can be moved independently and detached from the rest of the train, while a *train* is made up of a collection of these subunits. Railway vehicles are to be classified in terms of:

- vehicle type (e.g. high-speed vehicles, self-propelled passenger coaches, hauled passenger coaches, city trams, diesel locomotives, electric locomotives, freight vehicles);
- number of axles per vehicle;
- the brake type (e.g. cast-iron block, composite or sinter metal bock, disc braked); and
- the noise reduction measures fitted (dampers, screens).

The number of vehicles for each type should be determined on each of the track sections and expressed as an average number of vehicles per hour. The track and support structure must also be classified. The following items are considered:

- type of track base (ballast, slab track, ballasted bridge, non-ballasted bridge embedded track);
- railhead roughness (level of maintenance);
- rail pad type;
- additional acoustic measures (rail damper, barrier, absorber plate on slab track);
- rail joints; and
- curvature of rail.

Two separate source heights are considered: 0.5 and 4.0 m relative to the railhead. Both sources are positioned above the centre of the track (Figure 5.8). These sources represent six different source mechanisms: (1) rolling noise, (2) traction noise, (3) aerodynamic noise, (4) impact noise, (5) squeal noise and (6) noise due to additional effects such as bridges and viaducts.

CALCULATION DETAILS

Similar to the treatment of the road traffic noise method in CNOSSOS-EU, the railway method describes the sound power emission of a specific combination of vehicle types and track types in terms of the sound power characteristics of each vehicle. The traffic flow on the track is then represented by source lines and associated sound power per metre length (in octave bands). The sound power per metre due to all rail vehicles is the energy sum of all contributions from all vehicles on each track section.

ROLLING NOISE

Rolling noise is dependent on four factors: wheel roughness, rail roughness, the vehicle transfer function to the wheel and to the superstructure, and the track transfer function. Wheel and rail roughness contributes to

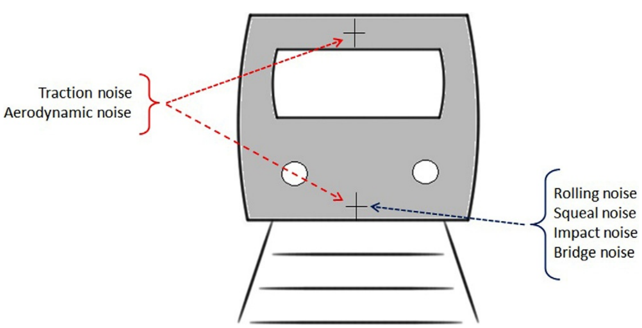

FIGURE 5.8 Sketch of source positions for each source mechanism in the CNOSSOS-EU method.

vibration excitation at the point of contact between the rail and the wheel. The transfer functions describe the mechanical vibration and sound generation on the surfaces of the wheel, rail, sleeper and track substructure (Kephalopoulos et al., 2012). The total effective roughness level is determined as the combination of the rail and wheel roughness and a contact filter to account for the filtering effect of the contact point between the rail and wheel. The total effective roughness level, coupled with two speed-independent transfer functions, is used to calculate the overall rolling noise.

TRACTION NOISE

Traction noise is generalised according to three characteristic operating conditions: constant speed, acceleration and idling. Several traction noise sources are identified including noise from the power train, noise from the fans and cooling systems, and intermittent sources such as compressors or valves. As each source behaves differently at different operating conditions, the source strength of each is obtained from measurements under controlled conditions.

IMPACT NOISE

Impact noise occurs when vehicles pass over crossings, switches or rail joints. In many cases, impact noise can dominate over rolling noise. The CNOSSOS-EU model accounts for impact noise by including it in the rolling noise term and including a supplementary impact roughness level to the total effective roughness level on each track section. Impact noise depends on the severity and number of impacts per unit length or joint density. The default impact roughness level is given for a joint density of one joint per each 100 m of track.

SQUEAL

As a train moves through a curved section a high pitched tone may be emitted as a result of lateral stick–slip phenomena in the contact area between wheels and rails (de Vos, 2012). This is called curve squeal. It is dependent on curvature, friction, speed and track geometry. The noise emission due to curve squeal should normally be verified by site measurements especially in the case of city trams. However, CNOSSOS-EU proposes a simple correction (Table 5.9).

TABLE 5.9 Simple Corrections for Curve Squeal

Curve Radius, R	Correction to Add to Rolling Noise Sound Spectra for All Frequencies [dB]
$R < 300$	8
$300\ \text{m} < R < 500\ \text{m}$	5

AERODYNAMIC NOISE

Aerodynamic noise is given as a function of speed and source height. It is only relevant at speeds in excess of 200 km/h.

ADDITIONAL EFFECTS

The CNOSSOS-EU method is also likely to include noise emission predictions for additional effects. For example, the passage of a vehicle over a bridge will be accounted for by an increase in rolling noise. This is based on data from measurements taken over a bridge in specific cases. Other sources related to the operation of railway (e.g. noise at stations, depots, bells, etc.) are to be treated as industrial noise sources and do not form part of the railway emission model.

5.3 AIRCRAFT NOISE

Aircraft noise affects a much smaller proportion of the population compared to road and traffic noise. However, aircraft noise has probably received greater attention in the media and among the general public compared to other noise sources. This is most likely because aircraft noise is regarded as the most annoying source of transportation noise. It is often cited as a reason against airport expansion and is one of the most common complaints raised by residents living in the vicinity of airports. In fact, aircraft noise has received so much attention that, thanks to technological developments, individual aircraft has become 75% less noisy over the last 30 years (Guarinoni et al., 2012). Although noise from individual aircraft has been reduced, the total exposure to noise from aircraft for residents in communities near airports is estimated to have increased worldwide. This is due to the growth in the number of aircraft movements at airports all across the world.

Because of the foregoing, noise modelling and mapping around airports is not a new development. Aircraft noise footprints are commonly used for forecasting the impact of new developments, quantifying the noise trends around airports and evaluating new tools. Thus, aircraft models have adapted and have become more sophisticated over time (Khardi and Abdallah, 2013).

BOX 5.7

AIRCRAFT NOISE COMPLAINTS

In December 1903, the Wright brothers were responsible for the first flight of an aeroplane in North Carolina, USA. The first flight lasted only 12 s and covered just less than 40 m. In 1911, just 8 years later, the first

(*Continued*)

BOX 5.7 (*cont'd*)

editorial complaining about aircraft noise was published. AERO magazine published an editorial under the title 'On the fitting of silencers' which reported that the tremendous racket associated with aeroplanes plays a considerable part in prejudicing the public against those machines (Testimony of C.E. Burleson, 2007). However, it was probably not until the 1960s, following the successful introduction of the jet engine into commercial airline service that aircraft noise became an issue of substance (Smith, 1989). This followed a number of lawsuits in the United States and major public outcry in Europe.

5.3.1 Aircraft Noise Sources

Aircraft can be propeller driven or driven by jet engines. There are three general types of jet engines used in aircraft: turbojet engines, bypass engines and turbofan engines. Jet engine noise is generated primarily by the interaction of the high-velocity exhaust gasses with the relatively still atmosphere through which the aircraft passes; as the gasses mix, the resulting turbulence creates large pressure fluctuations, which radiate as sound (Long, 2006). Although engine noise is a significant mechanism of aircraft noise, there are other contributory sources. The air flow around the airframe is another source of noise and anything that affects the aerodynamics of the aircraft – such as the nacelles (the cover in which the engine is housed), wings, trailing edge flaps, leading edge slats – can lead to increased noise levels. For example, when the landing gear is lowered on an aircraft, the air flowing around the aircraft becomes disturbed which leads to an overall increase in noise level.

The noise emission of an aircraft also depends on its various stage of operation. The noise from the same aircraft taking off and landing can be quite different due to the changing contribution of different source components to the overall noise level. Aircraft noise can also be quite directional (this means the sound radiating from the source may be greater in some directions than others). At the front end of the engine, high-frequency tonal components of the compressor fans are radiated from the intake; thus, there is a greater high-frequency noise component on the approach side of an airport compared to the takeoff side.

The engine thrust which influences noise generation varies with speed, weight and the climb rate of the aircraft. Thus, to calculate the noise level at a receiver point on the ground, the flight path (describing the movement of an aircraft in three dimensions) and details of engine power and speed along this path must be described. Details of these variations are required to accurately model the source (i.e. the aircraft). If the flight paths are changed, perhaps due to diversions, communities that were previously unaffected by aircraft noise can become exposed.

The source mechanisms behind the generation of helicopter noise are quite different to jet engines. A major source of helicopter noise is 'blade-slap'. Blade slap occurs as the helicopter blade interacts with a vortex formed by the blade preceding it (Wilson, 2006). Other sources include compressor noise, the tail rotor, the gear box, engine exhaust and airframe noise.

BOX 5.8

NOISE FROM GROUND OPERATIONS AT AIRPORTS

Noise from ground operations is not generally considered in the noise prediction of aircraft noise. Noise from ground operations can range from taxiing of aircraft to the runway, servicing and related activities associated with the running of an airport (such as baggage handling) and other sources of industrial noise. The noise from ground operations is usually negligible compared to noise from the movement of aircraft; however, it is best practice to assess ground noise separately to aircraft noise.

5.3.2 Aircraft Noise Calculation Methods

Aircraft noise modelling is significantly more detailed when compared with noise modelling for other transportation modes. However, there is long-standing experience in aircraft noise assessment and prediction methods. In addition, associated aircraft performance databases, such as the Aircraft Noise and Performance (ANP) Database, have been established and defined at an international level (Kephalopoulos et al., 2012). Most aircraft noise models are empirical tools that calculate the impact of aircraft noise around airports; results are based on a series of stored noise profiles of different aircraft under varying flight conditions. Traditional aircraft noise models are 'integrated' meaning that they utilise a database of SELs from complete flyovers and consider time-integrated noise metrics (Plotkin, 2011).

ECAC-CEAC Doc 29 Version 3 (Europe)

The END-recommended interim noise computation method for aircraft noise is ECAC-CEAC Doc 29, 'Report on Standard Method of Computing Noise Contours around Civil Airports' (1997). This is the second version of the document and replaced the 1986 version. It describes how to calculate noise contours around civil airports. Doc 29 Version 2 focused mainly on the algorithms for implementation in a computational model and contained little advice on the practical application of the methodology (ECAC.CEAC, 2005a).

The Commission Recommendation of 2003 noted that the European Civil Aviation Conference (ECAC, *or Conférence Européenne de l'Aviation Civile*, *CEAC*) had launched a revision of its Doc 29 in 2001 with a view to producing a state-of-the-art noise modelling method. While this was not completed prior to the publication of the END, it was recommended that attention should be paid to the revised version of the method (European Commission, 2011). The 3rd edition of Doc 29 was published in December 2005 and addressed previously identified limitations of Version 2. Doc 29 Version 3 is split into two separate volumes:

- Volume 1 (Applications Guide) (ECAC.CEAC, 2005a) is for noise modellers, e.g., the acousticians who produce the noise map and the policymakers and planners who use maps to inform decision making;
- Volume 2 (Technical Guide) (ECAC.CEAC, 2005b) is for developers of aircraft noise models. It presents algorithms and internationally agreed best practice for the generation of aircraft noise contours. It also provides a link to an international database describing essential ANP data.

A major development within Version 3 is that the methodology now includes a link to a comprehensive international ANP database housed at www.aircraftnoisemodel.org. A key dataset included in the ANP database is the 'Noise-Power-Distance' (NPD) relationships that describe aircraft noise data in terms of slant distance from the flight path and for different modes of operation (e.g. different power settings).

SUMMARY OF CALCULATION DETAILS

Calculations are performed at receiver points (generally in a grid) surrounding the airport to determine the noise level at each receiver from aircraft movements as they follow a specified flight path to and from the airport under specified flight configurations. Figure 5.9 presents the five basic steps implemented in ECAC-CEAC Doc 29 Version 3.

STEP 1 Raw data are collated describing the airport (runway geometry, topography of the surrounding environment) together with operational details (runway usage by different aircraft, temporal distribution of movements, aircraft operating procedure, meteorological conditions). This information acts as an input to the aircraft noise model.

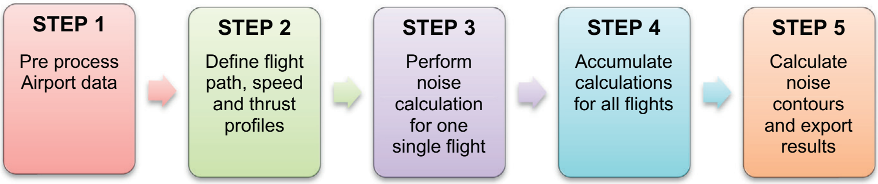

FIGURE 5.9 The noise contour generation process. *Adapted from* ECAC.CEAC (2005b).

STEP 2 Each aircraft movement is defined in terms of its flight path. The noise emission from each movement along a flight path is dependent on the acoustic characteristics of the aircraft, and engine power, in particular, is one of the main factors influencing noise emission. Flight paths can change due to a wide range of variables (e.g. varying meteorological conditions, aircraft weight, air traffic control constraints, among others). Thus, the modelled flight path generally describes a statistically central flight path. Usually, flight path information is generated through analysis of radar data describing the actual paths flown or alternatively may be derived from a set of procedural steps dictated by airport traffic control. The flight path must also be divided into a number of different segments using standard equations and segmentation methodologies.

STEP 3 The noise level at a receiver point on the ground for one single event is calculated. This forms the core building block of the modelling process. L_{max} and L_E (the single-event sound exposure level) values are tabulated in the ANP database as functions of propagation distance for specific aircraft types, flight configurations and power settings. Because the ANP database applies to specific reference conditions, some conversion may be required to apply the data to varying scenarios. For example, the NPD data describe the noise associated with an infinitely long flight path where flight path parameters remain constant. Various corrections are applied to this infinite flight path noise level to correct for the varying flight path parameters in order to calculate the noise contribution for each flight path segment (Kephalopoulos et al., 2012).

STEP 4 Step 4 involves repeating step 3 for the different aircraft categories using all the different flight paths and all receiver points (in the case of noise mapping these are likely to be in the form of a grid of receiver points). The overall results are then determined by summing the results for each receiver point.

STEP 5 Finally, noise contours are generated by interpolating between receiver grid points. When receiver points are rectangular spaced grid points, their accuracy is very much dependent on the chosen grid spacing. The finer the grid spacing (its resolution), the more accurate the noise contours are likely to be. However, a finer grid resolution will significantly increase the required calculation time. To address this issue, EAC Doc 29 allows calculations to be performed over an irregular grid to refine the interpolation between receiver points in critical areas.

BOX 5.9

A NOTE ON NOISE CERTIFICATION TESTS AS SPECIFIED BY ICAO

The International Convention on International Civil Aviation (ICAO) has set out permissible noise levels for individual aircraft in terms of the Effective Perceived Noise Level (ICAO, 2008). These permissible noise levels are determined by means of a standardised noise measurement procedure. The measurement method involves three monitoring positions for which different limits are set: along the approach path, the take-off/flyover path and at a lateral/sideline position. Test aircraft perform defined arrival and departure procedures, and noise measurements are taken at these reference points. Measurements are repeated to ensure accuracy and results are corrected to standardised meteorological conditions. Data from the results of these tests contribute to the ANP database (along with other aircraft performance data).

FAA – Integrated Noise Model (United States)

Since 1978, the US Federal Aviation Authority (FAA) standard methodology for the assessment of aircraft noise has been the Integrated Noise Model (INM). INM is a computer programme used by over 1000 organisations in over 65 countries with the user base increasing every year (Federal Aviation Authority, 2008). The computational model is facilitated by a Windows-based graphical user interface which interprets a DataBase File (DBF) structure allowing easy, external manipulation of the model's input/output data (Fleming et al., 1995b).

The latest updated version (7.0c) was released in January 2012. In the United States, the model is the required tool for Federal Aviation Regulation (FAR) Part 150 noise compatibility planning, FAR Part 161 approval of airport noise restrictions and for FAA Order 1050 environmental assessments and environmental impact statements (Federal Aviation Authority, 2007). The National Aeronautics and Space Administration (NASA) also contributed to development of the database within the model as well as the core acoustic computational model (Fleming et al., 1995b).

INM is considered a line source model with calculations performed over one-third octave bands. INM also maintains a comprehensive NPD and associated aircraft performance database which is continually augmented with input data from aircraft manufacturers as well as through supplementary FAA and NASA sponsored field measurement studies (Fleming et al., 1995b). The model takes account of geometric divergence, atmospheric absorption, terrain shielding and ground effects.

INM is not designed for single-event noise prediction but rather, for estimating long-term average noise levels using average input data. The model output includes both the noise level at specifically selected locations and noise contours around an airport. Results can be exposure-based, maximum-level-based, or time-based. In the United States, the annual day–night average sound level (DNL or L_{dn}) is generally used for quantifying airport noise. Thus, the INM model uses the concept of an average annual day for airport noise indicators.

The model includes basic assumptions on how aircraft are operated during take-off and landing; INM includes typical flight profiles describing altitude, speed and engine power for takeoff and landing. The contribution of each aircraft type and flight path is determined for each receiver location and cumulated for day and night periods. INM standard profiles start at 6000 ft. above the airport for approaches and end at 10,000 ft. above the airport for departures (Federal Aviation Authority, 2007). However, in some cases, it may be more appropriate to use actual data recorded on site instead of generic profiles.

INM uses NPD data to estimate noise accounting for specific operation mode, thrust setting, source–receiver geometry, acoustic directivity, and other environmental factors. The noise, aircraft flight profile and flight path computation methodologies implemented in INM Version 7.0 are compliant with European Civil Aviation Conference (ECAC) Doc 29 (3rd Edition) (Federal Aviation Authority, 2008). The fixed-wing aircraft portion of the INM database is harmonised with ICAO's ANP database which accompanies ECAC's Doc 29. All fixed-wing aircraft submittals to the INM database will also be considered for implementation in the ANP database. The main advantage of the INM is that it is packaged software that is ready to use. However, this might also be considered its biggest disadvantage; some might view it as a 'black-box' with undisclosed source code (Butikofer, 2012).

BOX 5.10

THE AVIATION ENVIRONMENTAL DESIGN TOOL

At present, the FAA in the United States is in a transition phase in aircraft noise modelling. They recently releases a new tool, the Aviation Environmental Design Tool (AEDT). It examines fuel-burn, emissions and noise and facilitates a thorough consideration of all of aviation's environmental effects. The objective of the tool is to develop the capability to characterise and quantify the interdependencies among aviation-related noise and emissions, impacts on health and welfare and industry and consumer costs under different policy, technology, operational and market scenarios (Noel et al., 2009).

Upon the release of AEDT Version 2b (late 2014), analyses in the USA that currently require the use of INM will then be required to use AEDT instead. However, the noise prediction methodology contained with AEDT is very similar to that contained in INM.

CNOSSOS-EU (The Proposed Common European Method)

CNOSSOS-EU Working Group 5 was responsible for the development of a common noise prediction method for aircraft noise. This group considered two existing aircraft noise calculation methodologies to form the basis of CNOSSOS-EU:ECAC Doc 29 3rd Edition and the German aircraft noise prediction method, Anleitung zur Berechnung von Lärmschutzbereichen (AzB). A key consideration during deliberations was that these two methods have different noise and performance database structures; AzB relies on a German national database, while Doc 29 Version 3 utilises the international ANP database.

CNOSSOS-EU is required to align with other EU instruments including Directive 2002/30/EC on the establishment of rules and procedures with regard to the introduction of noise-related operating restrictions at community airports. Furthermore, the European Aviation Safety Agency (EASE) will use the CNOSSOS-EU method for European regulatory impact assessment. It was concluded, therefore, that Doc 29 and the ANP database were better suited to the additional requirements imposed by Directive 2002/30/EC and this method was selected to form the basis of CNOSSOS-EU.

In order to ensure that the method is consistent across Europe, the Doc 29 method must be adjusted. For example, guidance on the procedure to be applied and the fidelity/resolution of the required meteorological data are required (Kephalopoulos et al., 2012). Current guidance defaults to an air temperature of 15 °C and a headwind of eight knots (4.1 m/s). Such guidance has yet to be developed and will need to consider seasonal meteorological effects, and day, evening and night effects (Kephalopoulos et al., 2012).

The modelling of noise from helicopters has also been highlighted as an issue of concern. In contrast to fixed-wing aircraft noise, there is no internationally agreed helicopter noise calculation methodology (Kephalopoulos et al., 2012). It is proposed that the ANP database will be supplemented with helicopter noise and performance data from AzB 2008 or from a Member State's existing national method. Further research is required in this area.

Furthermore, the CNOSSOS-EU method proposes to supplement the existing ANP database with General Aviation (GA) data from the AzB 2008 database. This will require converting data from the AzB database to the format required for use with Doc 29 Version 3. A robust validation process of ANP data should be formalised at the ICAO level. In particular, significant improvements are required in the approval process for ANP data to ensure high-quality model input (Kephalopoulos et al., 2012). The ANP database must also be supplemented with data for additional GA aircraft, helicopter and military aircraft operating at EU airports.

Finally, a database to facilitate the calculation of ground noise from engine run-up (testing) should be included. This is necessary to allow the calculation of ground borne noise at airports. In terms of strategic noise mapping, such activities are treated as industrial noise sources (see Chapter 6).

5.4 LIMITATIONS AND FURTHER CONSIDERATIONS

The development of strategic noise maps across Europe represents the biggest and most ambitious environmental noise assessment undertaken to date across the globe. Strategic noise maps have been developed for all EU Member States, by leading European experts using the best available methods and tools. Overall, the noise mapping initiative represents a significant step forward in the understanding of environmental acoustics and the impact in terms of human exposure to noise pollution. In order to progress the current state of the art, it is important to address the limitations of existing calculation methods so that the development of noise maps can be improved.

CNOSSOS-EU offers significant potential improvements in this regard. When formally introduced, it will be the only method developed exclusively for strategic noise mapping under the END. Its major benefit is that it will offer a degree of consistency in calculation approach across all

Member States. At the moment, this consistency is lacking; even the most basic representation of the road source varies between line and point sources across different national calculation methods.

A key consideration during the development of CNOSSOS-EU was ensuring it would be a 'fit-for-purpose' model. This means that the community has to decide how accurate strategic noise maps really need to be. The desired level of accuracy directly impacts on the complexity of the model. In its present form, CNOSSOS-EU attempts to balance the complexity of the noise calculation process with computational time. Therefore, the method has stopped short of modelling all source mechanisms in order to improve calculation efficiency. It was also developed taking cognisance of the requirements of the END; this does not mean it is defined by the minimum requirements of the END, but rather these minimum requirements should set the low-water mark for the calculation method. CNOSSOS-EU should instead strive to be the most advanced noise prediction method available, one that is capable of being applied to local noise assessments for detailed mitigation design and planning as well as for strategic assessment at the national level. It should also be capable of evolving in line with new research in the area that improves understanding of noise modelling.

5.4.1 Road Traffic Noise

Current road traffic noise prediction methods are outdated and are being used in situations for which they were never originally intended. CNOSSOS-EU represents a significant step forward in this regard. It will incorporate many aspects of today's best practices in noise emission and sound propagation modelling. In terms of frequency analyses, it is proposed that CNOSSOS-EU will perform calculations across octave bands. This is consistent with the recommended interim method for road traffic (although two extra octave bands outside the scope of the recommended interim method, at centre frequencies of 63 and 8000 Hz, are considered in CNOSSOS-EU) and certainly represents an improvement when compared to methods that only predict an overall A-weighted sound pressure level. However, for detailed assessments involving annoyance or tonal assessments – which may be needed, for example, with the increasing number of electric vehicles on major roads – a detailed consideration of frequency spectra for different vehicle types is required and the CNOSSOS-EU method will have to be adapted to perform such studies.

The manner in which road traffic noise is divided into vehicle categories is an aspect that will be improved by CNOSSOS-EU. The current default approximation assumes just two categories (light and heavy), whereas CNOSSOS-EU divides vehicles into five classes in accordance with definitions set out in Directive 2007/46/EC. However, it is worth noting that the Harmonoise model proposed five broad vehicle categories which were divided into 18 subcategories (Jonasson et al., 2004). The intention was to model the five main categories initially but, as new data were collected for each subcategory, it would then be possible to model each subcategory. At present, determining datasets for 18 separate vehicle categories is probably beyond the capabilities of most noise-mapping authorities but such detailed data may exist in the future. Today, some authorities may even struggle with the proposed five categories. Some of the vehicle categories set out in Directive 2007/46/EC are classified according to weight. This may be troublesome for authorities who do not have the capability of capturing vehicle weight with existing traffic counters.

The treatment of low-noise road surfaces is an area in need of further research. The variation in acoustic properties of road surfaces is large, and there is no common procedure for the assessment of the acoustic properties of road surfaces (Kephalopoulos et al., 2012). The CNOSSOS-EU method will allow Member States apply their own regional road surface corrections, provided these corrections are documented and reported. Ideally, corrections for low-noise road surfaces should be derived from national datasets to account for national differences. These corrections should all be compared to the hypothetical reference surface described in CNOSSOS-EU and documented. This may eventually lead to a European road surface database and may facilitate the development of more effective low-noise road surfaces.

Most road traffic noise prediction methods in use today mix engine noise and rolling noise because emission quantities were originally derived from single microphone pass-by measurements. The CNOSSOS-EU method of separating rolling noise and propulsion noise is a welcome development and is now considered best practice internationally. However, in order to maximise the effectiveness of this development, the model should be refined to include separate source heights, as initially proposed in the Harmonoise method. This would allow the contribution of each source mechanism to be divided between multiple source positions. If both source mechanisms are combined at one position (usually close to the ground), the contribution of rolling noise and engine noise cannot be separated and the effectiveness of some mitigation measures might be either over- or underestimated. For example, a noise barrier beside a major road might not be designed sufficiently high if the engine noise from a heavy vehicle is modelled at a height of 0.05 m (see Figure 5.10). This is only likely to be an issue at specific locations where barriers and receivers are close to the road, so might it not be enough to warrant the related increase in computational time, but the model should be capable of performing more detailed calculations when desired. This would enable the improved assessment of potential mitigation measures.

CNOSSOS-EU also includes corrections for the acceleration and deceleration of vehicles. These corrections are important because the acoustic

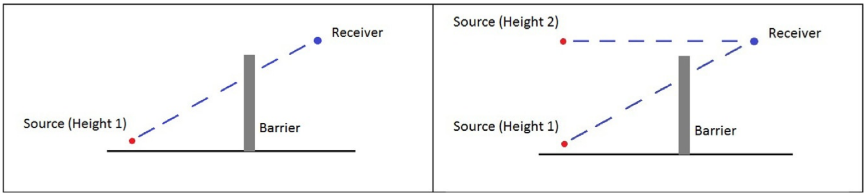

FIGURE 5.10 Sketch of different source positions at the influence on noise mitigation measures.

characteristics of intermittent traffic flow are considerably different to free-flowing traffic in free-field conditions. Yet for the purpose of strategic noise maps, the effects of acceleration and deceleration can be neglected (Kephalopoulos et al., 2012) because, generally speaking, the average sound pressure level for accelerating and decelerating traffic does not depart significantly from the level assumed for a steady speed across a junction (Watts, 2005). However, this is very much associated with the use of energy based indicators such as L_{den} and L_{night}. Academic research has pointed out that current noise measurement techniques and noise indicators do not readily accommodate the assessment of intermittent noise of large vehicles driving at night which is associated with high levels of community annoyance (Schreurs et al., 2011). Accordingly, annoyance assessments should account for varying noise at junctions and this requires alternative indicators. The form that these indicators ultimately take will dictate how the various emission models should be developed.

BOX 5.11

SUPPLEMENTAL INDICATORS TO CALCULATE ANNOYANCE

In the first phase of noise mapping, supplementary noise indicators, see Chapter 4, were rare and confined to indicators such as L_{max} or L_{eq} at 2 m. Many different noise indicators exist and their use may maximise the value of strategic noise mapping. They are often used to take account of situations that are not appropriately described with the recommended EU noise indicators, L_{den} and L_{night}. Examples include, L_{max}, Perceived Noise Level, Sound Exposure Level (SEL), or even % Highly Annoyed (%HA) and % Highly Sleep Disturbed (%HSD). It is also worth questioning if the dose response relationships describing %A or %HA (which were based on extensive surveys carried out in USA and Northern Europe) are also applicable to the polar and subtropical climates of Northern and Southern EU Member States, respectively (Wolde, 2003).

Finally, another limitation of noise prediction methods lies in their inability to include driver behaviour and how it varies from one nation to the next in calculations. For example, different attitudes to horn use in Brazil and England have been cited as a reason for the varying levels of accuracy of the CRTN method (the UK's road traffic noise prediction method) when utilised in the two countries (Filho et al., 2004). Of course, given that no method claims to predict horn use or driver behaviour, it is probably somewhat harsh to label this as a limitation of calculation methods *per se*. Some standards do go beyond what would normally be considered within the scope of a prediction model. The German RLS 90 method, for example, includes a method for calculating noise for parking lots which is uncommon for most calculation methods (Steele, 2001). It may be appropriate for future versions of CNOSSOS-EU to consider aspects outside the scope of the current model as further research is conducted in the area.

5.4.2 Railway Noise

The CNOSSOS-EU method for railway noise is not yet complete, but the draft version gives a good indication about the level of detail that will be included. The manner in which roughness (for both rail and wheel) is considered in the standard represents an improvement on the current state of the art. For example, the UK CRN method assumes that the rail head is comparatively smooth and this assumption tends to underpredict rolling noise. This was addressed in the United Kingdom through the introduction of a back-end correction to enable predictions made using CRN reflect typical UK rail conditions (Hardy and Jones, 2004).

There is also variability in rail noise emission across Europe. The Dutch railway noise prediction model assumes a lower rail roughness level than is the case in Poland and the Polish railway conditions differ from those that were described in the Imagine method (a predecessor of CNOSSOS-EU) (Scwarc et al., 2011). Similar issues were noted in Latvia where measured noise levels exceeded those predicted by the Dutch method. These differences were attributed to differences in Latvian and Dutch railway track and rolling stock vibration response functions (Baranovskii, 2011). It is clear that some form of regional validation for the railway noise emission model will be required. Similar to regional corrections for road surface noise, it will be possible to assess the variation across different states and establish a database of all corrections. This will ensure comparability across different countries, provided a uniform regional correction measurement procedure is adopted and implemented.

With regards to frequency analyses, the CNOSSOS-EU railway noise emission model will describe the source in octave bands. In fact, emission from all sources will be described in octave bands and the CNOSSOS-EU propagation model will perform calculations across these bands, thereby ensuring model consistency. However, further detailed spectral information would be beneficial if future studies are to perform more detailed annoyance analyses.

The CNOSSOS-EU method utilises two separate source heights. This is not as detailed as the German Schall 03 method which considers four different noise sources to differentiate between engine noise, rolling noise and aerodynamic noise; yet, it is more detailed than those methods that consider only one source height. The second source height in CNOSSOS-EU will be important when considering mitigation close to the source. Overall, the use of two source heights should be appropriate for strategic noise mapping.

Sources of noise outside the scope of the prediction model should also be considered. The fact that CNOSSOS-EU will consider additional noise sources such as curve squeal and support structures is a positive addition. However, train warning signals are not accounted for in the current version of the method even though they can be a significant source of annoyance. Noise from shunting yards, or train stations should be modelled as industrial sources. It is important that these sources are considered as these stationary sources are often more annoying than noise from moving trains.

Finally, it is worth noting once again that the CNOSSOS-EU method will predict an L_{eq}-based noise level. It may be advantageous if it was adapted to calculate noise levels represented by different indices.

5.4.3 Aircraft Noise

The level of uniformity across the world in aircraft noise emission modelling is significantly higher than for road and rail noise. Most models have now been developed taking cognisance of common international databases. However, ground-based activities at airports have not received as much attention as noise from aircraft themselves. While these activities are generally not modelled, there is little doubt that they are considerable sources of noise and therefore should be included in noise assessments. The most appropriate manner to assess these noise sources is to treat the airport itself as an industrial source and this issue is discussed in more detail in Chapter 6.

L_{eq} based indicators such as L_{den} and L_{night} are not the most appropriate indicators to assess disturbance from aircraft. This has already been acknowledged with the development of the *EPNL* noise indicator. While the END requires aircraft noise to be evaluated in terms of L_{den} and L_{night}, these indicators should be complemented with a more realistic annoyance-based indicator(s). Further research may need to be conducted to establish appropriate metrics, but whatever metric is developed it should be possible to present this information using a strategic noise map.

The manner in which input data are collated and entered into a noise model by the operator is a key step in any noise modelling process. This has an even larger impact in the case of aircraft noise than for road or rail noise because of the complexities involved in the modelling process. It is important that clear guidance is provided with the forthcoming CNOSSOS-EU method to ensure that the model is applied consistently across Europe. Indeed, the model will also need to be validated rigorously across Europe (and further afield if it is to be implemented across the world) to ensure it is robust. For example, differences between the industry supplied NPD curves and actual monitored noise performance have been reported at UK airports (Jopson et al., 2002). Typical flight profiles observed in the United Kingdom have been noted to be quite different to the default profiles contained in INM with virtually all airlines in the United Kingdom using minimum safe takeoff power to prolong engine life (Jopson et al., 2002).

In Europe, strategic noise maps are required for airports with over 50,000 movements a year. However, noise from smaller airports can also be annoying particularly during peak periods throughout the year. It may be appropriate to extend the requirement to include smaller airports. Finally, other factors including helicopter noise and military aircraft need to be considered in more detail for more holistic aircraft noise assessments.

5.5 CONCLUSION

A key requirement of any noise assessment is a clear understanding of how the noise is generated at source. This chapter details the emission models of transportation sources with various national computational methods forming the basis for discussion. It is clear that each model differs in a number of key aspects. Although not discussed here, the associated propagation models also vary from standard to standard. This is the central problem with the development of noise maps across different jurisdictions – results from one method cannot be reliably compared or combined with another. Table 4.3 in Section 4.2.1 lists the calculation methods used for each type of noise source for the first phase of noise mapping in Europe and it provides an indication of the level of modelling variability across Europe.

There is no doubt that the use of different calculation methods results in significantly different noise modelling results and therefore assessments of the population exposed to varying noise categories. Differences of 5 dB between calculation methods are not uncommon, and these differences seriously undermine the possibilities for comparison of results

(Wolde, 2003). Very often, these differences arise due to varying interpretations of national standards. Studies have shown differences of 6–10 dB (A) when calculating different road traffic situations using the Austrian, German, French or Dutch methods (Nijland and van Wee, 2005). However, it does seem that the CNOSSOS-EU model will advance the current state of the art and enable improved emission modelling at a consistent level across Europe (and the world). This method should also have the capability of modelling a wide variety of action strategies for noise mitigation currently outside the scope of current methods. This will provide a tool for the development of real and effective action plans for noise mitigation at both a national and a local level.

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CHAPTER

6

Industrial and Construction Type Noise

While transportation sources tend to dominate management plans for environmental noise pollution, there are many other potential sources of environmental noise. Sites of industrial activity, shipping ports, wind turbines, construction sites, landfills and mining sites are all examples of noise sources that are likely to require some form of a noise impact assessment. Noise assessments for such sources face different challenges than those for transportation noise. For transportation sources, it can be assumed that the overall noise level from all traffic movements over a complete year can be calculated by examining a standard movement of a certain class of vehicle and extrapolating the results to represent all movements over one complete year. This is not the case for sites of industrial activity where no "catch-all" classification approach exists. Industrial noise can vary from one site to the next and, in practice, each source on-site must be measured to obtain the noise emission value required to produce an accurate noise impact assessment. Industrial noise may also include particularly annoying characteristics such as intermittent noise, impulsive elements, audible tones and low-frequency noise. Any assessment that attempts to assess noise annoyance should also consider these.

Noise assessments are often performed to assess the impact a noise source might have on a local community. These assessments may include a strategic noise map, but very often these longer-term assessments are inappropriate because they tend to mask the impact of short-term noise pollution problems. For industrial noise, the sources under consideration may be transient in nature, may be quite seasonal (such as noise from farming activities) or may only exist for a short period of time (such as construction noise). Furthermore, noise from each of these sources can be quite different and assessments often follow guidelines and criteria specific to the type of noise under investigation; for example, the guidelines informing noise assessment at wind farms do not apply to the noise assessment of a landfill. Separate consideration of the source informs the appropriate assessment methodology to be utilised.

Bearing that in mind, this chapter focuses on the assessment of industrial noise, with particular emphasis on the emission of industrial sources (for noise mapping and impact assessments). The different options for obtaining emission values for different sources are explored. Subsequent to this, the chapter discusses other noise sources that are not normally considered in noise mapping studies but which may be prevalent in certain situations and are important when assessing noise impacts on a surrounding population.

6.1 A NOTE ON NOISE CRITERIA

The history of community noise annoyance assessments began in 1978 when Schultz analysed data from several social surveys from road, rail and aircraft noise (Schultz, 1978). He related the percentage of people that were highly annoyed to different sound exposure levels. His dose–response relationships were subjected to some criticism. Kryter, for example, argued that separate relationships for ground and air traffic gave a better representation of dose–response relationships (Kryter, 1982). Despite the criticisms, Schultz's work has gone on to be used widely in practice. More recently, Miedema and Vos compiled the largest dose–response relationship study to date, which was subsequently updated in 2001 (Miedema and Oudshoorn, 2001; Miedema and Vos, 1998). This led to the %HA measure which describes the percentage of people who are highly annoyed from noise and this has been widely used ever since.

These dose–response relationships are often used to set and justify noise design goals/criteria and predict the level of annoyance a community will experience. For example, in Australia, the New South Wales Environment Protection Authority aims to set noise criteria to ensure at least 90% of an exposed population are protected from being highly annoyed for at least 90% of the time (where possible) (New South Wales Environment Protection Agency, 2000).

When considering the potential noise impact in terms of the response of a population, it must be acknowledged that the response varies widely depending on the noise source. At exposure levels higher than 40 dB(A), the expected percentage of annoyed persons indoors due to wind turbine noise is higher than due to industrial noise from stationary sources at the same exposure level (Janssen et al., 2009). Table 6.1 shows the estimated percentage of highly annoyed related to threshold values of 45, 50 and 55 dB L_{den} for a variety of different sources (European Environment Agency, 2010). The level of annoyance induced by a source varies significantly but aircraft and wind turbine noise are considered to be the most

TABLE 6.1 Estimated Percentage of Highly Annoyed for Different Noise Sources

	Percentage of Highly Annoyed				
L_{den} [dB(A)]	Road (%)	Rail (%)	Aircraft (%)	Industry (%)	Wind turbine (%)
55	6	4	27	5	26
50	4	2	18	3	13
45	1	0	12	1	6

annoying sources. Because of the varying relationship between noise annoyance and the type of noise source, different noise criteria must be developed for different sources of noise.

The manner in which noise criteria are set is also worth considering. For industrial noise in Ireland, the EPA suggest a noise limit of 55 dB L_{Aeq} for the daytime (08:00 to 22:00) and 45 dB L_{Aeq} for the night-time (22:00 to 08:00) to be applied at nearby sensitive receivers. These limits might be considered a "pivot threshold", in that it serves to identify a critical dividing line between what is considered to be a significant and non-significant impact, even though there are no specific details to determine the relative degree of significance (Wood, 2008). Such thresholds have the advantage of simplicity, ease of application and arguably facilitate consistency of practice in noise appraisal. One disadvantage of using such a pivot threshold is that, when used in isolation, it could potentially underplay impact significance (Wood, 2008). One possible alternative would be to introduce a "relative noise increase criterion", which would require the adoption of both rural and urban background values (King and O'Malley, 2012). This method compares expected noise levels with existing noise levels and if the noise is expected to increase by a predefined amount, mitigation will be required.

Finally, authorities should also be aware of industrial noise "creep". Noise creep refers to the gradual increase in background noise level due to changing industrial activity. This is a particular problem in areas where industrial activity is expanding. For example, if two industrial sites in an area each meets a noise criteria of 45 dB, then the total noise level will be 48 dB. If two more compliant sites are opened, the total may then increase to 51 dB.

6.2 INDUSTRIAL NOISE

Industrial noise can be anything from the noise emitted from steel making plants, coal fired power stations, car assembly plants, furniture-making workshops, train depots or the loading and unloading of trucks at a distribution centre. Other activities can be classified as industrial activities or even their own subset of industrial activities, such as mineral extraction sites. Readers should note that the considerations contained in this section are applicable to all types of industrial activity.

6.2.1 Industrial Noise Annoyance

Dose–response curves for industrial noise have not been developed to the same extent as those for transportation noise. This is probably because industrial noise is less widespread than transportation noise, and industrial activities vary significantly from site to site which makes it more difficult to establish a stable dose–response relationship (Berry and Porter, 2004). However, we know from previous research that industrial noise is more annoying than transportation noise at equivalent noise levels (Miedema, 1992). These greater levels of annoyance may be related to the presence of annoying characteristics in (e.g. tonal components) in industrial noise sources. A single tone contributes more to the aversiveness of a noise than an equivalent amount of energy distributed over a wider range of frequencies (Berry and Porter, 2004). Because of this, a 1995 UK National Physical Laboratory (NPL) study sought to develop effective penalties for increased annoyance from tonal noise (Porter, 1995). Figure 6.1 outlines the results from subjective listening tests including the response to different levels of tonal noise, noise from a compressor and road traffic noise. The study used these to calculate "effective penalties" for industrial and tonal noise at different overall noise levels (Table 6.2); note the tonal noise source had a higher effective penalty.

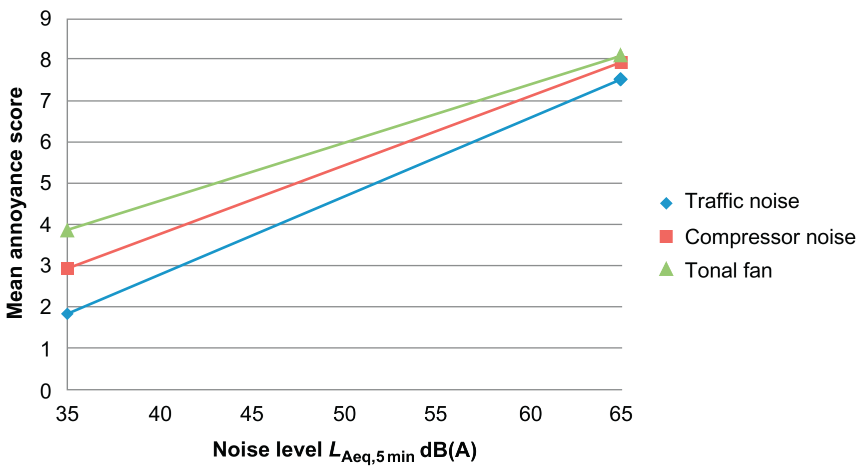


FIGURE 6.1 Example of NPL study results showing response to different levels of traffic noise, industrial noise and tonal noise, at different overall noise levels. *Adapted from Porter, (1995).*

TABLE 6.2 Calculated Effective Penalties Using Traffic Noise as a Baseline (Porter, 1995)

	Penalty (Traffic Noise as a Baseline)			
Noise	**35 dB(A)**	**45 dB(A)**	**55 dB(A)**	**65 dB(A)**
Compressor	5.8	4.5	3.3	2.1
Tonal fan	10.7	8.2	5.6	3.0

Impulsive noises are also more annoying than continuous noises, particularly at low noise levels, while the difference in annoyance is lower at higher noise levels. Results from a separate NPL study found that the level of annoyance from a pile driver at around 45 dB(A) was equal to that of road traffic noise at 60 dB(A). However, at higher noise levels (in excess of 70 dB(A)), no difference in annoyance was observed (Berry and Porter, 2004). This suggests that it is not a straightforward task of simply adding a penalty for impulsive noise as the level of annoyance is also related to the overall noise level. In fact, ISO 1996-1 notes that no mathematical descriptor exists that can define unequivocally the presence of impulsive sounds. It does however outline three different categories for types of impulsive sounds and provides examples of each (Table 6.3). Thus, if a noise source is similar to those in Table 6.3, it may be considered as having impulsive elements.

In truth, the level of annoyance from an industrial noise source can be increased by a wide variety of factors, some of which are related to the noise content (tonality, impulsiveness, intermittency, low-frequency content) while others are related to factors outside of traditional acoustic considerations. A 2003 study in the Netherlands compared noise annoyance from shunting yards (a seasonal industry) and other industries (Miedema and Vos, 2004). The study found increased annoyance for shunting yards compared to other sites; this was thought to be partly due to vibrations from shunting yards and noise from through trains. Of all sites assessed, the seasonal industry was deemed to be least annoying. It suggests that the

TABLE 6.3 Examples of Impulsive Sound Sources

Type of Sound Source	Example
Regular impulsive sound source	Examples include slamming of car door, outdoor ball games, etc.
Highly impulsive sound source	Examples include hammering on metal or wood, nail guns, pile driving, coupling impacts in rail-yard shunting operations
High energy impulsive sound source	Examples include quarry and mining explosions, sonic booms, demolition or industrial processes that use high explosives

relatively low annoyance from the seasonal industry is related to the presence of a relatively quiet period. Furthermore, aversion to the industry itself, in terms of people's perceptions of it, may increase the overall level of annoyance associated with it (Crichton et al., 2013).

6.2.2 Developing Noise Maps of Industrial Sources

The potential impact that a site of industrial activity might have on a community either now or in the future can be assessed by determining the noise emission at source and evaluating the resulting level at a nearby receiver. This can be achieved through a single point-to-point assessment (that might form part of an Environmental Impact Assessment, for example) or it may include a number of receiver positions (e.g. a grid of receivers for the development of a strategic noise map). Either way, the emission at source must be determined. Thus, the development of a strategic noise map for an industrial source will require the same source data as a single assessment.

In recent years, the development of strategic noise maps for industrial sites has been driven by the END which specifically requires these sites (including ports) to be mapped within agglomerations. However, the legislation does not explicitly define what constitutes an industrial activity so the development of maps for these sources is somewhat at the discretion of Member States (European Commission Working Group Assessment of Exposure to Noise (WG-AEN), 2006).

BOX 6.1

INDUSTRIAL NOISE AND NOISE MAPS UNDER THE END

Strategic noise maps for agglomerations must include noise from sites of industrial activity (including ports) along with road traffic, rail traffic and airports. Outside of agglomerations, the END does not require noise maps to be developed for industrial noise. The END does not explicitly define what constitutes an industrial activity; however, by way of an example, it refers to those industrial activities defined in Annex I of Directive 96/61/EC concerning integrated pollution prevention and control (IPPC). These include energy industries (such as mineral oil and gas refineries, coal gasification and liquefaction plants), the production and processing of metals, mineral industries (such as installations for the manufacture of glass), chemical industries, waste management facilities and other activities. Each site is made up of multiple activities which each represent separate noise sources. The amount and extent of these sources vary significantly across each industry.

For the first phase of noise mapping, a total of 120 agglomerations across the EU reported exposure figures for industrial noise but 25 of these reported zero exposure within the reporting threshold level (de Vos and Licitra, 2013). Austria and Ireland did not report any exposure for industrial noise; it is hard to believe that there are no industrial sites in those nations that warrant reporting under the terms of the Directive. For industrial noise, the total exposure exceeding 55 dB L_{den} across Europe amounted to 686,000 inhabitants (minimal compared to transportation sources) (van den Berg, 2009). However, the approach towards assessing industrial noise across Member States was highly variable and, therefore, only limited conclusions can be drawn from the data. In the Netherlands, industrial noise maps were based on the detailed permits that each industry is required to hold, whereas in Ireland, it was simply assumed that all industrial sites operated within the confines of their IPPC licences. This assumed that noise produced at the industrial site did not exceed 45 dB(A) beyond its boundary and therefore did not need to be mapped.

Simplified approaches to the mapping of industrial sources are common because it is impractical to measure the sound power of every industrial source within an agglomeration. However, it is not best practice to assume all industrial sites are in compliance with operating permits. It is clear that some degree of consistency to the treatment of industrial sources across Europe is required. Unfortunately, there is currently no standard method to calculate industrial noise sources largely because of their variability.

The WG-AEN Good Practice Guide on Noise Mapping takes a step towards achieving some level of consistency and offers, *inter alia*, generic guidance on the typical sound power emitted from various types of industry (European Commission Working Group Assessment of Exposure to Noise (WG-AEN), 2006). Other more detailed databases describing the sound power and spectra of separate activities likely to take place in an industrial facility are being developed. Their development will undoubtedly assist authorities in the generation of strategic noise maps for industrial sources.

In practice, the most difficult aspect of a noise assessment for an industrial site is obtaining an accurate representation of noise emission. Sometimes an industrial site may be a collection of hundreds of different noise sources. To definitively develop a noise model of just one industrial site would require a tremendous amount of data gathering (including site measurements to determine source emission) and it might be considered unfeasible to produce such detailed noise models for all industrial sites in an agglomeration. Furthermore, access to industrial facilities can often be quite limited which may adversely affect the veracity of any noise measurement taken to estimate the sound power of the source. It is for these reasons that simplified approaches are often adopted.

The level of detail and the type of information required for each industrial site are dependent on the desired accuracy of the noise model, what it will be used for and what, if any, action will be taken on the basis of the modelled results. Industrial sites can be modelled as point, line or area sources. A simple assessment, using area sources to represent the emission of an industrial site, will typically require the following information (Environmental Protection Agency, 2011): the location of industrial area and the source height, a description of the industrial process, and the sound power emission level(s) (including directivity) for operations on the site. If, however, a high level of accuracy is required, more detailed information may be necessary. Unfortunately, in most cases, such information must be obtained the hard way, which includes (Santos et al., 2008) spending several weeks on-site in order to develop a full understanding of how the industry operates, close observation of all sound sources in order to measure the sound power of each, and accurately inputting the position of all sources present on-site. The CNOSSOS-EU method has produced a definitive list of all data required to represent each noise source in a site of industrial activity (Kephalopoulos et al., 2012) (Table 6.4).

6.2.2.1 Industrial Noise Emission

The key issue in developing a strategic noise map for industrial noise sources is determining the noise emission. There is no standard emission model for industrial noise; the sound power of the source(s) must be either measured or estimated. Undoubtedly, the most reliable way to capture information on the sound power of the source is through measurement. However, measurements may be time-consuming, expensive to conduct and it might not be possible to apply a consistent measurement procedure across all industrial sources within an agglomeration. An alternative is to

TABLE 6.4 Complete Set of Input Data for a Noise Source in an Industrial Site

Data Requirements
Emitted sound power level spectrum in octave bands
Working hours (day, evening, night on a yearly averaged basis)
Locations (including elevation) of the noise source
Type of source (area/line/point)
Dimensions and orientation
Operating conditions of the source
Directivity of the source

use default data contained in international databases, albeit accepting that a certain degree of accuracy may be lost in the generation of the results.

6.2.2.2 Determining Sound Power by Measurement

There are a number of international standards describing measurement methods to determine the emission of a source. Generally, the measurement methodology involves measurements being recorded at a reference distance from the source under investigation and usually at a number of positions enveloping the source. Measurement results may then be used to calculate the sound power of the source. Generally, this is based on an average of all measured results. Corrections to account for reflections and background noise may also be included in the methodology.

For the development of strategic noise maps, the END recommends ISO 9613-2: "Acoustics – Abatement of sound propagation outdoors, Part 2: General method of calculation". This method develops an engineering method for calculating the attenuation of sound during outdoor propagation at a distance from a number of point sources. The contribution of each source is combined to give the overall equivalent noise level at the position of the receiver. ISO 9613-2 does not contain any emission data on sources. However, suitable noise emission data (input data) can be obtained from measurements carried out in accordance with one of the following methods:

- ISO 8297 (1994) "Acoustics – Determination of sound power levels of multisource industrial plants for evaluation of sound pressure levels in the environment – Engineering method",
- EN ISO 3744 (1995) "Acoustics – Determination of sound power levels of noise using sound pressure – Engineering method in an essentially free field over a reflecting plane",
- EN ISO 3746 (1995) "Acoustics – Determination of sound power levels of noise sources using an enveloping measurement surface over a reflecting plane".

ISO 8297 (1994) specifies an engineering method for determining the sound power levels of large multisource industrial plants relevant to the evaluation of sound pressure levels in the environment. The method is limited to large industrial sites where most of the equipment is operating outdoors. The standard requires sound pressure level measurements on a closed path surrounding the plant with individual sources within the site treated as a single source at the geometrical centre of the plant. This requires access to all sides of industrial sites, something that is often difficult to achieve in practice (Stephenson and Postlethwaite, 2003).

In order to determine the sound power level produced by the source, EN ISO 3744 (1995) specifies a method for measuring the sound pressure levels on a measurement surface enveloping a noise source. The measurement method is suitable for use with a single source and requires unrestricted access to the source. Measurements are often conducted in controlled test environments such as a semi-anechoic room, an outdoor space and an ordinary room provided that certain conditions are met.

EN ISO 3746 (1995) is quite similar to EN ISO 3744. It is a survey-grade method based on ISO 3744, where the environmental requirements are substantially relaxed and a correction of up to 7 dB is allowed. This allows measurements to be made with machinery *in situ* within its existing working conditions (Payne and Simmons, 1999). Both ISO 3744 and ISO 3746 standards were updated in 2010. ISO 3744 and ISO 3746 are only suitable for determining the sound power level of individual sources of limited dimensions (small) and are not at all suitable for the assessment of source groups or entire companies (Wolfel, 2003). ISO 8927 is more suited for these purposes. However, practitioners should not be restricted to using these standards. For example, alternative testing procedures have been developed in Australia to measure sound power levels of large mine haul trucks which also include dynamic testing. These are based on:

- ISO 6393:2008(E) "Earth-moving machinery – Determination of sound power level – Stationary test conditions"; and
- ISO 6395:2008(E) "Earth-moving machinery – Determination of sound power level noise emissions – Dynamic test conditions".

BOX 6.2

MEASURING INDUSTRIAL NOISE

It is clear that the best way to determine the sound power levels of an industrial site is to perform detailed on-site assessments, identify individual sources and determine their sound power characteristics. However, performing such an assessment for a large industrial site is resource intensive and depends on each individual site being assessed. Measuring and collecting the relevant sound power data for a petrochemical plant of 25,000 m^2 might take about three person-days, whereas the assessment of a small manufacturer of wooden stairs might only require a half-day assessment (Witte, 2007). Furthermore, at some industrial sites, the location of the noise source may vary over time, such as at open cut (caste) mines and quarries.

6.2.2.3 Determining Sound Power by the Use of Default Parameters

If it is not possible to conduct measurements to determine the sound power of an industrial site, it may be possible to estimate the sound power levels from manufacturer supplied data (e.g. using CE-labels) (Witte, 2012). Alternatively, authorities may refer to a database describing the sound power levels and spectra for a large number of different industrial sources under various operating conditions. Such a database has been developed through the Imagine Project (Witte, 2007) and the company, DGMR, has developed a software tool (SourcedB) for easy access to this database.

The SourcedB database contains details of the sound power measurement methods, sound power calculation formulae (based on operating conditions like power consumption, rpm, etc.) as well as spectral information for a wide range of sources. Different types of sources are also referenced including point sources (e.g. small hand-held machines), line sources (e.g. a rotary kiln for cement works) and area sources (e.g. a shunting yard). For simplified assessments, the database also includes default values for typical sound power levels radiated by specific industrial activities per unit area (Witte, 2007). Activities such as petrochemical plants, power plants and ship yards can be described in this manner.

Figures 6.2 (a) and (b) present screenshots of the SourcedB database.

6.2.2.4 Effect of Operating Conditions

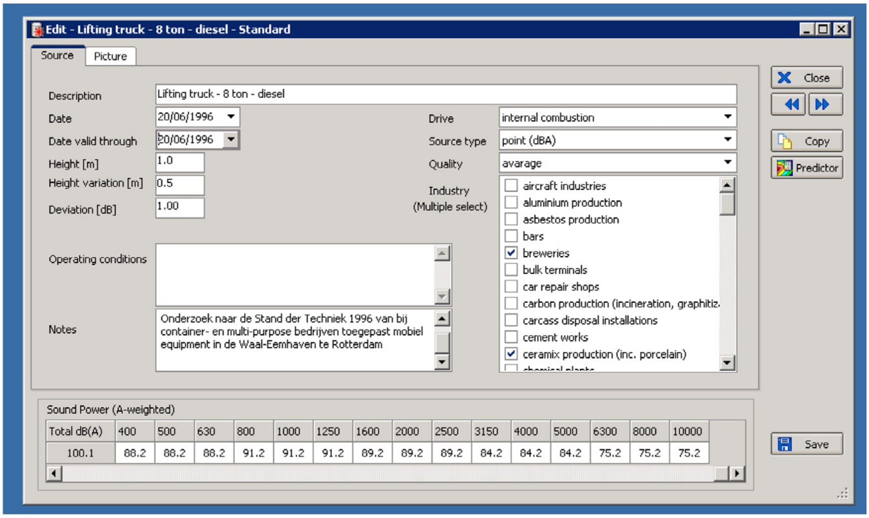
Measurements performed under the international standards identified above often report the noise emission under typical operating conditions. Noise emissions can significantly change with differing conditions of the source; differences in emission level can exist between a machine being run at full power and when idling, a lathe cutting timber or metal, or a drill cutting different material types. Features added to the source, such as silencers, limiters and screens, can also affect emission levels. All of these operating conditions must be taken into account when estimating emissions from industrial sites.

Because L_{den} and L_{night} are long-term indicators, operational times must also be considered. The forthcoming CNOSSOS-EU method includes a correction for the operational time of industrial sources. This correction, C_{w}, is added to the source sound power to determine the corrected sound power that should be used for calculations over each period. It may be calculated from Kephalopoulos et al. (2012):

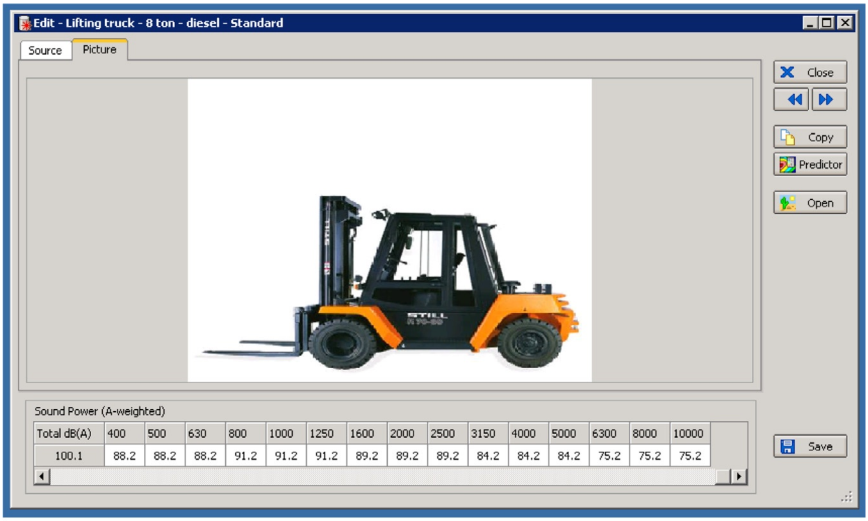
$$C_{\mathrm{w}} = 10\log_{10}\left(\frac{t}{T_0}\right)[\mathrm{dB}] \tag{6.1}$$

where t is the active source time per period based on a yearly averaged situation in hours and T_0 is the reference period of time in hours (day = 12 h, evening = 4 h and night = 8 h). Thus, for a constantly operating source ($t = T_0$), the correction will be zero, whereas a source that only operates for 50% of the day will yield a correction of approximately −3 dB.

As well as considering the operating times throughout a 24-h period, the operating days over the week, month and year should also be considered.



(a)



(b)

FIGURE 6.2 (a) Screenshot of SourcedB – data describing a lifting truck. (b) SourcedB also includes pictures of sources for clarification purposes.

A plant operating 100% of the time will not require any correction, whereas a company that works for 8 h in the day period and does not operate at weekends or holidays will result in a long-term average correction of 3.6 dB (Witte, 2012). The directivity of the source must also be considered. This will be dependent on the position of the equivalent sound source relative to nearby surfaces (Kephalopoulos et al., 2012).

6.2.2.5 Modelling Industrial Noise Emission for Noise Mapping

For industrial noise assessments, the most dominant source of uncertainty is related to the source positioning and sound power (Witte, 2012). Thus, an accurate representation of the source is required for noise assessment as well as an accurate representation of geometric features that are likely to result in screening or reflection effects. If one considers the potential range of sources over an entire industrial site, it is easy to see how a noise assessment can become rather complex.

For noise modelling, the source of industrial noise can either be a point source, line source or area source. A point source may be taken to mean a source whose dimensions are much smaller than the distance through which propagation occurs. A line source is a source with one dimension greater than the others, and this is significant compared to the propagation distance. As the distance from the source increases, a line source will gradually evolve into a point source. Area sources tend to have large dimensions overall compared to the propagation distance; the roof or facade of a factory is a good example in this regard.

For the purposes of strategic noise mapping under the END, the Wolfel Interim Method Report recommends using global sound power levels of the entire industrial complex, thereby disregarding the actual distribution of individual sources (Wolfel, 2003). Calculations should be performed separately for each octave band. However, it is often the case that only overall A-weighted sound power levels are available. In such cases, propagation calculations should be performed assuming the attenuation terms that would be used when considering a frequency of 500 Hz.[1]

The report describes three possible sound power level formats for representing the total noise emission of an industrial site:

- Global source: an area source expressed as sound power per metre squared.
- Zonal source: sound power levels can be assigned to several distinct area sources each of which encloses a group of emitting sources.
- Point or line source: individual sources can be used when detailed information on the sound power levels and location of individual equipment exists and when the positions of buildings and potential barriers on the industrial site are known.

A toolkit to be used in the development of noise maps for industrial sources was also developed to assist EU Member States implement the END (European Commission Working Group Assessment of Exposure

[1]The level of attenuation varies with frequency. To calculate the attenuation when only A-weighted sound power levels are available, we assume the same attenuation terms that would be used in calculations at a frequency of 500 Hz.

TABLE 6.5 Default Emission Values for Different Types of Industry (European Commission Working Group Assessment of Exposure to Noise (WG-AEN), 2006)

	Default Value for L_w'' [m^2]		
Type of Industry	**Day [dB(A)]**	**Evening [dB(A)]**	**Night [dB(A)]**
Area with light industries	65	65	65
Area with commercial uses	60	60	60
Ports	60	60	45

to Noise (WG-AEN), 2006). The toolkit applies over a range of emission data availability with scenarios ranging from a full dataset spanning the day, evening and night-time periods, to scenarios where no data are available at all. Where no data are available, the recommended procedure is to consult existing databases for individual industrial sound sources with associated sound power levels. Otherwise, the default values presented in Table 6.5 are suggested.

BOX 6.3

INDUSTRIAL NOISE AND CNOSSOS-EU

The forthcoming CNOSSOS-EU method will include a methodology for the assessment of industrial noise sources. The preferred approach for CNOSSOS-EU will be to use site measurements (Kephalopoulos et al., 2012). Measurements to determine the sound power and spectra to be used to model industrial noise may be taken according to a number of international standards. In cases where site measurements are not possible, the calculation method will provide a database describing typical sound power levels for each source as well as likely working hours and directivity. This database is due to be finalised during Phase B of CNOSSOS-EU.

6.3 PORT NOISE

In the past, port activities were limited to the handling of ships and their cargos. In recent decades, these activities have evolved to include a wide range of interests including the management of individual estates which exposes port authorities to environmental regulations and concerns typical of other large industrial operations (van Breeman, 2008). Nowadays ship operations at ports, including cargo handling and related activities, often result in significant noise emissions. Thus, the END specifically requires port noise to be assessed as industrial noise within agglomerations.

To date, environmental noise from port activities has probably not received as much attention as other noise sources, most certainly in academic literature. Recently, Murphy and King (2014) monitored noise levels in the vicinity of Dublin port, Ireland, and results highlighted the extent to which port noise can be a significant environmental stressor. For guidance on the assessment of noise from ports, the EU-funded NoMEPorts project (Noise Management in European Ports) published a "Good Practice Guide for Port Area Noise Mapping and Management" (van Breeman, 2008) which outlines a common approach for the development of strategic noise maps for port area noise in the context of the END. The objective of the NoMEPorts project, which included 14 partners from 8 countries, was to reduce noise, noise-related annoyance and health problems of people living around industrial port areas.

There are a number of potential sources associated with port noise. The NoMEPorts project summarises the sources as a collection of both industrial sources and transportation sources (Table 6.6). Despite the fact that transportation noise may not necessarily be considered an industrial source, port noise assessments should take into consideration all traffic-related sources within the limits of a particular port study area (van Breeman, 2008).

Similar to a general industrial noise assessment, the key requirement of a port noise assessment is the accurate representation of the source. This requires the collection of all relevant noise source and operational data. In most cases, this will involve significant data gathering and noise measurement. Sound power levels can be obtained by either measurements taken on-site or through the use of a default database. Measurements taken

TABLE 6.6 Different Sources of Port Noise (van Breeman, 2008)

Port Noise	
Industrial Sources	**Transportation Sources**
Port services and facilities	Road traffic
Terminals (cargo handling, warehousing)	Rail traffic
Industrial areas	Air traffic
Machinery, workshop	
Vessel repair or maintenance	
Shunting yards	
Vessels when berthed (engine noise)	

on-site will provide more reliable data but this will be a time-consuming and expensive option. Default datasets can be used and the NoMEPorts project recommends that these data be accompanied by some on-site measurements. In this case, measurements act a validation exercise for modelled data rather than forming the basis of sound power assessments.

A number of lessons were identified by the NoMEPorts project for port noise mapping and are worth outlining for the reader. They include standard best practice procedures for port noise mapping:

- Collaboration between all stakeholders. This can be achieved by establishing a local working group consisting of representatives from all parties involved.
- An overview of input data requirements and the availability or otherwise of such data should be identified at the outset.
- After developing an inventory of all noise sources, screening for significance should take place to avoid unnecessary data collection.
- Gaps in the noise data can be filled by default values from international databases, for example, through the Imagine source database or by way of expert advice.

6.4 AIRPORTS AS INDUSTRIAL SOURCES

One of the key considerations of any noise mapping assessment is identifying where transportation noise ends and industrial noise begins. Noise mapping authorities are usually only concerned with noise sources that they are responsible for under legislation. It has been noted that railroad noise stops at the entrance of a shunting yard; once inside the site, it becomes industrial noise (Witte, 2004). The same could be said for a heavy goods vehicle delivering equipment to a factory; the moment it leaves a public road it can be considered industrial noise. Thus, if a noise mapping body is responsible for a transportation source, should they also consider cases where this source becomes industrial? This issue is quite significant in the case of aircraft noise.

There has been some debate as to whether or not noise from activities at airports that are not directly associated with aircraft movement should be considered in the development of strategic noise maps (European Commission Working Group Assessment of Exposure to Noise (WG-AEN), 2006). Such activities may include taxiing, engine testing, and the movement of plant and vehicles operating within the airport. Ultimately, the END legislation is not specific in this regard and the decision rests with the Member State or an individual national or local authority beyond the EU where no strategic mapping legislation exists. However, the WG-AEN recommends that all noise sources, particularly when their noise contribution is greater than 55 dB(A) L_{den} or 50 dB(A) L_{night}, should be mapped as industrial noise (European Commission Working Group Assessment of Exposure to Noise (WG-AEN), 2006).

The forthcoming CNOSSOS-EU model recognises that ground-based fixed sources at airports (including engine run-up) should be modelled with the same propagation methodology that is used for industrial noise (Kephalopoulos et al., 2012). The data to describe the source of these activities (engine run-up, directivity patterns, spectral information) should be contained in the international Aircraft Noise and Performance database (see Chapter 5). However, this database needs to be updated to enable any such calculations and clear guidance on how to utilise these data in conjunction with a propagation model to develop a noise map for this type of industrial site is required (Kephalopoulos et al., 2012).

6.5 WIND FARM NOISE

Wind farms (a collection of wind turbines) are being heralded as a new source of green energy and are becoming increasingly commonplace. This section describes how wind turbine noise should be modelled and assessed. It should be noted that while noise maps have not been developed for wind farms in the context of the END, noise maps are often created for such developments during the preparation of the associated Environmental Impact Statements (King et al., 2012). Indeed, noise is often reported as the most annoying aspect of wind farm developments; although degree of this annoyance may also be related to the level of visual intrusion (van den Berg et al., 2008). It may be that in locations where wind farms are perceived as having a negative impact on local scenery, the probability of noise annoyance, regardless of the A-weighted sound pressure level, is increased (Pedersen and Larsman, 2008). Furthermore, the perception of wind turbine noise may be affected negatively by the elevated position of the source.

Generally, wind turbines will generate noise that may be described as a combination of tonal, broadband, low-frequency and impulsive sounds through various phases of operation (King et al., 2012). This results in a

BOX 6.4

WIND FARMS AND THE END

Noise from wind turbines is not considered when developing strategic noise maps under the END. Noise from industrial sites is only assessed within the boundaries of an agglomeration and wind turbines tend to be located in rural areas. Furthermore, wind turbine noise is usually much lower than noise from other industrial sources.

combination of mechanical and aerodynamic noise. Some authors have reported concerns associated with amplitude modulation. Amplitude modulation is a fluctuating noise (a noise level rising and falling in a regular pattern) and is related to the speed of rotating turbine blades. This fluctuating component may increase the level of annoyance associated with the turbine (Lenchine, 2009) and should be an important consideration in assessments of annoyance from wind turbines (Pedersen, 2003). Current understanding of amplitude modulation is not very well developed and more research is required to understand its nature and its association with noise annoyance. Concern also exists with issues related to low-frequency noise and infrasound. However, several studies in Australia have shown that low-frequency noise and infrasound emitted by wind turbines is at levels no different to that normally experienced in the environment (Evans et al., 2013a,b; Turnbull et al., 2012).

Wind farm developments often have a setback distance (i.e. a minimum distance to the nearest sensitive receiver), which can be for safety reasons or environmental concerns. This varies across nations and can range from 300 to 1000 m (Gamboa and Munda, 2007). Usually, the permissible limits for wind turbines are quite low, often as low as 45 dB L_{90}. Accordingly, their impact in terms of the long-term indicator L_{den} tends to be minimal (compared to other sources). However, when other factors such as low-frequency noise content and amplitude modulation are considered, supplemental indicators (which might include those outlined in Annex X of the END) should be employed to assess the noise impact of the turbines. The use of A-weighting is not appropriate when low-frequency noise is present. Some consider G-weighting, which has been designed for infrasonic assessments, may be suitable for wind farm assessments, particularly when low frequency noise may be an issue.

What makes wind turbines unique from other noise sources is that the level of noise produced at the source is dependent on the prevailing wind speed, i.e., the turbine tends to make more noise as the wind blows faster. However, this does not necessarily mean that high wind turbine speeds are directly related to increases in annoyance. As the wind blows harder, noise from environmental sources (trees, bushes, the wind itself, i.e., the background noise) also increases, and the two source types (turbine and environmental) tend to change at different rates. As such there is a wind speed where the noise from the turbine reaches a peak when it is compared against the background noise. This point is called the critical wind speed, i.e., the speed at which the noise from the turbines is at its highest level when background noise is subtracted (a worst case scenario).

Noise assessments are often conducted at this critical wind speed. Thus, before any noise modelling is undertaken, the critical wind speed must be determined by measurement. Background noise levels are measured and results are compared with typical turbine sound power curves that describe the relationship between the wind speed and sound power.

King et al. (2012) have identified errors associated with the use of a single critical wind speed for wind farm noise assessments, particularly during the night-time, and recommend that assessments be conducted over a range of wind speeds instead of the critical wind speed alone. The Institute of Acoustics (UK) recently released guidance on the assessment of wind farm noise and also recommends noise assessment over a range of speeds (Cand et al., 2013), which is consistent with the methodologies used in countries such as Australia and New Zealand.

6.5.1 Wind Farm Noise Emission

In order to model the noise from a wind farm, manufacturers generally provide sound power levels for each type of turbine. These data are usually available for a range of wind speeds and are supplied across octave bands from cut-in speed through to rated power. The data are generally referenced to a height of 10 m. Table 6.7 presents sample sound power data describing a 3 MW wind turbine, while Figure 6.3 provides an example comparing the sound power/wind speed relationship between four turbines commonly used in Ireland. When the sound power is known for all wind speeds, calculations may then be conducted for each wind speed and, together with detailed meteorological information, the long-term noise level may be established.

BOX 6.5

WIND SHEAR

Sound power data used for predictions are generally based on measurements taken for IEC 61400-11 (IEC 61400-11, 2006). This standard requires hub height (the distance from the ground to the axis of rotation, i.e., the centre of the turbine blades) wind speeds to be standardised to a 10 m height. Wind speeds taken on-site during a background noise assessment must also be referenced to a height of 10 m. However, wind speed will vary with height above the ground level, generally increasing with increased height.

ETSU-R-97 presents a simple method to correct wind speeds to a height of 10 m using a ground roughness length (The Working Group on Noise from Wind Turbines, 1996). However, this method holds significant potential for error. Differences in the wind shear between day and night periods have been observed. Describing the wind shear in terms of only the surface roughness, and not on atmospheric stability, is not a good predictor for night-time wind profiles (van den Berg, 2004). This is precisely why new guidance on the collection of wind speed has been developed and it requires wind speed measurements at a minimum height of 10 m (Cand et al., 2013).

TABLE 6.7 Example Sound Power Levels for a 3-MW Wind Turbine, Referenced to a Height of 10 m

Wind Speed [m/s]	L_w [dB(A)]	Octave Band Levels							
		63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
5	100.9	82.1	86.9	91.5	93.5	95.9	94.6	90.5	79.1
6	104.2	85.7	90.9	94.0	96.5	99.1	98.2	94.3	83.7
7	106.1	89.7	93.3	96.1	98.3	100.8	100.1	96.2	85.7
8	107.0	91.8	94.0	97.3	99.6	101.8	100.5	96.7	86.7
9	106.9	92.3	94.2	96.9	99.5	101.7	100.4	96.4	86.6

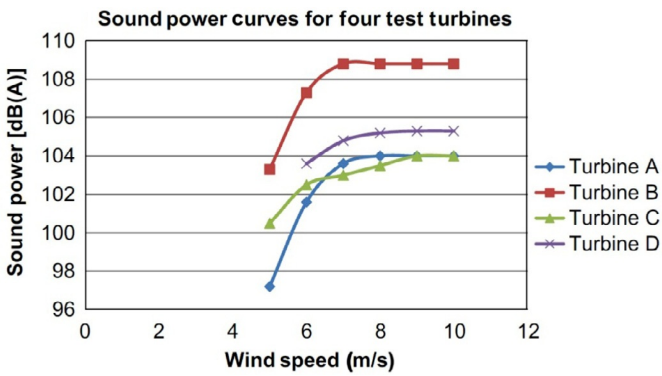


FIGURE 6.3 Different source profiles for different turbines (King et al., 2012).

6.5.2 Background Noise Assessment

Permissible noise limits for wind farms are often expressed relative to the background noise across a range of wind speeds, i.e., a relative increase criterion (e.g. 5 dB(A) above background noise). Therefore, a detailed assessment of the background noise is required prior to the development of a wind farm. This involves a background noise survey that requires at least 1 week of continuous noise monitoring. Good practice suggests at least 20–30 measurements should be taken within 2 m/s of the critical wind speed (The Working Group on Noise from Wind Turbines, 1996). Measurements recorded during periods of heavy rainfall should not be used in the analysis given that noise levels are raised by the sound of the rain itself. In Australia and New Zealand, good practice involves the acquisition of approximately 2000 valid measurements of 10 min (the equivalent of 2 weeks) and at least 500 of these points should include the worst case wind direction.

It is generally regarded that windshields will be effective up to wind speeds of 5 m/s (BS 4142, 1997). In higher wind speeds, the wind passing over the diaphragm of the microphone of the sound level metre can generate noise interference. However, in the case of background noise assessments, noise measurement in wind speeds of up to 12 m/s may frequently be required. Measurements in conditions at these high wind speeds may be influenced by the wind itself and may not be a true representation of the background noise environment (King et al., 2012). New guidance suggests that microphones should be housed within enhanced-performance windscreens to reduce the effects of flow-generated noise at the microphone (Cand et al., 2013); care must be exercised using standard wind shields only designed for low-wind velocities (usually windshields with a diameter less than 100 mm).

During noise monitoring periods, meteorological conditions (including wind speed and direction) must be monitored simultaneously with background noise measurements. Wind speed and sound pressure levels can then be plot to determine the relationship between background noise and wind speed. A third-order polynomial is usually appropriate to describe this relationship (Cand et al., 2013) although higher order polynomials have been used successfully (King et al., 2012). Figure 6.4 presents such a relationship.

6.5.3 Noise Limits for Wind Farms

Noise limits for wind farm developments are generally set relative to background noise levels at nearby noise-sensitive receivers. For example, a daytime lower fixed limit of 45 dB(A) or a maximum increase of 5 dB(A)

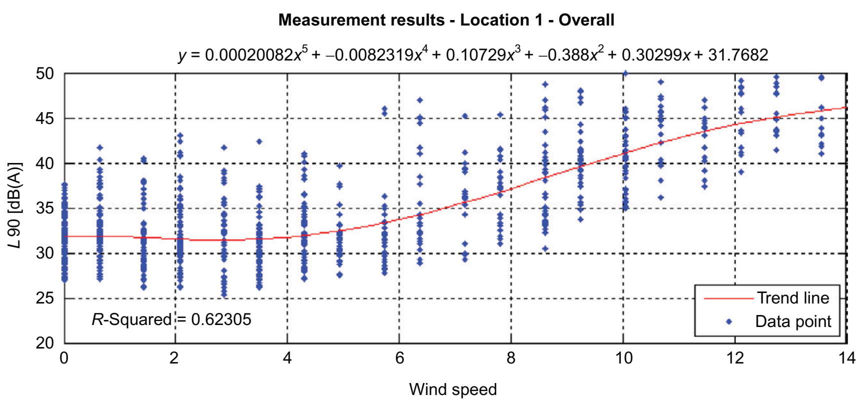


FIGURE 6.4 Example result from a background noise survey relating the background noise level with wind speed.

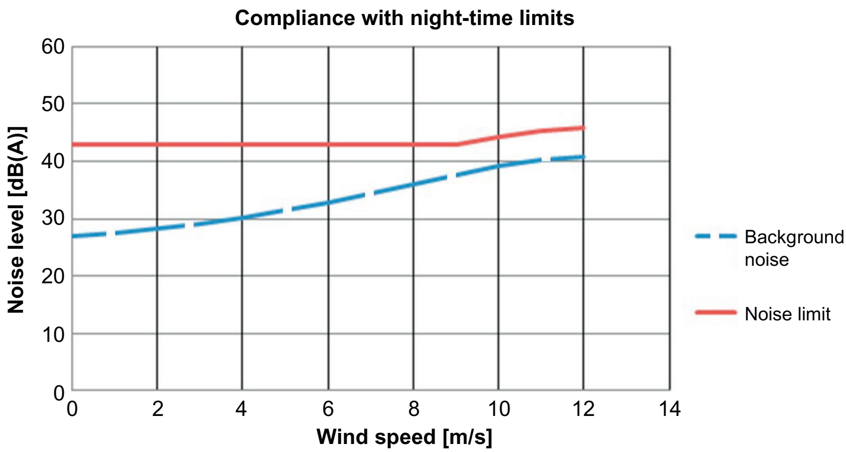


FIGURE 6.5 Night-time noise limit set relative to background noise level at different speeds.

above background noise at nearby noise-sensitive locations is common and is recommended in ETSU-R-97 (The Working Group on Noise from Wind Turbines, 1996). However, in very quiet areas, where background noise is less than 30 dB(A), the use of a margin of 5 dB(A) above background noise may unduly restrict wind energy developments which should be recognised as having wider national and global benefits (The Working Group on Noise from Wind Turbines, 1996).

Separate noise limits are generally applied for daytime and for night-time. During the night, the protection of external amenity becomes less important and the emphasis is on preventing sleep disturbance. In the UK, a lower fixed limit of 43 dB(A) external to the property has been deemed appropriate to protect sleep inside properties during the night. Figure 6.5 displays how the background noise level for a test location varies with wind speed. In this example a flat limit of 43 dB(A) during the daytime is observed, up until a wind speed of approximately 9 m/s, at which point the background level plus 5 dB(A) becomes the appropriate criterion.

6.6 CONSTRUCTION NOISE

Noise from construction can often occur very close to noise-sensitive receivers and its characteristics can change throughout the lifetime of a construction project. It can start with demolition, proceed to excavation works and highly impulsive piling works, before evolving to more continuous noise as the construction progresses. Noise levels can also vary throughout the day, and depending on the permissible limits enforced, might even continue through the night-time period. Given the nature of activities involved, it is not always possible to mitigate noise levels down to acceptable levels using the standard mitigation measures that might be appropriate for use in an industrial context. However, construction noise is generally transient and by its very nature construction noise will only be present for a finite-time period. Because of this, it is not appropriate (or indeed very useful) to develop strategic noise maps for this type of noise source. Nevertheless, it should be mitigated against as part of any serious overall environmental noise abatement strategy.

Many factors affect the impact that construction noise has on the local community: the location of the site in relation to sensitive receivers, hours of operation, the existing ambient levels in the area and the characteristics of the noise itself. Another consideration might include the level of communication between the site operator and local residents. It has been well established that people's attitude to noise can be influenced by their attitudes to the source or activity itself (BS 5228, 2009). Construction noise tends to be more readily accepted by local residents if they feel the site operator is taking all possible measures to avoid unnecessary noise. In fact, a simple rule of thumb indicates that good public relations may result in a 5 dB noise bonus, while bad relations are equivalent to a 5 dB penalty (Wassermann and Parnell, 2008).

6.6.1 Sources of Construction Noise

There are many sources of noise associated with a construction site: the movements of vehicles (usually including a high percentage of heavy vehicles), breaking up concrete, cutting steel, ground excavation, drilling, pumping, welding, etc. In the UK, BS 5228 (2009) is used for noise and vibration control on construction and open sites. BS 5228 provides a range of sound level data on construction site equipment and site activities. This data should be used for informative purposes. Some examples are presented in Table 6.8 (BS 5228, 2009).

6.6.2 Hours of Activity

Construction noise is often controlled by restricting the times during which construction can occur. Many authorities restrict construction activities to normal working hours and do not allow activities to take place over weekends or public holidays. For example, in South Australia because

TABLE 6.8 Typical Noise Levels for Various Construction Activities

Equipment	L_{Aeq} at 10 m
Breaking up concrete with pulverizer mounted on excavator	76
Breaking stud partition with lump hammer	69
Breaking windows with lump hammer	81
Clearing site with a dozer	75
Loading lorries with tracked excavator	79
Water pump (size 6 in.)	65
Precast concrete piling – hydraulic hammer	89
Small cement mixer	61
Diesel scissor lift (idling)	70
Petrol hand-held circular saw	91
Angle grinder (grinding steel)	80
Hand-held cordless nail gun	73

construction noise results in an adverse impact on amenity,[2] it is restricted from operating on a Sunday or a public holiday. For all other days, it is restricted to hours between 07:00 and 19:00.

In some exceptional circumstances, construction may need to take place outside of these hours. Examples include the delivery of oversized plant structures, emergency work, and maintenance and repair of public infrastructure where work during the standard hours might disrupt essential services. In such cases, regulators might encourage a range of work practices to minimise the construction noise impact rather than focusing on meeting stringent noise criteria.

Noise may be minimised from construction by the operator implementing best practice work methods. Some examples include:

- scheduling of particularly noisy activities during less sensitive periods of the day;
- choosing plant and equipment that is the quietest and most suitable for the project. This may include ensuring noise reduction devices are installed on plant (for example, fitting more efficient exhaust sound reduction equipment, use of machines inside acoustic enclosures);

[2]Identified as continuous noise levels exceeding 45 dB(A), or a maximum noise level exceeding 60 dB(A) (Construction Noise and Information Sheet, 2011).

- ensuring all equipment is well maintained and operating within specifications;
- making use of mitigation measures where appropriate (e.g. acoustic screens);
- employing work practices which minimise noise activities. These may include restricting waste material from being dropped at excessive heights and line chutes and dump trucks with resilient material.

BS 5228 sets out methods and criteria for assessing the significance of noise effects. One such method includes the ABC method. This method sets threshold values to determine if there will be a significant effect at dwellings for three different categories (A, B and C). The threshold values are different for each ABC category and different time periods. The ambient noise level is determined for the appropriate period and then rounded to the nearest 5 dB. This is then compared to the total noise level, including construction noise. If the total noise level exceeds the appropriate category values, a significant effect is deemed to occur.

6.7 MINING MINERAL/EXTRACTION SITES

Unlike manufacturing type facilities that can be located in appropriate industrial estates, mining and extractive industries need to be generally colocated with the resource being mined. This places significant limits on the ability of operators and responsible authorities to manage noise from these sites, particularly if they are 24 h operations. Sources of mining noise include blasting, mobile equipment such as bulldozers, haul trucks and excavators, fixed plant equipment such as conveyor belts and crushers, screens and preparation plants.

In many cases, it is neither reasonable nor feasible to mitigate to the accepted noise goals. In these cases, there may be the option for negotiation (in terms of offering suitable compensation) with the impacted community in return for increased noise limits. Such negotiated agreements should be developed through a process of community consultation and dissemination of information on how best available techniques will be adopted. Also the public should be notified of scheduled activities that will result in high noise levels such as blasting. However, there are options available to the site operator for certain aspects of the work and best available techniques for noise control should be adopted. In New South Wales, the practice of applying receiver-based architectural treatments (e.g. façade insulation, acoustic glazing) is included in a suite of measures currently available to large-scale mining operators.

BOX 6.6

OPEN CUT COAL MINING, AUSTRALIA

Australia supplies around 35% of the world market in thermal coal. Most of this is sourced from large open cut operations on the eastern seaboard of Australia (NSW and Queensland) where single mines often range from 20 to 50 million tonnes per annum and cover areas of 5–10 km in length.

The major noise issue for these mines relates to their diesel-electric haul trucks which have a capacity of up to 300 tonnes and produce sound power levels of greater than 125 dB(A). With fleets of up to 80 trucks, it is generally not possible to meet stringent noise criteria as low as 35 dB(A) without significant attenuation (Parnell et al., 2009). To achieve a sound power level of around 115 dB(A) requires an attenuation package that costs in the order of $1 million (a 25% additional cost) to each haul truck.

Even after taking all reasonable and feasible measures, there are often numbers of residences which experience excessive noise levels and are required to be purchased. This demonstrates the significant cost of undertaking noisy activities.

6.8 CONCLUSION

The assessment of industrial noise is quite different to that of transportation noise. Whereas transportation noise can generally be predicted given a set of input datasets, no such predictive techniques exist for industrial noise. The best way to determine the emission of an industrial source is through measurement. In some cases, this is not possible and international databases or previous similar experience may be utilised to make an informed estimate. If best practice is to be followed, this poses two significant problems for any authority who wishes to assess all existing sites of industrial noise across a city region. First, all sites must participate in some sort of measurement campaign which requires a tremendous amount of resources. Second, all measurements must be conducted in a standard uniform fashion. Given the variation in the type of noise, the times of operation and the location of noise sources across each industrial site, it is not always possible to do this. Inevitably, default values or some simplifications will be introduced to the assessment procedure.

Similar to transportation sources, industrial noise may be perceived in a completely different manner across different industries. Industrial noise often contains more intrusive acoustic characteristics such as impulsive or tonal elements and as such industrial noise often attracts more stringent noise criteria than the transport sector. These intrusive characteristics tend to increase noise annoyance and should be included in any noise assessment aiming to assess the acoustic impact of a site.

There are a number of different methodologies and procedures used to assess different types of industrial sources. This chapter has summarised the main procedures behind traditional industrial sources as well as highlighting the different procedures guiding the assessment of port noise, wind farm noise and construction noise.

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CHAPTER

7

Noise Mitigation Approaches

7.1 INTRODUCTION

At the outset of the book, we established why environmental noise is not only an environmental problem but also a public health problem. In short, humans that suffer from prolonged exposure above recommended guidelines limit values – 40 dB(A) for night-time – exhibit a range of detrimental health effects. In response, scholars and policymakers have reacted to search for and implement best-practice and cost-effective solutions that form part of a broader coherent and longer-term strategy to reduce noise exposure. In the EU, this is being achieved, albeit with varying results, through the requirement for competent authorities to devise action plans for cities and major roads, railways and airports beyond agglomerations being noise mapped under the terms of the EU Environmental Noise Directive (END). In addition, noise maps and action plans are required for major roads, railways, airports and industrial sources beyond urban areas. While similar approaches have been applied beyond the EU, they have not been completed within the context of a strategic plan for noise reduction but as *ad hoc* measures to reduce noise in particularly problematic 'hot spots'.

The following section of this chapter deals with the principles and conceptual basis of the noise action planning process being implemented under the END. Thereafter, the key approaches for noise mitigation are discussed, focusing in detail on various source and propagation measures that are commonly utilised. The final section of the chapter provides best-practice case studies of noise mitigation for the key sources of noise pollution – road, rail and air as well as an urban soundscape approach before some concluding remarks are provided for the reader.

7.2 STRATEGIC NOISE MITIGATION: THE NOISE ACTION PLANNING PROCESS

As mentioned already in Chapter 4, noise action planning is a concept that was developed under the terms of the END. It is well known that noise mitigation approaches have been around for decades but the development of legally binding obligations to devise a strategic approach for noise reduction and management of major sources across the EU is a major development in environmental noise and public health policy. Noise action planning under the END is the world's largest and most ambitious programme of strategic noise reduction. Although it is far from being perfect (as we will see), it proffers a strategic approach towards noise mitigation that can be moulded, shaped and improved so that more effective noise reduction can be achieved in the future.

According to the END, action plans refer to 'plans designed to manage noise issues and effects, including noise reduction if necessary'. It also states that noise action plans aim at 'preventing and reducing environmental noise where necessary and particularly where exposure levels can induce harmful effects on human health and to preserve environmental noise quality where it is good'. Overall, their function is to:

- protect the health and well-being of citizens;
- improve quality of life;
- structure and prioritise noise abatement measures through stocktaking and assessment of the noise situation;
- involve the general public and particularly those members of the public affected by action planning measures being implemented in their area.

While action planning focuses on noise reduction approaches, formalising these measures in a plan involves the coordination with other objectives and strategies for urban development. These include land use and transport planning, traffic management, promotion of eco/noise-friendly transport, the reduction of car use, and revitalisation of cities as liveable places. They also incorporate road and rail network engineering, as well as airport and industry planning. In addition, long-term action planning measures will need to embed noise reduction strategies in every aspect of the urban planning system so that noise reduction is a consideration throughout the urban development process, from the acoustic design and insulation characteristics of buildings and infrastructure to improving the broader soundscape of areas. Generally, a noise action plan will:

- set noise reduction targets either in terms of dB reductions or reductions in the population exposed above a certain threshold;
- describe the measures that will be used to achieve reductions;

- establish reduction priorities and a realistic schedule for implementation of abatement measures;
- outline expected costs of the measures proposed;
- outline the financial means available or otherwise for plan implementation;
- establish accountability, i.e., identify the agency and key individuals therein responsible for plan implementation and for monitoring of any measures being put in place.

Of course, noise action planning relies heavily upon the strategic noise mapping process; indeed, it is only after this process has been completed that action plans are devised (see Figure 4.1). In particular, the strategic noise mapping process allows for the identification of areas of poor sound quality or areas where noise limits are exceeded. Moreover, it also allows for the geographic identification of residential buildings with the highest levels of population exposure to excessive noise. These areas are generally referred to as 'noise hot spots' (Licitra and Ascari, 2013) which, once identified, can be targeted for abatement measures. However, action planning is not only a set of measures for implementation. On a broader level, it is a structured and coherent process that (Kloth et al., 2008, p. 11):

- quantitatively and qualitatively assesses noise mapping results in order to detect 'noise hot spots' which can lead to the establishment of priorities for intervention;
- involves relevant local authority departments, relevant stakeholders and the public in the noise assessment process;
- links the action planning process to other relevant local strategies and plans;
- develops interventions and potential solutions for identified noise problems in conjunction with the relevant actors;
- implements action planning measures with the support of all the actors involved.

Action plans should include noise maps and descriptions of the noise problems with a clear identification of their geographic location. In terms of description, the estimated population exposure should be included as well as detailed descriptions of the noise abatement measure(s) being adopted. As mentioned in Chapter 4, the END does stipulate minimum required elements for noise action plans (see Table 4.4). But there is currently no standardised approach for action planning. Nor is there likely to be one in the future: each location is different in terms of its overall traffic composition, urban form, land intensity and population density, urban development process, building geometry and insulation, road surface characteristics, and land use and transportation planning system. Thus, action planning measures must be cognisant of the context of the area in which they are being implemented meaning, for example, a standardised approach for action across the world's cities would likely be unworkable. Rather, a series of source, propagation and receiver-based mitigation measures prioritised in terms of their noise reduction effectiveness would likely be more suitable as a standardised basis for noise reduction interventions.

Despite no standardised approach for action planning being available, there are a number of guidance documents available that outline approaches for the preparation of noise action plans. These are often national guidance documents or deliverables of European Framework (FP) projects (e.g. Silence, Qcity). To take some examples, in Denmark the exceedance of national noise limit values was used as a basis for establishing priorities for action plans, while in Germany the exceedance of non-binding noise trigger values served to initiate the implementation of mitigation measures.

Figure 7.1 provides an overview of a nine-step process for noise action planning. It is adapted from the recommendations of the SILENCE project (see www.silence-ip.org) who devised the *Practitioner Handbook for Local Noise Action Plans* (Kloth et al., 2008). It is important to remember that action planning is a component of the broader strategic noise mapping process. Moreover, action planning is often a complex process so the steps described in Figure 7.1 are not usually linear in nature. In fact, some of the steps identified often happen in parallel; indeed, a step already completed may need to be reconsidered on the basis of new information that might be forthcoming. At the outset (step 1) of the action planning process, it is of paramount importance that key responsibilities are assigned to

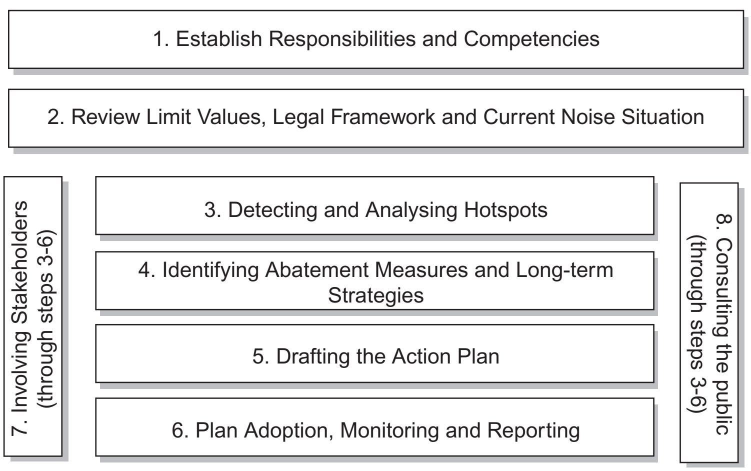

FIGURE 7.1 Overview of the action planning process. *Source: Adapted from Kloth et al. (2008).*

individuals and agencies. In particular, a leadership role is crucial for plan creation and implementation but it is also extremely important that work on specific areas of the action plan process is not only clearly delegated but is done so after core competencies/expertise have been established.

Step 2 involves the responsible authority reviewing the existing contextual framework within which a noise action plan is to be created and implemented. This involves identifying existing noise limit values at the national, regional and local level in individual nations/states. As well as reviewing the data outputs from noise mapping, it also involves identifying the noise indicators that are used in specific countries/states and how these might be different or otherwise to noise indicators that are utilised at an international, Federal or EU level. As part of the review process, noise measures already in place should be identified and mapped and any unresolved noise issues (i.e. noise conflicts) should be noted. Finally, the range of policy options available for noise abatement in a specific location should be considered as well as the manner in which any potential action plans to be implemented could be integrated with other existing plans and the broader planning process.

Step 3 involves the process of detecting and analysing noise 'hot spots'. This first of all involves establishing agreed upon criteria for identifying locations that will be considered as 'hot spots'. The definition of hot spots is quite flimsy at present and it would be preferable if the EU provided more guidance on action planning as part of the END (Guarinoni et al., 2012). In its absence, a useful working definition is that hot spots are areas where the level of noise is very high or the level of population exposure to noise exceeds predefined national limit values or international guideline values. Thereafter, the process of identifying them should be undertaken using the results from the strategic noise mapping process as well as any additional information gained from steps 2 to 8 of the process. In order to detect hot spots, maps can be created displaying the difference between the actual noise level and the exceedance of noise limits (which can be defined by individual states); Kloth et al. (2008) refer to such representations as 'conflict maps'. Conflict maps must then be integrated with population data to detect conflict areas with the greatest population exposed and thereby set priorities for mitigation.

Step 4 involves identifying and prioritising specific short-term mitigation measures as well as longer-term strategies for noise reduction and reduction of the number of people affected by noise 'hot spots'. As part of this step, a specific plan should be developed outlining the noise mitigation measures to be adopted, a strategy for their implementation as well as an implementation timeline. In terms of prioritising the measures to be implemented, cognisance must be taken of the cost-effectiveness of the measures being proposed, the general merits or otherwise of any proposed measure(s), as well as information on the likely impact of the measure(s) for reducing population exposure at a specific location (i.e. the number of people benefiting from reduced noise because of the abatement measure).

Step 5 is an administrate step which involves drafting the action plan. A draft action plan should provide a summary of the noise problems in the area under consideration as well as an outline of measures that will be put in place to address noise pollution problems at a broad and local level. Therefore, it should contain a coherent noise reduction strategy as well as a detailed account of those responsible for specific aspects of the strategy implementation and its overall implementation. Finally, it should also contain information on the resources available for plan implementation together with an outline of the results expected in terms of reduced exposure if the plan is implemented in full.

Adopting, monitoring and reporting of the action plan is the next step of the action planning process (step 6). This step is crucial because if the pan is not adopted, the noise mitigation measures contained therein will likely not be implemented or only implemented in a piecemeal manner. Thus, it is important that noise action plans have the political and administrative support necessary for their implementation. Once adopted, the authority with lead responsibility for the plan must ensure that plan implementation is monitored carefully. They must also ensure that regular progress updates are provided to the relevant stakeholders and the general public on plan implementation including any obstacles that may have been encountered or pragmatic alterations or deviations from previously agreed measures that might have been undertaken.

There are two additional steps associated with the action planning process. They are: involving stakeholders (step 7) and consulting the general public (step 8). However, they should be seen not as individual steps *per se* but as a more lateral process to be conducted as part of steps 3–6 in the action planning process (Figure 7.1). Step 7 involves selecting and actively involving relevant stakeholders in a meaningful manner. To date, there has been some negative criticism of the manner in which stakeholders, including the public, have been involved in the noise mapping and action planning process within the EU in particular (Murphy and King, 2010). But the criticism generalises across the spectrum with responsible authorities tending not to take the stakeholder consultation process seriously enough (European Commission, 2011). Based on the suggestions of the SILENCE report, a strategy identifying potential participants that will be involved as well as the stage at which they should be included in the process should be established. A list of potential stakeholders and why they should be included in the process are provided in Table 7.1.

Step 8 is a significant step in the process (which should also occur throughout steps 3–6) – consulting the general public. It is crucial that the general public are consulted in a meaningful way because noise action

TABLE 7.1 List of Potential Stakeholders and Their Role in the Noise Action Planning Process

Stakeholder	Reason
Transport and urban planning authority/road maintenance authority	- Revise transport and urban development plans to account for action planning proposals - To implement noise mitigation measures
Land use planning authority	- Provide future information on future development expectations and their expected impact on traffic volumes and its composition - Integrate noise mitigation strategies in the land use planning process
Urban renewal/regeneration	- Provide information on areas designated for renewal - Consider noise issues when/if redesigning roads and completing/upgrading buildings - Integrate noise issues as part of broader consultation process
Waste management authority	- Reduce noise being emitted by collection fleets via management/technical measures - Manage collections times in order to minimise early morning sleep disturbance
Air quality officer	- Provide information on potential impacts of noise mitigation measure on air quality - Explore potential integration of mitigation approaches for noise and air where possible (see King et al., 2009)
Health/Fire authorities	- To support awareness raising about the detrimental effects of environmental noise - Develop and implement standards for using emergency sirens
Communication officials	- Advise on and support the development of a coherent public consultation scheme - Develop information material for awareness-raising purposes

Source: After Kloth et al. (2008).

plans rely heavily on the general public's acceptance and support for noise abatement measures. Achieving this involves consulting the public about noise abatement measures that are being proposed for implementation and receiving their suggestions for improvements/amendments. This process could also involve the general public identifying noise hot spots that may not have been identified as part of the noise mapping process as well as acting as a validation mechanism for 'hot spots' already identified through strategic noise mapping. It is important to note that identifying noise 'hot spots' quantitatively (via decibel levels identified during noise mapping) is not the only means of uncovering problem areas; they can also be identified qualitatively by assessing noise complaints in a particular area. It is important also that public consultation occurs at different scales: national, regional and local. The national and regional level consultation should be a broader process where the public are made aware of broader medium- to long-term noise abatement strategies and provided the opportunity to contribute to them. However, at the local level where specific noise 'hot spots' have been identified, the local residential and business community should be consulted about specific measures being proposed for mitigation.

To summarise, the foregoing provides an outline of the noise action planning process for noise mitigation and abatement. While it is set out in a series of steps, the process is not strictly linear in that some of the steps may occur in parallel or indeed may need to be revisited on the basis of new information that might arise throughout the process. However, what is provided in Figure 7.1 is a set of best-practice steps that should be adhered to, albeit not strictly in that order, by responsible authorities and practitioners who are charged with undertaking the noise action planning process in a particular area.

7.3 MITIGATION APPROACHES

The problem of environmental noise pollution is not one that can be easily reduced over the short term. It requires a coherent strategy of long-term and medium- to short-term measures aimed at reducing exposure. Long-term measures are generally those that are aimed at reducing noise levels on a broader scale while medium- to short-term measures tend to be focussed on mitigation of more specific and localised noise conflicts.

Raising awareness is a crucial aspect of noise abatement. The reason being that public awareness of noise as an environmental problem is crucial for public acceptance, political will and subsequent implementation of the majority of other measures outlined in the forthcoming discussion. Indeed the EU, in particular, have recognised the relationship between public awareness and the potential for the implementation of other noise mitigation measures to the point that it is a core objective of the END (see Chapter 4). The role of raising awareness is primarily an educational one; that is, to educate the population about the detrimental health effects associated with noise but also to inform them how their behaviour as individuals can either contribute to or reduce noise as an environmental and/or health problem. With regard to the latter, this may relate to anything from the way in which they drive or indeed use their car, to their behaviour in relation to noise in their home, i.e., playing music. It is also meant to raise the awareness of major noise producers (i.e. transport companies and industry) as to how they could manage, reduce and eradicate excessive noise in sensitive locations or areas of noise conflict. In this sense, any awareness-raising strategy must define the key groups that are priorities for targeted communication. The key target groups and subgroups for raising awareness in relation to noise are outlined in Table 7.2. Awareness

TABLE 7.2 List of Potential Target Groups and Subgroups for Raising Noise Awareness

Target Group	Subgroup
Citizens	City dwellers City workers Tourists Public transport users Car drivers Cyclists and pedestrians Parents of babies and small children Migrants/minorities Elderly people Shop owners
Public transport operators	Rail and bus operators (public and private) Airlines (public and private)
Planning sector	Development control and forward planners Land use and transport planners Environmental planners
Freight delivery sector	Truck drivers Logistics operators for industry Shop owners and related business
Waste management sector	Public and private waste management operators Drivers of waste collection fleet
Educational sector	School children Teachers Parents
Health sector	Hospital staff General practitioners Public and private health services Hospital patients
Media	Journalists Regional and local newspapers Papers/magazines specific to target groups
NGOs	Environmental groups/other interest groups Community organisations Research institutes Environmental consultancy companies
Government/policymakers	City councils Regional and national authorities

Source: Kloth et al. (2008) and van den Elshout (2006).

raising can be achieved through a number of avenues including direct advertising to the public, leaflets, posters, websites, questionnaires, information desks in noise hot spots, focus groups, and educational outreach programmes in schools among other potential avenues.

The need for a systematic approach to managing noise complaints is a necessary prerequisite to reducing the problem of environmental noise. While strategic noise mapping and action planning have been important processes in aiding understanding, assessment and mitigation of environmental noise, the value of citizen complaints in relation to environmental noise is crucial for determining those most affected by excessive noise and thus noise annoyance. It is imperative therefore that local, regional and national authorities take a systematic approach to dealing with noise complaints from the general public. This involves having a clear strategy on how they should be dealt with, what data should be recorded in relation to complaints, how to respond to citizens making complaints, and guidance on how information should be shared between various agencies to promote better and more holistic noise abatement strategies. In the same way that we should not rely only on noise mapping data to determine noise problems, we should also not rely only on noise complaint data for noise management and detection. It is well established that certain groups make fewer complaints to local authorities (e.g. migrants, children and people from lower socioeconomic backgrounds) and thus are likely to be under-represented in noise complaint data. Therefore, it is important that a range of data is used including noise mapping, action planning, measurement and noise complaint data when assessing the noise situation in an area and the appropriate response that might be required.

7.4 SOURCE-BASED ABATEMENT

Without any doubt, the most effective noise control and regulation measures are those that target a reduction in noise emitted at the source. However, for a noise control strategy to be truly effective, it must, given the variation of specific cases of exposure, attempt to utilise abatement measures that target noise reduction at the source as well as at the receiver. Table 7.3 provides a list of the main source-based noise abatement measures and their potential for widespread reduction of noise levels. In the following discussion, details are provided on the effectiveness of each measure individually.

7.4.1 Legislation (Regulation)

By far the most effective and cost-efficient method of reducing noise at source is via legislation which sets out permissible noise levels at the point of manufacture (for vehicles and outdoor machinery). Obviously,

TABLE 7.3 Source-Based Noise Mitigation Measures

Measure
Legislation
Low-noise road surfaces and maintenance
Traffic management
Low-noise tyres
Low-noise vehicles
Driver Behaviour

enforcement of limits is crucial to the effectiveness of any legislation. As such, they must be tightly controlled by regular audits, tests and inspections to ensure compliance. Permissible noise limits should be set for the major emitters of noise including all transport vehicles and modes (with different limits being set for different modes of transport) as well as outdoor machinery. Most countries have these limits already in place either at the national or supranational level but reducing them would have a major impact on noise emission exposure. Moreover, not only is the legislative approach the most effective in terms of reducing noise but it is also the most cost-efficient method of achieving environmental noise reductions, and it is a cost which is borne in the majority by the private sector through investments in research and technology to improve the noise efficiency of their products rather than by the public purse.

In the EU, road traffic noise reductions at the source are mandated by reducing the permissible sound level of motor vehicles, thereby reducing noise across the entire road network. In 1970, the Motor Vehicle Directive (70/157/EEC) established permissible sound levels for motor vehicles and also harmonised the associated testing methodology (see Table 4.1). The permissible noise limits stipulated in the Directive range from 74 to 80 dB(A) depending on the vehicle category. The categories range from passenger vehicles comprising of less than nine seats to vehicles intended for carriage of goods with an engine power of not less than 150 kW (Guarinoni et al., 2012). Since its adoption, Directive 70/157/EEC has been substantially amended several times, in an effort to account for the changing fleet composition in Europe.

7.4.2 Low-Noise Road/Rail Surfaces and Maintenance

As mentioned in Chapter 5, the main sources of road noise are engine noise and rolling noise. The latter relates to the interaction between the vehicle tyre and the road surface which generates noise while the former

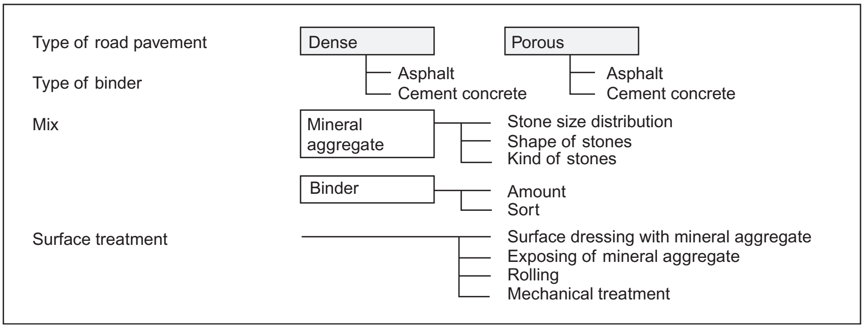

FIGURE 7.2 Acoustically relevant civil engineering properties of road surfaces. *Source:* *Kropp et al. (2007, p. 21)*

relates to vehicle engine and transmission noise which propagates from the vehicle directly and also as reflected noise from the road surface. In relation to the road surface, the key acoustically relevant civil engineering properties of road surfaces are given in Figure 7.2. Beyond these properties, there are three main characteristics which describe the acoustical behaviour of a road surface: surface roughness, porosity and elasticity. They are responsible for air pumping, influencing the excitation of tyre vibrations and sound radiation from tyres (Kropp et al., 2007). All of these characteristics can be represented via a set of parameters which provide information on the acoustical properties of the surface (see Figure 7.2). From this, it follows that different surfaces have different noise attenuation capacities. The ability of a surface to attenuate noise depends on a number of factors but the key factors are the texture of the surface, the texture pattern and the degree of porosity of the surface structure.

The most effective low-noise road surfaces currently available are porous asphalt and thin layer asphalt while there are a number of next generation surfaces currently showing some additional noise reduction potential. Thin layers have been designed and optimised for low-noise emission by the use of small maximum aggregate size (6 or 8 mm), creating an open surface texture and creating a smooth surface texture (Bendtsen and Nielsen, 2008). The open surface structure reduces noise generated from air pumping and the smooth even surface reduces the vibrations generated in the tyre which also reduces tyre/road noise (Bendtsen and Raaberg, 2007).

Porous asphalt reduces the air pumping effect and reduces the noise reflected from the vehicle engine because of its attenuation capacity which absorbs reflections. Thin layer asphalt (two porous layers) is more suitable for urban areas as the porous layer can get clogged with dust quite quickly negating its ability to absorb noise.

For both types of surface, the noise reduction effect is based on the low aggregate size (with 20–25% air void inbuilt) of the mixture which has a greater attenuation capacity for noise absorption. As a result, the surface absorbs noise and drains water – thus less water spray is observed by road users and overall noise is reduced. Ripke et al. (2005) found that single-layer porous pavements have an average noise reduction of 3–4 dB on highways (in relation to dense asphalt concrete). Two-layer porous pavements have a noise reduction potential of around 4 dB or more (in relation to dense asphalt concrete). Indeed Kropp et al. (2007) assert that up to 6 dB can be achieved with the most absorptive surfaces but they need regular cleaning to maintain their absorptive capacity (at least twice a year). For porous asphalts, the noise reduction effect decreases by 0.4 dB per year for light vehicles at high speeds and by 0.9 dB at low speeds. For heavy vehicles, this amounts to 0.2 dB at high speeds. No effect is assumed for low speeds. However, concern exists over the durability of these surfaces as well as the fact that they require frequent maintenance.

While low-asphalt solutions can be highly effective, they also tend to be expensive. However, Kloth et al. (2008, p. 71) assert that the cost of low-noise road surfaces relative to other abatement measures (barriers, insulation, etc.) remain relatively low with double-layer porous asphalt costing in the region of €30/$40/$m^2$ more than conventional surfaces. On a more general level, low-noise surfaces are effective mitigation measures, and the recent proposal from the SILVIA project (Sustainable Road Surfaces for Traffic Noise Control) to introduce a noise classification system for roads could improve road surface selection and management (Padmos et al., 2005). Moreover, low-noise asphalt has an additional (and considerable) advantage over other mitigation approaches (e.g. façade insulation) in that indoor and outdoor noise affecting all buildings near treated roads is reduced. Thus, the approach has the effect of improving the surrounding soundscape of the entire neighbourhood.

In Europe and beyond, the comparison of different road surfaces is problematic because different nations tend to use different surfaces as standard; for example, asphalt rubber concrete is used in Portugal, the Netherlands utilise porous asphalt as standard, Denmark's standard surface is a dense-graded asphalt concrete while Sweden generally employs a stone mastic asphalt (Bendtsen et al., 2008). The forthcoming CNOSSOS-EU method attempts to address these differences by developing a theoretical standard European road surface. It consists of an average of dense asphalt concrete 0/11 and stone mastic asphalt 0/11, between 2 and 7 years old and in a representative maintenance condition.

If we turn our attention to railways, existing research acknowledges that rolling noise is the most prominent source of noise when trains/trams

BOX 7.1

THE OPTIMAL ROAD SURFACE

In 2009, the Dutch Centre for Transport and Navigation, along with the Danish Road Institute, conducted a joint research project assessing the performance of available low-noise road surface types (Kragh et al., 2009). The goal was to identify pavements with the potential to reduce rolling noise by 10 dB with respect to the Dutch reference road surface, on high-speed roads (with a combination of light and heavy vehicles). The project identified a poroelastic road surface, produced by Yokohama and Nippon Road in Japan, as the most promising surface type. Measurement results suggested a reduction of 10 dB for passenger cars may be achieved, although a similar improvement for heavy vehicles was not estimated to be possible. A thin layer open-graded asphalt wearing course with small maximum aggregate size also showed some promise; this road surface was somewhat short of the desired 10 dB reduction. Overall, the project concluded that none of the available 'ready-to-use' commercial products are capable of providing desired 10 dB noise reduction. In order to obtain such reductions, a new surface with more porosity and/or a wearing course having an elastic skeleton needs to be developed.

are running. However, for non-electrified trains, engine noise dominates when they are stationary or travelling at low speeds. A large amount of train noise results from the interaction of steel wheels with steel rails. When a train is in motion, both the wheel and the track vibrate thereby creating noise (see Section 5.2.1, Chapter 5).

In a similar manner to those for road noise, there are two general approaches to controlling train noise at source: the first focuses on the engine noise of the train itself which can be abated generally through improvements in the fleet where old locomotives are replaced with lower noise locomotives. The second relates to rolling noise. Here, the conditions of the rail surface and the surface of the train/carriage wheels have a significant effect on the noise levels being generated. In fact, track and wheel irregularities can raise noise emission levels by anywhere between 10 and 20 dB compared to a reference condition with little or no irregularities (Paikkala et al., 2002). Defects in the wheel thread, loss of portions of the wheel thread due to mechanical or thermal fatigue, various rail surface defects and rail joints are the particular causes. In this regard, track measures can be utilised to reduce noise. The key approaches include rail and wheel absorbers to absorb vibrations and reduce rolling and squealing noise which can lead to a 2–3 dB reduction in noise. Another approach is acoustic grinding to smooth rail tracks and thereby reduce friction. The objective of rail grinding is to maintain and extend the service life of the rail. The process involves applying abrasive grinding stones to the surface of the rail, removing corrugations, burrs, and other surface defects. Typical rail grinding campaigns can lead to noise reductions of up to 3 dB, although this is dependent on local rail roughness conditions (Orteli and Hubner, 2010). However, rail grinding is generally not undertaken for acoustic concerns but to prevent rail defects and fatigue cracks (Thompson, 2009). Indeed, new technology now allows for high-speed acoustic grinding of rail tracks at working speeds of more than 80 km/h.

The use of continuously welded rail (CWR) also serves to reduce noise emission by removing rail joints and, therefore, impact noise. Jointed track can generate between 2 and 5 dB(A) more noise than CWR. The amount of rolling noise radiated by the track can be reduced by increasing the damping of the rail through the use of tuned rail dampers (preformed elements attached to the side of the rail). These dampers reduce the amplitude of vibrations transmitted along the rail and thereby reduce the noise radiated; noise reductions of up to 6 dB on ballast track have been measured using this technique (Thompson et al., 2007). Other technical measures might include wheel dampers, bogie shrouds (wheel covers) and low trackside barriers. Bogie shrouds are also used to reduce the noise from rail/wheel interaction and this can also reduce noise by around 2–3 dB.

Perhaps the most commonly used approaches for noise mitigation along railways include improving those associated with rolling stock. These include brake block technology and optimised wheels. In relation to the former, research has shown that new composite brake block technology (including K- and LL-blocks) rather than cast-iron brake blocks has the ability to reduce noise emission by 8–10 dB (Orteli and Hubner, 2010). This type of noise abatement measure involves retrofitting the fleet or a portion of the fleet with the new brake block technology. In Europe, this is already underway with countries such as Germany, Switzerland and the Czech Republic already retrofitting part of their fleet with the new technology.

In cities where light rail/trams are prominent, it is possible to reduce noise by purchasing new low-noise trams. Kloth et al. (2008) point out that the noise emissions from modern trams are at least 10 dB less than older trams (assuming a 30-year lifespan). In addition, the recently completed SILENCE project (www.silence-ip.org) developed a new track form and new floating slab designed to reduce ground borne noise without leading to a high level of low frequency noise which is a problem with existing tracks (see Kloth et al., 2008). Moreover, a further way to reduce tram noise in cities is to have, where possible, a lawn track (see Figure 7.3). This increases surface absorption of rolling noise from the tram and reduces potential reflections. In addition,

FIGURE 7.3 Lawned light rail track (Luas) in Dublin, Ireland.

a recent European project – the Hosanna project[1] – investigated the potential of a range of 'green noise abatement' measures to reduce noise in cities. They have suggested that roughness-based noise reduction using low parallel walls close to tramways can reduce noise considerably. For example, a 3.05-m-wide configuration of 16 parallel walls starting 1 m from the nearest track is predicted to reduce railway noise by more than 6 dB(A) at a 1.5-m-high receiver 50 m from the edge of the track (Hosanna, 2013).

7.4.3 Low-Noise Tyres

In a 2006 study, Sandberg (2006) investigated the variation in noise levels within different types of tyre class permitted in the EU. The study found a range of somewhere between 6 and 8 dB within certain tyre subcategories and 10 dB within the entire car category (and for the truck category) in terms of the differences in acoustic performance among several hundred tyres. Because tyres are generally not interchangeable between subcategories (Kropp et al., 2007), the range of optional difference is ultimately 6–8 dB for cars and ca. 5 dB for trucks. This suggests that there is

[1]HOlistic and Sustainable Abatement of Noise by optimised combinations of natural and artificial means.

considerable scope for noise reduction by utilising the best tyre technology which could be fast-tracked into the vehicle fleet through the introduction of legislation to reduce permissible noise limits and force manufacturers to adopted better technology.

In the EU, the latest piece of legislation on tyres is aimed at increasing the safety as well as the economic and environmental efficiency of road transport by promoting safe, fuel-efficient and low-noise tyres. The legislation, which has been effective since November 2012, establishes a framework for the provision of harmonised information on tyre parameters, including information on external rolling noise of tyres through labelling that allows consumers to make an informed environmentally friendly choice when purchasing tyres (see Figure 7.4). The noise rating provides the external noise emissions of the tyre in decibels but a noise classification is also shown for people who may not be familiar with the decibel system. The classification system (indicated by black sound waves) categorises the tyre in relation to forthcoming European tyre noise limits where:

- 1 black wave = Quiet (3 dB or more below the future European limit);
- 2 black waves = Moderate (between the future European limit and 3 dB below);
- 3 black waves = Noisy (above the future European limit).

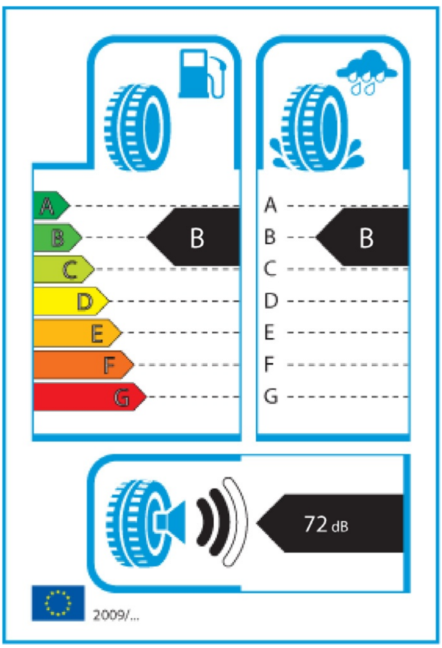

FIGURE 7.4 New EU tyre labelling system incorporating tyre noise information.

7.4.4 Driver Behaviour

The manner in which a vehicle is driven has a very significant impact on the noise that is emitted from the vehicle. For example, 32 cars travelling at 2000 revolutions per minute (RPMs), which is closely related to acceleration and deceleration in driver behaviour terms, produces no more noise than one car travelling at 4000 RPM (for stand-alone engines). Thus, promoting more passive and less aggressive driving styles can reduce noise by an average of 5 dB(A) for cars and commercial vehicles and by 7 dB(A) for motorcycles (Kloth et al., 2008). One of the most obvious ways in which more passive driving behaviour could be promoted is through the more widespread use of automatic gearing systems for vehicles which promote gradual transitions between gears at relatively low RPMs. While automatic gearing is common place in the United States, it is much less common in Europe and thus its promotion could be beneficial not only as a long-term noise abatement measure but would also be beneficial for reducing air pollution as well as reducing energy consumption. In addition, in-vehicle technology improvements that inform drivers about the optimum time to complete gear changes (i.e. ca. 2000 RPM) could be used to promote less noisy driving styles among the driving population. However, there is little doubt that awareness-raising campaigns must also be undertaken in terms of educating drivers about the negative externalities of aggressive engine driver behaviour. In this sense, ecodriving campaigns such as www.ecodrive.org and ecodrive training (see www.ecodrive.ie) can assist with increasing awareness about the environmental and monetary benefits of improved engine management while ensuring that noise is reduced.

7.4.5 Traffic Management

Traffic management measures, especially in cities, are thought to play a significant role in reducing not only noise emission levels but noise exposure levels at specific locations where sensitive receivers exist, i.e., residential areas. However, up until relatively recently, there was very little research in cities confirming the effectiveness of these measures. The most important measures are reductions in traffic volumes (and particularly the volume of heavy vehicles) and reductions in traffic speeds. However, noise reduction and population exposure reduction can be quite different in that a targeted reduction of traffic in a particular area could have a large impact on overexposure to noise especially in relation to noise limit values that are only slightly exceeded. If traffic volumes are reduced in cities, it is vitally important that average speeds are not allowed to increase. Very often noise reductions achieved in cities and beyond as a result of traffic volume reductions are offset by increases in traffic speeds because vehicles can travel faster on less busy roads. In a recent study, King et al. (2011)

found that banning private cars in Dublin city centre reduced noise levels by only 2 dB(A) partly as a result of buses increasing their speed due to less congestion. However, they also concluded that considerable potential existed for further reductions if the ban was accompanied by associated retrofitting of the bus fleet with quieter buses.

There is a relationship between noise emissions and speed in that propulsion noise increases with engine revolutions (RPMs). There is an overall tendency for increasing noise levels at higher gears and thus at higher overall speeds. However, the relationship is not linear and particularly at low speeds (below 30 km/h) engine noise tends to dominate. Andersen (2003) derived a speed-noise reduction relationship using measurement data from more than 4000 light and heavy vehicles, and the results of this relationship are summarised in Table 7.4. It can be seen that reducing speed between the 100 and 130 km/h category leads to no reduction in noise levels; it is only below 100 km/h that incremental reductions in noise are seen with reductions in the actual driving speed. In cities, the relationship between noise reduction and exposure (which goes to the heart of the effectiveness of mitigation measures) has only been studied recently. Murphy and King (2011) investigated the impact of speed reductions on population exposure to noise. They found that 10% and 20% speed reductions led to 2.0% and 3.7% reductions in exposure above 40 dB(A), L_{night}. In cities, speed reductions can be achieved through lowering of the speed limit in areas of the city where there are noise-sensitive receivers. However, any reduction in speed limits must be accompanied

TABLE 7.4 The Effect of Speed Reduction on Noise

Reduction in Actual Driving Speed [km/h]	Noise Reduction (LAE[a], dB) – Light Vehicles	Noise Reduction (LAE, dB) – Heavy Vehicles
130 to 120	1.0	–
120 to 110	1.1	–
110 to 100	1.2	–
100 to 90	1.3	1.0
90 to 80	1.5	1.1
80 to 70	1.7	1.2
70 to 60	1.9	1.4
60 to 50	2.3	1.7
50 to 40	2.8	2.1
40 to 30	3.6	2.7

[a] *LAE is the A-weighted sound exposure level (SEL).*
Andersen (2003).

simultaneously by political will. Moreover, any new limits imposed must be enforced by local, regional and national law enforcement officers. Otherwise, they tend to be ignored by the driving public.

Of course, the composition of traffic is important in the city. In most cities, heavy vehicles comprise a small proportion of the overall number of vehicles on the city's roads; light vehicles tend to dominate the average continuous sound pressure level, L_{Aeq}, and hence L_{den} and $L_{night.}$ On the other hand, heavy vehicles tend to influence the composition of peak or maximum noise levels (such as L_{max} or L_{peak}) which are more closely associated with annoyance and sleep disturbance (see Murphy and King, 2014). Peak and maximum noise levels can be seen as noise events which are short-term bursts of high noise levels that have the potential to induce awakenings and annoyance. Thus, traffic management measures that target the reduction of heavy vehicles (such as night-time restrictions) in noise-sensitive residential areas during the night-time period have the potential to reduce noise events. In this context, a recent study by Torija et al. (2012) found that the implementation of a range of measures in urban areas based on the identification and elimination of noticed sound events has the potential to reduce and/or eliminate harmful sound events in cities.

Other traffic management measures that may have a positive impact on noise levels, if implemented correctly, include traffic calming measures such as speed bumps although it should be noted that there is debate as to whether these are effective at reducing noise. While they do reduce average speeds along road links, they also tend to increase the number of accelerations and decelerations along the link which offsets noise reductions from lower speeds. In addition, the designation of one-way streets improves the flow of traffic in cities; a smoother flow of traffic tends to promote less acceleration and deceleration of vehicles thereby reducing overall noise emission levels.

BOX 7.2

THE POTENTIAL OF TRAFFIC MANAGEMENT MEASURES FOR NOISE REDUCTION

In a recent study in Dublin, Ireland, Murphy and King (2010) investigated the potential of action planning measures to reduce population exposure to environmental noise. According to their estimates, they found that more than 27% of the resident population were exposed to L_{den} values above 70 dB(A) while almost 85% were exposed to L_{night} greater than the WHO guideline value for night noise of 40 dB(A). However,

BOX 7.2 (*cont'd*)

their results demonstrated that significant reductions in population exposure to noise can be achieved by implementing traffic management noise action planning measures in urban areas. They simultaneously modelled a 10% travel demand and traffic speed reduction that could be enforced via night-time traffic restrictions in noise 'hot spots' along a specific reference route on the Dublin road network. Rather interestingly, their study found that population exposure above 40 dB(A) during night-time could be reduced by 5% using these traffic management measures.

7.4.6 Traffic Engineering and Modal Shift

Perhaps one of the most obvious ways to reduce noise is to introduce noise reduction as a primary consideration in traffic management and engineering. Given that the most significant source of environmental noise is road transportation noise, strategies and procedures that integrate noise reduction into decision-making when upgrading the transport network and the fleet that use that network could lead to substantial reduction in noise emission. For example, road surfaces need to be upgraded on a medium-term basis. Thus, low-noise road surfaces should be considered during such processes given that there are now cost-efficient options available (Guarinoni et al., 2012). Moreover, the public transportation fleet (including buses, cars and commercial vehicles) also needs to be upgraded regularly and there is no reason why less noisy vehicles should not be chosen during the upgrading process. Indeed, noise considerations also need to become a more comprehensive and integrated part of Environmental Impact Statements (EIS). King and O'Malley (2012) have pointed to improvements that could be made in such processes to better integrate noise into wider Environmental Integration Models (EIM). The idea of EIMs is that they integrate environmental issues into the planning, construction and operation of infrastructure schemes. Making noise issues a primary component in such models could certainly assist with wider strategies of noise reduction.

Encouraging modal shift from private vehicles (which are the main source of environmental noise) to public transport and other sustainable modes such as walking and cycling is not only important for noise abatement but it is also a policy objective that tallies very well with other environmental objectives such as reducing air pollution, energy consumption as well as promoting public health and well-being (see Murphy, 2009, 2012). Measures to encourage such a shift include, *inter alia*, more attractive, reliable, frequent, widespread and comfortable public transport (preferably rail based); high-quality cycling facilities including bicycle sharing (Murphy and Usher, 2013); park-and-ride facilities; mobility management plans as well as general marketing campaigns and financial incentives to promote modal shift.

7.5 PROPAGATION MEASURES

7.5.1 Land Use Planning

The role of land use planning in noise abatement is often underestimated. However, it has the potential to play an important role especially as part of a broader long-term strategy aimed at reducing noise. As pointed out by Murphy and King (2011, p. 493) '. . .tackling the problem of environmental noise adequately is likely to require the implementation of more than one noise mitigation measure. A more concerted approach is needed if levels of exposure are to be reduced and areas of good sound quality are to be protected'. Thus, all potential avenues that can achieve noise reduction need to be investigated and land use planning falls within that remit. Land use plans are essentially zoning plans which outline the future location and type (residential, office, retail, industry) of development activity that is to be permitted and not permitted (i.e. green space, parks, etc.) within urban and regional areas over a set horizon period (normally 5–15 years). Their potential use in noise abatement lies in their ability:

- to indicate quiet areas that are to be protected against any new noise immission;
- to designate noise-sensitive areas resulting from strategic noise mapping where any new noise immission should be prevented;
- to allocate land use in such a way as to ensure the distance between new (noise emitting) land uses and noise-sensitive areas is sufficiently large to prevent new noise immission to noise-sensitive areas;
- to ensure the smart allocation of land use to minimise the generation of additional (private) traffic throughout cities and regions and especially in noise-sensitive areas;
- to allocate land use in such a way as to promote modal transfer from private to public transport, cycling and walking;
- to implement noise abatement measures as part of a retrofitting process for cities and especially as part of new residential development in regeneration programmes, new development or on brownfield sites.

In relation to the latter point, there are a number of ways in which this can be achieved. The first is through the use of noise-compatible buildings as noise barriers which can be achieved through the land use planning and development control process. Best practice includes utilising buildings that are not noise sensitive as noise barriers for sensitive buildings. In addition, noise abatement can be achieved through the careful extension of existing commercial buildings to act as barriers to more sensitive residential buildings.

The second is through the appropriate development of land uses in such a way so that noise propagation is reduced. Again, this can be achieved through the land use and development control process. A typical example would include the use of noise proofed terraced housing instead of semi-detached housing in the first housing row facing a motorway/highway. In this way the front row would act as a barrier for semi-detached or detached housing carefully designed behind the first row. Taken together, it can be seen that if noise abatement considerations were integrated into land use and development control considerations, the potential for reducing noise pollution is considerable.

7.5.2 Building Design

Building design is very important for noise reduction inside the building. In particular, it is important that architects and urban planners are made more aware of the potential acoustical implications of not only a building's design but also building standards in terms of their insulation against noise. Specific areas where building design can influence noise immission (i.e. noise inside a building) include: (1) room layout and (2) geometry and orientation of the building. In relation to (1), room layout should ensure that rooms associated with less noise-sensitive activities (e.g. kitchens, bathrooms, utility and storage rooms) are placed towards the noise source (i.e. a road or rail line) while rooms that house more noise-sensitive activities, such as bedrooms for sleeping and the living room for relaxation, are located away from the noise source (see Figure 7.5). In this way, the rooms that tend to house less noise-sensitive activities act as a barrier for those that house more noise-sensitive activities.

In relation to (2), the geometry and orientation of buildings should be a primary planning and design consideration in relation to the indoor noise level not only within the buildings under consideration themselves but also other buildings within the vicinity. From a noise perspective, the extent of reflections is the primary consideration for geometry and orientation of the building; building geometry and orientation should be designed in such a way as to minimise potential reflections from key noise sources (i.e. roads, railways). In particular, the reflection of noise from one façade to another should be avoided. Figure 7.6 provides an example of best (a) and worst (b) practice in relations to noise-compatible building geometry and orientation which should be adhered to and integrated into

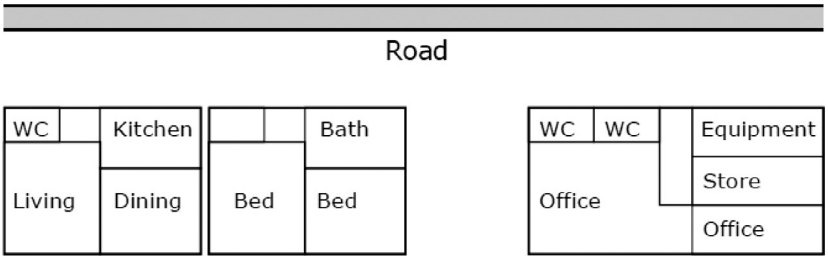

FIGURE 7.5 Noise-compatible room layout. *Source:* Nelson (1987).

building control guidelines and adopted as an evaluation criteria for the granting or otherwise of planning permission.

Indeed, buildings can also be designed with additional elements and geometrical configurations so that elements of the building are used specifically for noise abatement purposes. Elements such as balconies and wing walls can be used for this purpose. Orienting windows away from the noise source and protecting them with wing walls is considered best-practice acoustic design (see Figure 7.7). According to Kloth et al. (2008, p. 65), the noise reduction potential of balconies ranges from 5 to 14 dB(A) 'depending on the width of the windows, the angle between the road [noise source] and the window, the depth of the balcony and the height of the boundary wall'.

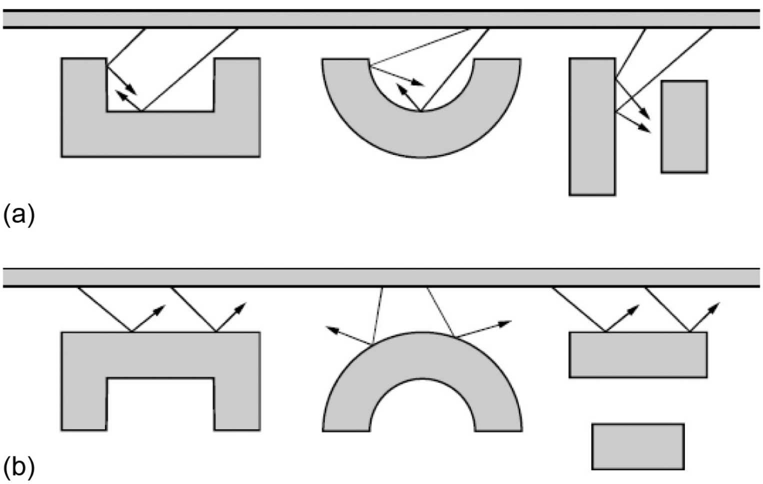

FIGURE 7.6 Noise reflection at buildings: (a) to be avoided and (b) preferred. *Source:* Nelson (1987).

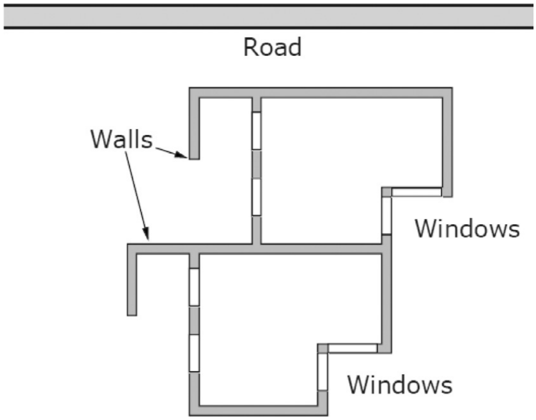

FIGURE 7.7 Illustration of how wing walls can be used to prevent noise immission. *Source: Nelson (1987).*

7.5.3 Barriers

Noise barriers are generally seen to be an effective means by which the propagation of noise can be mitigated. The first purpose built noise barriers were built in California in 1968 and, since then, noise barriers have steadily grown in popularity to mitigate against noise, with ever increasing research in the science of noise barriers (Pilton et al., 2006). Despite barriers being costly, they are used frequently to reduce noise propagation alongside roads or railway lines. In fact, noise barriers, including earth berms, are the dominant type of mitigation measure adopted in CEDR member states[2] to reduce road traffic noise (Bendtsen et al., 2010). The effectiveness of a noise barrier is governed by the path length difference (the amount by which the top of barrier cuts the line of sight between the source and receiver), provided the sound transmitted through the barrier is minimal. The mechanisms behind how a noise barrier attenuates sound are discussed in more detail in Section 2.6.4.

ISO 9613 limits the maximum attenuation of a thin noise barrier at 20 dB in any octave band and 25 dB in the case of thick noise barriers. However, in practice, a noise barrier will reduce noise levels by 3–7 dB, depending on their design and height (Arenas, 2008). Barriers are relatively ineffective at screening properties at some distance from the road as the barrier effect is not additional to the attenuation due to propagation over the intervening soft ground; instead, the barrier replaces this component of

[2]CEDR is the Conference of European Directors of Roads. A list of members is available here: www.cedr.fr/home/index.php?id=32.

noise attenuation (King and O'Malley, 2012). In some European cities, barriers that partially cover the road have been used, but these are very expensive architectural features.

In the past, simple reflecting barriers were often used along roads and rail lines but modern barriers tend to have absorptive surfaces on the traffic side which minimises the level of reflected sound. Barriers vary in their design and construction material with graphical descriptions of some of the more common types of noise barriers provided in Figure 7.8. Barriers can be constructed with a large range of materials including, wood, steel, aluminium, acrylic sheeting, concrete, masonry block and rubber mats. In CEDR Member States, concrete, wood and aluminium are the most prevalent barrier types (Bendtsen et al., 2010). The choice of barrier material should consider the local environs. Another common type of noise barrier is an earth berm, which is a mound of earth along the road. In general, an earth berm produces 3 dB more attenuation than a wall of the same height (Wilson, 2006). The most effective barrier types are (Kloth et al., 2008):

- *Absorbing barriers* are barriers with absorptive material on the traffic side of the barrier. This serves to absorb some of the incident sound and thus reduce reflections that might impact receivers on the opposite side of the road (the traffic side). However, research in the UK has suggested that reflections from the noise barrier have a very small effect on noise levels on the traffic side (<1 dB) (see Watts and Godfrey, 1999);
- *Capped barriers* are barriers with a specially designed cap section at the top of the barrier. Its function is to reduce the potential of sound waves travelling over the top of the barrier (see Figure 7.9). Watts et al. (1994) examined the performance for T-topped, multiple edge and double barriers compared to a simple plane barrier (2 m high). They concluded that the average increase in acoustic screening of 2-m high T-shaped, multiple edge and double barriers compared with a simple plane reflecting barrier of identical height ranged from 1.4 to 3.6 dB(A) depending on detailed design. Furthermore, the use of innovate barrier

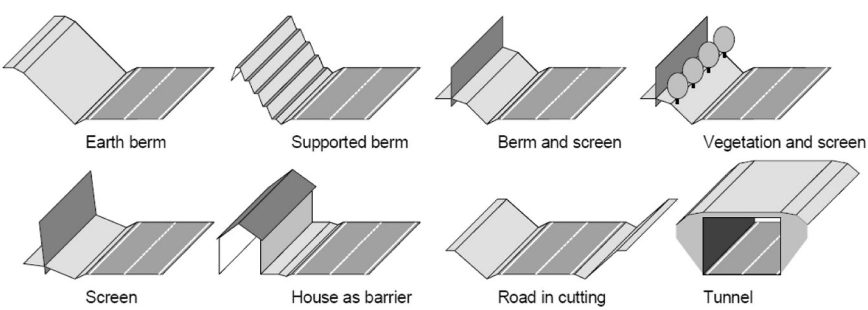

FIGURE 7.8 Range of potential noise barriers. *Source:* *Paikkala et al. (2002).*

FIGURE 7.9 Example of a capped barrier. *Courtesy: Douglas Barrett, Sanchez Industrial Design, Inc.*

designs such as a T-top barrier (with absorptive material placed on top of the horizontal portion) has the potential to reduce barrier heights compared to conventional noise barriers (Watson, 2006);

- *Angled and dispersive barriers* are barriers that reflect the sound upwards or in a direction away from noise-sensitive receivers through the use of tilted walls or contoured surfaces;
- *Embankments and earth berms* are natural barriers that can be created from earth material dug out during construction phase of a roadway or railway;
- *Covering barriers* are barriers which tend to offer complete cover of both sides and above the road, i.e., a tunnel or sound tube. Figure 7.10 demonstrates how covering noise barriers can be constructed in a manner which does not detract from an area's aesthetic qualities;
- *Random edge profile barriers* are barriers with different height along their length. The varying height is designed to create destructive interference effects that will reduce noise propagation over the barrier, i.e., the jagged edge causes a reduction in coherence of the diffracted signal being transmitted to the shadow zone as compared to a conventional straight edge barrier (Samuels et al., 2009);
- Vegetation can also be used as a noise barrier. However, their effectiveness in terms of noise reduction is minimal with 10 m depth of vegetation resulting in only 1 dB reduction in noise. Their real value

FIGURE 7.10 The *Sound Tube* along the Tullamarine Freeway, Melbourne, Australia. *Source: http://en.wikipedia.org/wiki/File:TullamarineFwy.jpg.*

though is in terms of their psychoacoustic performance: where people cannot see the noise source but see greenery instead it tends to lead to a subjective reduction in annoyance and disturbance (Yang et al., 2011). However, the impact of vegetation on annoyance is disputed with Watts et al.'s (1999) research concluding that vegetation barriers had little or no effect on perceived annoyance levels.

To ensure the most effective attenuation is achieved, the following design considerations should be adhered to (Mahon, 2013):

- The barrier must be sufficiently tall so that it blocks the line of sight between the source and receiver. Thus, the higher the noise barrier, the better the insertion loss, provided the sound insulation performance of the barrier is adequate;
- The length of the noise barrier must be long enough to cover an angle of at least 160° from the receiver. Alternatively, the distance between the receiver and the barrier end should be at least four times the perpendicular distance from the receiver to the barrier;
- The most effective barriers are solid and continuous. Where a break in the barrier is necessary, the barriers should overlap. These sections of barrier should ideally be finished with sound absorbing material and the overlap should be at least four times the opening width;
- Barrier placement in relation to the road (noise source) and receiver is critical. Optimal noise reducing effect is obtained if the barrier is

located as close as possible to either the noise source or the receiver because this maximises the path length difference;
- Finally, it is important that barriers contain no leaks due to holes, cracks, gaps and so on. These leaks will severely compromise the acoustic effectiveness of a barrier. For example, if a gap occupies just 3% of the surface area of a noise barrier with an expected transmission loss of 25 dB at 500 Hz, the actual transmission loss will be approximately 9 dB (Government of Hong Kong, 2003).

Several agencies have released guidance on the appropriate design of noise barriers. For further detailed information and design considerations, readers should consult:

- Noise wall design guideline, design guidelines to improve the appearance of noise walls in New South Wales, Roads and Traffic Authority, New South Wales, Australia, November 2006.
- Guidelines on Design of Noise Barriers, Highways Department, Government of Hong Kong SAR, Second Issue 2003.

7.5.4 Building/Façade Insulation

Sound insulation of dwellings includes sound 'proofing' the windows and outer walls particularly at the façade of the building which is directly exposed to noise. It is often seen as a last resort measure to reduce noise for noise-sensitive receivers. It can be very effective but also quite costly.

BOX 7.3

SONIC CRYSTALS

A relatively new type of noise attenuator is the use of sonic crystals (Figure 7.11). Sonic crystals are a collection of thin beams (usually cylinders) positioned in a manner to scatter sound waves at specific frequencies. An example of a sonic crystal is the Kinematic Sculpture by Eusebio Sempere at the Juan March Foundation, Madrid, Spain. In 1995, acoustic tests were performed on this structure and they showed that the sculpture was a good attenuator of sound at certain frequencies due to the spacing of the beams (Martinez-Sala et al., 1995). Since then sonic crystals has been an increasing research area. Recently, researchers examined if an array of trees, arranged in a periodic lattice, could function like a sonic crystal to improve the sound attenuation from a mass of trees, with some success (Martínez-Sala et al., 2006).

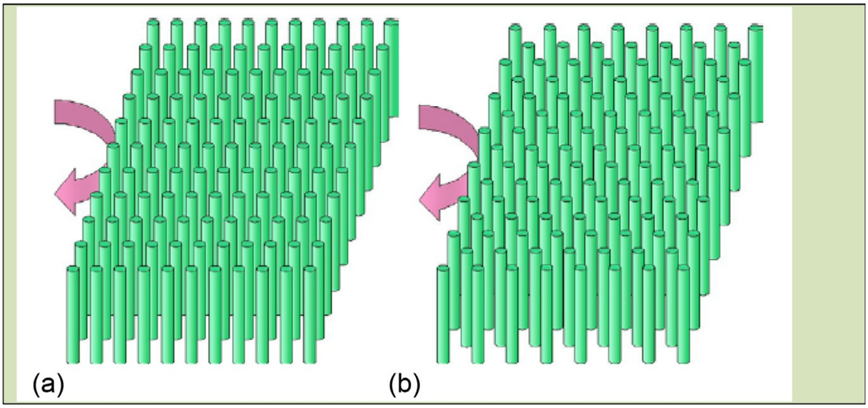

FIGURE 7.11 Two-dimensional square-lattice structure of sonic crystals. *Source: Miyashita (2005).*

Modern windows with double and triple glazing can reduce noise by somewhere in the region of 30 dB with the best achievable thought to be in the region of 40 dB (Kloth et al., 2008). However, the research of Tadeu and Mateus (2001) concluded that the acoustic performance of triple glazing systems is highly dependent on the quality of the frame being used for the glazing. The insulation characteristics of the walls are also important as well as the sound quality of the doors; solid well-fitting doors can achieve noise reductions of between 35 and 40 dB (Kloth et al., 2008). Generally, new windows that are installed for sound reduction purposes should have a sound reduction index of R'w > 35 dB that should be measured after installation.

In terms of wall insulation, sound insulation can be linked closely to improved thermal insulation. Generally, insulation placed between the vertical members of an external wall will play a significant role in reducing sound transmission through the wall. Thus, the two are compatible and insulating buildings for energy improvements also has the effect of reducing internal noise levels. The results from a recent Norwegian study found that an average equivalent noise reduction inside the dwellings of 7 dB was obtained from façade insulation (Amundsen et al., 2011). These results are important because the Norwegian façade insulation programme was on a scale not undertaken before and encompassed 2500 dwellings where before and after annoyance surveys were undertaken. Aside from the noise reductions in term of dB levels, the results showed that annoyance was reduced from 42% being highly annoyed before the programme to 12% afterwards. Thus, the programme had a very significant effect on dwellers' subjective assessment of noise-related disturbance. In terms of a noise reduction strategy however, the key caveat with façade insulation is that the benefit only accrues to the dwelling being treated whereas other solutions have the potential to have broader noise reduction benefits to the surrounding community.

7.6 CASE STUDIES IN NOISE ABATEMENT

This section provides an overview of some best-practice cases of noise abatement strategies around the world. Each of the key sources of environmental noise is considered together with an example of a soundscape approach for improving the sound environment in cities.

7.6.1 Roads

The city of Annecy has a strong tradition of good practice in road traffic noise management and control. In the 1970s, heavy goods vehicles were banned from the city centre and around this time the city also reduced speed limits from 50 to 30 km/h. It is a medium-sized city (ca. 51,000 inhabitants in 2007) in the Rhone-Alpes region in South East France. In 1992, it was nominated for a Golden Decibel[3] in the 'Action for Silence' category. Since then, the city has had a progressive noise policy and has made a concerted effort to tackle noise even before the END legislation was introduced. The city's noise policy addresses many types of noise sources. In 1994 the city buried recyclable glass depots to reduce the impact of noise from breaking glass, but its policies in road traffic noise management are worth noting.

The tradition of progressive noise management has continued in recent years. In 2003, the city of Annecy was highlighted by the Sustainable Mobility Initiatives for Local Environment (SMILE) project as an example of good practice in road traffic noise abatement in Europe. In April 2007, the city launched the Agenda 21 action programme which commits the city to five key themes (Ville d'Annecy, 2007). This programme includes the promotion of sustainable travel to allow free access to the city without harming the community and encourages alternative modes of 'soft' transport (such as walking, biking and skating). Most recently, to tackle urban congestion, the LIFE + Urbannecy project was launched. This project aims to develop a new logistic tool to reduce the environmental impact of parcel deliveries (greenhouse gas and particulate matter emissions) and improve the quality of life (by reducing traffic and noise) in Annecy city centre.

[3]In 1991, the French National Council for Noise Reduction created the Golden Decibel award. It has subsequently been managed by the Noise Information and Documentation Center in France.

The city also developed a noise action plan (for its major roads) as required under the Environmental Noise Directive (Ville d'Annecy, 2013). This summarised a number of the city's policies in road traffic noise control and abatement. The city has adopted a range of noise control and abatement measures:

- The city has introduced several bye-laws and decrees, most notably Decree No. 2006-1099 of 31 August 2006 on the fight against neighbourhood noise and amending the Public Health Code (regulations);
- The city encourages the adoption of low-noise vehicles (such as electric vehicles) for public services such as refuse collection;
- A noise taskforce was created in 1985 and the Municipal Police conduct regular inspections of motor vehicles with offending vehicles being subject to a fine;
- A positive purchasing policy has been adopted by the city and it systematically selects quiet processes and equipment for municipal services working on public highways;
- Road maintenance in the city involves the gradual replacement of conventional road surfaces with low-noise surfaces;
- They city has also instigated various awareness campaigns for drivers of two-wheelers since 2000. This involved representatives from the Municipal Police checking the output of noise levels of two-wheelers at various schools – this had the dual purpose of informing adolescents about the regulatory thresholds to be adhered to and also increasing awareness of environmental noise;
- Speed zones in the city centre have been reduced and this has been complemented with the creation (and then extension) of a pedestrian zone in the city centre to reduce noise levels in the city centre;
- The city has developed traffic management plans to reduce the volume and speed of traffic as well as altering the nature of the flow.

However, a valuable lesson has been learned by the city of Annecy. Some of the traffic management strategies employed in the city has inadvertently moved noise from the city centre to other parts of the city. As a consequence, noise complaints rose from areas which previously had no complaints. This implies that care must be taken when dealing with noise which is why a holistic approach to traffic management should be taken. Often the best solution might be a mixture of a number of approaches as opposed to just one mitigation measure.

7.6.2 Railways

Switzerland has one of the world's most advanced programmes of noise abatement for railways (Orteli and Hubner, 2010). It has a long history of railway noise abatement and initiated noise mapping of the railway system as far back as the early 1990s. It also has specific legislation on noise limit values for protection of its citizens which are outlined in Table 7.5.

As part of a national referendum in 1998, Switzerland decided to invest heavily in a major public transport programme between 2000 and 2015. Of the €20 billion to be invested into railways, ca. €1.5 (7.5%) was allocated for a comprehensive noise abatement programme to reduce noise exposure by two-thirds up to 2015. It also had a legal basis and was signed into law as the Federal Act on Railways Noise Abatement (2000) with additional legislation following. The programme is funded through taxes on heavy vehicles, VAT and fuel taxes, and through the capital markets. It had three core elements: retrofitting of Swiss rolling stock, erection of noise barriers and improved noise insulation of windows. As part of the programme, the Swiss government have funded the retrofitting of the entire Swiss rolling stock with composite braking systems (K-blocks). The plan included the installation of composite brake blocks on 24,500 wagons which would benefit 120,000 people in terms of noise reduction (Sperlich, 2003). By the end of 2004, the passenger fleet had been retrofitted with freight vehicles due to be completed by 2015.[4] The state has also funded the erection of noise barriers in noise-sensitive locations; the government plan to have 300 km of noise barriers in place by 2015 (with 207 km already in place as of 2013) at a cost of approximately €1 billion (Orteli and Hubner, 2010). In relation to façade insulation, 81,000 windows amounting to approximately 27,000 households have been retrofitted at the end of 2012. The new windows must have a sound reduction index of R'w > 35 dB which is measured after installation. It is

TABLE 7.5 Noise Limit Values for Existing Railways in Switzerland

	Planning Values		**Regular Values**		**Alarm Values**	
Sensitivity Level	**Day dB(A)**	**Night dB(A)**	**Day dB(A)**	**Night dB(A)**	**Day dB(A)**	**Night dB(A)**
I (Special areas, e.g., hospitals)	50	40	55	45	65	60
II (Residential zones)	55	45	60	50	70	65
III (Mixed zones)	60	50	65	55	70	65
IV (Industrial areas)	65	55	70	60	75	70

Source: Oertli (2009).

[4]As of 2013, all Swiss national railway wagons (SBB) have been retrofitted (6267 wagons). Approximately, an additional 3500 private wagons have to be retrofitted with about 1000 of these completed.

noteworthy also that the government is the predominant funder of noise abatement up until 2015. However, beyond that period, if additional traffic is planned on a given line or if the speed is increased in such a way as to increase noise levels above predefined ceilings, Swiss Federal Railways (SSB) must simultaneously implement noise reducing measures (Oertli, 2009).

Other noise abatement measures have also been instituted with national legislation initiating a programme of differentiated track access charging. Since January 2002, a noise reduction bonus has been in place which stipulates that all (including foreign) infrastructure users who meet new low-noise standards for rolling stock will be afforded a financial bonus. For companies to qualify for the bonus, the use of quieter advanced brake technology is necessary (composite blocks [KK- or LL-blocks], disc brakes or comparable). Infrastructure companies are awarded a bonus of CHF 0.01 per axle kilometre travelled by charging vehicles that are not fitted with nosier cast-iron brakes (Orteli and Hubner, 2010). In even more recent initiatives, additional measures have been added to the programme such as rail lubrication to mitigate curve squeal while the noise of steel bridges has been reduced with the incorporation of elastic elements (Oertli, 2009). Moreover, the Swiss government have recently announced its intention to ban cast-iron brakes on all rolling stock by 2020. Given that none of the Swiss rolling stock will have these brakes in place by 2020, it will effectively force foreign rail operators to retrofit their rolling stock in order to utilise Swiss railway infrastructure.

Overall, it can be seen that the approach to railway noise abatement in Switzerland has comprised a major strategic and concerted effort on many levels. It has also been accompanied by allocation of significant resources which, importantly, was endorsed by the public through a referendum providing the programme and its subsequent implementation with much-needed political and public support.

7.6.3 Urban Soundscapes

The 'soundscape' concept is an idea put forward by Schafer (1977, 1994) to describe perceptions of the acoustic environment in a landscape setting. He recognised the need for integrating the knowledge and skills of the various disciplines that have an interest in the acoustic environment (Brown, 2010). Schafer was concerned with the negative connotations associated with the notion of noise pollution and suggested that more emphasis should be placed on the positive sounds associated with a particular environment. The soundscape concept intersects not only with the field of acoustics including sound quality, human acoustic comfort in buildings and music

BOX 7.4

RAIL NOISE ABATEMENT IN DENTON COUNTY, TEXAS, USA

Some examples of noise mitigation for commuter rails are evident in the Denton County Transportation Authority (DCTA) A-Train Commuter Rail Project, in Texas, USA. Mitigation measures include noise barriers, quiet zones (where train warning horns are not sounded at roadway crossings), wayside horns and residential sound insulation. Figure 7.12 shows an example of a wayside horn. A wayside horn may be used in place of a locomotive horn and these are commonly used in railroad quiet zones. In these zones, the locomotive is not required to sound the locomotive's horn at a crossing. The wayside horn may be positioned to direct the sound to the required area (the intersecting roadways). It can therefore operate at a lower level and reduce overall ambient noise levels.

FIGURE 7.12 Wayside horns utilised for rail-noise abatement. *Source: Courtesy of Harris Miller Miller & Hanson Inc.*

but also with non-acoustic fields such as wilderness and recreation management, urban and housing design, and landscape planning and management (Brown, 2012).

As a result of the popularisation of the idea, there has been a significant increase in emphasis on soundscape research in recent years. In particular, it has been evoked as a potential approach for the preservation and maintenance of areas of good acoustic quality such as quiet areas which are considered to be important for general well-being and quality of life (Memoli and Licitra, 2013). Thus, pleasant artificial sounds can be introduced in places that are generally of good sound quality but are potentially under threat from unwanted noise in order to mask unwanted sounds and preserve areas perceived as being acoustically pleasant. In some cases, artificial sounds can be introduced to enhance the sound quality of a generally good noise environment while in others they can be introduced to mask unwanted sounds entering a good sound environment under threat. Thus, measures introducing artificial sounds have the potential to be used as part of action planning strategies in cities.

In terms of best practice, Stockholm won the 2010 European Soundscape Award[5] for its support for the development of soundscape planning in the city. The city has implemented a number of measures to promote better urban soundscapes. These include the implementation of a unique noise scoring system – Noise Quality Score. The rationale for the system has its roots in a soundscape approach and assumes that many of the factors which cause noise can be avoided if they are taken into consideration in the design, planning and development of new infrastructure of cities. In addition, the city has funded the erection of three permanent sound installations at one of Stockholm's central squares – Mariatorget – at the south end of the city centre. The square was upgraded in 2010 and, as part of the redevelopment, soundscape concerns took centre stage. Architect Björn Hellström created permanent sound installations in the park in collaboration with the City of Stockholm. Their purpose was to transform and acoustically reimagine the square. The approach provides a best-practice example of soundscape improvement in a noise polluted city square. One of the installations provides rhythmic sound through a loudspeaker to the background noise being produced by a fountain in the central square. Indeed as part of the 'Play Stockholm' initiative at the square, the musical character of different parts of the city is provided as background noise in the square[6] (Memoli and Licitra, 2013).

[5]Awarded by the Noise Abatement Society in England in cooperation with the British Department for Environment, Food and Rural Affairs (Defra) and The European Economic Area (EEA).

[6]See http://kymatica.com/playstockholm/.

7.7 COST-EFFICIENCY ISSUES

The development of policies for noise abatement simply cannot occur without due consideration of the available financial resources at one's disposal. Thus, the relative cost-efficiency of individual abatement measures is important for determining which measure or set of measures to be implemented. Due to resource constraints, it may often be the case that the most efficient noise reduction measure cannot be prioritised because it may be too costly. In those circumstances, it is important that policymakers are aware of and evaluate the most efficient noise reduction measures available within their budgetary constraints.

With respect to road noise, a number of key abatement measures exist and have been tested in the field with respect to their cost-effectiveness. The most important measures include noise barriers, low-asphalt roads, low-noise tyres, façade insulation, traffic and land use management measures. In a recent Norwegian study, Klæboe et al. (2011) found that façade insulation was a more cost-effective measure[7] than a low-noise asphalt solution. The study suggests that a policy mix of low-noise asphalt and façade insulation is an even more efficient approach if cost-benefit analysis rather than cost-effectiveness analysis is used to evaluate the mitigation approaches. Similar conclusions have also been drawn in a recent study by the Forum of European National Highway Research Laboratories (FEHRL). It would seem to be the case that low-noise road surfaces could be best utilised in more densely populated areas whereas façade insulation is likely to be more appropriate as a solution in sparsely populated areas.

Noise barriers tend to be the least cost-effective approach despite being useful in specific cases. A recent study on cost-effectiveness of noise abatement measures in the Netherlands suggests a better performance of source measures compared to noise barriers and window insulation. The Dutch study found the most cost-effective measures for noise abatement to be the introduction of low-noise tyres because this had a considerable effect on reducing noise but no had side-effects; it also cost very little given that the noisiest tyres could effectively be removed from the market through emission legislation (Nijlanda et al., 2003). The introduction of legislation on tyre labelling (effective 1 November 2012) should assist consumers in making tyre choice on the basis of their noise emission characteristics. Other mitigation measures that have demonstrated success but have yet to be evaluated in the literature in terms of their cost-effectiveness/cost-benefit include urban traffic management and land use measures. Land

[7]The average cost per apartment for insulation in the Norwegian study was estimated at EUR 28,125 when applying an exchange rate in the year 2006 of 8 NOK to 1 EUR.

use management measures would seem to be particularly effective because it involves putting distance between the source of transport noise and the receivers. This can be done through thoughtful road and/or railway network design.

For railway noise, the most cost-effective measures are once again those taken to prevent noise at source. The most commonly used approaches include improving those associated with rolling stock (brake-block technology, optimised wheels), track measures (rail absorbers,[8] acoustic grinding to smooth rail tracks) and noise barriers. Results from the STAIRRS project (Strategies and Tools to Assess and Implement noise Reducing measures for Railway Systems) analysing the cost-effectiveness of railway noise reduction on a European scale found that improving the braking system of rolling stock was the most cost-effective measure (Oertli, 2003). A more recent study for the European Commission came to similar conclusions suggesting that the most cost-efficient solution is to retrofit the fleet with low-noise brake blocks (EC, 2007). However, this is dependent on the evolution of the noise abatement performance of low-noise brake blocks over time because little research has been conducted on this specific issue. The STAIRRS study also found noise barriers to have poor cost-efficiency especially if the barrier exceeds 2 m in height. Overall, as with the case of road mitigation measures, the most cost-effective approach is to utilise a mix of measures. Track measures in combination with rolling stock measures tend to be highly cost-efficient. However, the best results can be achieved via a solution combining low-noise break blocks, optimised wheels, tuned rail absorbers, grinding and noise barriers not higher than 2 m (Oertli, 2003). This mix of abatement measures protects close to 95% of the population and is relatively cost-efficient. Yet solutions for abatement do tend to be expensive. Oertli (2006) suggests that to reduce noise levels below 60 dB, annual costs of between €20,000 and 100,000/km may be necessary.

Regarding aircraft noise, since the late-1990s there have been dramatic increases in noise restrictions at airports. Figure 7.13 shows, in particular, the exponential increase in the use of noise abatement approaches at airports. The most common approaches used for abatement at airports include imposing noise limits, preferential runways and in-flight noise abatement procedures, curfews, mandatory phase-out of noisier aircraft and other operational restrictions. However, there is no direct cost analysis of these measures in the literature so it is impossible to evaluate their cost-effectiveness adequately. However, one recent study was completed assessing the cost-benefit of the overall noise abatement strategy at O'Hare International and the results found that the benefit of implementing the

[8] Rail absorbers are fitted to tracks to reduce rolling and squealing noise.

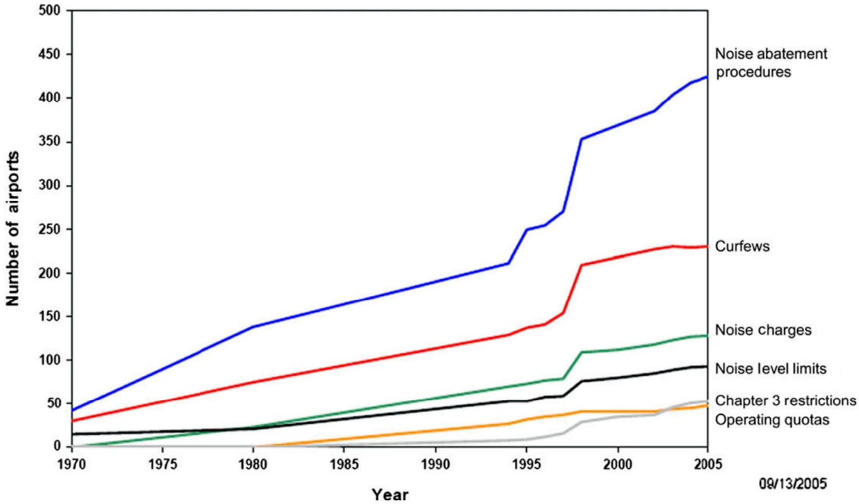

FIGURE 7.13 Trends in noise restrictions at airports. *Source: Girvin (2009) using Boeing data.*

programme outweighed the costs for the local community by a factor of 3 (Brown et al., 2004). Most of the advances in restriction of aircraft noise at source[9] have come from improvements in aircraft design and improved engine technology (Astley et al., 2007). In this regard, there is significant research on-going for developing quieter aircraft but this has occurred mainly as a result of stricter certification standards (Girvin, 2009).

7.8 CONCLUSION

Given the trajectory of this book to date, the current chapter provides an appropriate and logical penultimate chapter. The reason for this is that the ultimate goal of understanding the principles, modelling techniques and the effect of noise pollution on humans is to reach a stage where the harmful effects of excessive exposure can be reduced. In this regard, the foregoing chapter does exactly that. It focuses on the various approaches that can be utilised as noise reduction measures. Thus, an outline of the most commonly used source and propagation measures for noise reduction has been provided. In this regard, the chapter demonstrates that the most effective approach towards noise mitigation is to reduce noise at the source – this is not only the most efficient method from a technical perspective but these measures are also the most cost-efficient way in which to abate noise in

[9]Aircraft noise sources include airframe noise, jet-mixing noise, fan, and compressor turbine and combustor noise.

sensitive areas. The most effective approach for reducing noise at source is through legislation which focuses on reducing permissible noise levels of transportation and outdoor machinery vehicles at the point of manufacture. Having said this, it is important to remember that policies to reduce the extent of the noise problem in the future will need to look simultaneously at source and receiver measures so that a comprehensive and coherent strategy for noise reduction is put in place at a number of different levels.

The chapter also focussed on the concept of noise action planning introduced as part of the EU Environmental Noise Directive. The elements in the process were outlined, and best-practice case studies were provided in relation to noise control and reduction for the key sources of environmental noise – roads, railways and aircraft. Effectively, noise action planning represents the largest and most wide-scale programme of noise abatement in the world. It is fast becoming best international practice with regard to how responsible authorities and related policymakers can deal with noise control issues in a practical and inclusive manner. It is likely, therefore, that the principles enshrined in the EU noise action planning process will be improved upon and utilised in many jurisdictions around the world.

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CHAPTER

8

Conclusions and Future Directions

Environmental noise pollution is a complex issue. The previous chapters in this book illustrate the multifarious nature of issues surrounding the understanding and control of sound that is out of place. The problem with noise pollution though is that it is not only a complex issue but also a highly persistent one. As a public nuisance concern, it has been steeped in the awareness of the public consciousness for millennia but has not really been taken seriously enough by policymakers who have tended to prioritise other seemingly more pressing environmental issues. And so, despite centuries of scientific endeavour along with attempts to control and mitigate noise, the problem continues to rumble on. Indeed, the rise in the ownership and use of private transport over the last century has arguably turned the rumble of noise pollution into something of a roar.

Until relatively recently, there was certainly some truth in the notion of environmental noise as the forgotten pollutant. Others (such as air pollution and stench) have been given much greater attention in policymaking over the last century and, while they have not been eliminated entirely, they have certainly been controlled to a much more significant degree. In fact, one might be forgiven for thinking that the damage (in terms of public health and general annoyance) associated with noise pollution is not really improving at all. Certainly, of all pollutants, noise is one that is practically impossible to escape from in our daily lives. The rapid urbanisation of populations witnessed throughout the globe over the last century combined with the growth in private transport has meant that both neighbourhood noise annoyance and noise from transportation sources are becoming a more pressing problem.

However, these are not the only reasons why noise is still a major contemporary pollution issue. There are numerous reasons. A crucial additional one is alluded to by Goldsmith (2012) who informs us that because the ear evolved largely as a warning system, noise is considered by humans to be intrinsically disturbing. This relationship is what gives the ear its extraordinary sensitivity allowing it to detect even the slightest flows of wave energy in the air. As Goldsmith (2013, p. 269) points out: 'even a perfectly sound-proofed building is hardly better than a shoddy one if the smallest of its windows is broken'. Indeed, this is also what makes mitigating noise pollution such a difficulty – it is very much an all-or-nothing kind of business. In other words, partially mitigating noise will have very little effect on the level of disturbance being felt by a person subjected to noise. Moreover, precisely because some people are more sensitive to noise than others, it means that reducing noise below a certain level may be acceptable to one person but not to another who might still feel disturbed.

The issue of the subjective nature of noise annoyance poses quite a problem for those who are interested in developing and standardising units of measurement that convey the extent of the intensity of noise. We know that the decibel and the A-weighted system were developed precisely for this purpose, but they are far from being perfect. We also know that the various indicators used to measure annoyance and disturbance are fairly crude in that they do not adequately deal with the varying range of subjective human responses to different noise sources, nor do they deal adequately with different types of noise, in particular impulsive, intermittent and low-frequency noise. And of course, all of these issues pose problems for policymakers that are attempting to regulate the extent of noise.

It is also important that we do not forget the major societal changes that have occurred over the last half century which has made the problem of noise pollution even more difficult and complex to tackle. The traditional past societal arrangement of individuals working a typical 9–5 day has changed significantly with increasingly flexible working arrangements bringing about a more varied 'working day' which can often overlap with the night-time period. Of course, greater night-time activity means that that noise is becoming increasingly difficult to control during traditional sleeping hours between 11 pm and 7 am and this is where the major problem lies in terms of the health implications of noise-induced sleep disturbance and related secondary effects. Other changes in the way city regions are planned and organised over the last half decade have also impacted on noise pollution. The traditional past approach of mono-functional zoning where polluting activities (e.g. heavy industry, manufacturing) were separated from residential areas is no longer typical practice in urban and regional planning. The restructuring of western economies away from manufacturing industry to more service-oriented and 'cleaner' industry has allowed for more mixed-use zoning systems to be adopted. In fact, this approach is now considered best international practice in the vast majority of developed countries. Thus, employment, housing, retail and entertainment facilities now exist adjacent to each other in urban areas, meaning that the noise produced from the intermixing of these land use activities (e.g. commuting, socialising, shopping among others) is felt to a much larger degree by present-day households than by households under past land use arrangements.

While the tone of the foregoing discussion might suggest then that the problem of environmental noise is getting worse, it is merely attempting to reflect more broadly on the situation in which we find ourselves. There really is no concrete way to determine if noise pollution is better or worse now than it was a century ago because the socio-political context was very different then than what we have today. Moreover, how noise was understood, measured and controlled was also very different than current practices while modern technologies simply cannot be compared to those existing even in the relatively recent past. Broadly then, it is virtually impossible to compare the noise situation today with centuries ago because there is simply no common basis for such a comparison. Nor are we suggesting that noise is an insoluble problem or, more importantly, that no progress has been made in understanding environmental noise, its human impacts and how we might control it. On the contrary, progress has been very significant indeed. Many of the major noise sources discussed in this book – automobiles, trains, airplanes – are now subject to much stricter noise limits than they were at any point in the past. Noise from industrial equipment (and therefore industry more generally) is similarly subject to much stricter limits. In addition, many nations have legislated for night-time noise limits at the point of the receiver, modern homes tend to be built with better sound proofing, and mitigation measures have become more effective. And yet, the inescapable (and somewhat depressing) conclusion of the World Health Organisation (WHO) is that 'the trend [for] noise exposure is increasing in Europe compared to other stressors (e.g. exposure to second hand smoke, dioxins and benzene), which are declining' (WHO, 2011, p. 1).

On the face of it, all of this comes across as something of a contradiction – how can we be making progress while the problem is getting worse? The answer of course is that while progress is indeed being made, it is being achieved within the context of a massive increase in the volume of noise-related activity – populations are growing, population distribution is becoming increasingly concentrated and private vehicle ownership and use are increasing at the same time as the role of public transport is declining and these issues have placed significant limits on the impact of progress that has been made. In the context of this book, this is quite a crucial point. The reason is that, quite aside from the book's important description of the technical detail associated with noise pollution, the general narrative running through this chapter has focussed on conveying two key issues. The first is that it documents the *progress* that has been made over the recent past in understanding the nature of environmental noise pollution, its effect on humans and how it can be better understood and assessed to ensure more effective mitigation and control. The second issue relates to the book's implicit focus on the *limitations* of existing knowledge/understanding in the aforementioned areas of environmental noise pollution and how they might be improved in terms of both future research and practice.

8.1 PROGRESS

Perhaps the most important reason that has contributed to driving progress in our knowledge of environmental noise over the last half century relates to our understanding of the relationship between noise and human health. In particular, we now know much more about the relationship between doses of environmental noise and their direct and indirect health effects as outlined in Chapter 2. There is little doubt that our enhanced knowledge of the detrimental health impacts of long-term noise exposure, even at relatively low levels, has been the catalyst for environmental noise issues to become an important environmental and public health policy consideration.

In relative terms, there has been an explosion of research on the health effects of environmental noise over the last half decade. We have moved from a situation where the nature of dose–effect relationships was only partially understood to a situation where scholars now have a relatively good handle on the nature of the public health problem caused by exposure of populations to excessive environmental noise. As elucidated in Chapter 2, we now know that excessive exposure either causes or is directly associated with a range of health effects, not only primary effects such as sleep disturbance but also a range of secondary effects that are felt as a result of disturbed sleep. We know that the primary effects of noise exposure on health are in terms of annoyance, sleep disturbance, cardiovascular disease, tinnitus and cognitive impairment in children. For example, it is only in the last 20 years that a clear association has been established between noise exposure and higher incidence of cardiovascular disease which has been a major leap forward in understanding. Research has also taught us that annoyance and sleep disturbance resulting from noise pollution exposure act as a significant health stressor which can lead to and/or trigger more serious health problems.

Moreover, the emergence of the DALY[1] has only recently allowed for a quantification of the health effects of environmental noise at the EU level

[1]Daly is a disability-adjusted life year. See Chapter 3 (Box 3.1) for a broader explanation of its origin and Section 3.1 for technical details.

(see Table 3.1) which was not possible a half decade ago. Our understanding of not only the nature of the dose–effect health relationships but also the scale of the problem across the globe is considerably improved. Indeed, the scale of the problem is quite staggering and yet we still do not quite have a complete grasp of it. In 1999, the WHO estimated that almost 50% of European citizens lived in grey areas of acoustical discomfort. While the composition of the EU has changed considerably in the intervening period, the first phase of noise mapping (conducted in 2007) showed that approximately 40 million people across the EU are exposed to noise above 50 dB(A) from roads within agglomerations during the night with a further 22 million exposed outside agglomerations. Given that the WHO (2009) sets 40 dB(A) night-time as the value above which health effects are noticeable (see Chapter 3), these figures emphasise quite clearly not only the (almost) ubiquitous nature of the problem but the fact that the potential problems associated with the overexposure to noise pollution are at such a scale as to consider it a major public health issue for policy makers. But of course, the health effects are not confined to the EU – it simply happens to be the one continent for which we have decent data on the scale of noise pollution exposure. What the European case shows is that environmental noise is a global problem and no nation is immune from its associated problems.

As a direct consequence of improvements in our understanding of the noise–health relationship, noise policy and legislation have underwent very significant and positive changes throughout the EU. As it now stands, there is little doubt that the EU has the world's most progressive noise legislation and policy in terms of attempting to protect its citizens from the detrimental effects of excessive exposure to environmental noise pollution. Quite important is the fact that many other nations beyond the EU have looked towards what the continent has been doing and, while few nations have taken identical steps, there would certainly appear to be much more cognisance of noise as an environmental and public health problem in other nations as a result of EU legislative and policy changes. Since the 1970s, the EU has consistently legislated for stricter permissible noise limits on manufacturers of automobiles, trains, aircraft, outdoor equipment, recreational craft and household appliances. Table 4.1 (Chapter 4) provides a good illustration of the range of legislative Directives that have been issued in these areas. Utilising legislation to drive down permissible noise limits has forced manufacturers to improve their technologies in such a way that they now make much quieter vehicles and appliances than they did in the past.

There is little doubt also that the introduction of the Environmental Noise Directive (END) into legislation in 2002 has been important in getting to grips with the extent of the noise problem across the EU but it has, perhaps, been even more important in raising awareness of environmental noise as a major environmental concern as well as a public health problem. For the first time, the END has provided a strategic approach to assessing and controlling the environmental noise problem at a supra-national level and this has been a major progression. While the END still only provides estimates of the population exposed across the EU, it has provided the first real glimpse of the scale of exposure across the Union. And as mentioned already, the scale of the problem is considerable. Moreover, these estimates were used as the basis for quantifying the extent of the disease burden associated with night-time noise exposure across the EU in the WHO's recent *Burden of Disease from Environmental Noise* document. This would not have been possible without estimates of population exposure arising from the END. Moreover, the END has also provided a strategic framework for nations within the EU to work together, share information and best practice approaches towards understanding how best to assess and control noise as a pollutant. More broadly, it has facilitated enhanced co-operation among responsible authorities right across the EU and indeed within individual EU nations. All of this represents significant progress. Prior to its introduction, some nations did indeed take the problem of environmental noise seriously, but for others, it was barely on the policy radar. Effectively, because the END mandates a strategic approach across the continent, it has meant that all nations are at least ensuring minimum compliance and engagement with the problem of environmental noise pollution and this is a considerable step in the right direction even if there remains significant work to be done. Indeed, it is quite clear that it is only through a strategic approach that progress can be made on reducing the harmful effects of noise pollution for citizens.

On the technical side, there has also been considerable progress in noise prediction capabilities although perhaps not as much as one might like. Nevertheless, there are a number of significant achievements to note. Perhaps the most noteworthy relates to the ongoing development of common noise calculation models for road, rail, air and industry across the EU. It has long been argued that unless noise calculation is standardised across the EU, it is very difficult to compare the results of population exposure estimates (Murphy and King, 2010). At the EU level, research funding has been provided to support movements in this direction since the turn of the century beginning with the HARMONOISE project and culminating in the standardised CNOSSOS-EU noise calculation model which is due to be introduced and utilised by all nations in the 2017 round of strategic noise mapping. The development of a standardised model has not only been technically complex but also difficult at a practical level given the existing variation in national calculation models across the continent. The movement towards the completion and roll-out of such a model over the next few years represents a remarkable progression on what exists at present. Ultimately though, the success of the method will be judged on its rate of adoption across all Member States.

The efficiency of developing noise maps is intrinsically linked with the development of the personal computer. When the END was first initiated, it was a computationally intensive task to develop a noise map for an entire city. Even in the last 10 years, the computational efficiency of computers has increased exponentially and a city noise map can now be developed overnight. The possibilities behind harnessing this potential are only just being realised with the development of 3D and interactive noise maps. For example, real sounds can be linked to maps, or maps can be cross-referenced with noise complaints in a city, offering the general public an appreciation and understanding of the concepts associated with environmental acoustics.

Another significant development is the introduction of common indicators of annoyance (L_{den}) and sleep disturbance (L_{night}) across the EU as part of the END. While there are some concerns about the viability of these indicators for doing what they were introduced to do, their introduction has nevertheless ensured that there is a common basis for comparison (at least in terms of indicators) across the continent. This is important because prior to their introduction, a wide variety of indicators were used for assessing annoyance and sleep disturbance within individual nations. However, the use of supplemental indicators, which is catered for under the END, needs to be encouraged. In fact, future research should focus on the potential benefits of supplemental noise indicators which may be used in parallel with L_{den} and L_{night} in the strategic noise mapping process.

Acousticians now also have access to a range of noise-monitoring equipment that was previously unimaginable. It is now possible to measure noise over very long time periods and to monitor results in real time. It is also possible to remotely access real-time sound recordings and analyse frequency spectra at the click of a button. The key challenge for the future is to utilise this technology in the future development of noise and noise assessment studies and noise policy. The need for a single number noise indicator is needed so policy and guideline limits can be changed to offer more detailed noise criteria and thus enhanced protection for citizens. Consider, for example, the A-weighting system which was designed to reflect how the human ear responds to sounds at different frequencies. Modern sound level meters can now produce one-third octave analyses as standard, so design goals may be set in terms of third octave levels instead of an overall dB(A) figure.

The other main area of progress has been in relation to raising awareness. While we have no concrete data which shows that people are more aware of the problems associated with noise pollution now than they were in the past, anecdotal evidence as well as evidence from EU surveys of public attitudes would seem to suggest that there is indeed a greater awareness of noise pollution among the general public today than in the past. For example, a recent Eurobarometer survey showed that 44% of Europeans believe that noise affects human health to a 'large extent', an increase of 3% since 2006 (European Commission, 2010). The increase suggests, albeit tentatively, that awareness of noise-related health issues is increasing. There is little doubt that this improved awareness is related to the introduction of the END. The legislation mandates that the results of the strategic noise mapping process be disseminated to the general public. While there has been some problems with this (alluded to in the next section), it still remains that noise pollution information is now more accessible and readily available to the general population of the EU than at any time in the past. This is a significant achievement. Moreover, as well as raising awareness among the general public, understanding has also been raised among local authority officials, administrators and policymakers about noise pollution issues. The manner in which the END has been implemented among Member States effectively ensures that local, national and regional officials must co-operate and exchange information, data and knowledge about the noise mapping process in order to ensure national compliance. Moreover, there is now also a much greater degree of dialogue among national officials and policymakers across the EU than there has ever been before.

Perhaps one of the more slow moving areas in terms of progress in recent years has been in the area of noise pollution mitigation. Considerable research has been undertaken, and is ongoing, assessing how mitigation approaches can be improved both in a technical sense and how they can be made more cost effective in an increasingly strained financial environment. Improvements have been made in how buildings are insulated, in more efficient low noise road surfaces, better track and braking systems for railways as well as improvements for design of quieter aircraft, to point out only a handful of progressions. Indeed, researchers have also investigated more innovative solutions to noise mitigation though the concept of soundscapes which aims to focus more on the positive sounds associated with a particular environment (through masking negative sound sources) rather than emphasising the negative aspects of a place (see Chapter 7, Section 7.5.4). However, the pace of progress in this area could certainly be faster. In this respect, noise mitigation is one of the areas that simply must be targeted for significantly more research over the coming years if the problem of environmental noise pollution is to be reduced not only at the European level but also throughout the world.

Over the last two decades, the volume of research activity in the area of environmental noise pollution has increased quite substantially. There have been significant improvements in our understanding particularly of the devices used to measure noise and how noise is modelled at the source as well as how it propagates away from the source. Commercial software has also improved dramatically, meaning that noise calculations can be completed for much larger study areas than in the past. Moreover, since the introduction of the END into legislation there has been a raft of new research completed not only examining the extent of population exposure in various countries around the world but also investigating ways in which the strategic noise mapping process can be improved or utilised to assist with understanding other noise pollution issues beyond the remit of the END (e.g. noise insulation of buildings, 3D visualisation of noise mapping results). Chapter 4 (Section 4.4) provides details of some of this research, but it is far from being exhaustive. The upshot of the increase in research output in environmental noise pollution is that we now have a much better understanding of environmental noise issues and how they might need to be addressed than at any point in the recent past.

8.2 LIMITATIONS AND FUTURE RESEARCH PRIORITIES

The foregoing section has highlighted the extent of the progress that has been made with respect to environmental noise pollution over the last decade. Nevertheless, this does not mean that the situation is perfect and does not require any further investigation or scrutiny. Rather, there are significant areas where our understanding of environmental noise issues needs further improvement and if recent progress has taught us anything it is precisely that our knowledge is quite limited in a number of areas related to noise pollution, its negative effects and how to control them. In fact, it is the role of scholars, in particular, to identify areas that might be worthy of more scrutiny and offer suggestions for potential solutions that should be investigated through more targeted research that serves as evidence for improving policy.

While the END is symbolic of the significant progress that has been made in recent years, the sheer scale of its ambition as a large-scale noise assessment and reduction programme has meant that it was always destined for teething problems after it was introduced into legislation. One of the major weaknesses of the END and any environmental noise legislation is the lack of clearly stated limit values, particularly for the night-time period, above which noise levels are not legally tolerated. A recent report commissioned by the EU has pointed out that this weakens the impact of the END because it fails to set a common level of ambition for the EU with regard to noise quality (Guarinoni et al., 2012). While it is understandable that noise limits were not put in place immediately under the terms of the END, enough time has now passed and significant intellectual and administrative capacity been developed to ensure that the EU can now move towards even more ambitious noise reduction targets. These should take the form of limit values that are introduced progressively under amendments to the END legislation. Indeed, 19 Member States (out of 27) already have legally enforced noise limit values. If these are exceeded, measures to control noise and/or to insulate exposed populations are implemented. In some nations, financial penalties are also imposed on those responsible for the source of the pollution. This has led Guarinoni et al. (2012) to recommend that trigger values rather than legally binding limit values should be introduced in the short term with a view to moving towards imposing limit values in the medium term future across the EU.

In relation to the END, there is little doubt that more concrete guidance information needs to be provided to Member States on implementation. In this context, there is certainly scope for guidance information to be provided on strategic noise mapping, action planning, trigger values, the definition of quiet areas as well as specific ways in which results can be disseminated to the general public. In these areas, perhaps the most pressing need for guidance is in the area of noise action planning as well as in the definition of quiet areas. Both of these areas seem to be relatively poorly understood (European Commission, 2011), and the expectation of how the END is to be implemented in these areas is quite confused at present. In relation to action plans, while several Member States produced national guidance on action planning for the first phase of END implementation, many did not. However, the documents already produced by individual nations could certainly be used as a basis from which to develop EU guidance for future rounds of END implementation. Turning to quiet areas, it is clear that the END leaves considerable (perhaps too much) discretion at the hands of Member States in delimiting quiet areas. This needs to be addressed in future research and practice because at the moment, the preservation of areas of good sound quality appears very much as an afterthought in END implementation. Indeed, this has been recognised by the EU and the current EEA Expert Panel on Noise (EPoN) is currently working to produce a green paper on the management of quiet areas specifically within the context of END implementation (Guarinoni et al., 2012).

The introduction of the new annoyance and sleep disturbance indicators L_{den} and L_{night} has undoubtedly been important for standardisation purposes across the EU. However, our knowledge of the suitability of these indicators for adequately representing annoyance and sleep disturbance in the field remains fairly limited. To take L_{night} as an example, it is pretty rare for studies of sleep disturbance in the literature to cover the entire 8-h night-time period. In addition, very few studies have utilised the L_{night} indicator as an expression of sleep disturbance. In fact, it is quite likely that the L_{night} noise indicator underestimates the extent of sleep disturbance because it averages noise over a long period effectively smoothing out and downgrading the impact of intermittent and impulsive noise events that are known to have a highly negative effect on sleep patterns. Thus, our knowledge of the suitability of such indicators for doing what they are intended to do is somewhat flimsy. If we are to continue to use these indicators in future rounds of noise mapping and population exposure estimation at the EU level, research will need to prioritise investigating their suitability or otherwise for achieving their stated intentions. Bearing this in mind, future research should focus on improving the prediction of subjective sleep disturbance by adding the possibility within the END of utilising noise descriptors other than L_{night}. These could include descriptors penalising noise in the early or late part of the night-time period, descriptors of peak noise levels or noise events to assess the problem of intermittent or impulsive noise more effectively (e.g. SEL, L_{peak}, L_{max}).

While the END has been highly successful at seeking and enforcing international agreement on large-scale strategic noise pollution issues, it has been much less successful at utilising the results of the process to drive real change and action at the local level. In fact, the recently published END implementation report has pointed out that despite the wide-scale noise mapping and exposure estimation of EU populations, it is likely that noise pollution has not been reduced at all (European Commission, 2011). While this shortcoming is largely as a result of a lack of ambition with regard to action planning on behalf of some nations (others have done a very good job), it is also related to the relatively poor way in which results of the process have been disseminated to the general public. A number of scholars have pointed to the piecemeal way in which the public have been invited to engage with noise pollution results and much more could be done in this area (see Guarinoni et al., 2012; Murphy and King, 2010). It is crucial then that in the future, this aspect (public dissemination) of the END is given more thoughtful consideration because raising public awareness about the extent of noise pollution issues is likely to be very important for developing and enhancing public and indeed political support for future noise reduction measures through action planning as well as through further legislation and policy improvements.

There are also significant limitations with how population exposure is estimated across the EU. In large part, these limitations have been forced either by data or by modelling limitations at the national level. In the EU, the imminent standardisation of noise modelling techniques should eliminate the problem of modelling variations. However, the problems associated with data and the method of estimating population exposure have yet to be dealt with satisfactorily. If these limitations are to be addressed, serious consideration must be given to developing a standardised international database of noise input data for noise modelling and population exposure estimation. And there is no reason at all why this could not be done; to a large extent, we already have a template for how this could work with the international database on aircraft sound power characteristics (see Chapter 5). This general approach could be extended to include other data sources necessary for noise mapping across the EU. Moreover, the recent publication of the *Common Noise Assessment Methods in the EU* (Kephalopoulos et al., 2012) document does provide the basis for standardising how population exposure is estimated in Member States, but refinement and additional clarifications are needed prior to its completion. Ultimately then, there is considerable scope for improvement in understanding, controlling and ultimately reducing the problem of environmental noise pollution, but it is likely that a key pathway towards achieving this goal is through more research and standardisation of approaches not only across the EU but also worldwide. Movements in this direction would not only facilitate relative differences in exposure to be identified across the globe but also enable more concrete indications about the role of variations in best practice environmental noise policy to be delimited, shared and transferred across national boundaries.

While there has been a dramatic increase in the volume of research undertaken investigating the relationship between noise pollution exposure and its impacts on human health over the last two decades, there remains much work to do to improve our understanding in this area. In general terms, there is overwhelming evidence to suggest negative health effects from environmental noise exposure. However, there are many areas where significant *association* has been developed between noise exposure and health conditions, but more research needs to be undertaken to investigate the issue of *causality* more vigorously. For example, the recent WHO (2011) *Burden of Disease from Environmental Noise* report clearly points out that there are some areas where there is not yet sufficient evidence to say definitively that noise is responsible for a particular health condition. For example, while there is increasing evidence demonstrating an association between noise exposure and increased risk of cardiovascular disease, the existing evidence stops short of providing any definitive statement on causality. Indeed, even in terms of association, there are areas that are under investigated. While we know, for example, that there is a clear association between noise exposure from road traffic and increased risk of ischaemic heart disease, including myocardial infarction, there is less evidence for such an association with aircraft noise simply because of a lack of studies investigating the issue (WHO, 2011). In a similar vein, there have been very few studies that have investigated the relationship between rail noise exposure and cardiovascular disease and thus we must reserve judgement on the nature of these relationships until more evidence is made available. Indeed, the link between noise exposure and tinnitus, while well established, remains fairly poorly understood. In terms of hearing loss, the WHO (2011, p. 100) recently concluded that 'epidemiological studies linking hearing impairment to environmental noise exposure are so sparse that any generalisation can be considered exploratory and speculative'. Moreover, the WHO (2011) also suggest that there is not yet sufficient evidence to suggest that children are more vulnerable (in that they react differently) to noise exposure than other population groups despite some studies suggesting otherwise. In this regard, the reaction of children and other potentially vulnerable groups (e.g. the elderly) to excessive noise exposure needs to be investigated more definitively. On the other hand, existing evidence does suggest that there is a causal relationship between noise exposure and sleep disturbance and 'depending on noise levels, may impair behaviour and well-being during the subsequent period awake' (WHO, 2011, p. 55). There is also sufficient evidence, indicating a causal relationship between noise exposure and annoyance. Clearly then, while our present understanding of these relationships is much greater than at any time in the past, there are some relationships that will require much more significant scrutiny if we are to establish more definitive statements on the impacts or otherwise of environmental noise pollution on public health outcomes.

Finally, the role that technology can and will play in the future prevalence of noise pollution is likely to be considerable. Over the last half decade, the major improvements that have been seen in noise reduction emissions from transport vehicles, in particular cars and aeroplanes, have come primarily from improvements in engine and tyre technology. Looking to the future, there is little doubt that technology will remain pivotal to creating quieter urban and rural environments. One area where this is likely to be crucial in the not too distant future is in relation to the imminent development of electric cars. Given that road traffic noise is the most important source of environmental noise, there is a significant opportunity to reduce pollution and associated health problems through the wider substitution and use of these vehicles over chemically powered ones. Electric cars are much quieter than chemically powered ones although at the moment battery technology does not quite appear to be at a stage that would ensure their widespread adoption. Nevertheless, although they are likely to be equipped with sound that will act as a substitute for engine noise, if it is directional, short range and generally pleasing (or at least not annoying), these vehicles have the potential to allow for a significant reduction in annoyance and sleep disturbance.

Technology will also be important in other areas. The development of low-cost noise measurement devices is likely to play a greater role in the future. The development of noise apps for Smartphones, while currently not very reliable, is likely to become more important as technology improves in the future. It is likely then that the public could contribute much more significantly than at present in providing noise measurement data through mobile/cell phones in a form of 'citizen science' (D'Hondt et al., 2013). The technology utilised in mobile/cell phones is MicroElectroMechanical Systems (MEMS) microphones which can be constructed relatively cheaply and at a low cost. As the reliability of these microphones is improved in the future, they will undoubtedly provide a much better scope for measurement-based noise mapping or indeed low-cost validation of noise modelling results. We can only hope that these, together with other improvements, will provide for a much quieter future and that quite soon we can truly refer to environmental noise as the forgotten pollutant.

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