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

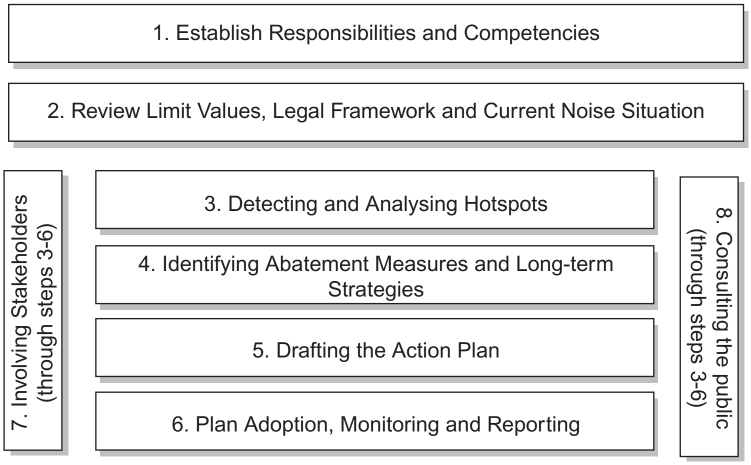

FIGURE 7.1 Overview of the action planning process. *Source: Adapted from Kloth et al. (2008).*

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

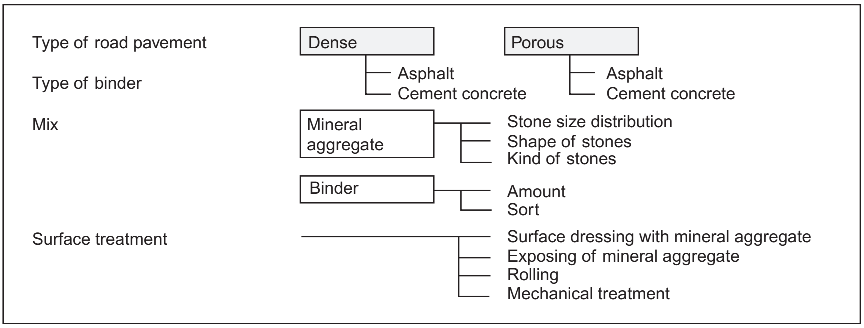

FIGURE 7.2 Acoustically relevant civil engineering properties of road surfaces. *Source: Kropp et al. (2007, p. 21)*

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).

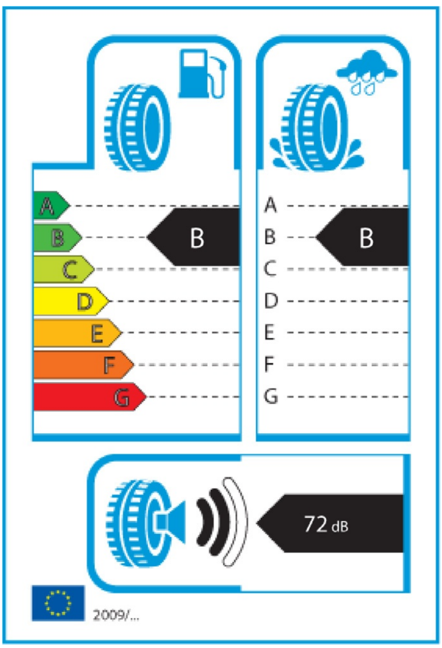

FIGURE 7.4 New EU tyre labelling system incorporating tyre noise information.

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

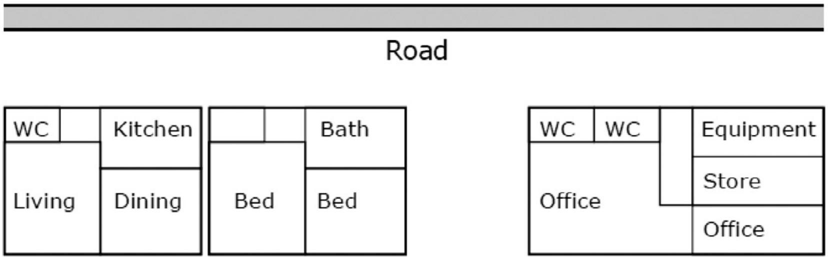

FIGURE 7.5 Noise-compatible room layout. *Source:* *Nelson (1987).*

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'.

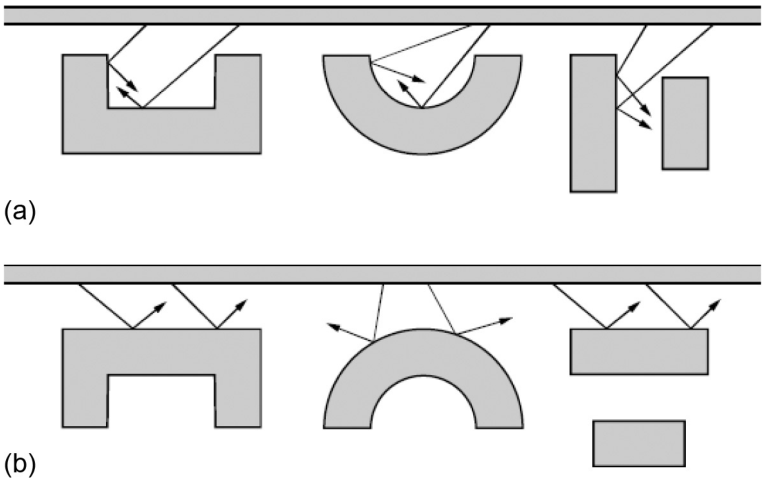

FIGURE 7.6 Noise reflection at buildings: (a) to be avoided and (b) preferred. *Source:* *Nelson (1987).*

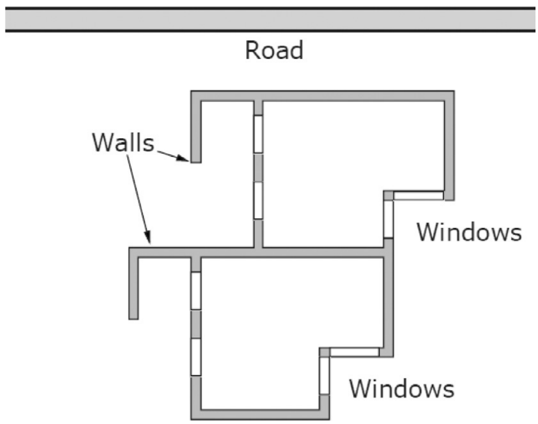

FIGURE 7.7 Illustration of how wing walls can be used to prevent noise immission. *Source: Nelson (1987).*

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

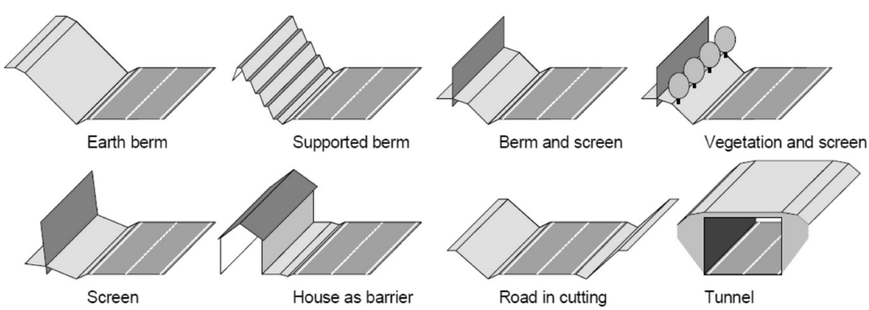

FIGURE 7.8 Range of potential noise barriers. *Source: Paikkala et al. (2002).*

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).

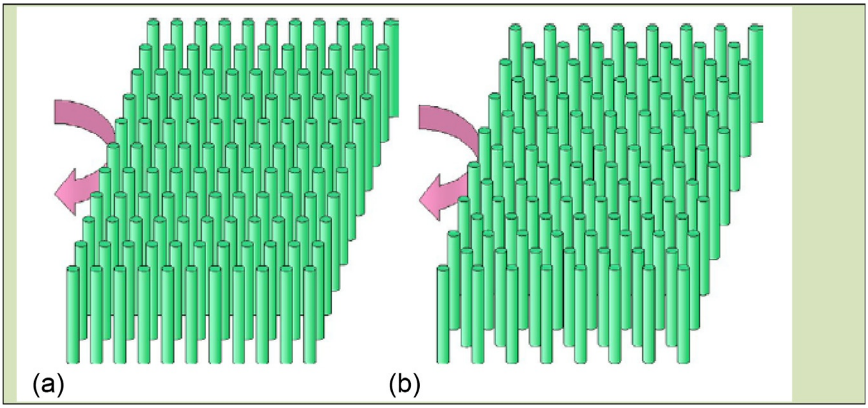

FIGURE 7.11 Two-dimensional square-lattice structure of sonic crystals. *Source: Miyashita (2005).*

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 $R'\text{w} > 35$ 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.

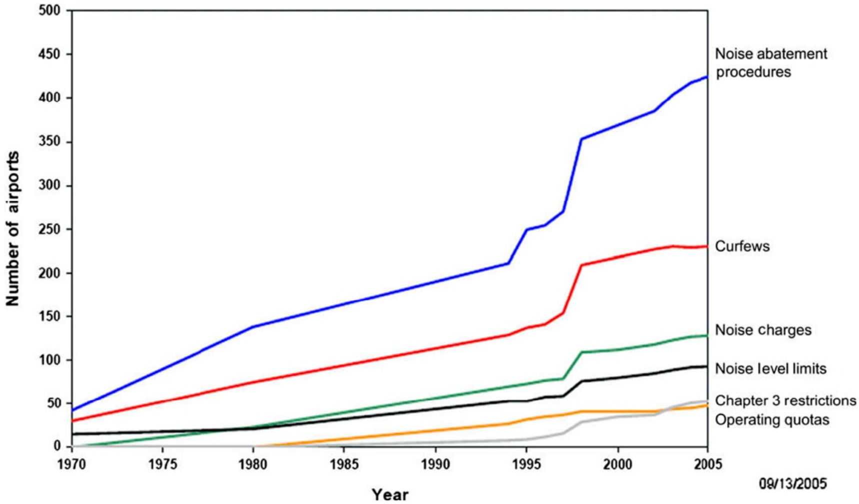

FIGURE 7.13 Trends in noise restrictions at airports. *Source: Girvin (2009) using Boeing data.*

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.

References

Amundsen, A.H., Klæboe, R., Aasvang, G.M., 2011. The Norwegian Façade Insulation Study: the efficacy of façade insulation in reducing noise annoyance due to road traffic. J. Acoust. Soc. Am. 129 (3), 1381–1389.

Andersen, B. 2003. Støjudsendelse fra biler på vejnettet. Danmarks TransportForskning, Lyngby, Report 2.

Arenas, J.P., 2008. Potential problems with environmental sound barriers when used in mitigating surface transportation noise. Sci. Total Environ. 405, 173–179.

Astley, R.J., et al., 2007. Predicting and reducing aircraft noise. In: ICSV14, Cairns, Australia, 9-12 July.

Bendtsen, H., Nielsen, E. 2008. DRI – DWW thin layer project – final report, Danish Road Institute, Denmark.

Bendtsen, H., Raaberg, J., 2007. Traffic safety and noise reduction – thin layers, Danish Road Institute, Technical Note 52, Danish Road Institute, Denmark.

Bendtsen, H., Kragh, J., Nielsen, E. 2008. Use of noise reducing pavements – European experience, Danish Road Institute, Technical Note 69.

Bendtsen, H., et al., 2010. Noise management and abatement. In: Conference of European Directors of Roads (CEDR), Paris.

Brown, A.L., 2010. Soundscapes and environmental noise management. Noise Control Eng. J. 58 (5), 493–500.

Brown, A.L., 2012. A review of progress in soundscapes and an approach to soundscape planning. Int. J. Acoust. Vib. 17, 73–81.

Brown, J., Seidman, J., Solanki, N., Neinstein, D., Factor, S., 2004. O'Hare International Airport Noise Pollution: A Cost-Benefit Analysis. Available at:http://www.areco.org/OhareAnalysis.pdf.

European Commission, 2007. Impact assessment study on rail noise abatement measures addressing the existing fleet, TREN/A1/46-2005.

European Commission, 2011. Report from the Commission to the European parliament and the Council on the implementation of the Environmental Noise Directive in accordance with Article 11 of Directive 2002/49/EC. 1.6.2011 COM(2011) 321 final, Brussels.

Girvin, R., 2009. Aircraft noise-abatement and mitigation strategies. J. Air Transport Manag. 15, 14–22.

Government of Hong Kong, 2003. Guidelines on Design of Noise Barriers. Government of Hong Kong Highways Department, Hong Kong.

Guarinoni, M., Ganzleben, C., Murphy, E., Jurkiewicz, K., 2012. Towards a Comprehensive Noise Strategy. European Union, Brussels.

Hosanna, 2013. Novel Solutions for Quieter and Greener Cities. Alloffset AB, Sweden.

King, E.A., O'Malley, V.P., 2012. Lessons learnt from post EIS evaluations of national road schemes in Ireland. Environ. Impact Assess. Rev. 32, 123–132.

King, E.A., Murphy, E., MacNabola, A., 2009. Reducing pedestrian exposure to environmental pollutants: a combined noise exposure and air quality analysis approach. Transp. Res. D. 14 (5), 309–316.

King, E.A., Murphy, E., Rice, H.J., 2011. Evaluating the impact on noise levels of a ban on private cars in Dublin city centre, Ireland. Transp. Res. D. 16 (7), 532–539.

Klæboe, R., Veisten, K., Amundsen, A.H., Akhtar, J., 2011. Selecting road-noise abatement measures: economic analysis of different policy objectives. Open Transp. J. 2011 (5), 1–8.

Kloth, M., Vancluysen, K., Clement, F., Ellebjerg, L., 2008. Practitioner Handbook for Local Noise Action Plans. Available at:http://www.silence-ip.org/site/fileadmin/SP_J/E-learning/Planners/SILENCE_Handbook_Local_noise_action_plans.pdf.

Kragh, J., Bendtsen, H., Handberg, K., 2009. Super quiet traffic: international search for pavement providing 10dB noise reduction, Report 178-2009, Danish Road Institute, Denmark.

Kropp, W., Kihlman, T., Forssén, J., Ivarsson, L., 2007. Reduction Potential of Road Traffic Noise. Alfa Print, Stockholm.

Licitra, G., Ascari, E., 2013. G_{den}: An indicator for European noise maps comparison and to support action plans. Sci. Total Environ. http://dx.doi.org/10.1016/j.scitotenv.2013.07.014.

Mahon, J., 2013. Good Practice Guide for Noise Barrier Design. National Roads Authority, Dublin.

Martinez-Sala, R., Sancho, J., Sanchez, J.V., Gomezs, V., Llinares, J., Meseguer, F., 1995. Sound attenuation by sculpture. Nature. 378, 241.

Martínez-Sala, R., Rubio, C., García-Raffi, L.M., Sánchez-Pérez, J.V., Sánchez-Pérez, E.A., Llinares, J., 2006. Control of noise by trees arranged like sonic crystals. J. Sound Vib. 291, 100–106.

Memoli, G., Licitra, G., 2013. From noise mapping to annoyance mapping: a soundscape approach. In: Licitra, G. (Ed.), Noise Mapping in the EU: Models and Procedures. CRC Press, Florida, pp. 371–391.

Miyashita, T., 2005. Sonic crystals and sonic wave-guides. Meas. Sci. Tech. 16, R47–R63.

Murphy, E., 2009. Excess commuting and modal choice. Transp. Res. A. 43 (8), 735–743.

Murphy, E., 2012. Urban spatial location advantage: the dual of the transportation problem and its implications for land-use and transport planning. Transp. Res. A. 46 (1), 91–101.

Murphy, E., King, E.A., 2010. Strategic environmental noise mapping: methodological issues concerning the implementation of the EU Environmental Noise Directive and their policy implications. Environ. Int. 36 (3), 290–298.

Murphy, E., King, E.A., 2011. Scenario analysis and noise action planning: modelling the impact of mitigation measures on population exposure. Appl. Acoust. 72 (8), 487–494.

Murphy, E., King, E.A., 2014. An assessment of residential exposure to environmental noise at a shipping port. Environ. Int. 63: 207–215.
Murphy, E., Usher, J. 2013. The role of bicycle-sharing in the city: analysis of the Irish experience, Int. J. Sustain. Transp. http://dx.doi.org/10.1080/15568318.2012.748855.
Nelson, P., 1987. Transportation Noise Reference Book. Butterworth, London.
Nijlanda, H.A., Van Kempena, E.E.M.M., Van Weeb, G.P., Jabben, J., 2003. Costs and benefits of noise abatement measures. Transp. Policy. 10, 131–140.
Oertli, J., 2003. The STAIRRS project, work package 1: a cost-effectiveness analysis of railway noise reduction on a European scale. J. Sound Vib. 267, 431–437.
Oertli, J., 2006. Developing noise control strategies for entire railway networks. J. Sound Vib. 293, 1086–1090.
Oertli, J., 2009. Railway noise abatement in Switzerland: a progress report, 8th European Conference on Noise Control 2009, EURONOISE 2009. In: Proceedings of the Institute of Acoustics 31 (Part 3).
Orteli, J., Hubner, P., 2010. Railway Noise in Europe: A 2010 Report in the State of the Art. International Union of Railways (UIC), Paris.
Padmos, C., Morgan, P.A., Abbott, P., van Blockland, G., Roovers, M.S., Bartolomaeus, W., Anfosso-Ledee, F., 2005. SILVIA Project Deliverable, Classification Scheme and COP Method. Available at:http://www.trl.co.uk/silvia/Silvia/pdf/Main_Outputs/SILVIA-DWW-025-14-WP2-141005.PDF.
Paikkala, S.-L., Talasch, W., Kihlman, T., Nikitara, I., Stocker-Meier, E., Curcuruto, S., Clinton, F., Nagel, E., Ross, B., Kuiper, J., Parjala, E., 2002. Inventory of Noise Mitigation Methods. European Commission, Brussels.
Pilton, A., Collins, G., Chapman, R., Gross, N., 2006. Noise Wall Design Guideline: Design Guidelines to Improve the Appearance of Noise Walls in NSW. Roads and Traffic authority, New South Wales, Australia.
Ripke, O., Andersen, B., Bendtsen, H., Sandberg, U., 2005. Report of Promising New Road Surfaces for Testing, Deliverable F.D4 of the SILENCE project. Available at:In: http://www.silence-ip.org/site/fileadmin/public_reports/SILENCE_F.D4_180805.pdf.
Samuels, S., Tsitsos, C., Parnell, J., 2009. The performance of noise barriers in attenuating road traffic noise. In: Proceedings of Euronoise 2009, Edinburgh, Scotland.
Sandberg, U., 2006. Tyre/road noise, vol. 2 appendices – appendix A: literature survey, final report SI2.408210, FEHRL, Brussels.
Schafer, R.M., 1977. The Tuning of the World. Knopf, New York.
Schafer, R.M., 1994. The Soundscape: Our Sonic Environments and the Tuning of the World. Destiny Books, Rochester.
Sperlich, P. 2003. Noise abatement: implementation in Switzerland.
Tadeu, A.J.B., Mateus, D.M.R., 2001. Sound transmission through single, double and triple glazing: experimental evaluation. Appl. Acoust. 62, 307–325.
Thompson, D., 2009. Railway Noise and Vibration: Mechanisms, Modelling and Means of Control. Elsevier, UK.
Thompson, D.J., Jones, C.J.C., Waters, T.P., Farrington, D., 2007. A tuned damping device for reducing noise from railway track. Appl. Acoust. 68, 43–57.
Torija, A.J., Ruiz, D.P., Alba-Fernandez, V., Ramos-Ridao, Á., 2012. Noticed sound events management as a tool for inclusion in the action plans against noise in medium-sized cities. Landsc. Urban Plan. 104 (1), 148–156.
van den Elshout, S., 2006. Communicating Air Quality. A Guidebook on Communication with the Public about Air Quality. Available at: http://citeair.rec.org/downloads/Products/CommunicatingAirQuality.pdf.
Veisten, K., Akhtar, J., 2011. Cost-benefit analysis of low-noise pavements: dust into the calculations. Int. J. Pavement Eng. 12, 75–86.

Ville d'Annecy, 2007. Agenda 21 Annecy: programme d'actions 2007-2014. Ville d'Annecy, Annecy.

Ville d'Annecy, 2013. Plan de prevention du bruit dans l'environnement des grandes infrastructures de transports terrestres sur la commune d'Annecy. Ville d'Annecy, Annecy.

Watson, D., 2006. Evaluation of benefits and opportunities for innovative noise barrier designs, Arizona Department of Transportation, Report Number FHWA-AZ-06-572.

Watts, G.R., Godfrey, N.S., 1999. Effects on roadside noise levels of sound absorptive materials in noise barriers. Appl. Acoust. 58, 385–402.

Watts, G.R., Crombie, D.H., Hothersall, D.C., 1994. Acoustic performance of new designs of traffic noise barriers: full scale tests. J. Sound Vib. 177, 289–305.

Watts, G., Chinn, L., Godfrey, N., 1999. The effects of vegetation on the perception of traffic noise. Appl. Acoust. 56, 39–56.

Wilson, C.E., 2006. Noise Control (Revised Edition). Krieger Publishing Company, Florida.

Yang, F., Bao, Z.Y., Zhul, Z.J., 2011. An assessment of psychological noise reduction by landscape plants. Int. J. Environ. Res. Public Health. 8 (4), 1032–1048.