CHAPTER

5

Transportation Noise

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.1 ROAD TRAFFIC NOISE

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

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

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

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

5.1.1 Rolling Noise

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

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

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

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

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

5.1.2 Engine Noise

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

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

BOX 5.1

ELECTRIC VEHICLES

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

FIGURE 5.1 Acoustic tests involving an electric vehicle in Ireland.

5.1.3 Road Traffic Noise Calculation Methods

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

NMPB96 (France)

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

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

BOX 5.2

NMPB 2008

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

CALCULATION DETAILS

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

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

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

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

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

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

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

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

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

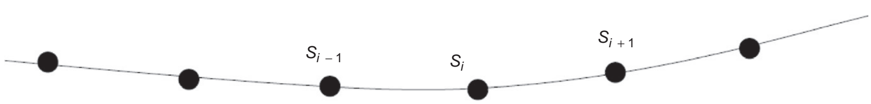

FIGURE 5.2 Segmentation of a road source into a collection of point sources.

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

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

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

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

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

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

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

TABLE 5.2 Values for the Spectral Correction, R_j

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

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

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

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

CRTN (United Kingdom)

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

BOX 5.3

THE ORIGIN OF CRTN

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

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

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

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

CALCULATION DETAILS

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

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

or

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

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

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

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

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

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

For concrete, the correction is:

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

For bituminous surfaces, it is:

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

BOX 5.4

COMPARING XPS31-33 AND CRTN EMISSION MODELS

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

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

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

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

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

Traffic Noise Model (United States)

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

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

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

CALCULATION DETAILS

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

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

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

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

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

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

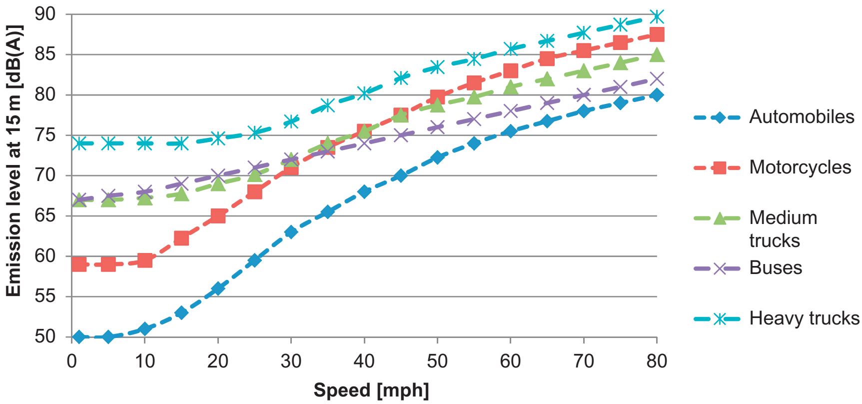

FIGURE 5.3 A-weighted noise emissions for separate vehicle categories under cruise conditions. *Adapted from Federal Highway Administration (1998).*

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

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

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

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

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

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

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

CNOSSOS-EU (The Proposed Common European Method)

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

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

CALCULATION DETAILS

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

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

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

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

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

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

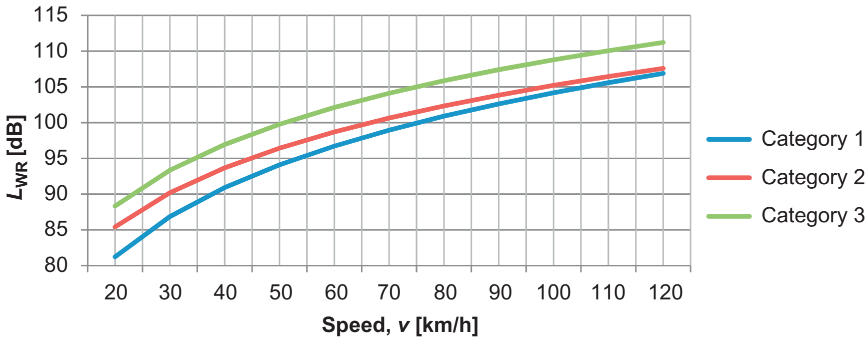

FIGURE 5.4 The variation of rolling noise with speed for the first three categories. Note that the CNOSSOS-EU method does not calculate rolling noise for powered two wheelers.

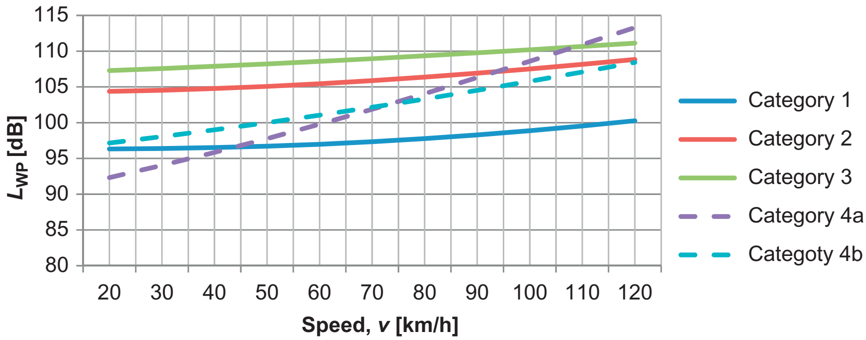

FIGURE 5.5 The variation of propulsion noise with speed for each vehicle category.

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

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

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

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

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

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

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

OTHER CONSIDERATIONS

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

5.2 RAILWAY NOISE

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

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

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

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

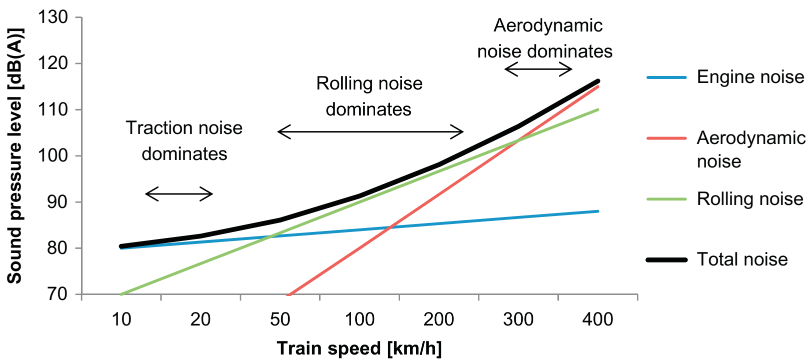

FIGURE 5.6 Approximate Relationship of different railway noise source mechanisms with speed. *Adapted from de Vos (2012).*

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

5.2.1 Rolling Noise

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

BOX 5.5

ROUGHNESS

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

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

BOX 5.5 *(cont'd)*

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

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

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

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

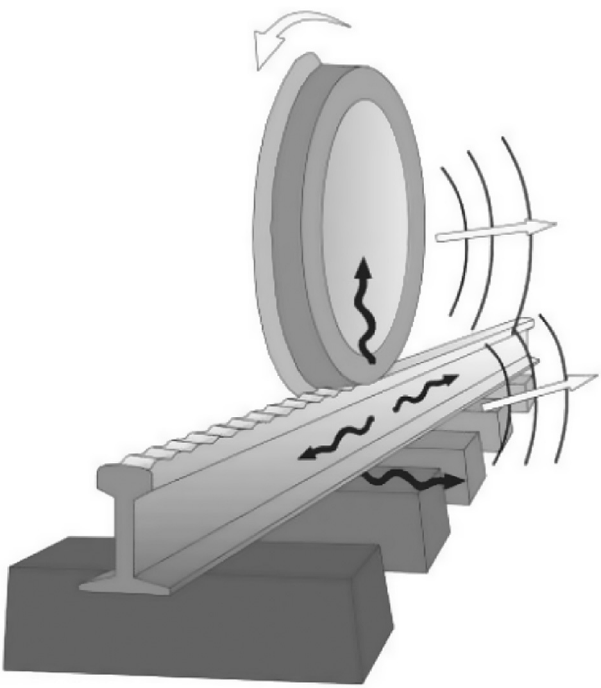

FIGURE 5.7 The mechanisms behind the generation of rolling noise.

5.2.2 Engine Noise

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

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

5.2.3 Aerodynamic Noise

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

5.2.4 Other Sources

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

5.2.5 Railway Noise Calculation Methods

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

Reken-en Meetvoorschrift Railverkeerslawaai (The Netherlands)

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

CALCULATION DETAILS

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

TABLE 5.4 Different Train Categories

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

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

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

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

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

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

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

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

TABLE 5.5 Emission Values as Functions of Railway Category, c

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

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

TABLE 5.6 Description of Different Track Types

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

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

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

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

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

Calculation of Railway Noise (United Kingdom)

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

CALCULATION DETAILS

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

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

or for diesel engines under full power:

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

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

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

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

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

Adapted from Department of Transport (1995).

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

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

Adapted from Department of Transport (1995)

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

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

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

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

BOX 5.6

CRN AND THE END

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

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

CNOSSOS-EU (The Proposed Common European Method)

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

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

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

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

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

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

CALCULATION DETAILS

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

ROLLING NOISE

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

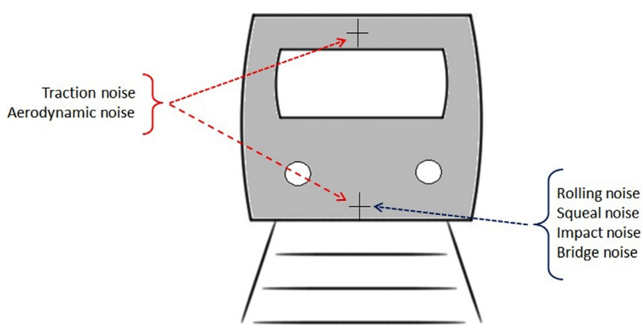

FIGURE 5.8 Sketch of source positions for each source mechanism in the CNOSSOS-EU method.

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

TRACTION NOISE

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

IMPACT NOISE

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

SQUEAL

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

TABLE 5.9 Simple Corrections for Curve Squeal

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

AERODYNAMIC NOISE

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

ADDITIONAL EFFECTS

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

5.3 AIRCRAFT NOISE

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

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

BOX 5.7

AIRCRAFT NOISE COMPLAINTS

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

(*Continued*)

BOX 5.7 (*cont'd*)

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

5.3.1 Aircraft Noise Sources

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

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

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

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

BOX 5.8

NOISE FROM GROUND OPERATIONS AT AIRPORTS

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

5.3.2 Aircraft Noise Calculation Methods

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

ECAC-CEAC Doc 29 Version 3 (Europe)

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

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

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

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

SUMMARY OF CALCULATION DETAILS

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

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

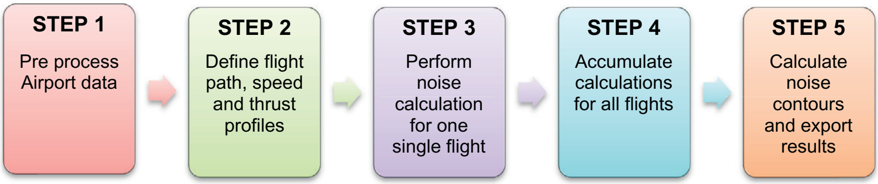

FIGURE 5.9 The noise contour generation process. *Adapted from* ECAC.CEAC (2005b).

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

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

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

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

BOX 5.9

A NOTE ON NOISE CERTIFICATION TESTS AS SPECIFIED BY ICAO

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

FAA – Integrated Noise Model (United States)

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

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

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

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

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

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

BOX 5.10

THE AVIATION ENVIRONMENTAL DESIGN TOOL

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

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

CNOSSOS-EU (The Proposed Common European Method)

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

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

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

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

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

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

5.4 LIMITATIONS AND FURTHER CONSIDERATIONS

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

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

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

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

5.4.1 Road Traffic Noise

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

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

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

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

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

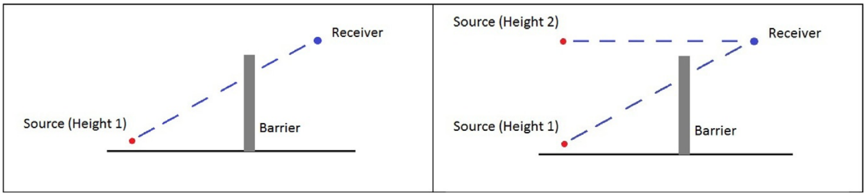

FIGURE 5.10 Sketch of different source positions at the influence on noise mitigation measures.

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

BOX 5.11

SUPPLEMENTAL INDICATORS TO CALCULATE ANNOYANCE

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

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

5.4.2 Railway Noise

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

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

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

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

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

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

5.4.3 Aircraft Noise

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

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

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

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

5.5 CONCLUSION

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

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

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

References

Abbott, P., Nelson, P., 2002. Converting the UK traffic noise index LA10,18h to EU noise indices for the purposes of noise mapping, TRL Limited, Project Report PR/SE/451/02.

Acoustique, 2001. Bruit des infrastructures de transports terrestres (XPS31–133). AFNOR.

Annex 16 to the Convention on International Civil Aviation, Environmental Protection, Volume 1 Aircraft Noise. International Civil Aviation Organization, July 2008.

Baranovskii, A., 2011. Adaptation of RMR noise propagation prediction method for Latvian railway conditions. In: Transbalticia 2011: The 7th International Conference, Vilnius, Lithuania.

Bernhard, R.J., Sandberg, U., 2005. Tyre-pavement noise: where does it come from? In: TR News, Transportation Noise: Measures and countermeasures. Transportation Research Board, Washington, D.C.

Besnard, F., Jelong, J., Doisy, S., Steimer, V., 1999. Updating the vehicle noise emission values used in French Traffic Noise Prediction Models. In: Internoise 1999, Fort Lauderdale, Florida, USA.

Butikofer, R., 2012. Aircraft noise. In: Noise Mapping in the EU: Models and Procedures. CRC Press, Taylor and Francis Group, Boca Raton, Florida, pp. 129–158.

Clausen, U., Doll, C., Franklin, F., Franklin, G., Heinrichmeyer, H., Kochsiek, J., Rothengatter, W., Sieber, N., 2012. Reducing railway noise pollution, Directorate General for Internal Policies (Transport and Tourism), European Parliament, Brussels, March 2012.

Department of Transport, 1995. Calculation of Railway Noise 1995. Her Majesty's Stationery Office, UK.

de Vos, P., 2003. How the money machine may help to reduce railway noise in Europe. J. Sound Vib. 267 (3), 439–445.

de Vos, P., 2012. Railway noise. In: Noise Mapping in the EU, Models and Procedures. CRC Press, Taylor and Francis Group, Boca Raton, Florida.

DGMR, 2002. Harmonoise Technical Report: The engineering model definitions. HAR30TR-020828-DGMR01.

Dittrich, M., Zhang, X., 2006. The Harmonoise/IMAGINE model for traction noise of powered railway vehicles. J. Sound Vib. 293 (3–5), 986–994.

Dutilleux, D., 2013. Road traffic noise. In: Noise Mapping in the EU: Models and Procedures. CRC Press, Taylor & Francis Group, Boca Raton, FL, p. 77.

ECAC.CEAC Doc 29 3rd edition, 2005a. Report on the standard method of computing noise contours around civil airports. Volume 1: Applications Guide, European Civil Aviation Conference, December 2005.

ECAC.CEAC Doc 29 3rd edition, 2005b. Report on standard method of computing noise contours around civil airports. Volume 2: Technical Guide, European Civil Aviation Conference, December 2005.

European Commission, 1996. Future Noise Policy, Com (96) 540, Brussels, November 1996.
European Commission, 2003. Commission Recommendation 2003/613/EC of 6 August 2003 concerning the guidelines on the revised interim computation methods for industrial noise, aircraft noise, road traffic noise and railway noise, and related emission data. Off. J. Eur. Commun. L212, 49–64.
European Commission, 2011. Commission to the European Parliament and the Council on the implementation of the Environmental Noise Directive, Brussels.
Federal Aviation Authority, 2007. Integrated Noise Model (INM) Version 7.0 Users Guide.
Federal Aviation Authority, 2008. Integrated Noise Model (INM) Version 7.0 Technical Manual.
Federal Highway Authority, 2012. Code of Federal Regulations, Title 23 – Highways Part, Section 772.9 – Traffic noise prediction. US Department of Transportation.
Federal Ministry of Transport, 2000. Building and Housing; Association of German Transport undertakings; VDV Promotional Group, Light Rail in Germany, Bundesministerium fur Verker, Bau- und Wohnungswesen (BMVBW).
Filho, J.M.A., Lenzi, A., Zannin, P.H.T., 2004. Effects on traffic composition on road noise: a case study. Transp. Res. D. 9, 75–80.
Fleming, G., Rapoza, A., Lee, C., 1995a. Development of national reference energy mean emission levels for the FHWA Traffic Noise Model, Report No FHWA-PD-96-008 and DOT-VNTSC-96-2 John A. Volpe National Transportation Systems Center.
Fleming, G., Rapoza, A., Lee, C., 1995b. Development of national reference energy mean emission levels for the FHWA Traffic Noise Model, Report No FHWA-PD-96-008 and DOT-VNTSC-96-2 John A. Volpe National Transportation Systems Center.
Gidlöf-Gunnarsson, A., Ögren, M., Jerson, T., Öhrström, E., 2012. Railway noise annoyance and the importance of number of trains, ground vibration and building situational factors. Noise Health. 14 (59), 190–201.
Guarinoni, M., Ganzleben, C., Murphy, E., Jurkiewicz, K., 2012. Towards a comprehensive noise strategy, Policy Department Economic and Scientific Policy, European Parliament.
Guide du bruit des transports terrestres, fascicule prévision des niveauxsonores. CETUR, 1980.
Hardy, A., Jones, R., 2004. Rail and wheel roughness – implications for noise mapping based on the calculation of railway noise procedure, Department for Environment, Food and Rural Affairs (DEFRA) Report Number AEATR-PC&E-2003-002 (UK), March 2004.
Hardy, A., Jones, R., Wright, C., 2007. Additional Railway Noise Source Terms for Calculation of Railway Noise 1995. Department for Environment, Food and Rural Affairs (DEFRA), London, UK.
Federal Highway Administration, 1998. FHWA Traffic Noise Model Users Guide. US Department of Transportation, Report N. FHWA-PD-96-009 and DOT-VNTSC-FHWA-98-1.
Highways Agency (UK), 2008. Design Manual for Roads and Bridges. Department for Transport, UK.
Jabben, J., Potma, C., 2004. Monitoring noise emissions from railway lines. In: Internoise 2004: The 33rd International Congress and Exposition on Noise Control Engineering, Prague, Czech Republic.
Jonasson, H., Watts, G., Sandberg, U., Ejsmont, J., van Blokland, G., Luminari, M., van der Toorn, J., 2004. The Harmonoise source model for road vehicles. In: Internoise 2004, The 33rd International Congress and Exposition on Noise Control Engineering, Prague, Czech Republic.
Jopson, I., Rhodes, D., Havelock, P., 2002. Aircraft noise model validation – how accurate do we need to be? In: Institute of Acoustics UK, Action on Environmental Noise, Stratford upon Avon, UK, November 2002.
Kephalopoulos, S., Paviotti, M., Anfosso-Ledee, F., 2012. Common Noise Assessment Methods in Europe (CNOSSOS-EU). European Commission Joint Research Centre, Luxembourg publications Office of the European Union.
Khardi, S., Abdallah, L., 2013. Optimization approaches of aircraft flight path reducing noise: comparison of modeling methods. Appl. Acoust. 73, 291–301.

King, E.A., Rice, H.J., O'Malley, V., 2009. Assessing the suitability of using the recommended interim method for road traffic noise mapping in Ireland. In: Euronoise 2009, Edinburgh, Scotland.

Long, M., 2006. Architectural Acoustics. Elsevier, San Diego.

Manvell, D., Ballarin Marcos, L., Stapelfeldt, H., Sanz, R., 2004. SADMAM – combining measurements and calculations to map noise in Madrid. In: The 33rd International Congress and Exposition on Noise Control Engineering, Internoise 2004, Prague, Czech Republic.

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 Policy Pract. 46 (1), 91–101.

Nijland, H., van Wee, G.P., 2005. Traffic noise in Europe: a comparison of calculation methods, noise indices and noise standards for road and railroad traffic in Europe. Transp. Rev. 25, 591–612.

Noel, G., Allaire, D., Cointin, R., 2009. Assessment of the Aviational Environmental Design Tool. In: Eighth USA/Europe Air Traffic Management Research and Development Seminar, ATM2009.

O'Malley, V., King, E., Dilworth, C., Kenny, L., 2009. Assessing methodologies for calculating road traffic noise levels in Ireland – converting CRTN indicators to the EU indicators (L_{den}, L_{night}). Appl. Acoust. 70, 284–296.

Plotkin, K., 2011. The role of aircraft noise simulation models. In: Internoise 2001, the 2001 International congress and exhibition on noise control engineering, The Hague, The Netherlands.

Schreckenberg, D., Schuemer-Kohrs, A., Schueme, R., Griefahn, B., Moehler, U., 1999. An interdisciplinary study on railway and road traffic noise: annoyance differences. In: Forum Acusticum: 137th meeting of the Acoustical Society of America and the 2nd Convention of the European Acoustics, integrating the 25th German Acoustic DAGA Conference, Berlin, Germany.

Schreurs, E., Brown, L., Tomerini, D., 2011. Maximum pass-by noise levels from vehicles in real road traffic streams: comparison to modeled levels and measurement protocol issues. In: Internoise 2011, Osaka, Japan.

Scwarc, M., Kostek, B., Kotus, J., Szczodrak, M., Czyzewski, A., 2011. Problems of railway noise – a case study. Int. J. Occup. Saf. Ergon. 17 (3), 309–325.

Service d'étudessur les transports, les routes etleursaménagements (SETRA), 2009. Road traffic noise prediction 1 – Calculating sound emissions from road traffic. Ministère de l'écologie, de l'énergie et du développement durable (France).

Smith, M., 1989. Aircraft Noise, Cambridge Aerospace Series.

Steele, C., 2001. A critical review of some traffic noise prediction models. Appl. Acoust. 62 (3), 271–287.

The Vehicles Technologies Office, September 17, 2012. Vehicles per Thousand People: U.S. Compared to Other Countries. The Vehicle Technologies Office, US Department of Energy.

Testimony of C.E. Burleson, 2007. Aviation and the Environment: Noise, Hearing before the subcommittee on aviation of the committee on transportation and infrastructure, House of Representatives. One Hundredth Tenth Congress, First Session, October 24.

Travaini, G., Schut, D., 2012. Rail Route 2050: The Sustainable Backbone of the Single European Transport Area. The European Rail Research Advisory Council, Brussels.

Watts, G., 2005. Harmonoise prediction model for road traffic noise. TRL Published Project Report PPR 034.

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

Wolde, T.T., 2003. The EU noise policy and the related research needs. Acta Acust. United Acust. 89 (8), 735–742.

Wolfel, 2003a. Adaptation and revision of the interim noise computation methods for the purpose of strategic noise mapping. WP 3.1.1 Road Traffic Noise – description of the calculation method", Commissioned by European Commission, DG Environment, CONTRACT:B4–3040/2001/329750/MAR/C1.

Wolfel, 2003b. Adaptation and revision of the interim noise computation methods for the purpose of strategic noise mapping. Work Package 3.2.1. Calculation and measurement guidelines for rail transport noise 1996 – Translation. Commissioned by European Commission, DG Environment, CONTRACT: B4-3040/2001/329750/MAR/C1.