

# TRAFFIC NOISE – BEST PRACTICE GUIDE

TECHNICAL COMMITTEE E.2 *ENVIRONMENTAL CONSIDERATIONS*  
*IN ROAD PROJECTS*

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# **TRAFFIC NOISE – BEST PRACTICE GUIDE**

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IN ROAD PROJECTS***

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## TRAFFIC NOISE – BEST PRACTICE GUIDE

In recent years, knowledge about the health effects of traffic noise has grown substantially. Many studies have found that long-term exposure to traffic noise is associated with various health impacts such as sleep disturbance, cardiovascular disease and depression. While there remain knowledge gaps concerning the risk for particular noise profiles, there is sufficient evidence to suggest that a large proportion of people living within major urban centres is at risk due to excessive noise level exposures. In addition, there appears to be a *city size* effect: the proportion of the population negatively affected by noise increases with city size.

Traffic noise is estimated to cost the European Union economy around EUR 40 billion per year, with this cost anticipated to increase as the proportion of population exposed to excess traffic noise increases over time, as cities increase in size and urbanisation increases population density. Currently, close to half of all Europeans are regularly exposed to traffic noise levels that are potentially dangerous to health.

Whilst the economic cost of traffic noise has been well quantified in Europe, noise pollution due to road traffic is a major global concern. For example, in Vietnam, traffic noise has become a serious problem in large cities like Hanoi and Ho Chi Minh City<sup>1</sup>. Similar concerns have been identified in other major cities around the world. A study into noise pollution in urban areas has identified that traffic noise is a ubiquitous issue with cities such as Guangzhou, Delhi, Cairo, Mumbai, Istanbul, Beijing, Barcelona, Mexico City, Paris, Buenos Aires and Moscow rated as the noisiest cities in the world<sup>2</sup>.

With changes in automotive technology and the rapid deployment of intelligent transport systems and automated vehicles, there is an optimistic view that the burden of traffic noise on the community will decrease. Battery powered vehicles for example, represent the most developed of the electric vehicle technologies, yet have only 2 to 3% penetration in almost all markets, apart from Norway. Similarly, the future of transportation is clearly focused on the role of automated vehicles which are predicted to run more efficiently and are widely assumed to deliver improved safety outcomes. Nevertheless, since the most significant source of traffic noise is the tyre-road interface, the deployment of electric and/or automated vehicle is not expected to reduce traffic noise.

The network-wide benefits of automated vehicles mask some potentially significant challenges. Automated vehicles have the potential to promote population dispersion by reducing the inconvenience of long commutes. The foreseeable future, therefore, is not necessarily less traffic noise, but more people over greater areas likely to be exposed to traffic noise.

Consequently, the need to manage and reduce traffic noise is even more important today. Increasing urbanisation coupled with new technology means that the complex interactions between transport, land use planning and public health outcomes must be assessed to enable effective strategies or interventions.

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<sup>1</sup> <https://www.asiaone.com/asia/honking-and-loud-music-worsen-noise-pollution-hcm-city>

<sup>2</sup> <https://www.weforum.org/agenda/2017/03/these-are-the-cities-with-the-worst-noise-pollution/>

# EXECUTIVE SUMMARY

This Best Practice Guide provides a summary of strategies and a suite of tools that are available to national road agencies to respond to traffic noise. It summarises the latest research on the health and economic impacts of traffic noise and using a range of case studies, explains the various mitigation measures available to significantly reduce noise emissions. Examples include planning (e.g. buffers), design of roads (cuttings, tunnels and grade), use of low noise pavement or quieter tyres, installation of barriers, as well as legislative requirements to control noise from vehicle tyres or ineffective mufflers.

Much of the work undertaken to date by road agencies has been focused on determining what mitigation measures should be employed to limit the impact of traffic noise to below defined guideline levels. This report, however, also provides information on the character of sound, on how the acoustic environment is perceived and understood and on its role in the functioning of the urban space. An understanding of *soundscape* will assist many agencies in designing mitigation measures that not only perform from an engineering perspective but contribute to the overall urban form and function.

Noise mitigation associated with road planning, design and construction is one of the aspects that typically appears late in the project planning agenda. It is often only considered when engineering design staff discover that a project might not meet relevant regulatory requirements with respect to noise. In these situations, regulations are seen as hindering the project. This demonstrates a lack of awareness of the importance an adequate sound environment has on the functioning of the urban space as well as the impact traffic noise has on public health. In addition, road agencies are constrained by the inconsistent approach to quantifying the economic impact of traffic noise, which, in turn, limits their ability to benchmark and justify noise mitigation. Consequently, there is a need to better understand and fully cost the impact of transport externalities such as traffic noise. In this respect, it is important that road agencies work closely with other transport and environmental regulators to achieve the best possible environmental outcomes.

Based on the increasing evidence regarding the health and economic impact of traffic noise, the technical committee has advocated for a stronger focus on traffic noise. PIARC has responded by creating a dedicated web page and portal to draw greater attention to this issue. This Best Practice Guide proposes that road agencies use this information for collaborating with other parts of government and key stakeholders, to influence land-use planning as one of the most important steps in avoiding and/or preventing further increases in the environmental burden on current and future generations due to traffic noise.

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## 1. INTRODUCTION

This report is produced by the PIARC-World Road Association working group TC E2 – Environmental Considerations in Road Projects. The working group was asked to address the following task:

*Evaluate and document traffic noise impacts; undertake examination of potential mitigation measures; reasonable and feasible noise mitigation measures, including regulations and guidance setting noise levels.*

This report complements the work of earlier PIARC committees, with some of the earliest specific discussion on traffic noise noting that:

*in an environmental context in which man, both perpetrator and victim, suffers the consequences of his choices, particularly in the absence of precautions, noise is probably the most significant environmental consequence. [1]*

A large proportion of the populations of major urban centres is exposed to excessive noise but based on qualitative data, road traffic noise is easily the largest source of excessive environmental noise exposure. Estimates for Europe suggest that around 30% of the urban populations suffer from excessive noise [2]. By comparison, recent Australian estimates yield figures in the range 11% to 22% for night-time exposure to road traffic noise over 50 dB [3]. As such, there appears to be a *city size effect*, whereby the proportion of the population negatively affected by noise increases with city size. This implies that the proportion of the total population exposed to excess noise will increase over time, as cities increase in size and population density.

When the European Commission presented its Green Paper on Future Noise Policy in 1996, it estimated the annual economic damage to the European Union (EU) due to environmental noise as potentially ranging from EUR 13 million to EUR 30 billion. The Green Paper considered that the key elements contributing to these external costs were a reduction of house prices, reduced possibilities of land use, increased medical costs and the cost of lost productivity in the workplace due to illness caused by the effects of noise pollution [4].

Subsequently, in its 2011 report on the implementation of the European Noise Directive (END, Directive 2002/49/EC relating to the assessment and management of environmental noise), the European Commission [5] estimated the social cost of rail and road traffic noise in the EU as being EUR 40 billion per year, of which 90% was related to passenger cars and goods vehicles.

In the 2011 report, *The burden of disease from environmental noise* [6], the World Health Organization (WHO) estimated the disability-adjusted life years (DALYs) lost due to exposure to environmental noise in western European countries. Although the report was based on a limited set of data, the WHO concluded sufficient information was available to quantify the burden of disease in western European countries from environmental noise for cardiovascular disease, cognitive impairment in children, sleep disturbance, tinnitus and annoyance.

In 2013, the Conference of European Directors of Roads (CEDR) [7] highlighted that the most cost-effective tool for noise abatement was reduction of noise emissions from new vehicles and tyres. This was closely followed by the use of noise-reducing pavements. Traditionally, road agencies have had limited influence on vehicle design and tyre performance criteria. However, since they are owners and operators of the road network they can make decisions regarding the location of roads, and specify design, construction and maintenance requirements. All these factors influence the

degree to which the community is affected by traffic noise. Noise reducing pavements are therefore an important tool in the noise abatement toolbox and further information can be found in the PIARC publication *Quiet pavement technologies* [8].

There has been an expectation that noise emissions by individual vehicles will have continued to decrease in recent years, partly in response to stricter regulatory requirements. However, any reduction has been offset by the growth in both traffic volumes and the duration of traffic peaks. A further factor is that the rise in daytime congestion is causing commercial vehicles to shift journeys to night-time hours [9], with the result that night-time disturbance caused by a given level of noise is increasing<sup>3</sup>.

While increases in traffic volume will lead to increases in total noise emissions across a certain range, noise levels on individual roads inevitably plateau as their maximum capacity is reached and can decrease as average travel speeds reduce due to rising congestion [10]. However, given that the majority of the annoyance due to traffic noise relates to night-time exposure, this effect is likely to be of limited relevance for the foreseeable future.

A common misconception is that, in time, the increased uptake of electric cars will address traffic noise. In practice, most car-related noise is now the result of the interaction of vehicle tyres with the road pavement, rather than mechanical or combustion noise emitted by vehicles<sup>4</sup>. This suggests that the achievement of further gains in reducing the noise levels will require action by multiple government agencies to consider, as a priority, more appropriate planning and building design in conjunction with further efforts to reduce noise at source.

Governments also have a critical role in funding. This is not only limited to noise abatement measures but also to road maintenance. Poor road condition results in high levels of roughness, rutting and patching, and causes higher levels of noise generated through the interaction of the tyres with the road or the rattling of heavy vehicles.

In October 2018, the WHO released *Environmental noise guidelines for the European Region* [11] that provide updated exposure-response functions and recommendations based on systematic reviews of the scientific evidence for health outcomes categorised as critical or important. These guidelines complement the 2009 *Night noise guidelines for Europe* [12]. They also supersede the 1999 *Guidelines for community noise* [13], except for circumstances not covered in the 2018 document (such as indoor guideline values, industrial noise and shopping areas).

The *Environmental noise guidelines for the European Region* strongly recommend<sup>5</sup> that policy makers implement suitable measures to reduce noise exposure from road traffic in the population currently exposed above guideline values for average and night noise exposure.

This Best Practice Guide provides an overview of the latest research on the health and economic impacts of traffic noise and identifies, using a range of case studies, the various mitigation measures available. This guide also advocates for road agencies to take a stronger role in influencing land use

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<sup>3</sup> A given measured noise level can cause greater disturbance at night, especially if it is disturbing sleep.

<sup>4</sup> There is likely to be significant noise reduction if/when trucks are eventually electrified.

<sup>5</sup> The strength of the recommendation is based on the evidence and confidence that the desirable effect of adherence to the recommendation outweighs any undesirable consequences. The quality of evidence for a net benefit suggests that the recommended guidelines should be implemented in most circumstances.

planning as a critical important step in avoiding and/or preventing further increases in the environmental burden on current populations and future generations due to traffic noise.

## 2. FUNDAMENTALS OF SOUND

This chapter provides an overview of the basic principles of sound and, by association, of the characteristics of traffic noise and its propagation in the context of a road environment.

### 2.1. WHAT IS SOUND?

Sound consists of pressure waves that move through the air. It may be thought of as particles of air vibrating back and forth creating changes in air pressure. As they move in one direction, they apply a force to particles ahead of them, causing them to also move in the same direction. Then when they bounce back toward their original position, they cause a vacuum which pulls other particles back. As a result, waves of high and low pressure move through the air. Sound waves are actually waves of pressure and waves of velocity. They carry energy, which is equal in amount to the pressure multiplied by the velocity. The human ear is sensitive to fluctuations in air pressure, which it senses as sound.

### 2.2. WHAT IS NOISE?

Noise is unwanted sound. This definition is subjective, because what one person perceives as a pleasant sound may be perceived as undesirable by another person. In the context of traffic noise, the focus is on high levels of sound generated by passing vehicles, from the perspective of people living adjacent to major roads. Traffic noise is mainly produced by the contact of the vehicle tyres on the road, but vehicle engines and exhaust systems also cause significant noise.

#### 2.2.1. Units of sound

When we measure sound, we usually determine the sound pressure level in decibels (dB). A value in the decibel scale is defined as the logarithm of a ratio of the measured quantity normalised to a reference value. In the context of sound pressure level, a reference pressure of 0.00002 Pa (20 micro pascals), is used which is roughly the threshold of human hearing. The sound pressure level in dB is determined from the sound pressure  $p$  (in Pascal, Pa) measured by a microphone and the reference pressure  $p_{ref}$  according to the equation below<sup>6</sup>.

$$L_p = 10 \times \log \left( \frac{p^2}{p_{ref}^2} \right) = 20 \times \log \left( \frac{p}{p_{ref}} \right) \text{ dB}$$

Because it is a logarithmic scale, the decibel system has useful properties to represent sound levels. Humans can hear from as low as 0.00002 Pascals to a threshold of pain around 20 Pascals. This huge range of numbers is compressed when converted to dB and works out at a convenient scale from 0 to 120 dB.

If we double the amount of energy in sound (for example if the number of vehicles producing sound is doubled) then the sound pressure level increases by three decibels (3 dB). This is approximately the smallest increase in sound level that can be clearly detected by most people. A 5 dB increase is clearly noticeable and if we increase the sound energy by a factor of 10 then the sound pressure level increases by 10 dB, which is perceived as a doubling in loudness (e.g. 60 dB sounds twice as

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<sup>6</sup> The logarithm of pressure squared rather than logarithm of pressure is used because sound energy is related to the square of the pressure.

loud as 50 dB). These calculations tell us that substantial increases in the volume of traffic make only small increases in how loud the traffic sounds.

### 2.2.2. Frequency of sound

Sound is also characterised by its frequency, which represents how many times the particles of air vibrate back and forth in one second. It is measured in units of Hertz (Hz). For example, a 100 Hz sound has one hundred rises and falls in pressure in one second. Most sound sources produce sound over a wide range of frequencies.

It is well established that the human ear cannot detect sound noises of very low frequency (less than about 20 Hz) or very high frequency (greater than about 40,000 Hz). In fact, the ear has reduced sensitivity at both low and high frequencies and has maximum sensitivity at medium frequencies around 1,000 Hz.

The variation in the sensitivity of the human ear is accounted for in the use of a frequency weighting in sound measurements. The weighting effectively turns down the low and high frequencies to simulate human hearing. Several alternative weighting curves are used to process sound measurements. The one that is most commonly used is the 'A' weighting curve. Noise levels that are 'A' weighted are designated dB(A). The instruments used for sound measurement have internal processes (filters) that apply the weighting to produce a final noise level in dB(A).

An illustrative graph of a frequency spectrum (the variation in sound level as a function of frequency) is shown in *figure 1*, both with and without A weighting. The horizontal axis is logarithmic and consistent with how humans perceive frequency.

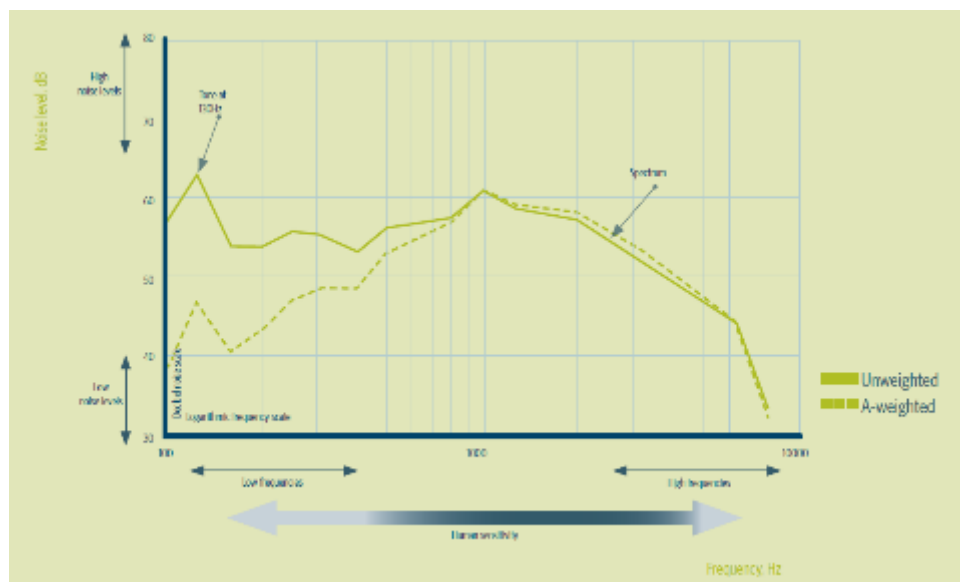


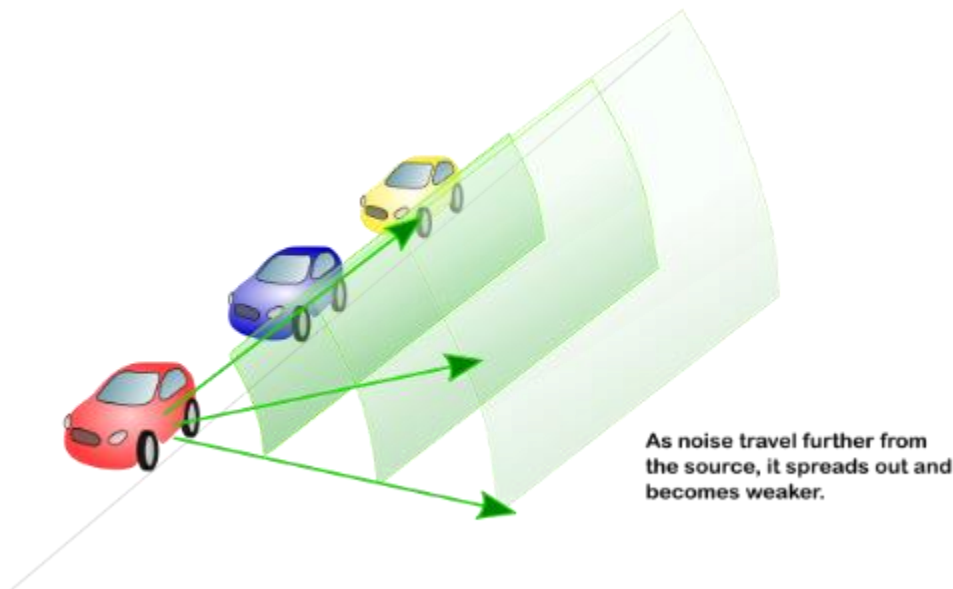
Figure 1: Sound spectrum. [14]

### 2.2.3. How does sound decrease over distance

The level of sound decreases with increasing distance from the source of the sound as shown in *figure 2*. The most significant reason is divergence of the sound waves. For traffic noise, as sound waves travel away from a road with dense, flowing traffic, they spread out over an increasing cylindrical area. This spreading out results in the sound energy reducing by about half each time

the distance from the road doubles, which equates to a reduction in the sound level of approximately 3 dB.

However, propagation of sound in the atmosphere is not so simple. A phenomenon called refraction can significantly change how much sound decreases over distances of more than around 100 m



[15].

*Figure 2: Divergence of sound waves.*

*(Source: J McIntosh, Department of Transport, Victoria, Australia)*

#### **2.2.4. What is refraction?**

Weather conditions can bend the path that sound travels along, significantly altering noise levels. The bending of sound waves is called refraction.

Refraction can increase or decrease the level of sound over long distances. This is because wind speed is generally greater at height than it is at ground level. Sound waves that rise up from a source (coloured blue in *figure 3*) are bent following the direction by the wind. On the downwind side, they curve back downward while on the upwind side of the noise source they curve upward. The effect of wind is to increase sound levels at ground level on the downwind side and increase them on the upwind side.

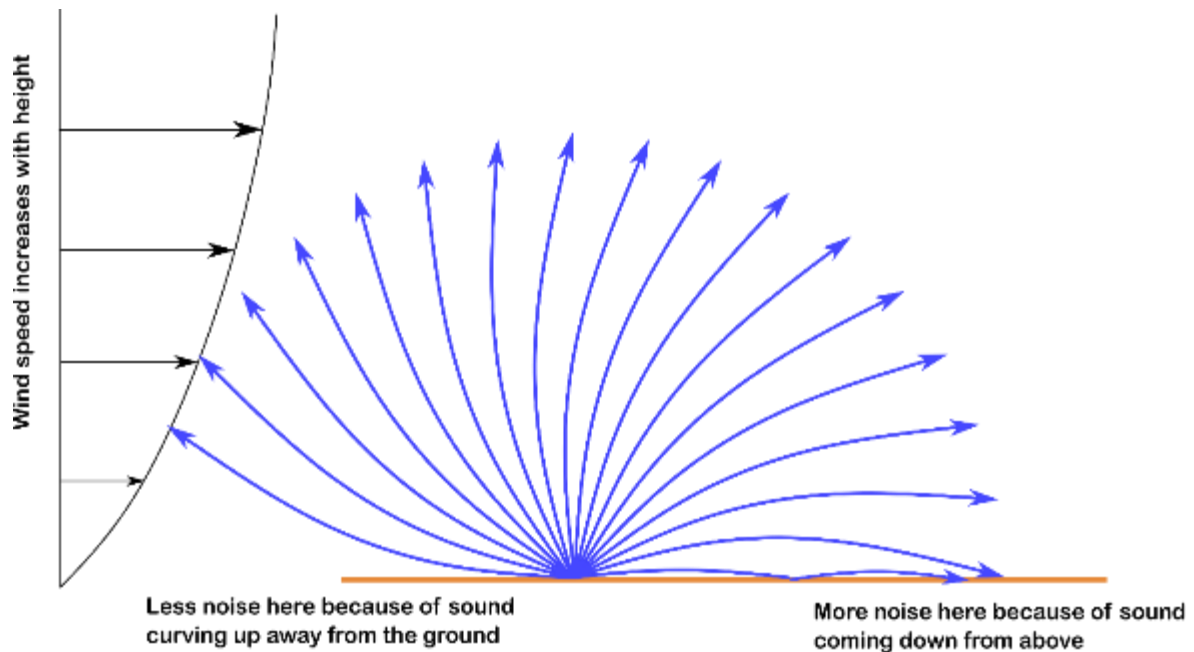


Figure 3: Refraction of sound

(Source: J McIntosh, Department of Transport, Victoria, Australia)

A similar refraction effect occurs when there is a temperature inversion in the atmosphere. This occurs on clear still nights and early mornings when cold air settles down to ground level, with warmer air above it. Sound waves travel faster in warm air than in cold air. As a result, sound that travels upward curves back down in all directions.

These meteorological effects are not significant at locations close to a noise source because the direct noise from the road is much greater than the noise increase from refraction. However, noise levels at locations several 100 m away from the road can vary by more than 10 dB due to refraction.

#### 2.2.5. What is diffraction?

Another phenomenon that can affect the propagation of sound waves is called diffraction. When sound waves pass obstructions, they bend slightly as shown in *figure 4*. This is caused by the sound waves 'stretching' into the air that is sheltered by the barrier. The diffracted noise is not as loud as the direct noise and gets weaker with increasing angle of diffraction.

The performance of noise barriers is limited by diffraction. Even if no sound passes through a noise barrier, sound can pass over the top and diffract downward. Traffic noise barriers are designed so that the level of noise passing straight through is insignificant compared with the noise diffracting over the top. The calculations used to determine the necessary height of a noise barrier work on the principle of determining the amount of diffraction. A barrier must be designed with sufficient height so that even with diffraction, the sound level at noise sensitive buildings will not exceed the intended noise level.

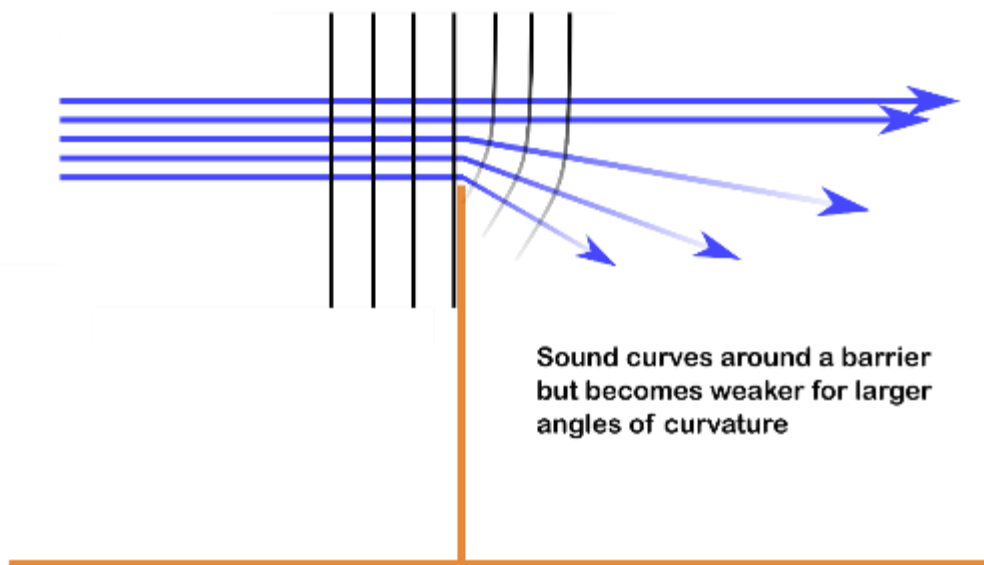


Figure 4: Refraction of sound.

(Source: J McIntosh, Department of Transport, Victoria, Australia)

#### 2.2.6. What is reflection?

Reflection occurs when sound bounces off a rigid surface. Surfaces such as solid walls are very effective at reflecting sound. Sound reflection inside the room of a building causes reverberation, an effect which makes rooms without carpet seem noisy. Hard ground surfaces like concrete are effective at reflecting sound, so is water. Reflection of sound can be represented making use of a virtual “image” of the source of the noise across the reflecting surface, similar to the image of a person’s reflection behind a mirror.

The combination of diffraction and reflection allows traffic noise to travel between houses, bending around the corners and bouncing off the walls.

#### 2.2.7. What is absorption?

Absorptive surfaces dissipate noise, converting sound energy into heat instead of reflecting it. Common sound absorptive materials include porous or fibrous materials. An example is a thick carpet that makes a room quieter.

Some traffic noise barriers, particularly in Europe and Japan, use absorptive materials to prevent noise reflection.

Most absorptive barriers make use of fibrous material such as fibreglass or rock wool, or certain types of porous, open cell foam. Sound waves penetrate the absorptive material, and friction between the air molecules and the surrounding fibres or foam cell walls generates heat. Sound energy is then converted to heat energy and the sound is dissipated.

It is worth noting that, in reality, there is no solid material that is a perfect sound absorber. Neither is there a perfect sound reflector.



### 3. NOISE CRITERIA

#### 3.1. NOISE METRICS

Management of traffic noise requires an objective understanding of actual and forecast noise levels. Unfortunately, there is no perfect measure of traffic noise, so a wide range of different metrics is used in different parts of the world. This can be confusing when comparing noise criteria in different countries. Moreover, the way in which noise is measured can also be a source of confusion. Consequently, it is meaningless to talk about noise levels without being aware of what *type* of level is being talked about.

As is well known, noise levels are normally specified in decibels (dB) of sound pressure. In a sound pressure context, a dB is 10 times the logarithm of the squared value of the magnitude of sound pressure normalised, by division, to a reference pressure set to by convention of 20 micro Pascals ( $\mu\text{P}$ ).

It is common for noise level measures to be *frequency weighted* to reflect that the human ear has a different sensitivity at different frequencies and cannot hear the highest and lowest frequencies well. A number of weightings can be used and the most common one is designated “A-weighting”. Another rating that is occasionally used is the *C-weighting*, which has more emphasis on lower frequencies.

However, a complication arises from the fact that traffic noise level varies over time. In one sense, it would seem advantageous to quantify peaks in noise level due to individual noisy vehicles passing by. These peaks are indeed the greatest cause of annoyance to affected people. However, peak noise levels depend more on the vehicles themselves rather than on the road environment. They are subject to different regulatory requirements, such as vehicle emission limits.

It is more useful for a road agency to make use of noise metrics that aggregate the contributions from all vehicles over the period considered and reflect the effect of the road pavement on noise levels. Most road agencies choose to use the A-weighted equivalent sound pressure level *L<sub>Aeq</sub>*, or one of its derivatives. *L<sub>Aeq</sub>* is the equivalent steady A-weighted noise level which contains the same acoustic energy as the actual fluctuating noise. *L<sub>Aeq</sub>* increases if vehicles are louder and if there are more vehicles.

*L<sub>Aeq</sub>* can be defined over any chosen time and it is common to specify separate *L<sub>Aeq</sub>* noise levels for daytime and night time. When *L<sub>Aeq</sub>* is used over a specified period, the length of the period in hours is stated. For example, an eight-hour night-time level of 52 dB would be stated as 52 dB *L<sub>Aeq</sub>*, 8h. For the night-time period, it may also be written as 52 dB *L<sub>Aeq</sub>* (night).

Two derivative noise metrics are *L<sub>dn</sub>* and *L<sub>den</sub>*. *L<sub>dn</sub>* (day-night average sound level) is the *L<sub>Aeq</sub>* level for the 24-hour day calculated after adding a 10-dB penalty to the night-time period. This penalty reflects that noise is more disturbing at night when people are trying to sleep. *L<sub>den</sub>* (*day, evening, night sound level*) is similar, but with a penalty of 5 dB for the evening period, as well as the 10 dB penalty for the night period. The hours that define the daytime, evening and night-time period vary between jurisdictions.

The END requires European Member States to report traffic noise levels in terms of both *L<sub>den</sub>* and *L<sub>Aeq</sub>* (night) metrics [5], making these metrics particularly important. They are also the reference

noise metrics used for exposure response relationships in the WHO environmental noise guidelines [11].

In some countries (notably the United Kingdom, Australia and Hong Kong), noise is specified in terms of the LA10 (18-hour) metric. This is the arithmetic average of the 90th percentile noise level for each hour from 6 am to midnight. LA10 is sometimes reported for individual hours.

Another way in which noise measurements vary is according to whether they include only noise coming directly from the source (called *free field* noise level) or include noise reflected back from a surface such as the wall of a building (called *façade* noise level). If noise is measured using a microphone placed one or two metres in front of a building, it will be a façade level. In general, a façade level will be three dB higher than a free field level.

Due to the logarithmic nature of noise levels, it is possible to convert from one metric to another, or to adjust for a façade by simply adding or subtracting dB. However, this conversion is only approximate – comparing different times of the day obviously depends on how traffic volume changes over the day. It was also observed that the relationships between noise metrics could be somewhat different for different categories of road [10], [16]. *Table 1* sets out approximate conversions.

Descriptor	Definition (*)	Advantages	Disadvantages	Approx. conversion from LAeq,24h (**)		
				Urban motor-way	Rural highway	Urban arterial
LA10 (18 hour)	Arithmetic average of LA10 noise levels for each hour from 6 am to midnight	Captures traffic-specific noise levels from the part of the day during which most traffic occurs.	Used in a diminishing number of jurisdictions making national and international comparisons of traffic noise difficult.	+3 dB	+3 dB	+3 dB
LAeq period	Hypothetical steady noise level that has the same acoustic energy as the actual fluctuating noise (equivalent level), over a specified time interval	The same measure can be used for traffic, railway, industries and other noise sources for any time of day that is of interest.	Not specifically sensitive to traffic noise, so noise tests can be more strongly affected by extraneous noise sources.	15h day: +2 dB 9h night: -3 dB	15h day: +2 dB 9h night: -3 dB	15h day: +1 dB 9h night: -3 dB
LDN	LAeq of full 24-hour day, but with a 10 dB <i>penalty</i> added to the hours from 10pm to 7am.	Allows both day and night noise levels to be assessed with a single number for convenience.	Over-simplifies variation of noise level over the 24-hour day period.	+3 dB	+4 dB	+4 dB
LDEN	LAeq of full 24-hour day, but with a 5 dB <i>penalty</i> added to the hours from 7 pm to 11 pm and a 10 dB <i>penalty</i> added to	Allows, day, evening and night noise levels to be assessed with a single number for convenience. Used as	Complex	+4 dB	+5 dB	+5 dB

Descriptor	Definition (*)	Advantages	Disadvantages	Approx. conversion from $L_{Aeq,24h}$ (**)		
				Urban motorway	Rural highway	Urban arterial
	the hours from 11 pm to 7 am.	a noise criterion in Europe.				
$L_{Amax}$	Maximum noise level. This is the level of the single loudest noise event in a particular time period.	Easy to measure with a suitably calibrated sound level meter.	Highly variable due to its sensitivity to particular noisy sources (usually defective vehicles)	No direct conversion	No direct conversion	No direct conversion

(\*) Time periods associated with these definitions may vary slightly between countries.

(\*\*) Conversions based on NZ Transport Agency's *noise metrics tool for urban motorways* [17].

Table 1: Traffic noise metric approximate conversions

A well-known conversion is the addition of three dB to a  $L_{Aeq}$  level to get a  $LA_{10}$  level [16]. This is valid only for heavy traffic that flows continuously and remains relatively constant for the period being considered. This conversion is sometimes used as a quality test for hourly traffic noise measurements; if the difference between measured hourly  $L_{Aeq}$  and  $LA_{10}$  departs markedly from 3 dB, then it is likely that the measurement is affected by noise sources other than traffic.

To conclude this section, it is important to highlight that:

- it is meaningless to talk about noise levels without being aware of the type of level or noise metric used
- it is also meaningless to provide results without mentioning the period measured and whether the level is free field or façade level.

An example of an on-line noise converter, the NZ Transport Agency's *Noise metrics tool* [17] is pictured in figure 5.

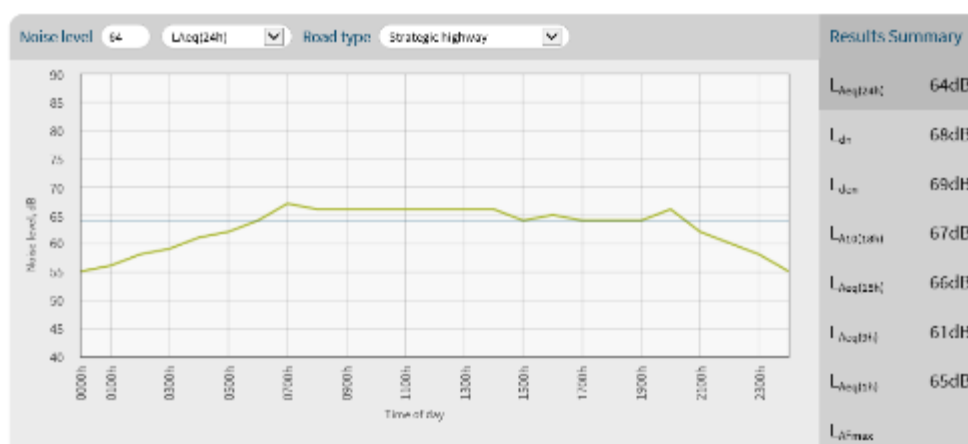


Figure 5: NZ Transport Agency noise metric tool. [17]

### 3.2. NOISE LIMIT AND GUIDELINE VALUES

WHO has defined recommended noise guidelines for road traffic noise for the European region [11], see *table 2*. In terms of their health implications, the recommended exposure levels can be considered applicable in other regions and suitable for a global audience (as the body of evidence was based on international studies and not limited to Europe). The WHO guideline values are public health-oriented recommendations, based on scientific evidence on health effects and on an assessment of achievable noise levels. It is stressed that the aim of the guidelines is to define an exposure level at which effects begin. The guidelines are strongly recommended and as such should serve as the basis for a policy-making process in which policy options are quantified and discussed. It should be recognised that in this process additional considerations of costs, feasibility, values and preferences should also feature in decision making when choosing reference values such as noise limits for a possible standard or legislation [11].

Recommendations	Strength
For average noise exposure, the WHO Guideline Development Group (GDG) strongly recommends reducing noise levels produced by road traffic below 53 dB Lden, as road traffic noise above this level is associated with adverse health effects.	Strong
For night noise exposure, the GDG strongly recommends reducing noise levels produced by road traffic during night-time below 45 dB Lnight, as night-time road traffic noise above this level is associated with adverse effects on sleep.	Strong
To reduce health effects, the GDG strongly recommends that policy makers implement suitable measures to reduce noise exposure from road traffic in the population exposed to levels above the guideline values for average and night noise exposure. For specific interventions, the GDG recommends reducing noise both at the source and on the route between the source and the affected population by changes in infrastructure.	Strong

*Table 2: Recommendations for guideline values for road traffic noise. A strong recommendation can be adopted as policy in most situations. [11]*

There is limited information regarding how many people across the world are exposed to noise levels above the WHO indicative limit values. For comparison, it is estimated that approximately 140 million people of 500 million in EU 30 – one out of 4 – are exposed to road traffic noise levels of 5 dB Lden or more [18].

Noise limits and guideline values are set by regulatory authorities to protect sensitive land uses adjacent roads, such as residential properties, from exposure to high noise levels.

Noise limits and guideline values vary significantly between countries and the limit or guideline value will be based on a number of factors, including the available scientific evidence, the cost-benefit assessment of their introduction, the traffic noise calculation methodology adopted and the priorities and goals that the regulating authorities have for reducing exposure to noise.

A database (Road Noise dB) documenting global road noise policies and criteria has been created by the PIARC Technical Committee E2 as an adjunct to this Best Practice Guide. It includes the existing noise limits and guideline values for numerous jurisdictions around the world. The database details the noise management requirements road agencies have for three different situations:

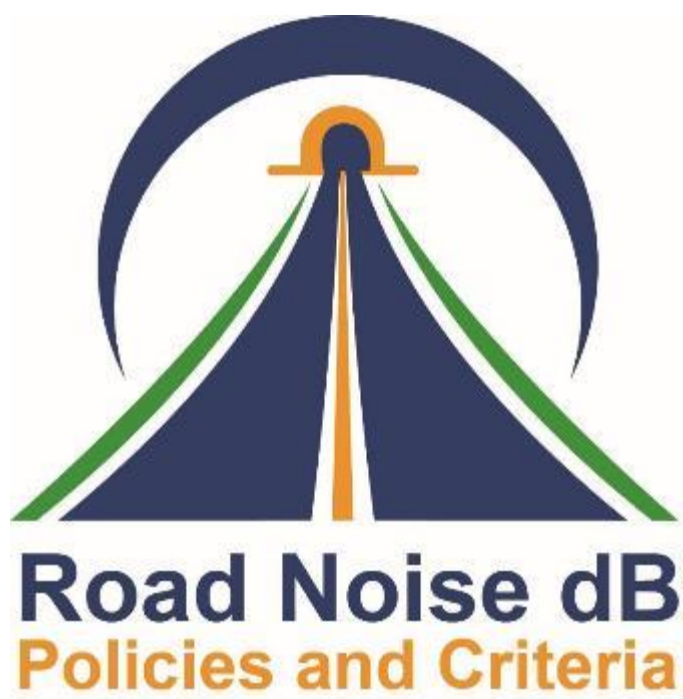
- when planning a new road
- when upgrading an existing road

- while managing noise from an existing road.

It provides information on the strength of the requirements (such as whether they are aspirational or legal limits to be achieved) and on noise monitoring obligations. The database is the most comprehensive listing of road noise policies and criteria currently available and can be accessed [here](#). (Note: any queries on the database can be sent to [noise@piarc](mailto:noise@piarc))

### CHAPTER 3: CONCLUSIONS

- When talking about noise levels, it is important to be aware of what type of level or noise metric is being used, the period of which the noise is measured and whether the level is free field or façade level.
- Noise limits and guideline values vary significantly between countries. The limit or guideline value will be based on several factors, including the cost-benefit assessment of their introduction, the traffic noise calculation methodology adopted and the priorities and goals that the regulating authorities have for reducing exposure to noise.
- PIARC Technical Committee E2 has developed a comprehensive road noise database that includes the policies and criteria for numerous jurisdictions around the world.



#### 4. HUMAN HEALTH AND ECOLOGICAL EFFECTS OF ROAD TRAFFIC NOISE

Traffic noise is an important public health issue, featuring among the top environmental risks to health. It has negative impacts on human health and well-being and is a growing concern among both the general public and policy makers throughout the world [19].



Hearing is a permanent process essential for human survival and communication. However, as we are not able to shut out noise, exposure can have a number of unwanted effects. Noise is a known psychological and physiological stressor. It can trigger a classic stress response, with activation of the autonomic nervous system and the endocrine system, leading to a cascade of effects, including rise in heart rate, blood pressure, and levels of stress hormones (cortisol, adrenalin and noradrenaline). This general stress response is a physiologic acute adaptation to stress, which may ultimately lead to pathophysiologic alterations if the exposure is chronic, resulting in health effects.

While the conscious experience with noise may be the primary source of stress during daytime, the unconscious response during night-time sleep is thought to play a particularly important role in the effects traffic noise has on health. Exposure to transportation noise at normal urban levels has been shown to result in disturbances from sleep stage changes to full awakening. Studies have shown that night-time transportation noise increases a number of biological risk factors, such as endothelial dysfunction, oxidative stress and blood pressure. Also, a disturbed sleep is known to be associated with major diseases, such as cardiovascular disease and diabetes, and potentially cancer [20].

Road traffic noise is a psycho-social stressor that affects subjective well-being and physical health. Noise disturbs communication, concentration, relaxation and sleep. Experimental laboratory studies, observational field studies and epidemiological studies all play important roles in elucidating the effects of environmental noise on cardiovascular health. *Figure 6* shows a proposed response path for the effects of noise on humans [21].



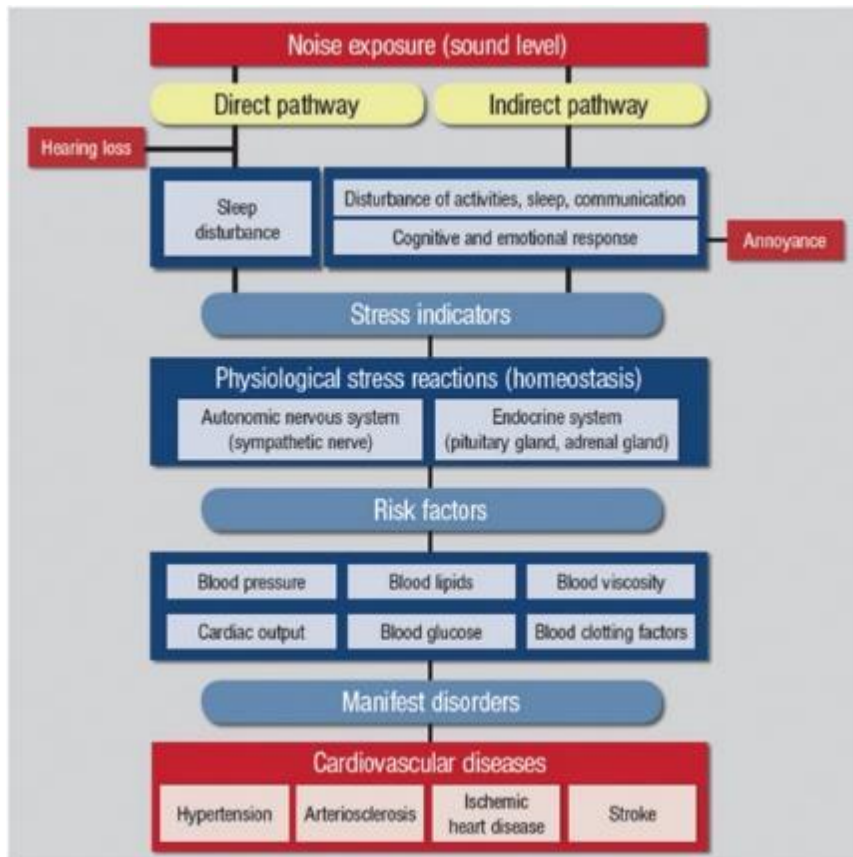


Figure 6: Noise effects reaction scheme. (Source: Adapted from Babisch [22])

Noise either directly or indirectly affects the autonomous nervous system (the part of the nervous system responsible for control of the bodily functions not consciously directed, such as breathing, heartbeat and digestive processes) and the endocrine system (which chemically controls the various functions of cells, tissues and organs through secretion of hormones). Subsequently these affect the metabolic homeostasis or the physiological balance of the organism thereby increasing the risk for specific diseases in the long run.

Indirect — in this respect — means the subjective perception of sound, its cognitive interpretation and the available coping abilities which play a role in the physiological reaction. Direct, on the other hand, means that the activation of the regulatory system is determined by direct interaction of the acoustic nerve with other parts of the central nervous system. This is particularly relevant during sleep, when autonomous responses to single noise events, including changes in blood pressure and heart rate, have been shown in subjects who were (subjectively) not sleep disturbed. [20]

The association of traffic noise with disease, such as cardiovascular disease, is based on a combination of evidence:

- experimental work carried out in the laboratory regarding the plausible biological mechanism to establish a causal association
- the consistency amongst study results (different study designs, different populations, different noise sources)
- the presence of an exposure-response relationship and the magnitude of the effect.

The question is therefore no longer whether traffic noise causes cardiovascular diseases; it is rather to what extent [22].

#### 4.1. HEALTH IMPACTS OF TRAFFIC NOISE

There is sufficient epidemiological evidence to indicate the etiological role of traffic noise in common diseases within the community [11].

WHO has estimated the environmental burden of disease due to traffic noise (expressed in disability adjusted life years (DALYs), which combines in one measure the time lived with disability and the time lost due to premature mortality in the general population. In its 2011 environmental noise report [6] WHO estimated that DALYs lost from environmental noise in the European Union Member States and other western European countries was equivalent to 61,000 years for ischaemic heart disease, 45,000 years for cognitive impairment in children, 903,000 years for sleep disturbance, 22,000 years for tinnitus and 654,000 years for annoyance. These results indicate that at least one million healthy years of life are lost every year from traffic-related environmental noise in the EU alone<sup>7</sup>. However, a lack of noise exposure data in many countries means that it is not possible to assess the burden of disease from environmental noise on a global basis.

Sleep disturbance is one of the most common complaints in noise exposed populations and has several short- and long-term health consequences such as tiredness, irritability and impaired cognitive functioning. Clear exposure-response associations exist between traffic noise and sleep disturbances. Since the auditory system is always open, noise may activate our alertness system even during sleep, thereby affecting several endocrine, metabolic and immune functions.

Traffic noise can cause non-specific physiological stress reactions and lead to cardiovascular problems in the case of chronic noise exposure. Stress can provoke the production of certain hormones (adrenalin, catecholamine, cortisol, etc.) that can have side effects like high blood pressure. Over an extended period, these effects can increase the risk of cardiovascular disease.

Physiological effects of noise during sleep, such as increases in blood pressure and heart rate, are seen from 35 dB  $L_{Amax}$  (inside) and awakenings occur from 42 dB  $L_{Amax}$  (inside). The 2009 WHO night noise guidelines [12] concluded that while there was insufficient evidence that physiological effects at noise levels below 40 dB  $L_{night}$  are harmful to health, there were observed adverse health effects at levels starting from 40 dB  $L_{night}$ . At 40 dB, about 3–4% (depending on the noise source) of the population still reported being highly sleep disturbed due to noise, which was considered relevant to health.

During the previous decades, research into the health effects of transportation noise focused on investigating the impact on cardiovascular disease. These studies consistently found that exposure to traffic noise, increased the risk of myocardial infarction, stroke and hypertension [6]. However, recent studies have suggested that traffic noise may also be a risk factor for other cardiovascular diseases, such as atrial fibrillation and heart failure [23].

In a study on road traffic noise and stroke based on 51,485 participants for whom complete data existed, 1,881 (3.7%) were admitted to hospital for their first stroke [24]. The average length of follow-up time was 10 years. The risk of a first stroke increased by 14% for every 10 dB increase in road traffic noise, in the range of 55 to 75 dB among all participants, after adjustments were made for possible

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<sup>7</sup> Based on the 2012 noise mapping in EU countries, it is estimated that environmental noise causes at least 10,000 cases of premature deaths in Europe each year (road traffic is the main source of noise exposure) [4]. By comparison, approximately 28,000 people lost their lives on the EU roads in 2012 (Refer <https://etsc.eu/12th-annual-road-safety-performance-index-pin-report/>).



confounders (incidence rate ratio (IRR) 1.14 for stroke, with a 95% confidence interval (CI) of 1.03 to 1.25). The participants' ages affected the strength of this link and the association between road traffic noise and stroke was stronger in people over 64.5 years old (IRR 1.27, 95% CI 1.13 to 1.43). There was no statistically significant association between exposure to noise and stroke risk for people under 64.5 (IRR 1.02; 95% CI 0.91 to 1.14).

More recently, studies have found transportation noise to be associated with other major diseases, such as diabetes – one of the largest public health challenges today, with more than 400 million people affected worldwide. Potential mechanisms behind an effect of noise on diabetes include reduced insulin levels and sensitivity due to increased levels of cortisol and disturbance of sleep. Sleep disturbance also results in changed levels of appetite-regulating hormones [25]. This is supported by a number of studies showing both aircraft and road traffic noise to be associated with obesity and higher levels of fasting glucose [26].

The EU-funded QUIET project (Health consequences of noise exposure from road traffic) has found that the more one is exposed to specific noise, the higher the risk of developing certain diseases in the long term. By way of example, the risk of diabetes increases by approximately 11% for every 10 dB increase in road traffic noise [27].

Other studies have shown that transportation noise may also be a risk factor for the development of cancer, including breast and colon cancer and non-Hodgkin's lymphoma. Noise may affect the carcinogenesis by effects of stress and sleep disturbance on the immune system, as well as through suppression of melatonin, a hormone known to have various anti-carcinogenic properties [26].

Furthermore, other studies have found an association between traffic noise and unfavourable lifestyle, including being physically inactive, smoking and increased alcohol consumption. These lifestyle-factors are well-known risk-factors for cardiovascular disease, diabetes and cancer [20].

For road agencies wanting to calculate the health burden in their own jurisdictions or the incremental change due to new road projects, organisations such as the National Institute of Public Health and the Environment in The Netherlands, have published guidance documentation [28]. This report outlines the methodology involved in a health impact assessment and describe how to assess and evaluate the cumulative health impacts of traffic noise on specific populations using indicators such as DALY or the number of people that experience adverse effects of noise.

## 4.2. TRAFFIC NOISE ANNOYANCE

Noise annoyance is defined as a feeling of displeasure, nuisance, disturbance or irritation caused by a specific sound [29]. Annoyance is an emotional state connected to feelings of discomfort, anger, depression and helplessness. A vast amount of research proves the association between road traffic noise and annoyance.

The impacts of noise on the population are normally investigated using questionnaires or interviews with a systematic approach which often follows ISO/TS 15666 [30], the relevant ISO standard for such investigations:

*Many socio-acoustic surveys have been undertaken with the aim of improving the overall understanding of annoyance due to road traffic noise. Responses from the public to annoyance are generally measured using a verbal scale. Questions are standardized in ISO/TS 15666:2003 in order to obtain global or generally consistent*

reactions that allow respondents to express their holistic experiences over time and locations in and around their home, without concern about specific incidents and contexts. The questions do not specify one particular combination of conditions because the aim is to obtain an overall response that integrates responses over a range of different types of experiences. A long-term approach “Thinking about the last (12 months or so),” is chosen to obtain a well-defined and stable noise situation. This is based on the premise that if the noise situation changes, the response will be affected for a year or so before the response stabilises in the new situation [31].

The calculation of dose-response curves typically uses data regarding the calculated noise level at the most exposed facade of each home and the respondent's related answers to questions about noise annoyance. The basis for the relationship between dose and response is the answer to the question: “Thinking about the last year or so, when you are at home, how much does noise from road traffic bother, disturb, or annoy you?” The respondents can give their answers on a numerical scale from 0 to 10 where 0 corresponds to “Not at all annoyed” and 10 corresponds to “Extremely annoyed”. Moreover, the respondents may state their annoyance by checking one of the fields “Not at all annoyed”, “Slightly annoyed”, “Moderately annoyed”, “Very annoyed”, “Extremely annoyed” or “Don't know”.

The percentage of persons highly annoyed is often used as a descriptor of noise annoyance in a population.

Figure 7 shows a dose-response curve describing the correlation between noise exposure at the façade of residential buildings and the percentage of the population that expresses being highly annoyed by noise from road traffic. This curve is based on many investigations in different European countries and has been adopted in the 2018 WHO noise guidelines [11]. At a  $L_{den}$  level of 53 dB (the WHO recommended value for average exposure, refer chapter 3.2), 10% of the population are highly annoyed. At around 68 dB, approximately 25% are highly annoyed.

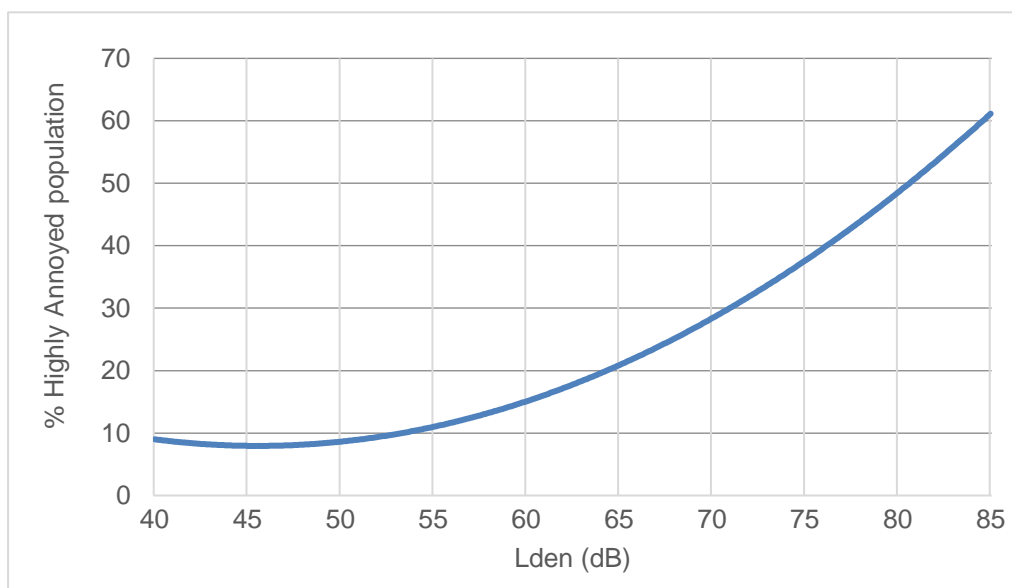


Figure 7: The percentage of “highly annoyed” population in relation to exposure to road traffic noise. The calculations are based on the regression equation  $\%HA = 78.9270 - 3.1162 \times L_{den} + 0.0342 \times L_{den}^2$ . [32]

An example of a dose-response survey can be found in a report by Fryd et al. [33]. The primary purpose of the study was to find out whether, for the same average level of road traffic noise, the annoyance experienced by residents along motorways is greater than that along urban roads. The survey involved approximately 7,000 respondents along motorways and urban roads in major cities in Denmark. It was found that, for the same noise exposure, people who live along motorways are significantly more annoyed by road traffic noise than people who live along urban roads: for a noise level  $L_{den}$  of 65 dB at the most exposed facade, the proportion of “highly annoyed” people along motorways is approximately 2.5 times that along urban roads. Besides, a level difference of more than 10 dB for the same degree of annoyance for the two road categories was observed: while 20% of the population was found to be highly annoyed for traffic noise from urban roads with an  $L_{den}$  of 68 dB, this proportion of highly annoyed people was reported for a motorway noise level of 57 dB [33].

Variations can be seen between socio-acoustic surveys. One of the two largest contributing factors is the geographical location of the survey. For example, with regard to location, the results of a community noise response survey in Vietnam [34] indicated a somewhat stronger tolerance to road traffic noise than observed in the EU or Japan: Vietnamese respondents reported annoyance at levels 5 to 10 dB higher than those at which European and Japanese subjects were similarly affected.

The second largest contributing factor is individual human factors, a number of which have been found to influence noise annoyance levels. These include noise and vibration sensitivity, use of vehicles, opinions on the safety of vehicles, and opinions on the importance of vehicles for society. These non-acoustical factors were all found to significantly influence the respondents’ annoyance levels.

Understanding community responses to road traffic noise can help in the planning of new road projects and their communication strategies. It can also help support the development of noise guidelines and limits.

Outside of socio-acoustic surveys, a community’s response to their annoyance with noise is generally indicated through complaints. However, complaints are not always the best indicator of annoyance in relation to traffic noise. For example, a community noise study was undertaken in Brisbane, Australia where 450 people within the city area were interviewed [35]. While the study found that residents rated traffic noise as their greatest concern of all community noise issues, this was not subject to the highest number of complaints (which was barking dogs and building construction). In this instance, the complaints were motivated by the residents’ perception of whether their complaints would be effectively addressed.

#### **4.3. IMPACTS OF TRAFFIC NOISE ON WILDLIFE**

Roadside verges provide important habitat for wildlife including insects, birds, reptiles and mammals, particularly in developed countries where large expanses of native vegetation have been cleared for agriculture or urban development and the road verge provides the only relatively undisturbed green space in an intensively managed landscape. However, this benefit can be tarnished due to the adverse impacts of roads on wildlife which may extend well beyond the road verge into the landscape including:

- Decreasing population density in adjacent habitats, often through increased death rates of certain categories of individuals.
- Causing behavioural changes, such as the active avoidance of roads for amphibians [36] and birds [37] [38].

- Visual disturbance due to passing vehicles and/or street lights – because both the level of traffic noise and the frequency of visual disturbance from passing vehicles increase with traffic volume, their effects are difficult to separate. However, other studies controlled for the visibility of cars in their analysis of bird densities in woodland habitats adjacent to and distant from roads and concluded that traffic noise had a greater effect on bird densities than did visual disturbance [37].
- Noise disturbance such as interfering or masking communication of acoustic signals for many animals including insects, frogs, birds and mammals [39]. A range of behavioural responses of birds to urban noise include singing at a higher frequency (pitch), thereby reducing acoustic interference from the low-frequency noise (a frequency shift); singing more loudly (an amplitude shift) and changing diurnal singing patterns to avoid peak traffic periods (a temporal shift) and modified call rate in amphibians. Traffic noise could hamper detection of song by birds of similar species, making it more difficult for birds to establish and maintain territories, attract mates and maintain pair bonds, and possibly leading to reduced breeding success in noisy roadside habitats [40]. Species that use passive acoustics for hunting are also likely to be disturbed by traffic noise with estimates of reduced hunting odds of 8% per dB for northern saw-whet owls [41].
- Noise triggering an avoidance response, so species are not active close to the road or will not cross roads (barrier effect as per below) which in turn reduces available habitat.
- Roads causing a barrier effect and obstructing migration and dispersal, thereby negatively affecting gene flow and consequently reducing biological fitness (i.e. the ability to survive and perpetuate genetic material).
- Roads causing either loss of habitat or habitat fragmentation, permitting or facilitating the introduction of invasive species into the landscape as well as transporting vehicle pollutants into the air, water and soil.

Traffic noise may be stressful for animals. Consequently, animals may move away from the noise-affected area, either temporarily or permanently. Permanent avoidance of areas affected by road noise will lead to a permanent decrease in the amount of habitat available for noise-sensitive species and create a barrier to movement [42]. Those species that exhibit particular behavioural traits and inhabit narrow ecological niches could be more vulnerable.

Noise avoidance has been shown to cause greater vulnerability of modelled populations than other avoidance factors, including road surface type, vehicle movement, or combinations of these [43]. A further study [44] concluded that traffic noise created a barrier to movement through culverts under roads for a range of mammals. However, neither study measured traffic noise impacts in the absence of extraneous factors associated with roads.

Most of the research studies that have found an effect of traffic noise have focused on groups such as birds and amphibians that rely on vocalisation to communicate. For mammals, traffic noise generally represents a largely auditory disturbance rather than a threat to communication, whereas for bats, acoustic trauma can potentially have immediate and severe consequences as bats rely on highly specialised vocalisation and auditory systems to maximise their ability to detect, locate, track and capture aerial prey and avoid predators [45].

However, one aspect of traffic noise that remains unclear is the potential impact of very low-frequency sound produced by vehicles – frequencies below 20 Hz known as infrasound – which are inaudible to

humans but audible to animals and therefore may adversely affect the distribution of species, and their abundances and diversity [46].

Figure 8 outlines the potential effects of roads on a population over time. In this diagram, the impact on wildlife due to traffic noise could sit in either “reduced habitat quality” and/or “reduced connectivity”.

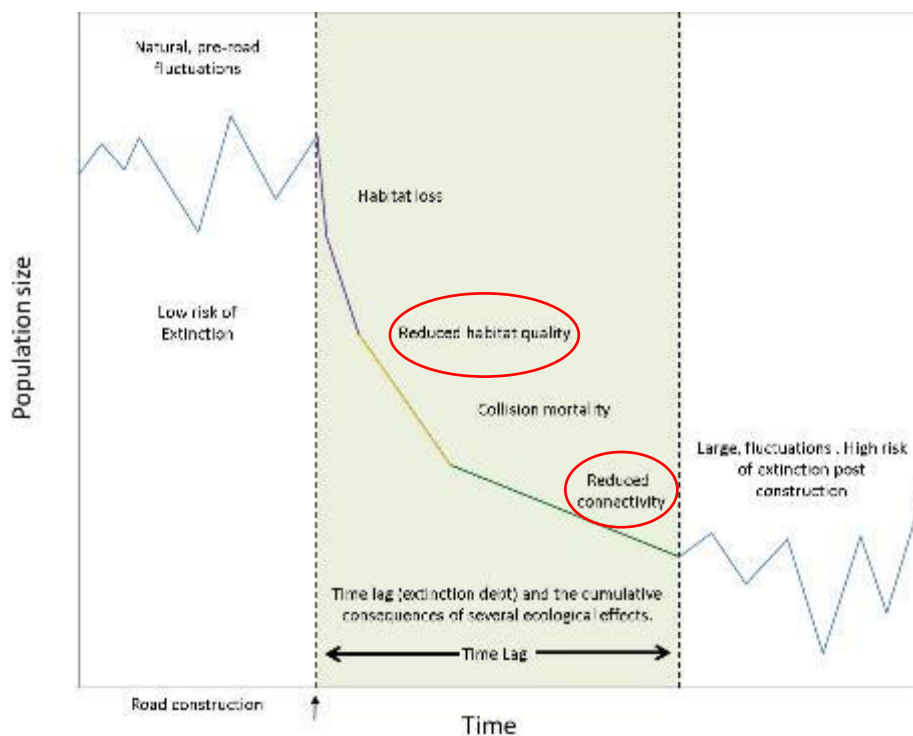


Figure 8: Potential effects of roads on a population over time. [47]

#### CHAPTER 4: CONCLUSIONS:

- The World Health Organization has classified noise from road traffic as the second worst environmental stressor affecting human health in Europe, behind only air pollution caused by very fine particulate matter.
- The primary adverse effects to the well-being of human populations are associated with sleep disturbance and cardiovascular diseases.
- There is increasing evidence regarding the effect of traffic noise on wildlife.

## CASE STUDY 1

### Framework to address the impact of traffic noise on endemic bat populations in New Zealand

#### Overview

Bats depend heavily on hearing to navigate and to detect preys. Several studies have identified negative effects of noise on bats from roads.

In recent years there has been increasing concern regarding the effects of roading projects on New Zealand's two endemic bat species. This has stemmed from a number of major projects occurring in areas where bats are present. How effects on bats are identified and managed has varied due to limited experience and no national framework.

In 2015, the NZ Transport Agency commissioned research on roading effects on bats (including noise) to better understand potential effects on New Zealand endemic bat populations and to develop a framework for managing these effects [48].

The research included a review of international literature, regulatory controls and management controls on a selection of New Zealand roading projects. In addition, local studies were undertaken including investigating traffic intensity and long-tailed bat activity.

#### Key findings

Roads present significant risks to bat populations. The potential risks/effects from increased noise (from construction and operation) include roost loss due to roost abandonment, and avoidance of areas causing severance of habitats. Local studies indicate long-tailed bat activity along highways is negatively correlated with night-time traffic intensity, although further study is needed to understand whether this is due to noise or light, or both. New Zealand bat populations are often small and already exist in fragmented habitats making them very vulnerable.

The current approach to assessing and managing effects is on a case-by-case basis resulting in inconsistencies in approach and a range of outcomes and costs. The outcome of the research is a framework that could be adopted to address these issues (as below).

#### Bat Management Framework

The framework sets out good practice for assessment, monitoring, management and mitigation of potential risks/effects to bat populations from roading projects.

During preliminary design of a roading project, consideration should be given to minimising the effects on bats by minor alterations to location (i.e. to avoid bat habitat/potential roosts), or design changes. At the project design and consenting stage, a detailed survey should be undertaken to predict and characterise the project's noise effects. Acoustic mitigation should be designed in consultation with a suitably qualified ecologist.



**NEW ZEALAND'S LONG-TAILED BAT**

Since 2017, the NZ Transport Agency has been working through the framework with project teams on roading projects with the aim of adopting this approach as good practice.

#### For further information

Smith et al. (2017) [48]



## 5. ECONOMIC IMPACT OF TRAFFIC NOISE

The economic estimate of traffic noise costs in the EU plus Norway and Switzerland was estimated in 2008 to be around EUR 45 billion a year, as thousands of people are thought to suffer an early death because of exposure to traffic noise, equating to at least one million healthy life years [2]. By comparison, the societal cost of road fatalities and injuries (rehabilitation, healthcare, material damages, etc.) in 2015 for this same region in the EU was established to be in the order of EUR 100 billion [49]. Accounting for inflation, this means that traffic noise is costing society at least half of that of road safety, yet it attracts only a fraction of the attention of regulators and road agencies.

According to the European Environment Agency (EEA), a number of EU member states have made their own analysis of the costs associated with exposure to noise [4]. In Sweden, the social cost of road traffic noise was estimated at over SEK 16 billion. In the United Kingdom, the Intergovernmental Group on Costs and Benefits estimated the social cost of environmental noise in England alone as GBP 7–10 billion per annum. The most severe health effects of noise, such as the impact upon cardiovascular disease, were estimated in the same report as costing GBP 2–3 billion per year. Effects on amenity, which reflect consumer annoyance through noise exposure, were estimated as costing GBP 3–5 billion each year. Furthermore, the impact upon productivity relating to factors such as reduced work quality because of tiredness or noise acting as a distraction was estimated to cost GBP 2 billion every year [4].

Economic quantification of the negative consequences of noise pollution is done by different monetisation techniques. Health impacts and annoyance, as well as willingness to pay to avoid impacts from noise, form the corner stone of such assessments.

### 5.1. MONETISATION OF ROAD NOISE EFFECTS

Generally, the monetisation of road noise effects can be split in two types of approach. One approach relates to the cost of lost productivity caused by exposure to road noise, which commonly requires the estimation of “disability-adjusted life years” (DALYs) as suggested by WHO. DALYs represent the economic value in terms of loss in productivity (due either to early mortality, or due to disability). This is an approach used for quantification and associated monetisation of road noise effects on health. Years of life lost (YLL) are a measure of mortality due to an environmental impact and are calculated as the number of deaths at each age multiplied by the standard life expectancy for each age. Years lost due to disability (YLD) measure the morbidity associated with environmental impacts and represent the number of disease/disability cases in a period multiplied by the average duration of disease/disability and weighted by a disease/disability factor [50]. As an example, a woman with a standard life expectancy of 82.5 years and dying at age 50 would suffer 32.5 YLL. If she additionally turned blind at aged 45, this would add five years spent in a disability state with a weight factor of 0.33, resulting in  $0.33 \times 5 = 1.65$  YLD. In total, this would amount to 34.15 DALYs.

Another approach to monetisation is based on social surveys carried out on samples of the population in which the respondents are asked how much money they would be willing to pay for a hypothetical outcome assuming it to be available on the market (e.g. how much a citizen will pay for less road noise).

*Figure 9* summarises the above-mentioned approaches for monetising the effects of road noise on health and quality of life.

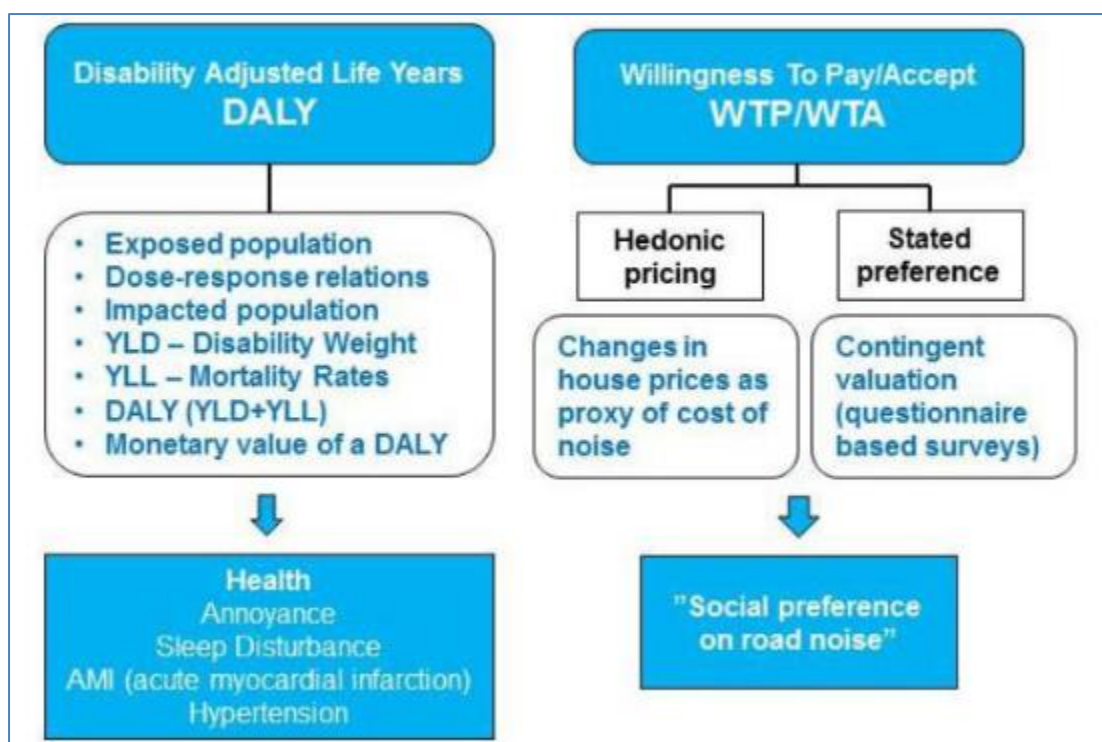


Figure 9: Two approaches for monetising the effects of road noise on health and quality of life. [51]

## 5.2. HEDONIC PRICING OF TRAFFIC NOISE

Infrastructure-based measures to reduce traffic noise are expensive and must compete for funding with other worthwhile uses of government funds. For this reason, it is important to be able to estimate the value to the community of reduced noise levels, to determine whether they represent good value for money and to balance this value against the cost of providing noise mitigation. Both the cost impact of noise and the cost of mitigation will vary between countries due to their individual economic circumstances. Estimating the cost of noise mitigation measurements is relatively straightforward; the value of the noise reduction is not so easy.

Ideally, the cost-benefit analysis of a noise reduction proposal should assess the value of the benefit to all people who will receive a benefit from it. Given modern noise mapping capabilities and appropriate valuations of noise, this can be achieved with noise modelling.

There are two approaches that can be taken to estimating the “cost of noise”:

- Revealed preference methods such as hedonic pricing, which compares observed sale prices of dwellings in noisy locations and dwellings in quiet locations to estimate the extent to which noise reduces prices.
- Stated preference approaches such as contingent valuation methods, in which people are asked how much they would need to be paid to accept high noise levels (or how much they would be prepared to pay for lower noise levels).

The analysis of the cost of noise can also be divided into amenity costs and health costs. Hence hedonic pricing reflects amenity impacts of noise rather than the health costs (i.e. health costs are not considered by purchasers of homes if they are not aware of these costs). Consequently, it is reasonable to assess health and amenity cost separately. Methodologies for assessing health costs



are well established in the field of health economics but depend upon estimates of the degree to which noise affects health.

While stated preference methods include survey questions specifically related to noise, they present a risk of misleading or of confused responses. In particular, people may quote unreasonable values if they want to protest against or express support for a specific infrastructure proposal. Alternatively, they may provide inaccurate responses if they do not fully understand the potential noise levels.

These issues can be avoided by hedonic pricing methods which use real prices from actual transactions. However, the sale price of a home depends on many factors and sophisticated analysis of very large sales data sets is required to separate the effect of noise from other considerations. A detailed discussion of hedonic pricing analysis of nearly 11,000 homes in the UK is reported by Bateman et al. [52].

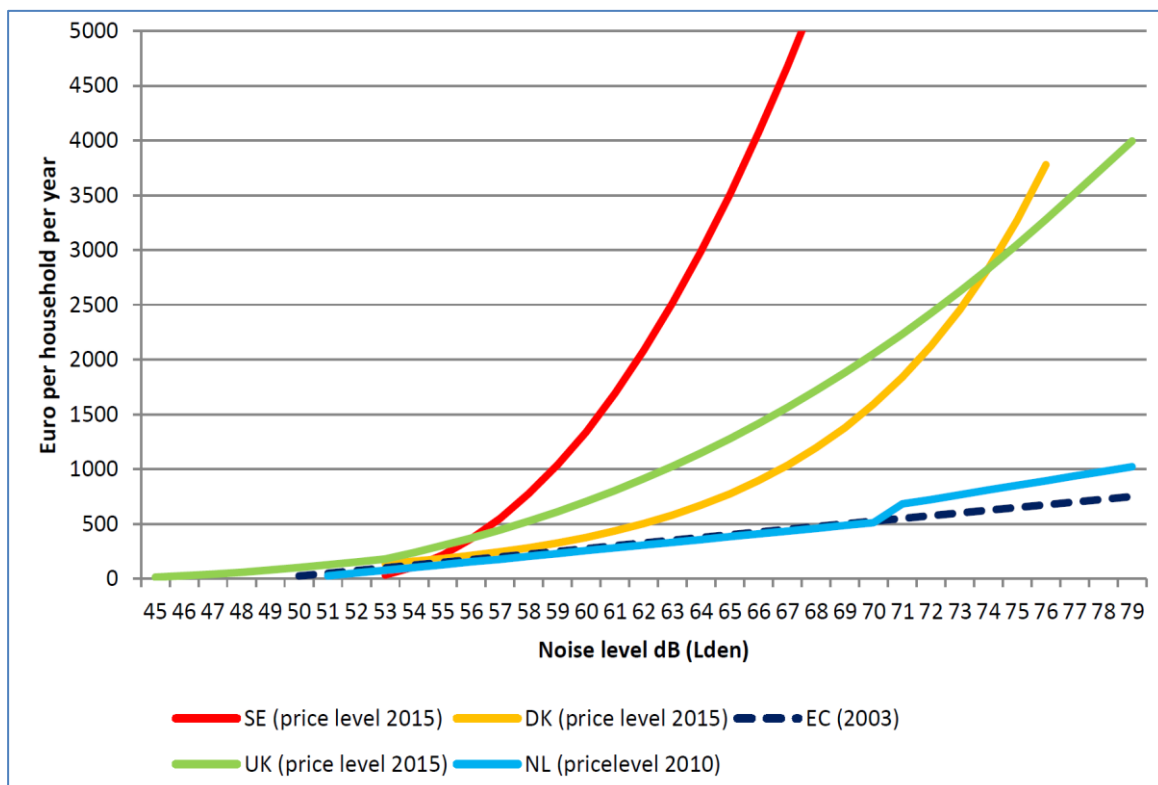
A large number of hedonic pricing studies have been published – generally indicating that noise reduces the value of homes by about 0.15% to 2.2% for each additional dB above a threshold of around 55 dB  $L_{Aeq}$  (day time). Expressing the cost of noise as a percentage of home price creates the obvious equity problem of valuing noise more highly in wealthy neighbourhoods than in poorer neighbourhoods. This could lead to a conclusion that new roads should be built through poorer neighbourhoods to minimise the amenity cost of noise. To avoid this equity problem, it is suggested that the hedonic price of noise be based on a percentage (say half of one percent [53]) of the average home price in a city or a country.

The UK Department of Environment, Food and Rural Affairs (Defra) reports monetary values for the cost of noise as a function of noise level but warns that the analysis is not sufficiently robust for use in major decisions [54]. The report is accompanied by a spreadsheet application for calculating the cost of noise that allows the user to input alternative cost assumptions using unit costs presented in *chapter 3, table 2*. Defra is planning to review its cost of noise in the light of the *Environmental noise guidelines for the European Region* from 2018 (refer *section 3.2* for further discussion on WHO guidelines).

When assessing the cost and benefits of noise mitigation measures, a particular complexity arises from architectural considerations in the design of noise walls. In some countries, the construction cost of noise walls is increased considerably to achieve high visual quality. In particular, architectural considerations may preclude low cost, mass produced noise walls. While it is undesirable for noise walls to be unsightly, it is inappropriate for the pursuit of architectural excellence to make noise walls unaffordable, resulting in suffering for those exposed to unreasonable noise. Proposals for noise walls should be based on cost estimates for conventional noise walls. Architectural merit can be considered for more expensive walls.

### 5.3. UNIT COST OF TRAFFIC NOISE

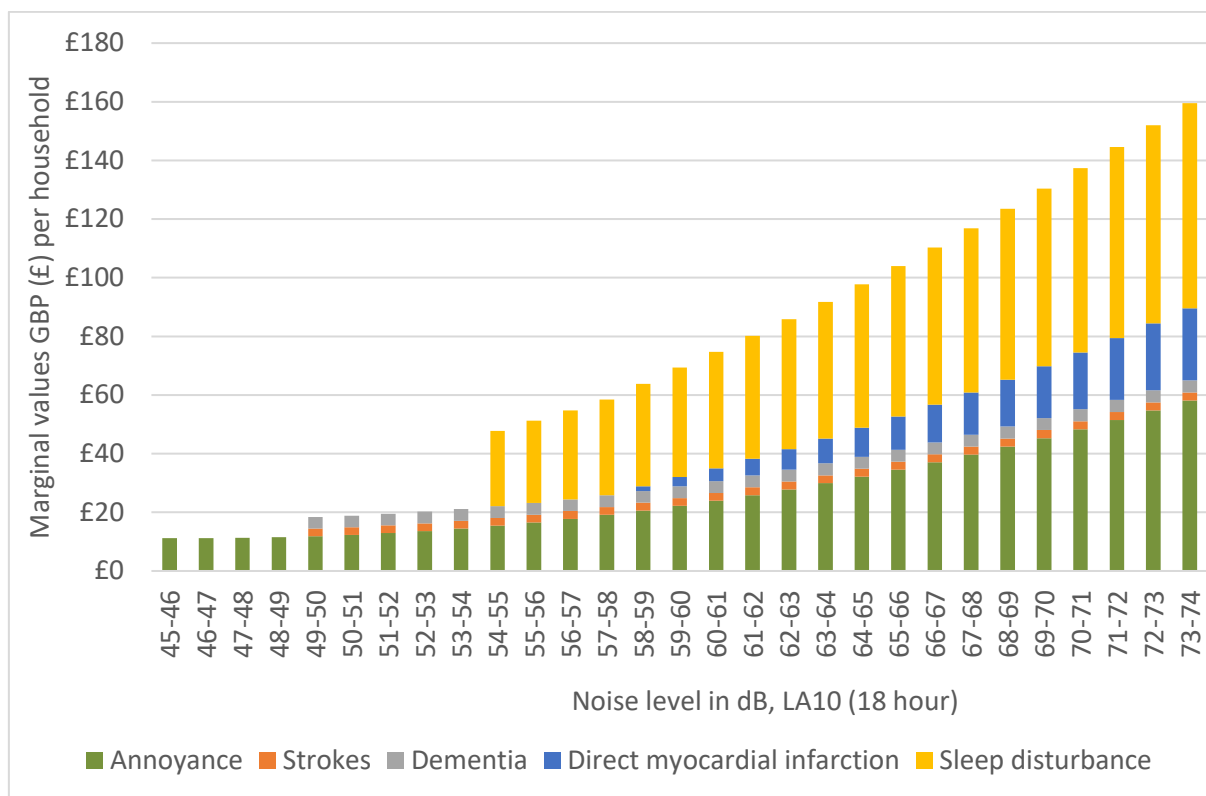
The Conference of European Directors of Road (CEDR) Task Group on Road Noise collected information on unit costs for road noise used in the pricing of road traffic noise in Denmark, Holland, Sweden and the United Kingdom [51]. These values are presented in *figure 10*, alongside with the EU Commission's valuation of noise from 2003. Several European countries have no unit prices for the cost of road traffic noise. It must be emphasised that prices in *figure 10* are not directly comparable because they are based on different methodologies. Nevertheless, they still give an overview of the large discrepancies in the pricing of road noise throughout Europe. Both the Swedish and Danish valuations of road traffic noise take both life quality (annoyance) and health considerations into account. In the UK approach, the values associated to amenity and noise annoyance for a variation in noise level of 1 dB are valued independently from the health values. A common trend is nevertheless observed: higher values associated with a 1 dB variation are observed as the noise level increases.



Legend: DK: Denmark, NL: The Netherlands, SE: Sweden, UK: United Kingdom; EC: European Community

Figure 10: Unit cost for road noise for four different countries and the recommended values from the EU Commission's position paper on the valuation of noise from 2003. [51]

The United Kingdom has more recently published information on unit prices of road noise as specified in the detailed analysis by Defra of the health effects of traffic noise [54]. *Figure 11* shows the marginal value, in GBP (£) per household per 1 dB interval change, for road traffic. Note, these values assume average habituation impact (i.e. tolerance to the effects of traffic noise after a period of exposure) across different demographics of the exposed population.



Note: The analysis leading to these values is not considered sufficiently robust for use in major decisions. They are also under review in the light of the *WHO environmental noise guidelines for the European Region* published in October 2018.

Figure 11: Road traffic noise marginal values GBP (£) per household per 1 dB intervals, 2014 prices. [54].

#### 5.4. VALUING ROAD NOISE IN DENMARK

The Danish National Road Agency uses cost-benefit analysis in connection with the preparation of environmental impact assessments of road projects. When planning a new road, or an enlargement of an existing road, investigations of several alternative routes or designs are carried out. The decision as to which option should be selected is based on assessments of the traffic outcomes and on the environmental and economic impacts of the project.

The Danish approach is based on a *noise exposure score* (NES) which is an expression of the accumulated noise load on all dwellings in an area [55]. Dwellings with high noise levels weigh more in the summation than dwellings with lower noise levels.

The NES is based on noise levels calculated outside noise sensitive buildings as free-field values at the location of the façade. These levels can be interpreted as those to which occupants are exposed when windows are open.

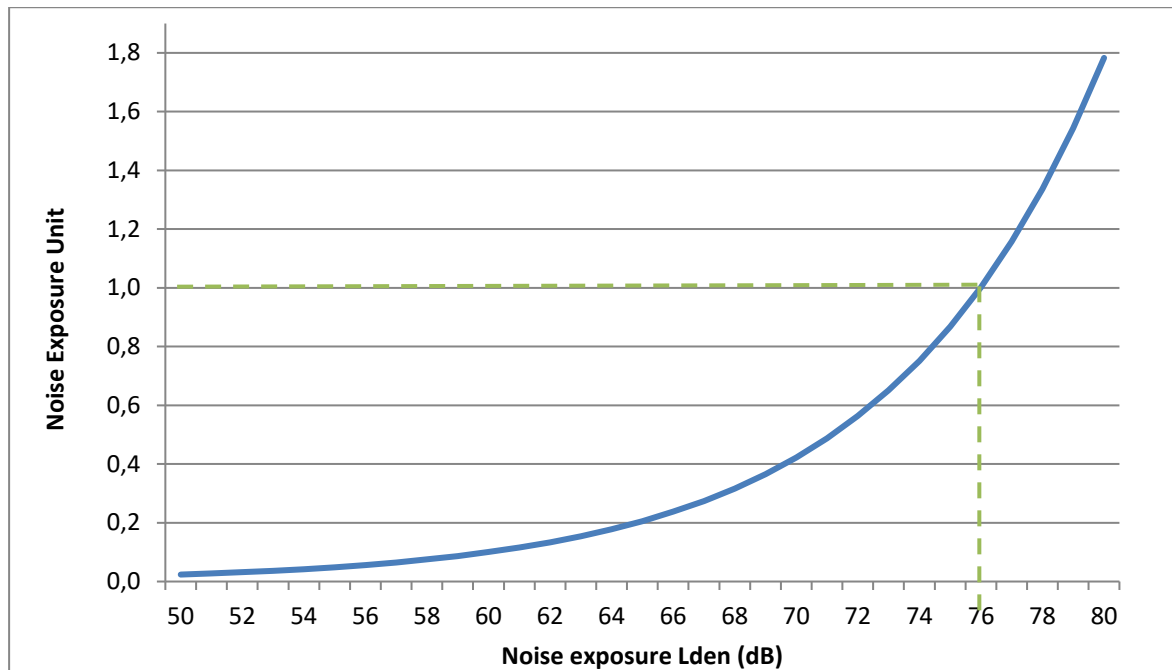
The NES is established summing the values of a *noise exposure unit* (NEU) derived, for each dwelling within the study area, from a dose-response relationship:

$$\text{Noise Exposure Unit} = 0.01 * 4.22^{(L_{den}-C)/10}$$

where C is a constant that then takes the value 44.

The NEU applies to all-year dwellings (housings, old people's homes, student residences etc.), summer houses and allotment sheds where it is permitted to stay overnight. It is determined from

free field noise levels calculated using the NORD2000 noise prediction method [56]. The relationship between the NEU and the noise level is shown in *figure 12*.



*Figure 12: Relationship between the noise exposure unit (NEU) and noise exposure (free field Lden dB) at the location of the façade. [51]*

In this example, if the study area includes 10 dwellings exposed to  $L_{den}$  levels of 76 dB (NEU = 1, refer *figure 12*) the total NES will be 10 (10 dwellings  $\times$  1 NEU). This score is equivalent to that for a study area comprising 50 dwellings exposed to 65 dB (50 dwellings  $\times$  0,2 NEU = 10 NES).

The monetary valuation of noise is based on a unit price attributed to NEUs, which reflect the loss of amenity and the health burden due to noise.

The amenity cost is determined using the hedonic method. It is assumed that the single individuals in the population are willing to pay to avoid noise nuisance and that this willingness to pay is reflected in property prices. All things being equal, properties in less noise-affected areas will therefore be more expensive than similar properties in more noise-affected areas. This difference is subsequently used as an estimate of the noise cost.

The health cost reflects the indirect economic losses in the form of illness, loss of earnings etc. The method determines the correlation between noise exposure and damage to health and health-related costs in the form of increased costs for hospitals etc. and costs associated with absence due to illness and deaths.

The cost per one NEU in Denmark is EUR 3,769 per year [57], calculated as the sum of EUR 1,862 for nuisance costs and 1,907 EUR for health costs (see *table 3*).

	Costs per NEU per year (EUR)
Amenity costs	1,862
Health costs	1,907
Total costs	3,769

Table 3: The costs of noise per noise exposure unit per year in Denmark (2015 values).

(Source: Danish Ministry for Transport [57]).

Eventually, the overall NES enables assessing the benefits of different noise-reducing strategies, prioritising between projects and comparing different solutions. It also allows estimating the socio-economic costs and benefits of interventions (e.g. speed control, traffic control, pavement maintenance strategy) that result in a reduction or increase of noise.

The Danish National Road Agency uses cost-effectiveness analysis in connection with prioritising noise barrier projects and plans to use this approach when ranking the use of noise-reducing asphalt in connection with general maintenance of the state road network [58].

In the light of the new noise guidelines from WHO [11] there will be a need to revise the unit cost of noise used in Denmark.

### 5.5. VALUING ROAD NOISE IN THE USA

An alternative cost-effective approach is used in the USA to determine whether noise mitigation is economically justified. Benefiting receivers are identified as dwellings for which at least a 5 dB noise reduction would result from the considered noise abatement measures. The maximum allowable cost per benefiting receiver for these measures is pre-defined by each state, taking into account a base allowable cost and project-specific additional factors. For example, the state of Illinois sets the allowable cost per benefiting receiver of up to USD 45,000 [59] incorporating:

- base allowable cost USD 30,000
- extra allowance for high noise levels ( $\geq 70$  dB(A) before mitigation) up to USD 5,000
- extra allowance due to noise increase ( $\geq +5$  dB(A) before mitigation) up to USD 5,000
- addition due to receiver existing before road. USD 5,000

To avoid under-estimating the value of the mitigation measure assessed, its noise reduction is modelled for all receivers likely to benefit from it, not only for the first row of dwellings affected by the road project.

It is then reasonably simple to determine whether a noise mitigation proposal is worthwhile, comparing the value of its noise reduction against an estimate of its engineering construction cost.

## CHAPTER 5: CONCLUSIONS

- Economic quantification of the impact of traffic noise can be undertaken where health impacts, annoyance and property value impacts are estimated.
- Methodologies for assessing health costs are well established in the field of health economics but depend upon estimates of the degree to which noise affects health.
- Generally, the monetisation of road noise effects is assessed relative to the cost of lost productivity caused by exposure to road noise, which commonly requires the estimation of *disability-adjusted life years* (DALYs). The DALYs combine mortality – years of life lost (YLL) – and morbidity – years lost due to disability (YLD) – into a single numerical unit.
- The analysis of the cost of noise can also be divided into amenity costs and health costs. It is commonly believed that hedonic pricing reflects amenity impacts of noise but not the health costs. Consequently, health and amenity costs should be assessed separately.
- The economic cost of noise and the cost of mitigation will vary between countries due to their individual economic circumstances. Estimating the cost of noise mitigation measures is relatively straightforward; however, valuing the benefit of interventions from the reduction in health impacts is more difficult.

## 6. PREDICTIONS

### 6.1. TRAFFIC NOISE MODELLING

For many road agencies, the choice of a numerical model to predict traffic noise will be determined by legislative requirements. In some situations, this choice can also depend on local expertise. This chapter highlights the range of methods available and discusses the variations of these methods in terms of complexity and their capacity to model specific situations. Detailed descriptions of road traffic noise models will not be given here, but they can be found in technical reports or within national guidelines or standards

The road traffic noise models widely used throughout the world are presented in *table 4*. The information in *table 4*, including a more detailed comparison of the models listed is expanded in *appendix 1*.

Some models may be simple but not capable of describing many specific conditions – for example, the model used predominantly in the UK, Australia, New Zealand and Hong Kong – *Calculation of Road Traffic Noise* (CRTN) – allows for performing point-to-point calculations relatively easily, even by hand, but does not handle meteorological effects on sound propagation nor different ground reflections (as is the case when sound reflects on both side of a noise barrier) or ground discontinuities [60]. Other models may be more capable of handling reflections – for example RVS allows for detailed analysis of the possible combinations of multiple reflections on the facades of the buildings – but they are not simple enough to be implemented coherently (i.e. following the same approach) from one situation to another as the final choice for several implementation aspects is left to the end user [60].

All models have a common form. They assume that a road is a line source of traffic noise and the noise level is generally the sum of:

- a base level which has been established empirically
- adjustments for parameters influencing the emission of noise (source strength)
- volume of vehicles and the number of heavy vehicles
- speed of vehicles
- adjustments for road gradient
- adjustments for road surface type
- corrections relating to the propagation of sound from the road to the receiver
- noise reduction with distance
- ground absorption
- attenuation by noise barriers and diffraction by obstacles
- reflection of sound
- angle of view (or segment angle).

If there is no legislative requirement for a specific method, then presumably any method can be chosen. It must be understood; however, that the emission component is standard specific. Emission and propagation components must be defined for the same standard. Unless adequate validation investigations have been conducted, components from different models may not be compatible, i.e. it is not possible to enter the road configuration in one model and then calculate the noise levels in accordance within another model.

Model		Country/region	Latest revision
ASJ RTN [61]	Acoustical Society of Japan- Road Traffic Noise	Japan	2013
CRTN [62]	Calculation of Road Traffic Noise	United Kingdom, Australia, New Zealand, Hong Kong	1988
CNOSSOS-EU <sup>8</sup> [63]	Common Noise Assessment Methods, European Union	European Union	2012
KHTN [64]	Highway Traffic Noise Prediction Program	Korea	2007
NMPB – routes [65]	Nouvelle Methode de Prediction du Bruit – Routes	France, European Union	2009
NORD2000 [56]	Nordic Noise Prediction Method	Denmark, Finland, Iceland, Norway, Sweden <sup>9</sup> , Estonia	2018
RLS-90 [66]	Richtlinien für den Lärmschutz an Strassen, 1990	Germany	1990
RMW [67]	Reken- en Meetvoorschriften Wegverkeerslawai	The Netherlands	2002
RVS4.02.11 [68]	Umweltschutz-Lärm und Luftschadstoffe – Lärmschutz (RVS)	Austria	2009
SonRoad [69]	SonRoad. Modèle de calcul du traffic routier	Switzerland	2018
TNM 2.5 [70]	Traffic Noise Model. Version 2.5	United States of America and Canada	2004
SANS 10210 [71]	Calculating and Predicting Road Traffic Noise	South Africa	2001

Table 4: Road traffic noise models (based on National Physical Laboratory (2011) [72] and amended with input from TC E2 members)

Each of the models has its share of advantages and disadvantages. In general, the levels evaluated with a statistical noise model are moderately reliable for standard traffic flow conditions such as constant speeds, no abrupt changes and the absence of any intersection [73].

When comparing one model with another, it is necessary to look at the purpose for which the model and its predictions are being used and, within each model, to review how specific effects that affect the source strength or the propagation calculation are considered. In most cases, noise modelling will be done by a specialist acoustician. In the absence of legislative requirements, a competent acoustic practitioner should be able to recommend an appropriate model for any given context.

<sup>8</sup> In 2015, CNOSSOS-EU became a new EU Commission Directive (based on a revised Annex II of the Environmental Noise Directive). It is mandatory for all EU Member States since 31 December 2018 to comply with the directive when planning and preparing strategic noise maps.

<sup>9</sup> Finland, Iceland, Norway and Sweden have not yet implemented NORD2000. These countries are still using the older Nordic prediction model from 1996 (NPM96).



Typically, this choice should be justified by a review of literature documenting the validation of the model for the specific circumstances.

The data inputs required to populate any of the traffic noise models are represented diagrammatically in *figure 13*.

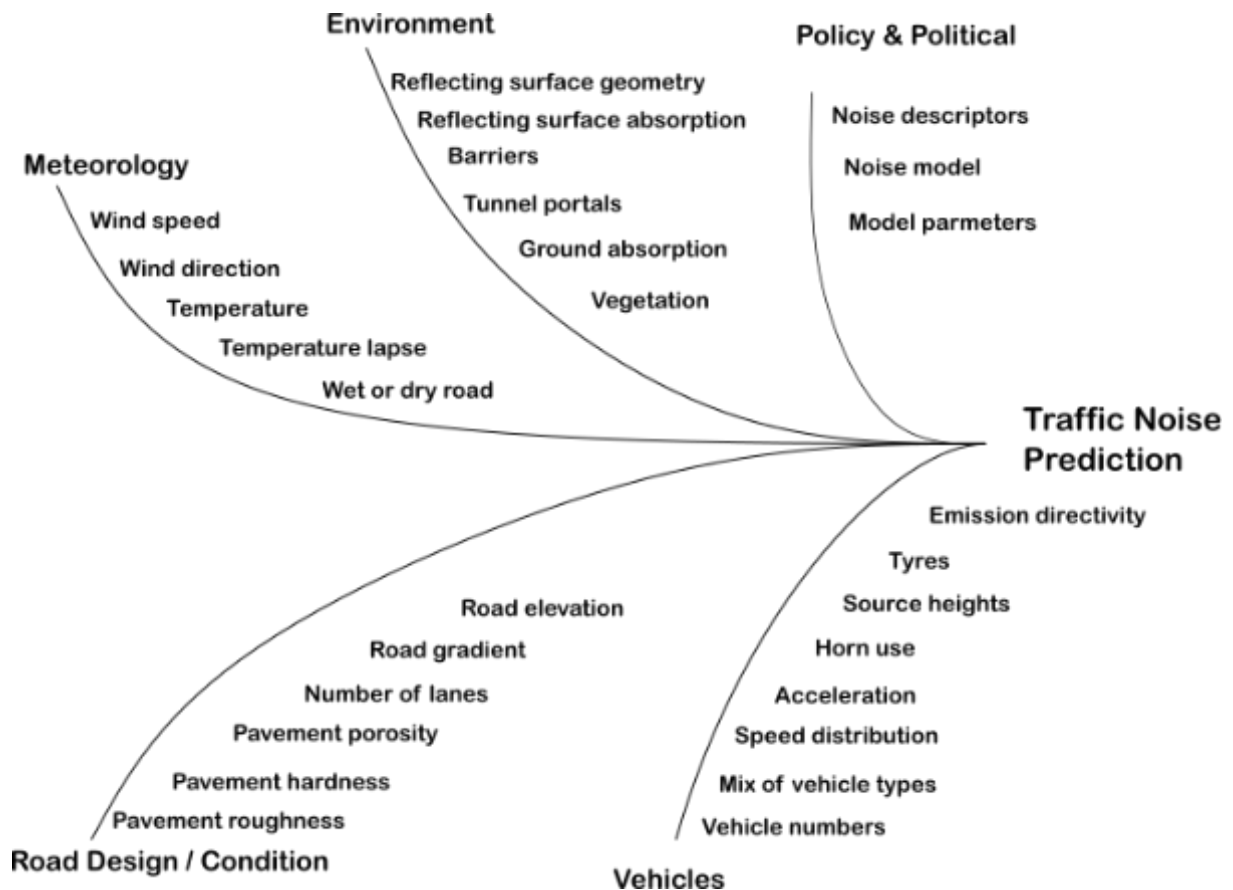


Figure 13: Data inputs for traffic noise prediction models (Adapted from Garg et al. [74])

Environmental noise models are used in a number of different decision-making applications or situations, for example:

- Forecasting the impacts of proposed changes to the environment (e.g. introduction of a new road; changes to an existing road; changes in the physical environment that affects noise propagation such as construction or removal of barriers or landscape features).
- Demonstrating compliance with local, state or national government requirements and subsequently prioritising funding for mitigation.
- Assessing and ranking different noise mitigation strategies (e.g. cost-benefit analysis).
- Designing noise mitigation measures such as noise barriers.
- Investigating results of measurement conducted in the presence of multiple noise sources, to better understand their relative influence on the total noise level, and identify key areas of concern before committing to expensive measurement studies.
- Developing strategic noise exposure mapping to inform environmental, health or economic impact assessments, or action plans for the mitigation of traffic noise (e.g. acoustic requirements for residential and sensitive-use buildings, land-use planning).

Irrespective of which model is chosen, the key information for all predictive studies is the systematic representation of the noise sources to be investigated and the physical environment through which noise will transmit to the receiver. Wherever possible, noise modelling should be supported and validated by a measurement campaign.

As mentioned earlier, the choice of a specific model may be determined by legislative requirements. However, regardless of the model chosen, it is important to understand its limitations and potential discrepancies. Such sources of inaccuracy or uncertainty might lead to a misrepresentation of the population exposed to unacceptable levels of traffic noise, leading to inappropriate levels of expenditure being allocated. Indeed, different calculations can easily under- or overestimate the population exposure to different noise level bands. The range of uncertainty can be significant and potentially reach up to a 3 dB error, which is equivalent of a difference in 50% of the traffic volume.

The most complicated model is not necessarily the most useful because the complicated models need detailed information and data which may not be available. Hence, the best model is the one that is “fit for purpose”, or best suited for its designated role or purpose.

An overall summary of the differences between most of the major internationally available traffic noise models is presented in *appendix 1*.

## 6.2. USING TRAFFIC NOISE MODELS

Studies have shown there can be very large discrepancies in the calculation results of noise models between countries [75] due to differences in calculation methodologies and assumptions. Such variations can be up to 10 dB(A). Therefore, when comparing different noise standards between countries it is important to consider the potential differences in the model calculation methods.

Key variations may be with regards to the calculation of

- the equivalent noise level (LAeq), such as the period over which the LAeq is calculated
- source emissions, such as different assumptions around source strength of cars and trucks
- sound propagation, including absorption by surfaces and attenuation due to barriers and meteorological effects.

Traffic noise models have become more comprehensive and complex thanks to increasing computer capability. Progress in computer speed and capacity has allowed significant progress in research on the propagation of sound, with extensive development of numerical methods. It also enables to implement more complex formulae and algorithms into noise models. Accuracy, precision, high computation speed and flexibility of a model, in conjunction with its suitability to generate noise maps, are pre-requisites for its efficiency. Thus, it is important to take all these factors into account when choosing a model.

## 6.3. ABILITY TO MODEL COMPLEX SITUATIONS

Some traffic noise prediction models are more suitable for relatively straightforward road configurations. For example, the simpler engineering models such as RLS-90 take the ground effect into account using empirical relationships involving the source to receiver trajectory (see *chapter 6.5*).

Traffic models such as CRTN, SonRoad and NMPB do not account for variation in noise impacts due to the presence of intersections. The Nordic model NORD2000 includes a correction for

deceleration and acceleration for vehicles approaching and leaving an intersection but it recommends using cruising vehicle emission values. The Dutch model (RMW2002) includes a maximum correction of 2.4 dB at the centre of the intersection depending on its type and on the day-time traffic intensity up to 150 m. The German model (RLS90) also includes a correction factor for signalised intersections up to 100 m. Correction factors for transient driving condition near an intersection are introduced for US (TNM) and Japanese (ASJ RTN-Model) traffic noise prediction models.

NORD2000 was developed to address some of the earlier limitations associated with the need for strategic mapping. For example, NORD2000 enables sound propagation over complicated terrain to be managed so there is a consistent interpretation, not reliant on subjective interpretation by the users.

#### 6.4. VEHICLE INPUT DATA

Another reason for the differentiation between traffic noise models relates to the databases used for the classification of vehicles. Large variations in the source emission factors can be observed between models, with differences up to over 6 dB(A) for light vehicles and up to over 4 dB(A) for heavy vehicles [60]. The influence of traffic speed may also be accounted for differently. An example for asphalt pavement is provided below for RLS vs CRTN and RVS.

$$C_{\text{speed}} = 27.7 + 10 \cdot \log[1 + (0.02 \cdot v)^3] \quad (\text{RLS})$$

$$C_{\text{speed}} = -68.8 + 33 \cdot \log[v + 40 + 500/v] \quad (\text{CRTN})$$

$$C_{\text{speed}} = 48.8 + 20 \cdot \log[v/50] \quad (\text{RVS})$$

These equations are valid for passenger cars only.

Speed dependence was amongst the most important parameters affecting the result, along with the pavement type and the road gradient and the way the road is represented by line sources.

The NORD2000 calculation model also separates tyre/road noise from propulsion noise (engine and exhaust noise). Thus, the model can be used to estimate the effects of changing road surfaces or tyres [76]. It is also possible to calculate the effect of studded tyres and of vehicle acceleration. The tyre/road noise generation factor can besides be corrected for variations in air temperature.

*Figure 14* presents the source emission levels for light and heavy vehicles for default Danish conditions (constant speed on dense asphalt concrete with 11 mm maximum aggregate [referred to as AC 11d] aged eight to nine years; air temperature 20 °C). It shows the maximum pass-by noise levels for a passenger car (P) and for a 5-axle heavy truck at constant speed. Rolling noise dominates light vehicle noise above 40 km/h and heavy vehicle noise above 70 km/h.

The source emission levels in NORD2000 are determined by a fitting process based on measured pass-by noise levels (both sound exposure levels LAE and maximum noise levels  $L_{AFmax}$  at each of two heights: 4 m above the ground and 0.2 m above the ground).

When calculating annual average values of road traffic noise level  $L_{den}$ , NORD2000 allows for additional corrections that account for specific conditions such as the acoustic performance of asphalt type, the average air temperature (which, in Denmark is 8 to 9 °C), and the fact that the road surface for a part of the year is wet due to rainfall [56].

By comparison, KHTN classifies vehicles as passenger cars, buses, small trucks, medium trucks, and large trucks in consideration of the specificity of the expressways of Korea, which have a high percentage of freight vehicles (28.5% of freight vehicles on the highway in 2017).

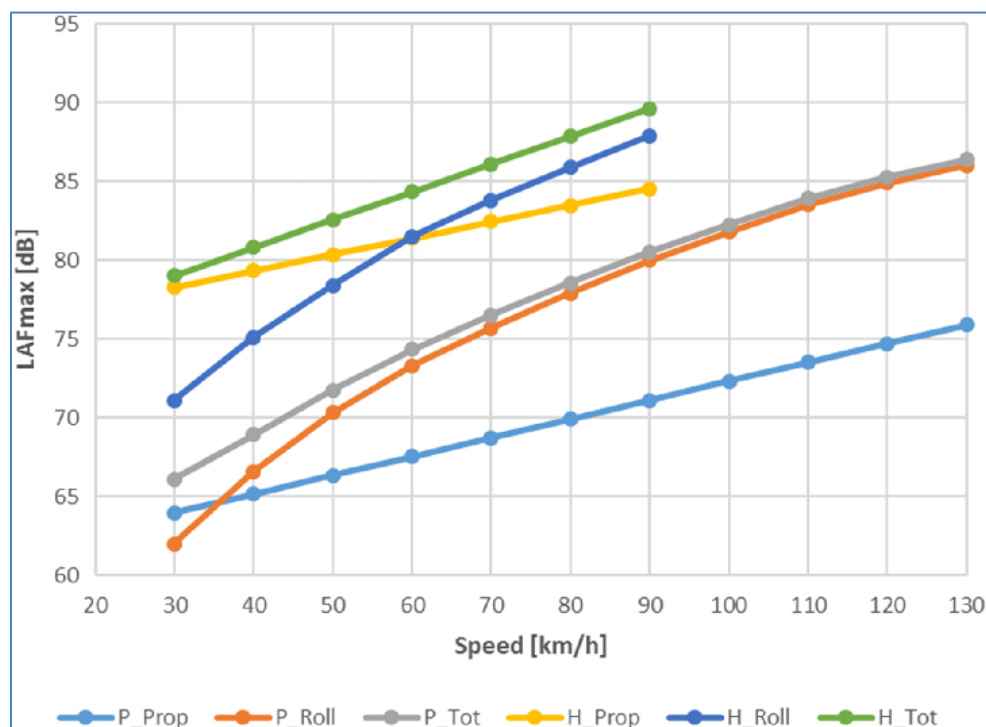


Figure 14: Propulsion noise (Prop), tyre/road noise (Roll) and total noise (Tot) for passenger cars (P) and heavy vehicles (H). Data based on the NORD2000 prediction model: distance, 7.5 m. [56].

## 6.5. GROUND EFFECT

At low frequencies, pressure doubling generally occurs due to the presence of the ground, adding up to +6 dB. In the mid-range frequencies and over soft ground, however, a ground effect dip can be observed over a relatively broad range of frequencies. This dip can result in significant reduction in sound level [77]. This dip is caused by the interaction between the direct and reflected sound pressure waves over soft ground, which often creates substantial destructive interference across a broad range of frequencies between 200 Hz and 1 kHz. The softer the ground and the lower the source and receiver heights (relative to the separation distance), the greater the ground attenuation.

Different models are used to take ground influence into account. The simpler engineering models, like RLS 90 or CRTN, produce an empirically based level increase with reflecting ground or attenuation with absorbing ground depending on the geometry for the source to receiver trajectory. More recent methods, such as SonRoad and NORD2000, model the coherent superposition of direct and reflected sound waves including phase relations based on the frequency dependent impedance of the ground. This impedance is a function of ground characteristics such as the flow resistance and porosity [77].

## 6.6. METEOROLOGICAL CONDITIONS

Between road traffic noise models, meteorological conditions and their influence on the propagation of sound are accounted for differently. The approach to model the ground effect and

shielding and diffraction by noise barriers can also vary. This can be a substantial source of discrepancy. An overall effect is difficult to identify, but for each single component of the propagation (i.e. diffraction, ground absorption, refraction due to wind or temperature gradients), up to 5–10 dB differences among models can commonly be observed [60].

For reliable predictions, atmospheric conditions should be measured at site, so that the calculated noise levels can be adjusted by a series of factors accounting for the effect of non-standard conditions [15].

### 6.7. OTHER FACTORS

The more recent models recommend differentiating the propulsion and rolling noise components of vehicle noise. This allows associating the increase of emission with gradient only to engine noise and increase in speed to tyre noise. The road surface corrections vary in different models [74]. The correction term is formulated using the running speed of the vehicle, running mode including acceleration and deceleration [78], and the age of the pavement in some models such as ASJ RTN. Some recent models present a frequency-based correction to rolling noise.

Sound absorptive properties of building facades and reflections from parallel facades, horn noise in some countries, road tunnels/bridges/viaducts and types of roads are also influencing factors affecting the noise level predictions.

Recent developments for some noise models have also included the modelling of two-wheel vehicles and electric vehicles [79].

### 6.8. NOISE CONTOUR MAPS

The noise models define mathematical calculations to predict traffic noise but are *implemented* via a range of computer software packages to generate noise contour maps. A range of proprietary software packages is available, and open source and GIS-based packages are being developed [80] [81]. These packages allow a user to create a map of an environment by importing or entering geographic data. They generally offer a selection of alternative models, for which the user must enter the necessary inputs. It should be noted that the US Federal Highway Administration (FHWA) offers a stand-alone package for its *Traffic noise model* (TNM).

The use of noise contour maps is particularly important in visualising and communicating noise impacts to key stakeholders and affected community members (see *chapter 8.7* for further discussion).

## CHAPTER 6: CONCLUSIONS

- Each of the calculation models available to predict traffic noise, has its share of advantages and disadvantages.
- The choice of model is often determined by legislative requirements.
- Regardless of the model chosen, it is important to understand its limitations, its potential discrepancies and the circumstances for which it has been validated.
- There can be very large variation [up to 10 dB(A)] in the calculation results of noise models between countries due to variations in calculation methodologies and assumptions.
- Wherever possible, noise modelling should be supported and validated by measurements.

## 7. MEASUREMENT

Measurements of traffic noise can be used for a number of different tasks and purposes:

- quantification and evaluation of the acoustic quality of single vehicles and tyres;
- quantification and evaluation of the acoustic quality of the road surface; and
- quantification and evaluation of the noise impact of the road traffic.

Each of these tasks requires a specific measurement method. When the measured results are compared with given requirements, for example, noise values defined by law, the measurement method has to meet the specifications the values are based on.

This chapter describes the most important measurement methods. These methods are used throughout the world and provide results that can be compared with one another, when undertaken consistently with the relevant reference standard.

Table 5 contains an overview of the measurement methods and their fields of application and table 6 provides a summary of the advantages and disadvantages associated with each method. Practical issues associated with each measurement method are outlined in more detail in the following sections.

Full designation	Command variable	Description	Purpose	Relevant standard
<b>Measurement of individual vehicle noise</b>				
Statistical Pass-By (SPB) Controlled Pass-By (CPB)	Maximum sound pressure level occurred during the passing of a single vehicle	Measurement of the noise produced by a single road vehicle next to the road track	Quantification and evaluation of the acoustic characteristics of vehicles, tyres and road pavements	ISO 11819-1 [82] ISO 11819-2 [83]
<b>Measurement near tyre-road interface</b>				
Close ProXimity (CPX)	Average sound pressure level at a short distance from a tyre rolling along a given road section	Measurement of the noise produced by a reference tyre when rolling over a given pavement	Quantification and evaluation of the acoustic characteristics of road pavements	ISO 11819-2 [83] in combination with ISO/TS 11819-3 [84] (reference tyres) and ISO/TS 13471-1 [85] (temperature correction).
On Board Sound Intensity (OBSI)	Average sound intensity level at a short distance from a tyre rolling along a given road section	Measurement of the noise produced by a single tyre	Quantification and evaluation of the acoustic characteristics of road pavements	Standardised in the USA through AASTHO T 360-16 [86].
<b>Measurement of road surface characteristics</b>				
Road surface texture (texture)	Roughness depth of the road pavement as a function of the roughness wave length	Measurement of the deviation of the road surface from a perfectly flat surface within very short sections of the road surface and with high	Quantification and evaluation of geometrical characteristics of the road surface being involved in the mechanical vibration excitation	ISO 13473, parts 1, 2 and 3 [87]



Full designation	Command variable	Description	Purpose	Relevant standard
		resolution in vertical and longitudinal direction	of the tyre. It is a proxy measurement relevant for understanding tyre/road surface noise.	
Road surface sound absorption (alpha)	Sound absorption coefficient of the road surface as a function of the acoustic frequency	Measurement of the sound absorption coefficient of semi porous and porous road surfaces	Quantification and evaluation of the ability of a road surface to lessen tyre/road noise by reducing the sound energy being reflected at the surface	ISO 10543-2 [88].
<b>Measurement of traffic noise impacting sensitive receivers</b>				
Environmental monitoring at point of Interest	Long term, average or statistical sound pressure level measured at a receiver point in distance from the road	Measurement of the noise produced by all traffic on a given road section	Quantification and evaluation of the noise received in areas where people are living or working	The standards that relate to environmental monitoring are specific to each jurisdiction and/or country

Table 5: Measurement of noise and acoustic characteristics of road vehicles and pavements; important methods and their application. (Source: Müller-BBM)

Advantages	Disadvantages
<b>The advantages and disadvantages of the SPB and CPB</b>	
They are the most widely and frequently used methods for assessing the influence of road surface characteristics on the vehicle noise emission. Therefore, a broad-based data collection of measurement results is available all over the world.	They are costly and time-consuming measurement procedures, particularly for SPB on lightly trafficked roads where it will take a long time to measure a sufficient number of vehicles.
They involve simple measurement procedures	Substantial acoustic requirements are needed for the test site.
No special measurement equipment needed.	Point measurements are used. Only the road surface in one cross section of the road can be addressed by the measurements. Due to a non-homogenous road surface the measurement results can be significantly different at a different test site on the same road section.
Measurement results are accurate and show a very good potential for being repeated and reproduced.	Noise levels represent the overall vehicle noise, not only the tyre/road noise. Future SPB measurements may be affected by technical changes in the vehicle fleet, in particular by electric vehicles, thereby making it difficult to compare SPB measurements from different time periods in terms of road surface assessment (for assessing the technological change

Advantages	Disadvantages
	of the vehicle fleet acoustically this may be an advantage). CPB makes use of one or several selected vehicles, the choice of which may affect how it represents the broader traffic.
	SPB or CPB measurements cannot be conducted on heavily trafficked roads, but instead are carried out in light traffic time intervals, often during the night between midnight and 4 am.
<b>The advantages and disadvantages of CPX and OBSI</b>	
They are documented within standardized measurement procedures	They require specialized measurement equipment, which represents a significant investment
Measurements of the tyre/road noise without interference from other sound sources are possible	There are substantial acoustic requirements for the test equipment
When reference tyres are used, sound level variations occurring during a measurement, or differences in sound levels observed between different tests can be traced back to variations of the acoustic characteristics of the road surfaces	Reference tyres are hard to get and need special maintenance and storage conditions
Continuous measurement of the tyre/road noise, which makes these measurement procedures suitable to monitor the acoustic quality of entire road networks with minimum expenditure of time	No universal conversion of CPX or OBSI levels into SPB levels and vice versa. To some extent, reliable conversions are possible for specific types of road surfaces. In general, CPX and OBSI noise levels cannot be simply related to traffic noise levels.
Measurement results are accurate and show a very good repeatability and reproducibility	Technological changes of the vehicles or tyres and their effect on traffic noise cannot be assessed
<b>Advantages and disadvantages of environmental monitoring at sensitive receivers</b>	
They represent direct measurement of the road traffic noise impact at the receiver's location	Measurements are sensitive to interferences, meteorological conditions and variations in traffic characteristics. Measurement conditions need to be carefully and comprehensively documented
For single measurement points, no special measurement equipment needed	A single measurement gives nothing more than a random sample of the noise impact
Noise impact levels can be used to calibrate and update computational acoustic models that are used to generate noise maps	Measurement results need to be normalized with respect to reference conditions in order to be comparable with each other

Table 6: Advantages and disadvantages of different noise measurements.

(Source: Müller-BBM)

## 7.1. ROADSIDE NOISE - STATISTICAL AND CONTROLLED PASS-BY MEASUREMENT

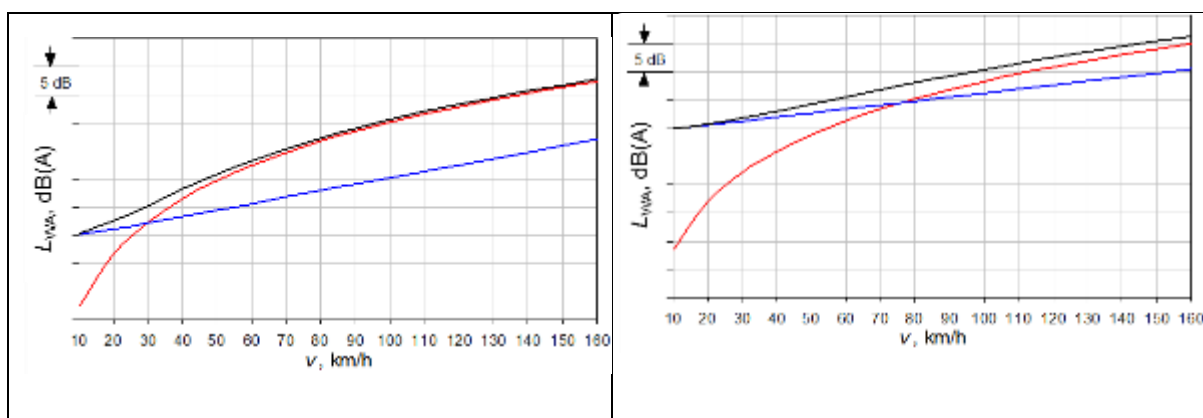
Pass-by measurements register the sound pressure that occurs when a single vehicle passes by. When measuring the pass-by noise of vehicles that are part of the traffic flow on a “live” road section, the specific types of vehicle as well as their engine components and tyres are unknown. The data record of measured vehicles is composed randomly. The measuring result for a specific vehicle category, e.g. passenger cars, is based on a high load of traffic and is gained statistically. Accordingly, this type of measurement is called a statistical pass-by (SPB).

The measurements can also be based on well-known and well-defined vehicles and tyres, driven by trained operators. In this case, the measuring results are achieved in a controlled way and are known as controlled pass-by (CPB). CPB measurements apply to acoustic homologation or conformity in the production testing of vehicles and tyres.

In addition, the handling of the vehicle can also make a difference. In instances where the engine is idling, or even turned off during the pass-by, such measurements are referred to as coast-by measurements rather than pass-by measurements.

CPB as well as SPB measurements can be used to assess the acoustic performance of road surfaces. A vehicle's overall noise consisting in a combination of propulsion noise and tyre/road noise. In general, this means both these components blend into the pass-by noise level. However, tyre/road noise dominates the overall vehicle noise for speeds above 30–40 km/h.

In *figure 15*, the findings of a comprehensive study on road vehicle noise sources, carried out within the framework of a European Commission research programme [89], illustrate the facts. The diagram on the left reveals the A-weighted sound power level  $L_{WA}$  of the rolling noise (red), the engine and propulsion noise (blue) and the overall noise (black) of light vehicles as a function of speed. The diagram on the right shows sound power levels for heavy vehicles.



Left: light vehicles; right: heavy vehicles.

Red: rolling noise; blue: engine and propulsion noise; black: overall noise.

*Figure 15: A-weighted sound power level  $L_{WA}$  of the main noise sources of road vehicles depending on speed.*  
[89]

On average, the curves shown in *figure 15* are valid for vehicles driving at a constant speed on a dry and flat road surface made of stone mastic asphalt 0/11<sup>10</sup> or dense asphalt concrete 0/11, not older than two years and in good condition. The values are related to an air temperature of 20°C and apply to the average European vehicle fleet in different categories. The light vehicle category is characterised by non-studded tyres, an average tyre width of 187 mm, 19% diesel cars and 10.5% delivery vans. The heavy vehicle category comprises trucks with four axles.

The diagrams in *figure 15* highlight the fact that the pass-by noise of light vehicles is generally not influenced by engine and propulsion noise. Measured pass-by and coast-by noise levels will be the same at speeds above 40 km/h. However, the situation is different for heavy vehicles. Even state-of-

<sup>10</sup> In d/D nomenclature, the first number, d refers to the minimum aggregate diameter and the second D refers to the maximum diameter. For example, 0/11 refers to an asphalt with aggregate size varying from 0 mm to 11mm and 5/10 refers to a mix with particles of no less than 5 mm and not more than 10 mm.

the-art vehicles produce engine sound levels that can be of the same order of magnitude as the levels for rolling noise, even at higher speeds.

Rolling noise can be measured in isolation by applying the coast-by method. The noise level is influenced by the characteristics of both the road surface and the tyres. Differences of up to about 6 dB can be observed for different passenger car tyres. Variations between tyres can also be different for different road surfaces. This is depicted in *figure 16*, which shows variations in tyre/road noise levels within a range of 16 dB. The results of coast-by measurements for a group of 12 different passenger car tyres travelling on different road surfaces illustrates the dependency of the tyre/road noise levels on both the type of road surface and the type of tyre. This means the application of pass-by or coast-by measurements for the acoustic characterisation of road surfaces should be based on a variety of vehicle equipped with a diverse range of tyres. In general, SPB measurements meet this requirement. In countries where winter and summer tyres are used alternately in the course of a year restricting such measurements to the summer season helps to harmonise the measurement results.

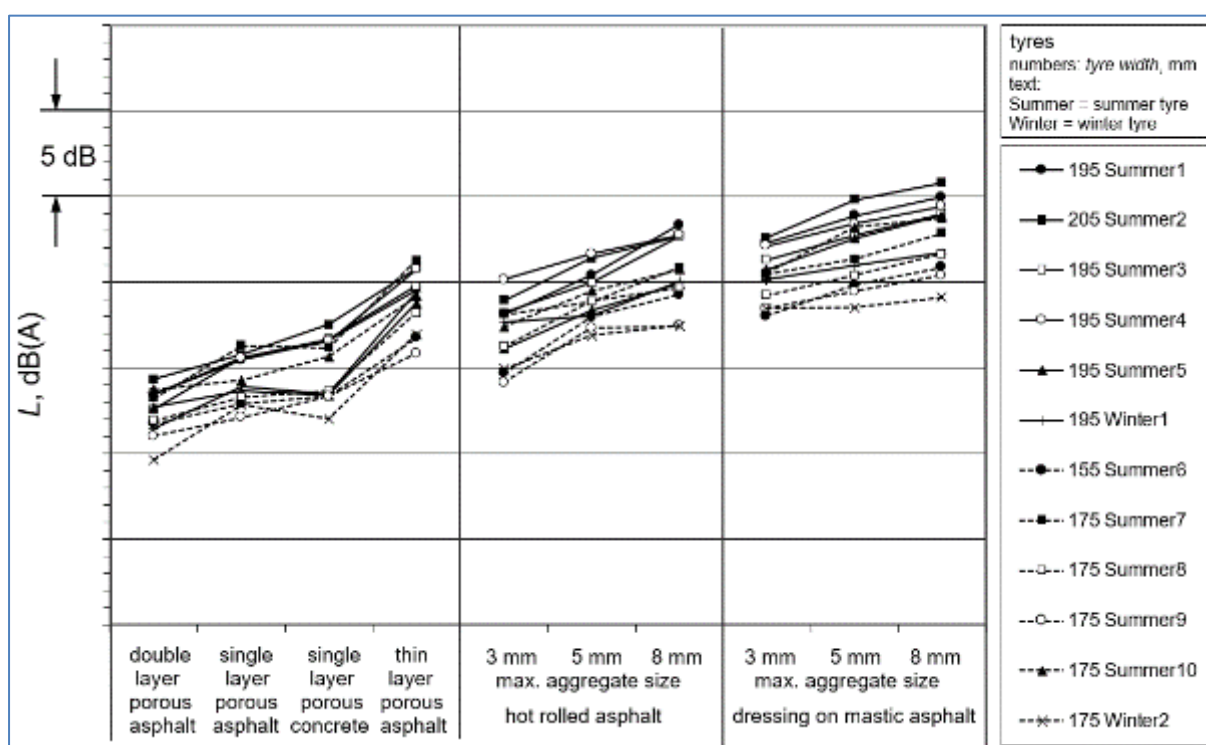


Figure 16: Tyre/road noise, registered by means of coast-by measurements with different tyres on a variety of road surface types. [90].

#### 7.1.1. SPB and CPB equipment set-up

The boundaries of the measurement and the set up for the SPB method are standardised through ISO 11819-1 [82].

Figure 17 shows the set-up of a SPB measurement installation in principle and in reality. The height of the microphone at 1.2 m above ground, more precisely at 1.2 m height above the centre of the first (right) road lane, is mandatory. Higher microphone positions, e.g. 5.0 m, may be used to avoid screening of the rolling noise of the vehicles by guide rails along the curbside. However, because standard SPB measurements have to be performed at a height of 1.2 m above ground, noise levels measured at different microphone positions cannot be compared.

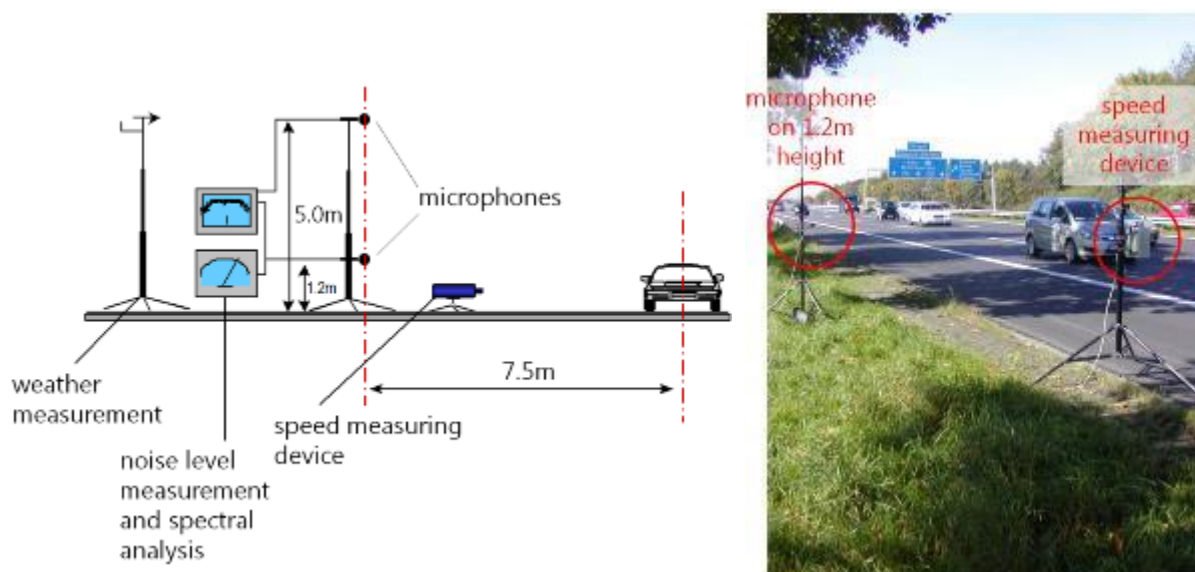


Figure 17: System set-up for SPB measurements. Left: positioning of the measuring devices (cross section); Right: real installation on the roadside of a German highway. (Source: Müller-BBM)

The configuration of the measurement site is also important. For example, obstacles can affect the measurement when they shield the sound or reflect it. If this occurs, comparison with measurements conducted at other sites would be difficult. *Figure 18* shows a situation where a guard rail partially shields the sound generated from the tyre/road contact for the lower microphone. The screening effect of guard rails can affect SPB measurements by 2 dB to 3 dB. The measurement position at 5.0 m height is not influenced by this obstacle. An alternative approach is to place the lower microphone closer to the road, e.g. 5 m instead of 7.5 m to the center of the lane to avoid the obstacle in between. As an example, such modifications are provided in the Swiss guideline for measurements of the acoustic quality of road surfaces [91] and should help to overcome the restrictive site requirements of ISO 11819-1. However, particular modifications can impair the ability to compare the SPB levels with those results of other measurement campaigns, especially those conducted in other regions or countries.

Another option would be to remove the obstacle from the test site before the SPB measurements are conducted. However, the road agency is unlikely to allow for this, due to the costs and technical efforts involved, as well as the road safety aspects.

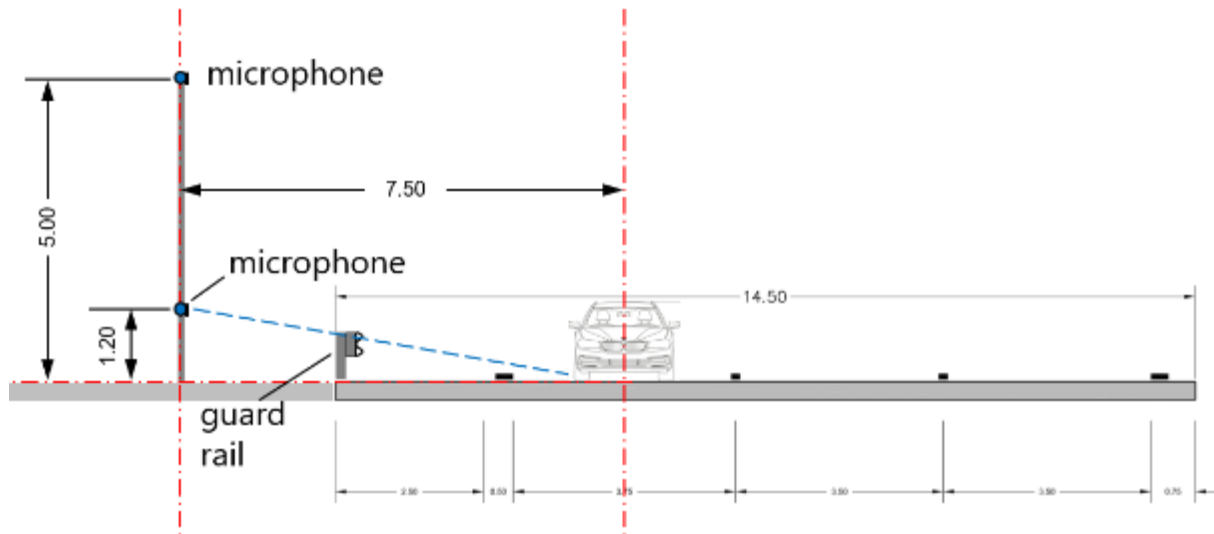


Figure 18: A guard rail affecting the sound propagation between the tyre/road contact and the microphone at 1.2 m height above the road surface. (Source: Müller-BBM)

Measuring the speed of vehicles is an integral part of SPB or CPB measurements. Speed is easily measured by means of radar detectors. Because the measurements are conducted off the road lane, the orientation of the radar beam towards the vehicles passing by plays an important role in ensuring the accuracy of the speed measurement.

A precise measurement of speed when the vehicle is passing the microphone is as important as accurate measurement of sound pressure level. The visibility of the radar operator is known to influence driver behavior and speed, which means that if there is a time delay between speed and sound pressure measurements, there will be an error. This can be avoided by using slant radar however, this makes the angular alignment of the radar critical to accurate measurement. For instance, skewing the radar by  $\pm 15$  degrees from the correct angle which is 45 degrees, would cause a speed error of more than 3%. The evaluation of the SPB levels, which depend on speed, would then include deviations of about 0.5 dB(A) [92].

The type of vehicles taken into account in SPB measurements is important given the need for statistical representation within the vehicle fleet and the key aspects of vehicle selection is described below. By comparison, CPB measurements are undertaken on defined vehicles and tyres.

CBP and SPB measurements can also be used for the measurement of noise from road joints [93] (see chapter 10.2).

### 7.1.2. Vehicle categorisation for SPB measurement

SPB measurements record the maximum noise levels for individual vehicles passing by. According to ISO 11817-1, the vehicles are categorised into at least two groups:

- 'light' vehicles (cars), i.e. passenger cars excluding other light vehicles
- 'heavy' vehicles, i.e. trucks, buses and coaches with at least two axles and more than four wheels.

The second group can be split into two sub-categories:

- dual-axle heavy vehicles (trucks, buses and coaches with two axles and more than four wheels)
- multi-axle heavy vehicles (trucks, buses and coaches with more than two axles).

SPB measurements need to be completed by accurate measurements of the vehicles passing the measurement point. Vehicles need to be assigned correctly to the appropriate category i.e. 1, 2a or 2b and the number measured in each category should be representative of the vehicle fleet in the local region or country, as appropriate to the investigations.

**7.1.3. Number of vehicles measured**

In order to make SPB measurements statistically reliable, a substantial number of vehicles within a vehicle category have to be measured. ISO 11819-2 stipulates the following:

- |  |             |
|--|-------------|
| • category 1 – light vehicles                | minimum 100 |
| • category 2a – dual-axle heavy vehicles     | minimum 30  |
| • category 2b – multiple-axle heavy vehicles | minimum 30  |
| • sum of categories 2a and 2b                | minimum 80  |

Adherence to these minimum requirements, limits the random deviation of the average maximum noise levels within one vehicle category to a 95% confidence interval of  $\pm 0.3$  dB for category 1 and of  $\pm 0.7$  dB for categories 2a and 2b.

**7.1.4. Selection of the measured vehicles**

The measurement of noise coming from a particular vehicle in a traffic stream is likely to be contaminated by the noise coming from vehicles travelling ahead or behind this vehicle. This is shown in *figure 19*.  $\Delta L$  is the difference in dB between the maximum sound pressure level measured during the pass-by of car 2 and the minimum sound pressure levels between car 1 and car 2, and between car 2 and car 3. For the measurement of the noise from car 2, the interference from car 1 and car 3 decreases as  $\Delta L$  increases. Level differences  $\Delta L$  of at least 10 dB indicate that there is no discernible contamination. ISO 11819-1 requires a minimum level difference  $\Delta L_{min.}$  of at least 6 dB. In practice, the person responsible for the measurements often tends to choose the minimum level difference  $\Delta L_{min.}$  to be as small as possible. This allows collecting valid data from a greater number of vehicles within a given time interval, especially in heavily trafficked situations. In other words, the time needed to measure the required number of vehicles will be significantly shorter with smaller level differences  $\Delta L$ .

However, this may lead the operator to discard pass-bys from low noise vehicles and skew the result of the SPB measurement campaign towards higher noise levels.



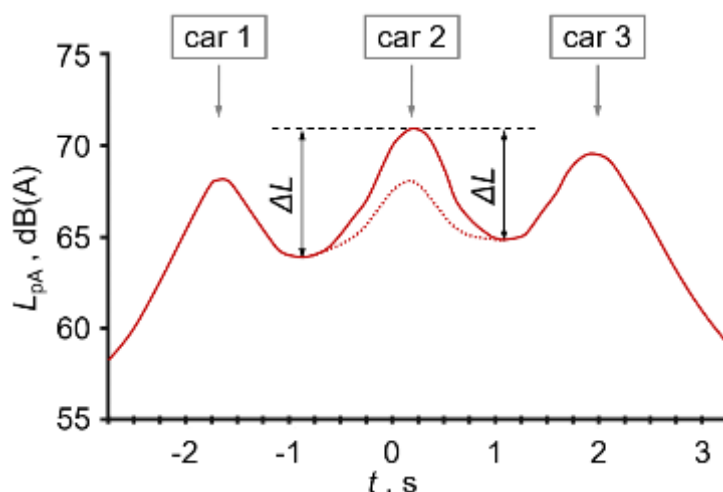


Figure 19: A-weighted sound pressure level  $L_{pA}$  as a function of time  $t$  caused by the passing of three vehicles (car 1, car 2 and car 3). Level difference  $\Delta L$  between the maximum and minimum sound pressure levels of car 2 with respect to car 1 and car 3. The dotted line is related to a low noise vehicle for the car 2 pass-by event.

(Source: Müller-BBM)

#### 7.1.5. Data analysis

For each vehicle category, the data set, comprising all the maximum sound pressure level/speed value pairs is subject to a linear regression of the levels against the logarithm of speed. Prior to this analysis, the noise levels are normalized for ambient air temperature, to ensure the SPB measurement results can be compared with those of other campaigns.

The air temperature is the most important parameter which could cause deviations of the noise level of the vehicles. The pass-by noise levels can deviate significantly from those measured at 20°C air temperature (reference temperature) by more than 0.5 dB in the temperature range from 5°C to 30°C. In addition to that, the temperature correction factors depend on the type of road surface [94]. Unfortunately, a generally accepted temperature correction does not exist. ISO 11819-1 refers to work in progress. However, it is certain that the tyre/road noise becomes quieter with increasing air temperature. The rubber of the tyre gets softer with higher temperatures which reduces the high frequency vibration excitation of the tyre and the rolling noise.

The general formula for the temperature correction  $C_T$  of pass-by levels is:

$$C_T = B * (20^\circ\text{C} - T)$$

with temperature correction factor  $B$  in dB/°C with  $B < 0$  (negative) and air temperature  $T$  during the measurements in °C. The correction is referenced to 20°C air temperature. Temperatures higher than 20°C lead to positive corrections  $C_T$  of the measured pass-by levels; temperatures lower than 20°C to negative ones, indicating the measured pass-by levels are higher at lower temperatures and lower at higher temperatures compared with those measured at 20°C.

Commonly, countries define their own temperature correction factors which are based on empirical studies or on practical experience within a country. As a rule of thumb, a temperature correction factor of  $B = -0.05$  dB/°C addressed the problem in a reasonable way.

In figure 20 the measurement results, i.e.  $L_{AFmax}$  and speed  $v$  value pairs are plotted by means of a scatter diagram on a logarithmic speed scale. The lines depict the results of the linear regression and the evaluation of the 95% confidence intervals.

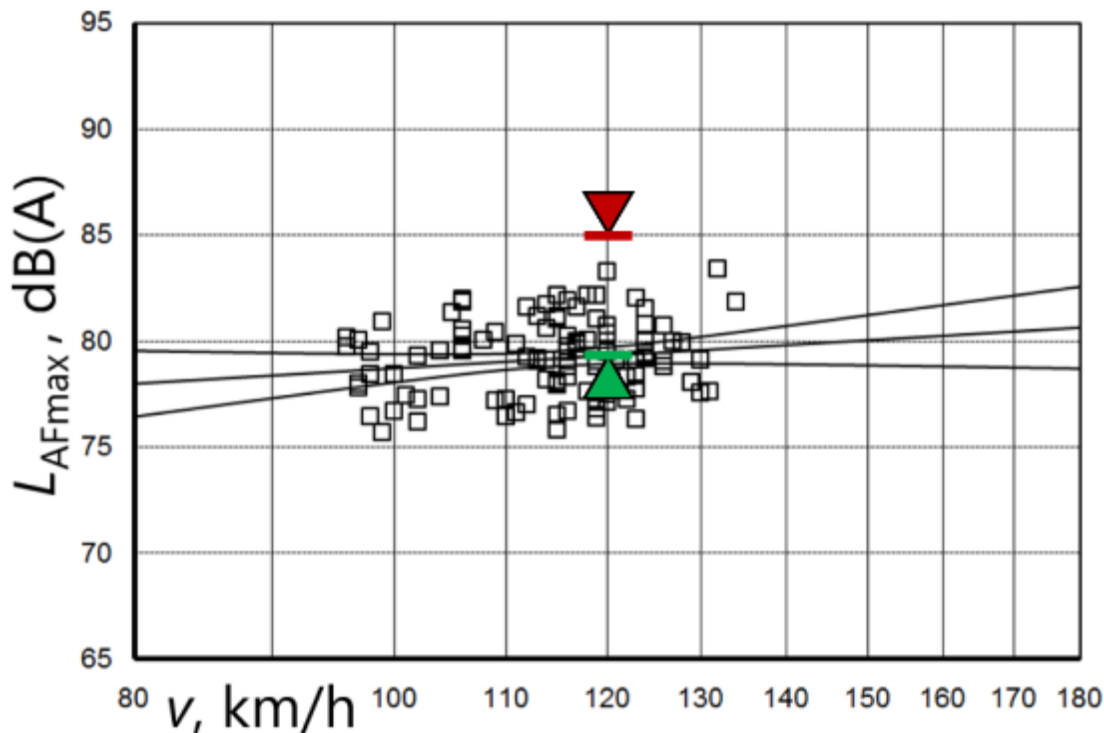


Figure 20. Scatter diagram of  $L_{AFmax}$  and speed  $v$  value pairs for 110 passenger cars. The red symbol refers to an arbitrarily chosen reference value for the assessment of the acoustic quality of the road surface at 120 km/h.

The green symbol refers to the average value of the pass-by levels at  $v = 120$  km/h. (Source: Müller-BBM)

The result of the SPB measurement can be read along the regression straight line as vehicle level  $L_{veh}$ . In the case depicted in figure 20  $L_{veh}$  is 79.6 dB(A) at  $v = 120$  km/h, marked by the green symbol. For assessments of the acoustic quality of the road surface on the test site, the vehicle level is compared with those for other types of pavements or for a reference surface evaluated for the same speed value. Assuming the reference level is 85 dB(A) for passenger cars driving at 120 km/h, marked by the red symbol in Figure 20 the characteristic value for the road surface  $\Delta L_{surf}$  in this case would be

$$\Delta L_{surf} = 79.6 \text{ dB(A)} - 85 \text{ dB(A)} = -5.4 \text{ dB(A)}.$$

Some road agencies specify the reference values for their network. A low noise road surface is one that is quieter than the defined reference level, meaning that the  $\Delta L_{surf}$  is negative. Commonly, the reference levels refer to measurements conducted at a couple of road sections with the same type of road surface. This is the reference surface, which is made from the most frequently laid type of asphalt or cement concrete in a country.

Usually, the SPB measurements for the reference surface, as well as for a road surface under investigation, are conducted a couple of years after construction. This is important, because the variations in acoustical behavior with time of different road surfaces with time may be different. Therefore, it is important to report the age of the pavement for the SPB measurement. In recent years, a number of road administrations in Europe have implemented programs for the acoustic monitoring of road surfaces to collect data over time (refer case studies 18 and 30). Measuring the road surface periodically helps to establish time series of  $\Delta L_{surf}$  values for specific types of road surfaces and to be able to assess the acoustic behaviour of a road surface over time.

## 7.2. NEARFIELD MEASUREMENTS OF THE TYRE/ROAD NOISE

Both the CPX and the OBSI measurement methods are based on the measurement of rolling noise in the nearfield of the sound source, which is the tyre/road contact patch. Within this region the sound field includes characteristics that are not measured when observations are made further away from the source, in the far field. Typically, the near field is limited to a distance from the source equal to approximately one wavelength of sound or equal to three times the largest dimension of the sound source - whichever is the larger.

The strength of a sound source is a determining factor for the noise impact in at receivers located away from the sound source. The strength of a sound source is characterised by its sound power, the sound energy per time unit, in Watts (W). Two quantities can be measured to determine the sound power of a sound source:

- sound intensity  $I$
- sound pressure  $p$ .

Since a significant proportion of the sound energy within the near field is not radiated into the far field, near field measurements should represent that part of the sound energy which is radiated. Measuring the sound intensity (OBSI method) helps to meet this requirement. Sound intensity is a directional acoustic quantity which can be used to measure the sound energy leaving the near field and travelling from the tyre towards a receiver point in the far field. Sound intensity is the sound energy per time unit and per unit area ( $W/m^2$ ).

An alternative method is to measure the sound pressure (CPX method). However, the sound pressure measurement needs to be free from disturbing sound reflections and interfering noise from other sound sources such as other vehicles. In this regard, the directive sound intensity method is more robust.

CPX as well as OBSI measurements can be used to characterise the acoustic performance of road surfaces. There are two main aspects which make these types of measurement more favorable in comparison with SPB or CPB measurements:

1. The tyre/road noise can be measured continuously along an entire road section.
2. The measured signals coming from the tyre/road contact are not influenced by noise from other sound sources like engine noise from the same vehicle, or noise from other vehicles.

### 7.2.1. Nearfield equipment set-up

#### Sensors and signal processing

The measurement set-up is characterised by placing several sound sensors in close proximity to the tyre whose tyre/road noise is to be measured. *Figure 21* shows the set-ups for CPX as well as OBSI measurements. It should be mentioned that just two of the six CPX sensor positions are populated for common CPX measurements. Sensors at positions 1 and 2 in *figure 21* (left) are mandatory, the other ones are optional and rarely used in practice. The distances  $d_1$  and  $d_2$  are 200 mm from the undeformed part of the tyre sidewall. The height  $h_1$  above the road surface is 100 mm. The distances of the sensors from the tyre for the OBSI measurement are different (*figure 21*, right). The sensors are half as close to the tyre as for the CPX measurement. In both cases, a sensor is placed at the leading edge and the trailing edge of the tyre/road contact point.

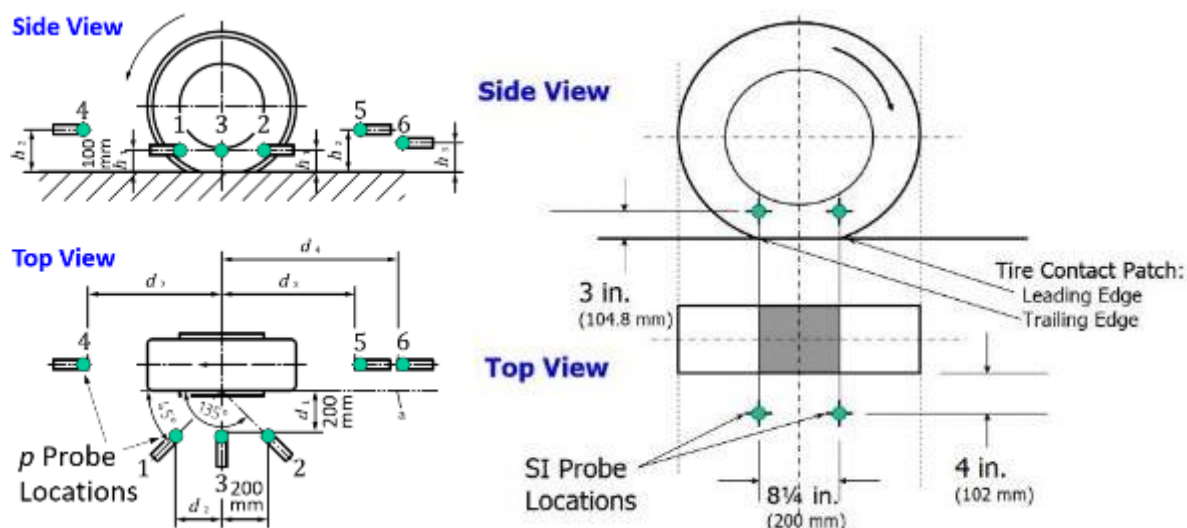


Figure 21. Near field measurement set-ups. Left: CPX measurement schema according to ISO 11819-2 [83]; right: OBSI measurement schema according to AASTHO T 360-16 [86]. Source: [95].

In both cases (CPX and OBSI), the sensors are common free field measurement microphones (sound pressure sensors,  $\frac{1}{2}$ " diameter). However, for the OBSI measurement two microphones build one sound intensity probe (si probe) and have to be paired exactly with respect to sensitivity, frequency and phase response. They are mounted in pairs (see figure 26c). The acoustic principle behind this sensor arrangement is that sound intensity can be measured by measuring the local sound pressure difference between two spatial positions which are quite close to each other. However, this method does need a specialised signal processing procedure.

The measurements at all sensor locations are done simultaneously. Therefore, a multichannel sound recording system is needed. This makes quite a difference in comparison with SPB or CPB measurements.

### Test vehicle

Either conventional or specialised vehicles can be used to mount the tyre and to move it along the road section under investigation. The measurement vehicles may be either self-powered or towed by a separate vehicle. One or two test tyres are possible. The test tyres may be surrounded by an enclosure. If a sound absorbing and insulating cap is used around the tyre, noise from other vehicles driving with the traffic stream is removed/reduced and the enclosure operates as a semi-anechoic chamber, providing optimal testing conditions in terms of acoustics.

Figure 22 shows what a CPX measuring trailer looks like in practice. Each is made according to ISO 11819-2 as a separate trailer, containing two test tyres within an enclosure, towed by a passenger car. Samples of the test tyres P1 and H1 according to ISO 11891-3 [84] are shown as well.

Different types of CPX trailers, with and without enclosure, with one or two test tyres, self-powered or towed, are shown in figure 23. Case study 2 also describes the CPX test vehicle utilised in New Zealand.



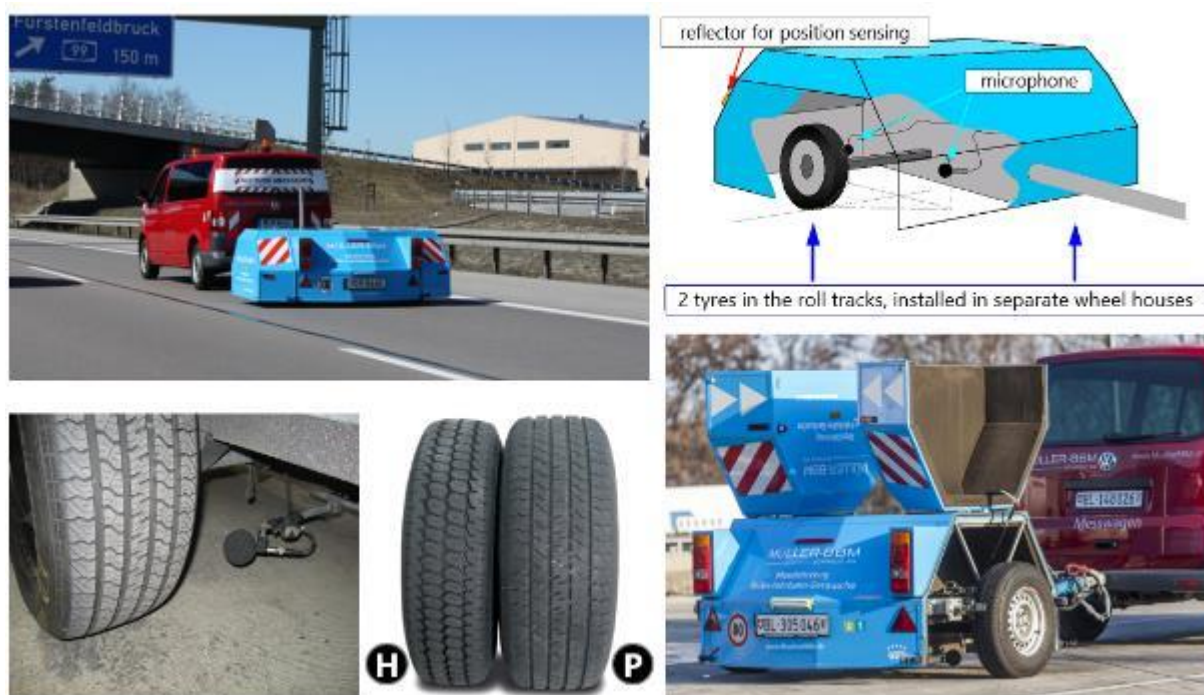


Figure 22: CPX measurement system in practice. (Source: Müller-BBM)



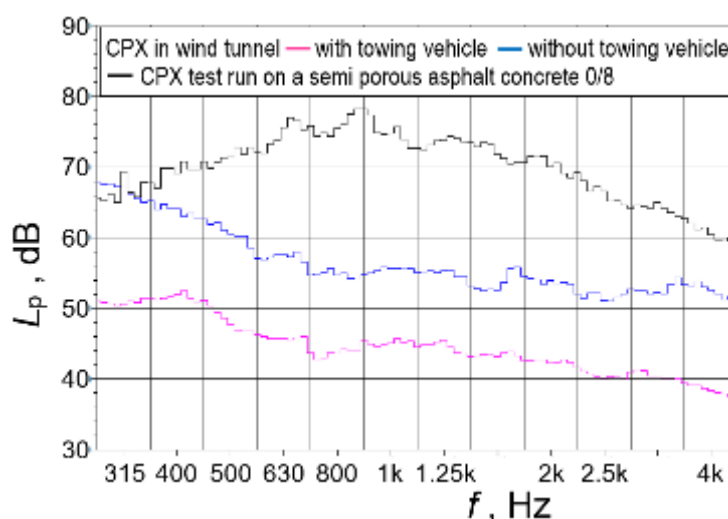
Figure 23. CPX measuring vehicles. a) open trailer with two test tyres operated by the Danish Road Directorate, Denmark (DRD). Source: M+P Consultants. b) closed trailer with two test tyres operated by Province of Noord-Brabant, The Netherlands. Source: M+P Consultants. c) open trailer with one test tyre operated by Tin Shun Consultants, Hong Kong, Source: [www.hktscl.com.hk](http://www.hktscl.com.hk) d) self-powered vehicle with one test tyre operated by the Transport Research Laboratory TRL, United Kingdom. [96].

In general, a test vehicle with sound absorbing enclosures around the tyres and towed behind a van provides the best undisturbed ambient conditions for measurements of the tyre/road noise. According to measurements in an acoustic wind tunnel, the configurations with and without towing vehicle in front of the CPX trailer makes a difference of more than 10 dB due to the air flow induced noise under the cap (see *figure 24b*).



24a) Above: CPX test vehicle in the wind tunnel.

24b) Right: Sound pressure level spectra for the noise measured during a real CPX test at 80 km/h driving speed on a low noise semi dense hot rolled asphalt with 8 mm max. grain size with tyre P1 (black curve), the noise under the enclosure with (red curve) and without (blue curve) the CPX test vehicle being placed behind the towing vehicle in an acoustic wind tunnel at a wind speed of 80 km/h. [97]



*Figure 24. Testing of air flow conditions and air flow effects on the noise being measured under the enclosure of a CPX test vehicle in an acoustic wind tunnel.*

The OBSI measurement method is much more focused on applying the measurement system to common and self-powered series-production road vehicles as is shown in *figure 25*. However, for use on public roads the technical modification of series-production vehicles needs to be approved by inspection authorities in many countries. *Figure 26* illustrates some details of the measuring equipment in a practical application.



*Figure 25. OBSI measurement system in practice. [95].*



26a) and 26b) Close-up view of the positioning of the sound intensity probes, probes protected by means of wind shields

26c) One sound intensity probe, consisting of two microphones, without wind shield.

*Figure 26: OBSI measurement system in detail. [98].*

### Test tyres

The test tyres are a crucial point concerning near field measurements that are to be used as a tool for the acoustical assessment of road surfaces. The tyre is an important component of the whole measurement system helping to reduce uncertainty by minimising the influence of tyre type. The use of standard tyres is essential for tests that aim to characterise the acoustical properties of road surfaces.

Worldwide there are just one or two types of tyres which are suitable for such testing and which can to be used on public roads and are produced using the same specified materials and structure. These are the so-called Standard Reference Test Tyres (SRTTs). These tyres are exclusively produced and sold by Michelin, France. The underlying specifications are defined by ASTM International (USA), Technical Committee F109 on tyres. The type of SRTT specified in ISO/TS 11819-3 [84] for CPX measurements (P1) and in AASTHO T 360-16 [86] for OBSI measurements is the ASTM F2493 SRTT [99]. For CPX measurements a second test tyre (H1) is specified [84] which is, in fact, a series-production tyre, not well specified, and to be phased out in near future. Originally, the test tyre H1, which shows a tough block tread profile and is made of very robust rubber compound for heavy loads, was intended to simulate the vibro-acoustic behaviour of truck tyres by means of a downsize tyre format.

### 7.2.2. Interpretation of measurements

#### Individual measurements

In general, the CPX levels (sound pressure levels in dB(A)) and the OBSI levels (sound intensity levels in dB(A)) of the tyre/road noise that have been recorded at each sensor position at each test tyre are averaged at regular intervals along the measured road lane. The test vehicle should travel at an almost constant speed. Typically, on rural roads and motorways a speed of 80 km/h is used. On urban roads, tyre/road noise measurements are conducted at 50 km/h.

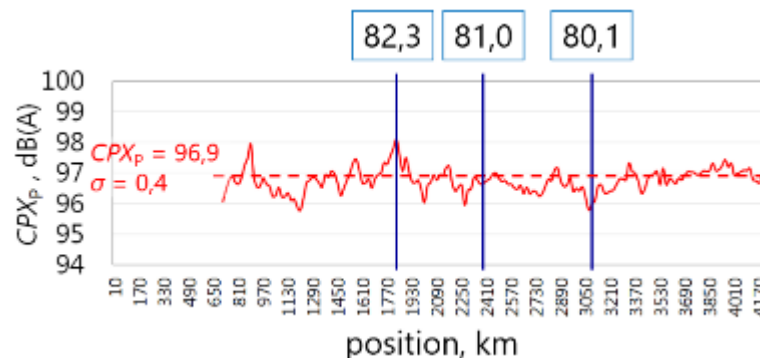
The measured road section is divided up into segments that are 20 m in length. For each segment the  $L_{99}$  sound level is determined. Thereafter they are averaged over all sensor positions, thus giving an



overall “CPX level” or “OBSI level” per 20 m road segment. In *figure 27* the result of a CPX measurement on a newly laid low noise thin layer asphalt is plotted. In this example:

- Travelling speed was 80 km/h and the road section 3,200 m long.
- Test tyre P1 has been used.
- The average value for the whole road section amounts to 96.6 dB(A).
- The standard deviation  $\sigma$  is 0.4 dB.
- The maximum deviation of the 20 m CPX levels is  $\pm 1$  dB which is low and proves a high quality road construction work. In most cases standard deviations of up to 0.6 dB must be expected and would not downgrade the quality of the road construction work.

In addition to that, the results of SPB measurements of cars at three different positions along the road section are indicated in *figure 27*. The average values for 120 km/h clearly correspond to the CPX levels at the specific positions. However, this example also reveals that SPB measurements are subject to the choice of the test site. One SPB measurement at a single position is quite untrustworthy.



*Figure 27: CPX sound pressure level in dB(A) as a function of the position along the measured road section. Dashed line: average (equivalent) sound pressure level CPXP and standard deviation  $\sigma$  in dB(A) for the levels of all 20 m sub-sections within the measured road section. The red curve represents the sequence of CPX levels for 160 road segments. Values in blue boxes: SPB levels in dB(A) for passenger cars, average speed  $v = 120$  km/h, measured at three different positions at the same road section. (Source: Müller-BBM)*

The benefit of using near field measurements of the tyre/road noise to understand the acoustic performance of road surfaces can be seen in *figure 28*. A CPX test run has been carried out at 50 km/h with both test tyres on an urban road section with four different road surfaces:

- a sub-section with an old surface (type unknown)
- two stone mastic asphalt (SMA) sub-sections with 8 mm and 11 mm maximum grain size
- a thin asphalt layer with grain size distribution 0 mm to 5 mm, the SMA and thin layer pavements not older than one year after construction.

Various aspects can be identified through these results:

- Repaving the road has improved the tyre/road noise.
- The degree of noise reduction varies between -0.5 dB and -7 dB, depending on the type of road surface.
- The surface type with the smallest grain size (thin layer 0/5) gives the best acoustic performance, the one with the biggest (SMA 0/11) the poorest. These findings agree with the principle of texture optimised low noise road surfaces described in chapter 9.3.

- The “good practice” pavements SMA 0/8 and SMA 0/11 show the best acoustic homogeneity which reflects a very good technical homogeneity. This, in turn, reflects that stone mastic asphalt can easily be handled by both mixing plants and road contractors.
- The low-noise thin-layer asphalt shows some more non-homogeneities, thus causing higher fluctuations of the CPX levels. The handling of asphalt mixes like this can be more challenging in practice.
- On the thin-layer low-noise asphalt 0/5 the measured tyre/road noise levels are significantly higher for tyre H1 compared to those for tyre P1. The level difference is nearly 3 dB on average. This is due to the block tread profile and the truck-like vibro-acoustic behaviour of the H1 tyre. Systematic measurements have shown that fine-graded road surfaces have adverse effects on the tyre/road noise of truck tyres (see chapter 9.3).

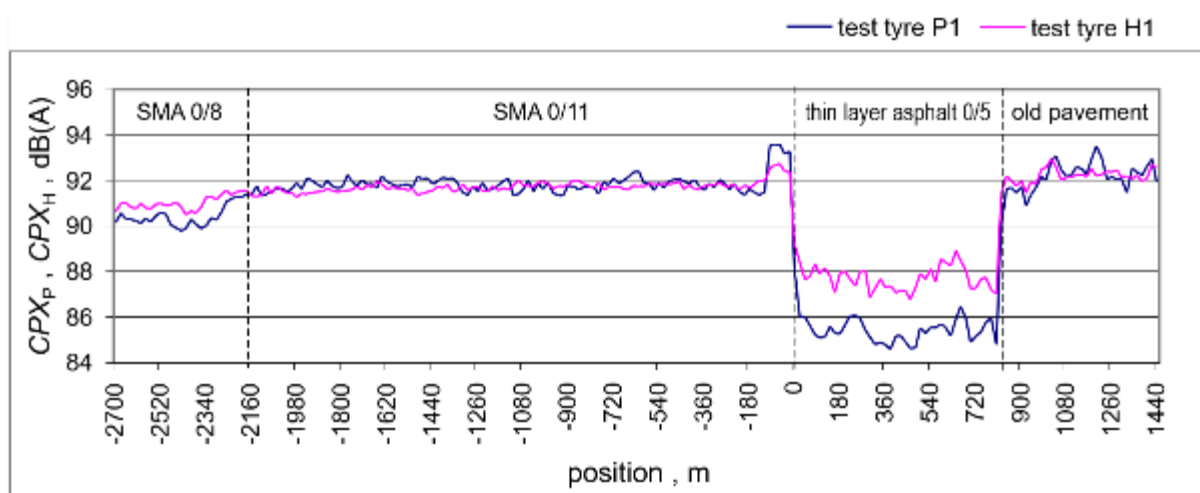


Figure 28: CPX sound pressure level in dB(A) as a function of the position along an urban road section, test tyres P1 (blue curve) and H1 (pink curve), speed  $v = 50$  km/h. (Source: Müller-BBM)

### Network measurements

CPX and OBSI measurements can be used beneficially to monitor the acoustic condition of entire road networks. Two aspects of an acoustic surveillance determine the manner and extent of such measurements:

- **Primary monitoring** – assessment of the acoustic robustness of new road surface types:  
After having been laid, different types of road surfaces do not show equal homogeneity and equal repeatability with respect to tyre/road noise levels. In terms of noise, they are more or less robust for variations of the material and deviations during the construction concerning material delivery, machinery, workmanship and experience of the workers on site. The quality of road surface production can be monitored by conducting tyre/road noise measurements shortly after completion of the road work, but not earlier than four weeks in order to give the road surface time to be run in and to remove the thin and sticky binder peel on top of the grains by traffic.
- **Acoustic road condition monitoring** – assessment of the acoustic quality of road surfaces depending on age:  
Acoustic properties of road surfaces change with time. In general, tyre/road noise levels progressively increase with age of the road surface. This ageing effect is different for different types of road surfaces [100] [101]. For road agencies it is important to know what degree of

acoustic degradation occurs on the roads in their network. This is particularly important, if noise reducing road surfaces are part of noise mitigation plans in road projects. Acoustic road condition monitoring supports road maintenance plans and reveals differences in ageing that can be due to different surface types, different traffic and meteorological conditions and even different road construction contractors. Therefore, acoustic monitoring helps defining good practice rules for noise reducing road surfaces in a region or a country.

Primary monitoring requires a single CPX/OBSI measurement with tyres P1 and H1. CPX/OBSI measurements within the framework of an acoustic road condition monitoring programme should be repeated year in and year out, preferably once a year. The ageing effect becomes obvious within a short period of three or four years already. *Figure 29* shows the ageing effect of a texture optimised impervious low noise asphalt with 5 mm maximum grain size TOA 5 in comparison with a standard stone mastic asphalt SMA 0/8 on urban road sections. The time plot clearly shows that the same type of road surface does not always give the same acoustic performance. The TOA 5 on road C gives the best acoustic performance in its initial state. However, with respect to ageing in dB/year, this surface loses its noise mitigation benefits more quickly than the other surfaces shown on the graph. After three years the TOA 5 on road B is no better than a standard SMA 0/8 on the same road with the same traffic on it. This demonstrates that time series of CPX/OBSI levels can tell us a lot about acoustic performance of road pavements.

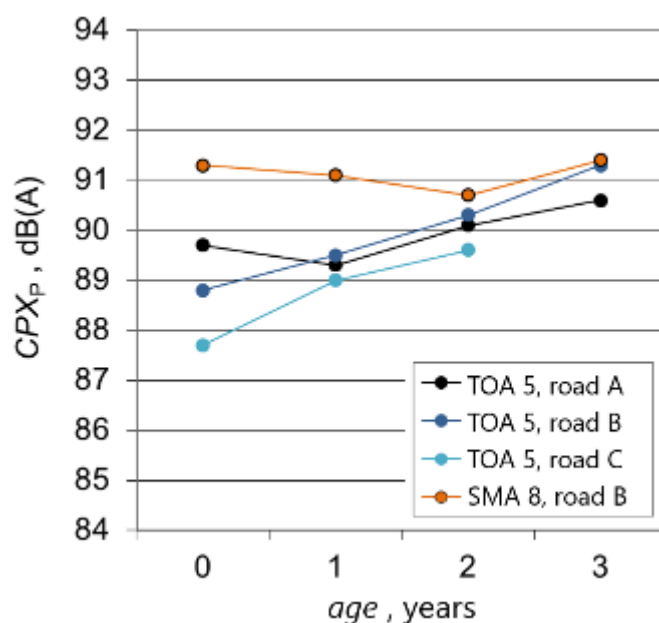


Figure 29: Ageing of road surfaces. CPX level in dB(A) depending on the age of the pavement after construction, test tyre P1, speed  $v = 50$  km/h; TOA 5 = texture optimised low noise asphalt, max. grain size 5 mm; SMA 8 = stone mastic asphalt 0/8. (Source: Müller-BBM)

### Comparison of CPX with OBSI levels

In principle CPX and OBSI measurements provide different results and need to be normalized to reference measurement conditions (including tyre, pavement, speed and temperature conditions) to make them comparable with each other. In this context, a comparison study has been performed by the Danish Road Institute, Denmark, in collaboration with Transtec Group Inc., USA [102]. CPX as well as OBSI measurements were performed on six different asphalt road surfaces (impervious as well as porous asphalt, maximum grain size between 6 mm and 11 mm) using the same tyres (SRTT) on the

same pavements, on the same day, at 50 km/h and at 80 km/h, respectively. The study concluded that there is a speed dependent difference between results obtained using the two methods. These differences are specified as follows:

$$\begin{aligned} L_{\text{OBSI}} - L_{\text{CPX}} = & \quad 3.1 \text{ dB(A)} \pm 0.09 \text{ dB at 50 km/h} \\ & 2.4 \text{ dB(A)} \pm 0.04 \text{ dB at 80 km/h} \end{aligned}$$

There are four important corrections required to refer measurement results to consistent conditions:

- correction for the speed, depending on the type of road surface  
CPX: according to ISO 11819-2, section 11.1 [83]
- correction for the temperature, depending on the type of road surface  
CPX: according to ISO/TS 13471-1 [85]
- correction for the hardness of the tyres used for the measurement  
CPX: according to ISO/TS 11819-3, section 9 [84]
- correction for the device (vehicle and measurement surroundings) used for the measurement  
CPX: according to ISO 11819-2, Annex A, section A.2 [83]

### Correlation with SPB levels

In principle, relating results of near field noise level measurements to SPB levels is a matter of complex conversion formulae. However, in many cases CPX and OBSI levels are related to SPB levels by means of simple linear regression equations that are based on the A-weighted single-number noise levels [103]. The relationship between CPX/OBSI levels and SPB/CPB levels is dependent on other factors including vehicle speed and pavement type. This complicates the determination of road-side noise levels based on CPX/OBSI.

## 7.3. MEASUREMENT OF ROAD SURFACE CHARACTERISTICS

The measurement of road surface characteristics represents an indirect method for the assessment of the tyre/road noise affected by the road surface itself. There are two main parameters which characterise the acoustic quality of a road surface:

- road surface texture
- sound absorption coefficient.

The measurement of sound absorption coefficients applies to semi dense and porous road surfaces only.

A texture measurement method is described in ISO 13473, parts 1, 2 and 3 [87]. Sound absorption coefficient measurements are conducted using bore cores from specimen that have been produced in the material testing laboratory or bore cores that have been taken out of the real road surface. An option to determine the sound absorption coefficient would be to place an impedance tube on top of the road surface. These measurements are undertaken consistent with ISO 10543-2 [88].

Indirect test methods require simulation models and calculation methods to convert the parameters of the surface characteristics to acoustic indicators such as CPX levels or pass-by levels. Models that are based on a physical description of the tyre/road noise depending on road surface characteristics are available. The SPERoN model [104] for example has been validated by means of comparisons of measured pass-by levels with pass-by levels that were calculated by means of measurement results

for the road surface texture and the sound absorption coefficient on the road section where the pass-by measurements were performed.

#### 7.4. ENVIRONMENTAL NOISE MEASUREMENT AT SENSITIVE RECEIVERS

When undertaking environmental noise measurements (both background and traffic noise), the following aspects need to be taken into consideration:

- the position of the microphone and the acoustic surroundings at the measurement location
- the relationship between the definitions within guidance levels or limit values
- the measured variable.

Usually, guidance or limit levels are based on so-called free field or “open window” noise impact levels, meaning that they do not include possible reflections arising from façades or windows next to the microphone. In order to be able to compare the measured noise impact levels with guidance or limit levels the measurement result must not contain any acoustic interferences that disagree with the boundary conditions defined within the applicable guidelines. There are four options to configure suitable noise impact measurements:

- Free field measurement.  
The microphone is positioned in such a way that no interfering sound reflections affect the measurement. However, guidance or limit levels are meant to comply with noise levels in close proximity to houses where people live. Usually, microphone positions in the free field are far from actual receiver points (refer *figure 30a*).
- Quasi-free field measurement.  
The microphone is in close proximity to sound reflecting façades. However, the microphone is positioned at a receiver point that is nearly not affected by sound reflections (refer *figure 30b*).
- Open window measurement.  
The microphone is positioned in the centre of an open window frame. The living room or bedroom behind it can be assumed to be sufficiently sound absorbing. The measured noise impact levels do not contain interfering sound reflections (refer *figure 30c*).
- Boundary layer measurement.  
The membrane of the microphone is positioned as close as possible to the façade. The microphone virtually becomes part of the façade, thus not being affected by sound reflections because they only become effective at a distance to the façade. However, due to a sound pressure stasis the sound pressure levels measured on the boundary layer in road traffic noise situations are about 5 dB higher than normal [105]. Therefore, the measured results have to be corrected for this physical effect. *Figure 30d* shows such a measurement configuration in practice. *Figure 31* illustrates this by means of a cross-section drawing.

In some jurisdictions where façade levels are specified rather than free field, noise measurements are performed using a microphone located a specific distance from a building façade.

*Figure 32* provides an example of environmental noise monitoring, noting placement of the equipment relative to the source and sensitive receiver and the results obtained.

30a)



30b)



30c)



30d)



Figure 30: Road traffic noise impact measurement. a) free field measurement; b) quasi-free field (substitutional microphone position); c) open window microphone positioning seen from inside; d) boundary layer positioning. (Source: Müller-BBM).

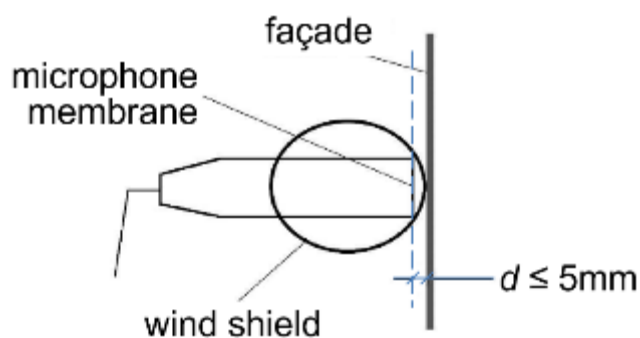


Figure 31: Boundary layer configuration for noise impact level measurements on closed façades. [106]





Figure 32: Environmental noise monitoring - road traffic noise measurement at a receiver point.

Top: the road inducing the traffic noise, noise barrier on the left; mid left: site plan showing the road (yellow) and the measurement location (red circle), mid right: microphone position (red circle) next to the house behind the noise barrier; bottom: time history of the A-weighted sound pressure level  $L_{pA}$  and equivalent sound pressure levels  $L_{Aeq}$  for the day and the night. The heavier trafficked and louder day time intervals alternate with the easier trafficked and quieter night-time intervals. On November 4 the average noise impact levels amount to 64.1 dB(A) for the day and 56.9 dB(A) for the night. Regarding all the measurement days the  $L_{Aeq}$  values are 63.1 dB(A) for the day and 57.1 dB(A) for the night. (Source: Müller-BBM).



Measurement results only represent what has happened during and at the location of the measurements. When measurements are compared with each other it is important to know how they have been derived. Traffic noise impact measurements need to also consider:

- the number of vehicles that passed the road for individual vehicle categories
- the (average) speed of these vehicles
- the road surface condition
- the distance between the road and the receiver point
- meteorological data
- the conditions affecting the sound propagation between the road and the receiver point like topography and acoustic properties of the terrain and sound screening as well as sound reflecting obstacles on the sound propagation path.

If the above information on measuring noise impact is not at hand, the easiest option is to use a sound level meter in combination with a free field sound pressure microphone. These microphones are available in weatherproof versions that make them suitable for long-term outdoor measurements.

Alternatively, improvised and spot sample measurements on site can be conducted by using the built-in microphones and signal processing capabilities of standard smartphones in combination with appropriate software applications. In recent years, several studies investigating the technical performance and practicability of these solutions have been published [107] [108] [109]. It is critical that smart phones used for noise assessment are calibrated due to the variations in hardware and software. Calibrated external microphones may provide greater accuracy.

Environmental measurements of noise at single receiver points usually do not accurately reflect the urban noise pollution in a larger area. Therefore, noise mapping strategies based on computational models have been developed for the effective visualization of noise pollution and its assessment (refer *chapter 8.7*). However, noise maps are static representations of a given situation characterised by calculated values for the strength of the noise sources and the sound propagation. In contrast to this, continuous measurements of the noise impact at numerous receiver points can provide data for dynamic noise maps. Time series of the noise levels can be used to demonstrate changes in noise within a city and to confirm the effectiveness of noise mitigation measures that have been undertaken. In this situation, a large number of acoustic sensors are required to be spread over a large area and established on a permanent basis, which is a costly exercise.

Capturing the noise level data recorded by hundreds or thousands of smartphones carried by people within an urban area could be an attractive alternative for dynamic noise maps. However, the data will not be free of interferences or based on reliable measurement conditions. A recent European funding project, the so-called “Dynamap” project (Dynamic Acoustic Mapping – development of low-cost sensor networks for real-time noise mapping) is a LIFE project,<sup>11</sup> whose aim is to develop a dynamic noise mapping system able to detect and illustrate the noise impact of road infrastructures in real time [110]. The implemented dynamic noise maps consist of pre-calculated basic noise maps that are prepared by using reference traffic and weather conditions. These basic noise maps are subject to a

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<sup>11</sup> The LIFE programme is the EU’s funding instrument for the environment and climate action. The current funding period 2014–2020 has a budget of EUR 3.4 billion.

dynamic updating process, which scales them by using information retrieved from stationary low-cost monitoring devices. These devices continuously measure the sound pressure levels of the primary noise sources present in the mapping area.

The Dynamap system consists of a series of noise monitoring devices installed along the road network. Each device can detect the noise level, eliminate the presence of anomalous noise events and transmit the data to a central unit, where they are processed and used to update the basic noise maps. The updating of the noise maps is implemented in a powerful open-source platform that is also used to collect, process, view and store the data. For further information see *case study 3*.

## CHAPTER 7: CONCLUSIONS

- Noise measurements can be divided into three classes: the first is near field measurement at the road-tyre interface; the second is roadside measurement and the third is noise immission at sensitive receivers.
- Traffic noise policies and guidelines typically deal with noise at sensitive receivers whereas road surface characterisation depends on nearfield and roadside measurements.
- It is important that adherence to international measurement standards is undertaken to ensure repeatability and reliability of measurements. Some of the measurement standards are still under development and consequently need to be implemented with care.

## CASE STUDY 2

### Development of a close proximity (CPX) measurement trailer to investigate practical reductions in New Zealand road surface noise

#### Overview

State highway road traffic noise comes mainly from vehicle tyres on the road surface. As many people are affected, even small improvements in road surface noise can provide worthwhile reductions in community noise exposure.

The NZ Transport Agency in collaboration with the University of Canterbury, has developed a close proximity (CPX) road surface noise measurement trailer to provide a tool to investigate practical reductions in road surface noise.



**CPX TRAILER WITH ACCESS HATCH OPEN**

#### CPX trailer

The New Zealand CPX trailer has been constructed in accordance with the international standard (ISO 11819-2) [83], as used for similar existing trailers in countries such as Australia and in Europe.

The trailer has two microphones mounted in an enclosed bay close to the bottom of a standardised test tyre. Sound levels are measured along the whole length of a test section of road, with the trailer towed at a speed of typically 80 km/h. Measurements are repeated for each traffic lane.

A large quantity of data is generated by a CPX trailer, so the road agency has developed software to quickly analyse and display results. Data is stored in compatible formats to other existing road data (e.g. roughness) and the software can efficiently compare different parameters.



*CPX levels on four expressway lanes*

#### Initial findings

The primary focus for the road agency has been porous asphalt surfaces as these are used in urban areas with the highest population densities.

Previous international research has established parameters that can be used to reduce noise from porous asphalt, such as smaller chip sizes and increased surface depth and void content.

The NZ Transport Agency has started a programme to optimise these design parameters for New Zealand porous asphalt. Initial trials indicate that improvements can be achieved for negligible cost.

Some potential improvements have become practical with the general introduction of stronger epoxy-modified binder to New Zealand porous asphalt. For example, higher voids can now be used without risking premature failure.

Internationally, CPX results often show significant longitudinal variations. The New Zealand Transport Agency has also found these variations in addition to variations between sites with the same surface specification. Quality controls are being investigated to reduce these variations, with initial examination of temperature and thickness regulation.

#### For further information

[environment@nzta.govt.nz](mailto:environment@nzta.govt.nz)

### CASE STUDY 3

#### The LIFE Dynamap Project: using low cost noise sensors to create real-time traffic noise maps in Italy

##### Overview

The DYNAMAP project (Dynamic Acoustic Mapping – Development of low-cost sensors networks for real time noise mapping) is a European Commission LIFE project aimed at developing a dynamic noise mapping system able to detect and represent the acoustic impact of road traffic in real time. The project is led by the Italian Road Agency ANAS, with the support of six European partners.

The driver for the project is the European Noise Directive 2002/49/EC (END) which requires Member States to update their national noise maps every five years to report on any changes in environmental conditions. Updating noise maps using conventional approaches can be time consuming and costly, and therefore more innovative solutions are needed.

Dynamap is an automated noise mapping system able to deliver both real-time dynamic noise mapping and longer-term evaluations, e.g. annual updates to maps. Although real-time noise mapping is not explicitly required by the END, it could lower the cost of noise mapping by 50% and provide additional benefits. These include provision of up-to-date public information via appropriate web tools and the potential to inform noise mitigation and management decisions.



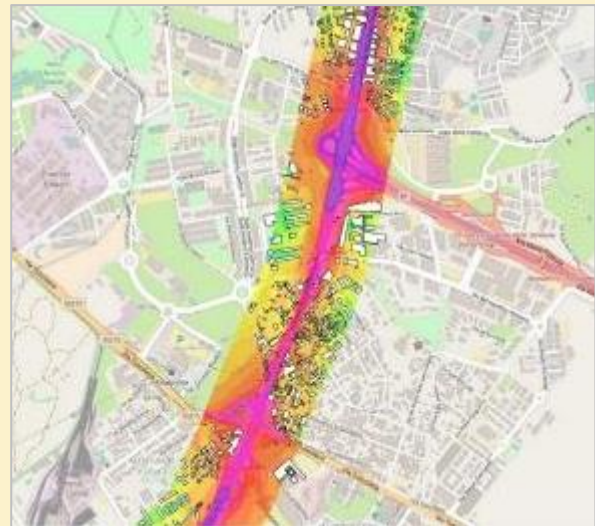
*Dynamap monitoring devices*

##### The Dynamap System

The Dynamap System comprises a series of low-cost monitoring devices (see figure bottom left) installed along the road network. The devices measure road traffic noise levels, eliminate the presence of anomalous noise events (i.e. noise events unrelated to road traffic) and send relevant data to a central unit, where they are further processed to update the noise maps. A powerful open source platform is used to collect, process, view and store the data.

The Dynamap system has been installed in two pilot areas: representing an agglomeration and a major road. The first pilot area is in the northern part of Milan, where 24 monitoring devices have been installed. The second pilot area is in Rome, along the motorway A90 where 19 monitoring devices have been placed.

*Dynamic noise mapping (Rome)*



The two pilot projects are being tested for a year to check their accuracy and reliability in providing both dynamic and statistical noise maps.

##### For further information

Sevillano et al. Dynamic acoustic mapping [111]

## 8. ASSESSMENT

This chapter addresses the key principles of noise impact assessment. Most roads, regardless of their scale, generate noise that has the potential to affect people in terms of their health or quality of life (wellbeing), the value of their property. They also impact on locations valued for their tranquility or soundscape, historic landmarks and wildlife.

Noise assessments are undertaken for a range of reasons including for environmental impact assessments and public health impact assessments. They can be conducted at a project level or a strategic level. Project noise impact assessments are used to determine the effect of the expected change in the acoustic environment as a consequence of a proposed roading development or intervention. A strategic noise impact assessment may also be undertaken for an existing situation or for new developments. The assessment generally focuses on an area (e.g. a town or a new land development) rather than a specific route or roading project, with a view to understanding the overall noise environment, the additional noise exposure that the new development may generate and where mitigation may be necessary.

### Definitions of key elements of a noise impact assessment:

**Noise impact:** The difference in the acoustic environment before and after the implementation of a proposal (also known as the magnitude of change). This includes any change in noise level and in other characteristics/features, and the relationship of the resulting noise level to any standard benchmarks.

**Noise effect:** The consequence of the noise impact. This may be in the form of a change in the annoyance caused, a change in the degree of intrusion or disturbance caused by the acoustic environment, or the potential for the change to alter the character of an area so there is a perceived change in quality of life or in quality of the environment. This will be dependent on the receiver and its sensitivity and on the exposure to traffic noise resulting from the project.

**Significance of effect:** The evaluation of the noise effect and, particularly if the noise impact assessment is part of a formal environmental impact assessment (EIA), deciding whether or not that impact is significant (negative or positive).

### 8.1. THE PURPOSE AND PROCESS OF ASSESSING TRAFFIC NOISE IMPACTS

There are many methods available for undertaking an environmental noise impact assessment. In any given situation the particular technique adopted must be tailored to the situation itself to ensure that all relevant factors are included as appropriate in the assessment. This chapter provides a generalised description of the process for conducting noise impact assessments, in the context of a new road transport project (refer to *figure 33*). It is also applicable for a strategic noise impact assessment.

Noise impact assessments as part of a road project are of great importance for the future environment in the vicinity of the road system. The noise impact assessment is the basis for decisions on the implementation of necessary measures to minimise and avoid adverse impacts on health, wellbeing and quality of the environment due to future road noise. At the same time there must be proportionality between invested funds and the effect of noise reduction measures in the project.



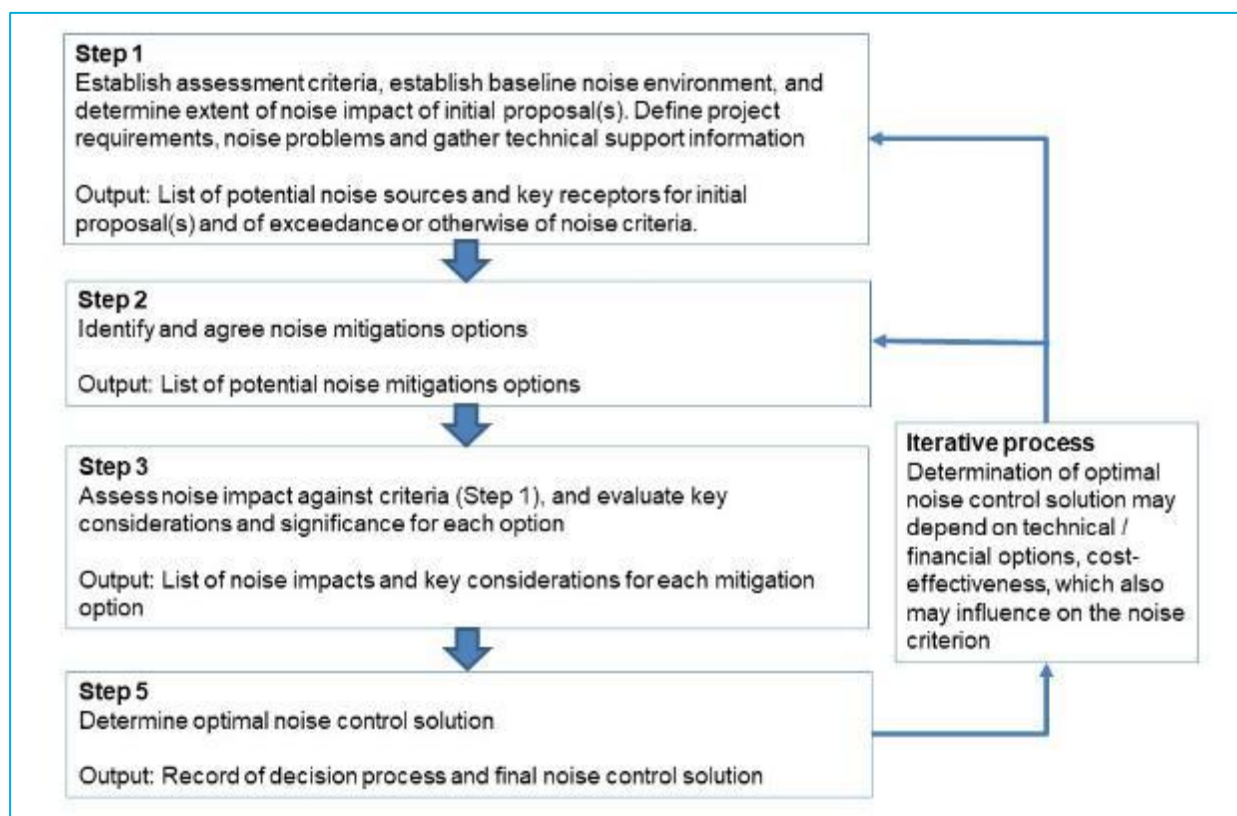


Figure 33: Simplified diagram of steps in undertaking a noise impact assessment as part of an EIA. Inspired by the I-INCE Guidelines for community noise impact assessment and mitigation.[112]

The different steps of a noise impact assessment can be briefly described as follows:

**Step 1:** Define the noise problem and establish an overview of options for noise reduction

### Understanding the project and the surroundings

This stage requires a comprehensive understanding of the project or area to be assessed.

Control of environmental impacts at the planning stage is instrumental to maximise the opportunities to avoid or minimise noise impacts. A small change in the layout or design of the proposal can result in a reduction in noise exposure that may otherwise need substantial and often costly retrospective remediation measures. For a new transport project, the road agency will identify what they need to construct and how this will be operated to achieve the competing objectives of the project. The initial plans will usually be optimised from this viewpoint. However, there may not be a good appreciation of the potential community noise impacts, which can mean little consideration is given to these early on in a project. It is important that someone with an understanding of these potentially adverse noise effects is involved at this first stage of the impact assessment.

Early in the planning stage of a road project, there may be limited information on the various elements of the proposal. An acoustic specialist can work with the road agency to minimise the noise at the source by suggesting low noise impact alternatives. Once the road agency has decided on a road alignment and on an initial design proposal, the acoustic specialist will also need to do some preliminary predictions of the potential for noise impact for the surrounding communities. For example, these initial estimates can result in an adjustment of the road alignment to ensure

greater distance from noise sensitive areas, thereby reducing the exposure to noise from the new proposal.

### Noise limits and criteria for noise abatement

The road agency may have specific guidelines or criteria for noise abatement. When this is not the case, it is important to establish noise objectives for the project (or for the area to be assessed, in the case of a strategic noise assessment). If prescribed limits exist (e.g. defined nationally), they can inform these objectives; and where there is scope to adjust the limits based on community views, variation could be considered in either direction, i.e. making the limits less or more stringent.

Criteria for noise abatement vary from country to country and possibly from project to project. National legislation generally does not define any legally binding noise limit values for road noise. Some countries have limit values that are usually followed when new road or urban development projects are designed and constructed, whereas guidelines are used in relation to existing housing and roads/highways. Assessment criteria can either follow a maximum allowable noise level or a population annoyance criterion (refer *section 4.2* for further discussion on annoyance criteria). For example, it is common for the maximum allowable noise level for dwellings to lie in a range of 55 dB to 60 dB (calculated as long-term average A-weighted equivalent sound pressure level e.g. as  $L_{den}$ ) when planning new roads [113].

### Establish baseline noise environment

Baseline noise, also referred to as pre-existing noise, represents the noise environment in an area prior to the construction and operation of a project to create a new or improved road or land use development that may affect it. For a strategic noise assessment, the baseline is the noise environment prior to undertaking interventions, such as noise mitigation measures, that are agreed upon as a result of the assessment. Baseline noise levels can serve several purposes in the assessment process. They provide information on the current noise climate that may form the basis or justification for the applicable criteria. They may also demonstrate that the noise environment is already unsatisfactory. In addition, the baseline noise levels can be referred back to when communicating the results of a noise impact assessment to residents and decision makers.

### Determine the assessment area

The assessment is conducted over an area that adjoins or surrounds the noise sources. While this area must be carefully specified, doing so can often become quite complicated. In a new road proposal, for example, the initial approach might be to constrain the assessment area to an area within a specific distance from the road corridor. The extent of the survey area on either side of the road depends on the expected traffic flow and speed, which are the primary indicators for determining the distribution of the noise impacts. The noise abatement criteria must also be observed, and it is important that the study area covers all potentially affected noise sensitive areas.

In the initial phase of a road project there may be insufficient information available to perform detailed noise calculations. Instead, simplified noise calculations can give an idea of the noise impact of a road in an early planning stage to determine the road's alignment before making detailed calculations. For example, the project team can get an indication of the approximate distance between the new road and noise sensitive urban areas in order to avoid conflicts. The topography can then play an important role.

This is illustrated in *table 7*, which shows that if a noise assessment criterion of 55 dB were to be used, then this would suggest that an appropriate assessment area would be the road corridor and an area within 1 km of either side of the road. The calculations reported in this table were performed in connection with an introductory workshop on determining possible road alignments for a new motorway. The prediction model used was NORD2000, with 50,000 vehicles a day, 12% heavy traffic, speed 110 km/h (light vehicles)/80 km/h (heavy vehicles), receiver height 1.5 m, flat terrain, no buildings.

Road situation	Noise level (Lden) relative to distance from road				
	50 m	100 m	250 m	500 m	1000 m
Road in terrain	72 dB	67 dB	63 dB	58 dB	55 dB
Road in cutting (2 m)	65 dB	60 dB	55 dB	52 dB	49 dB
Road on embankment (2 m)	73 dB	69 dB	63 dB	58 dB	55 dB

*Table 7: Example of calculations for a new road alignment.*

*(Source: Danish Road Directorate)*

Once the area of potential concern has been established, the noise impact from the proposal can be predicted. Quantifying the noise output, especially at such an early stage in the project, is not a simple matter and is subject to uncertainty. While commercial software with different noise prediction models are available to assist with such prediction, the assessment must give provision to the uncertainty inherent to the inputs and the assumptions that may have been made.

### Identify the receiver locations

All potentially affected (or benefiting) noise receiver locations within the assessment area must be located and specified. Sensitive receivers may include dwellings, other uses or facilities and animal habitat. Normally, the objective is to identify those locations most sensitive to or likely to be adversely affected by the road project. Receivers that may need to be considered when determining the baseline noise levels include:

- dwellings
- schools/college
- hospitals
- community facilities (including libraries, surgeries, health centres)
- places of worship
- open air amenities (such as recreational areas, sites of historic interest, areas of landscape value and the like)
- wildlife sites
- vacant land likely to be developed
- cemeteries
- farms, kennels
- commercial premises
- retail premises
- especially sensitive commercial/industrial installations.



### Determine the noise exposure

This is typically done by prediction. It is important to specify how the exposures have been determined and to justify the techniques adopted. In the case of predictions, the efficacy of the prediction model adopted must be stated, along with its accuracy.

The noise exposure can be predicted at the location of the building façade, or along a regular grid across the assessment area and presented in noise maps with noise contours. Another possibility is for the exposures to be presented as zones where specified noise levels are exceeded or where noise levels fall within a certain range, or to specific variations in noise levels. Again, they might be expressed in terms of the numbers of residents exposed to certain noise levels or range of levels. The decision about which format to adopt will depend on several factors; such as the nature and operation of the noise sources and the type of assessment criteria.

The baseline levels, predicted levels and selected criteria should enable a breakdown of the locations where noise criteria are achieved and where they are exceeded (and by how many decibels), before and after completion of the development.

#### Step 2: Identify and agree on potential noise mitigation options

This stage may require *brain-storming* ideas on potential noise management solutions, each of which should then be evaluated and assessed against considerations of what is reasonable and feasible for implementation.

The general strategy for noise control should consider the 'source-pathway-receiver conceptual model' as shown in *figure 34*.

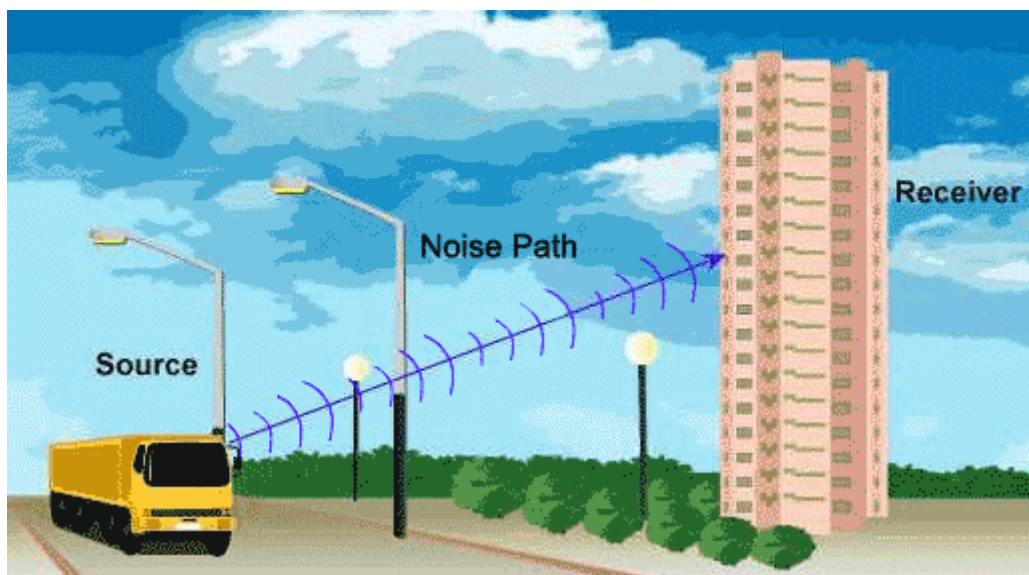


Figure 34: Source-pathway-receiver conceptual model.

(Source: Environment Protection Department of the Government of the Hong Kong S.A.R.)

To reduce traffic noise, the following methods should be considered:

- Reduction of noise at the source (refer chapter 9.3 for further information about low noise pavements).
- Reduction of noise during propagation between the source and the receiver – this could include noise barriers or earth banks located so that shielding of buildings and other

structures reduces the noise impact (refer chapter 9.7 for further information about noise barriers).

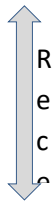
- Reduction of noise at the receiver – this could involve proposals to construct barriers enclosing residential areas. It could also involve strengthening the external walls, doors, windows and roofs of buildings exposed to excessive noise, in order to increase their ability to curb noise intrusion (refer chapter 9.8 for further information about the use of urban and building design methods in reducing the impact of traffic noise for the receiver).

The whole process should initially be carried out with the road agency and an acoustic specialist, and then explored with stakeholders, for example during community information and engagement sessions.

### Step 3: Assess noise impact of options

As recognised in *chapter 4*, there are many factors that affect how people perceive noise and respond to it. Guidance on assessing the magnitude of noise impact and the significance of the effects is presented in *table 8* and *table 9*. The guidance has been prepared by the UK Institute of Environmental Management & Assessment (IEMA) [114].

The aim of a noise impact assessment is not only to provide protection from adverse effects by foreseeing environmental problems and avoiding them., it is also to ensure that the public is informed early and given effective opportunities to participate in the decision-making procedures. Therefore, a noise impact assessment must ensure it explains the noise levels, the consequences (effects) of the change in noise levels in the sensitive areas, and the significance of the noise levels and changes.

Magnitude (nature of impact)	Description of effect (on a specific sensitive receiver)	Significance (as required in EIA)
Substantial	Receiver perception = marked change Causes a material change in behaviour and/or attitude, e.g. individuals begin to engage in activities previously avoided due to former environmental noise. Quality of life enhanced due to change in character of the area.	<p><i>More likely to be significant</i> Greater justification needed – based on impact magnitude and receiver sensitivities – to justify a non-significant effect.</p>  <p>Greater justification needed – based on impact magnitude and receiver sensitivities – to justify a significant effect. <i>Less likely to be significant</i></p>
Moderate	Receiver perception = noticeable improvement Improved noise climate resulting in a small change in behaviour and/or attitude, e.g. turning down volume of television, speaking more quietly, opening windows. Affects the character of the area so there is a perceived change in the quality of life.	
Slight	Receiver perception = just noticeable improvements Noise impact can be heard but does not result in any change in behaviour or attitude. Can slightly affect character of the area but not to the extent there is a perceived change in quality of life.	
Negligible	N/A = no discernible effect on receiver	Not significant

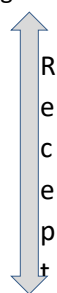
Magnitude (nature of impact)	Description of effect (on a specific sensitive receiver)	Significance (as required in EIA)
Slight	Receiver perception = non-intrusive Noise impact can be heard, but does not cause change in behaviour or attitude, e.g. turning up volume of television, speaking more loudly, and closing windows. Can slightly affect the character of the area but not to the extent there is a perceived change in the quality of life.	<i>Less likely to be significant.</i> Greater justification needed- based on impact magnitude and receiver sensitivities- to justify a significant effect. 
Moderate	Receiver perception = intrusive Noise impact can be heard and causes small changes in behaviour and/or attitude, e.g. turning up volume of television, speaking more loudly, and closing windows. Potential for non-waking sleep disturbance. Affects the character of the area so there is a perceived change in the quality of life.	
Substantial	Receiver perception = disruptive Causes material change in behaviour and/or attitude, e.g. avoiding certain activities during periods of intrusion. Potential for sleep disturbance resulting in difficulty in getting to sleep, premature awakening and difficulty in getting back to sleep. Quality of life diminished due to change in character of area.	
Severe	Receiver perception = physically harmful Significant changes in behaviour and/or an inability to mitigate effect of noise leading to psychological stress or psychological effects, e.g. regular sleep deprivation/awakening, loss of appetite, significant medically definable harm, e.g. auditory and non-auditory.	

Table 8: Relationship between noise impact, effect and significance. (Adapted from IEMA [114])

Table 9 suggests a methodology for describing the magnitude of the impact of changes in noise levels. This is also an example of how the impact of changes in noise can be communicated (refer to chapter 8.7 for further discussion on communicating traffic noise impacts).

Extent of noise impact	Noise impact magnitude	Magnitude rating
> 10 dB	Severe	Very high
5 to 10 dB	Substantial	High
3 to 5 dB	Moderate	Medium
1 to 3 dB	Slight	Low
< 1 dB	No impact	Very low

Table 9: Example of how changes in noise impact may be quantified. [112]

For a quantitative assessment of the noise impacts, the noise level change needs to be related to the sensitivity of the particular receivers so that the significance of the noise level change and of the noise impact can be determined.

Table 10 in chapter 8.7.3 shows the results of combining the methodologies presented in table 8 and table 9.

**Step 4:** Determine optimal noise control solution

The final conclusion of any assessment procedure will include a written summary of the precise basis on which the assessment procedure has been carried out. Earlier steps should have led to a structured evaluation of a number of noise management alternatives. The final step is to rank the available alternative options for noise management.

As with most planning decisions, noise is one of several environmental and cultural factors to be taken into account along with the social and economic merits of the specific development proposal. The most effective acoustical solution may not be the best compromise solution overall.

## CASE STUDY 4

### Traffic noise impact assessment: Wild Coast Toll Highway, South Africa

#### Project overview

A detailed operational noise impact assessment (NIA) was undertaken for the proposed N2 Wild Coast Toll Highway Project in 2007. The proposed highway would extend over approximately 560 km from the Gonubie Interchange near East London (Eastern Cape Town) to the Isipingo Interchange (south of Durban). The project included upgrading existing road sections and interchanges, and constructing new roads, interchanges and associated structures (e.g. toll plazas and bridges).

#### Assessment criteria

The NIA was complicated by the fact that two disparate procedures needed to be implemented to assess the impacts of road traffic noise and the required mitigation. These included procedures within the *South African National Standard (SANS) 10328, Methods for environmental noise impact assessment* [115] and those within the Noise Control Regulations (NCR).

SANS 10328 sets out the procedures for quantifying the predicted noise impact of a proposed development. The predicted impact is then assessed using SANS 10103 [116], which includes acceptable noise rating levels in line with WHO thresholds. The assessment of the estimated road traffic noise impact is established by determining the probable community response.

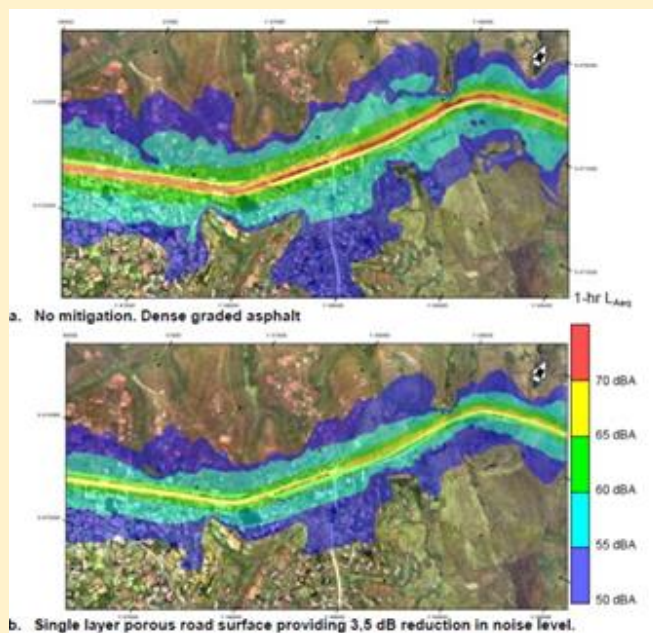
The NCR require that if predicted noise from the proposed development exceeds the legal limit of 65 dB(A) on surrounding land, noise mitigation measures need to be implemented to meet this limit.

SANS 10103 enables noise to be assessed as a function of land use during day and night-time periods. In contrast, the NCR specify a maximum allowable level (over an 18-hour period).

#### Methodology

The noise impact assessment involved the following tasks:

- Determination of predicted noise rating levels of road traffic on the proposed route passing through identified noise sensitive areas.
- Prediction of noise impact for each identified area by calculating the difference between the predicted and acceptable rating level.
- Assessment of the estimated noise impact by determining the probable community response from SANS 10103 and in terms of the NCR.
- Quantification of noise mitigation measures. The algorithms from SANS 10210 [71] were used to calculate the predicted noise levels with and without mitigation.
- Incorporation of digital terrain data with alignments and road elevations to generate noise contours at receivers (as shown below).



Modelled noise predictions

#### For further information

Proposed N2 Wild Coast Toll Highway – Final Environmental Impact Report, (2009) [117]



## CASE STUDY 5

### Traffic noise impact assessment: Highway 19 extension, Québec, Canada

#### Project overview

A noise impact assessment was undertaken in 2012 for the proposed Highway 19 extension project in Quebec.

The proposed highway extends over nearly 10 km from Highway 440 in Laval to Highway 640 in Bois-des-Filion. It involves a six-lane dual carriageway, four new interchanges as well as a new bridge. It was designed to relieve current traffic congestion on road 335.

#### Assessment criteria

The requirement for an environmental impact assessment was triggered by the Environmental Impact Assessment and Review Regulations. The Ministère des Transports, de la Mobilité durable et de l'Électrification des transports (MTMDet) follows the procedures for noise impact assessments (NIA), as defined in its road noise policy. The requirements for the impact assessment can be modified (with tightened criteria) in the government order authorising the project.

#### Methodology

As described in MTMDet's NIA requirements, the main tasks involved were:

- Definition of the study area based on identification of noise sensitive activities (up to 300 m on both sides of the road).
- Assessment of existing noise levels based on field noise measurements and modelled data using the FHWA traffic noise model (dB(A),  $L_{Aeq,24h}$ ).
- Modelling of traffic noise levels at road opening and 10 years later.
- Assessment of noise impact using the road noise policy's evaluation grid.

- Proposed noise reduction measures for areas with significant noise impact. The objective is to reduce noise levels to  $L_{Aeq,24h}$  55 dB(A) or lower if reasonably achievable.



Map showing noise impacts

#### Sensitive areas and mitigation

The study area was divided into 11 sensitive areas. A total of 3.4 km of noise walls were proposed with heights ranging from 1.5 to 6.5 m. Some of these walls will be acoustically absorbent on the roadside. After completion of the project, follow-up noise monitoring will be undertaken to confirm the noise barriers' effectiveness.

#### For further information

Ministère des Transports du Québec (2012) [118]

## 8.2. IMPACT ASSESSMENT CRITERIA

Typically, the aim of an environmental noise impact assessment is to describe and assess the noise exposures and impacts on residents in a community. In this context, the noise exposures are taken to be the values of the predicted or measured noise metrics at the most exposed façades of residential buildings. The noise impacts are then determined by comparing these exposures to criteria (refer *chapter 4* for further discussion on noise criteria). A wide variety of methods exists for evaluating noise exposure. The main distinction between different methods is the requirement for a “limit value” or the use of dose–response relationships based, for example, on noise annoyance.

## 8.3. TRAFFIC NOISE CRITERIA LIMIT VALUES

Limit values of a particular traffic noise criterion are those that should not be exceeded. Usually they are well documented and accompanied by a considerable amount of explanatory material which details how the criterion is determined and a compliance assessment conducted. For example, there may be different criteria for road traffic noise, depending on the project. The criterion may be more restrictive when it comes to planning a completely new road, as opposed to the expansion of an existing road, on the grounds that a green field project can result in a more significant change in the noise environment and generally presents a wider range of opportunities to avoid or minimise noise.

Worldwide, there are very different requirements for complying with noise limits. In some countries, there are mandatory requirements; other countries have guideline values or indicative noise limits that are not mandatory levels, but trigger action to consider noise mitigation. Finally, there are countries with no noise limits at all. At the same time, there are also differences in the noise metrics used in different countries (refer *chapter 3.2*).

## 8.4. REPORTING NOISE IMPACTS

Generally, there is no precise guidance available for reporting the overall significance of a noise impact. For residential properties, for example, the baseline and future noise level information will lead to each property being assigned a certain noise level or noise level change as a result of the proposal. Most likely this will be expressed in terms of the noise metric(s) used in the specific jurisdiction. From such analysis a range of different results for the project could be reported, for example:

- 10 dwellings will have an increase of 10 dB, or
- 100 dwellings will experience an increase of 1 dB, or
- five dwellings will experience a 10 dB increase, and 20 dwellings will experience a 3 dB increase.

It is not immediately possible to assess which scenario will have the greatest impact because the impact is also related to the sensitivity of the receiver. Therefore, it may be relevant to combine maximum allowable levels with population annoyance criteria as described in *chapter 8.5*.



## CASE STUDY 6

### Strategic traffic noise impact assessment in Mexico using measurements

#### Project overview

Between 2000 and 2012, the Mexican Institute of Transportation undertook a strategic road traffic noise assessment in Mexico. The aim was to understand the noise levels produced by traffic along the main highways across the country and use this information to inform the development of a national noise standard to protect residential areas adjacent to highways. The assessment approach involved both noise monitoring and modelling of road traffic.

#### Noise monitoring

Noise monitoring was undertaken adjacent to some key roads in Queretaro, Jalisco, Veracruz and Nuevo Leon States. Highway sections were chosen where there were residential areas exposed to high traffic noise levels. The highways were categorised according to their annual average daily traffic (AADT), volume of heavy vehicles, topographical location and population exposure.

The measurements were undertaken in favourable climatic conditions using precision sound level meters at 7.5 m from the highway and 1.5 m above the ground (see figure below). Equivalent sound pressure level (Leq) was taken to derive a 7-hour Leq.



Roadside noise measurement

The average results per state (by year) ranged from 73.6 to 82.4 Leq dB(A). Variations in noise levels were due to different factors such as traffic volumes, number of heavy vehicles, speed, gradient, type of road, type of pavement and maintenance of pavement.

Noise levels were found to increase over time at all the sites during the period from 2000 to 2012 reflecting an increase in AADT. The noise levels were highest at sites with rigid pavement when compared with asphalted pavement sections.

#### Noise modelling

To predict potential future changes in road traffic noise levels with increasing traffic volumes, statistical regression and correlation tools were used in the analysis of the monitored road traffic noise levels.

There was a strong positive correlation between the Leq values and AADT, indicating a future increase in noise levels with increasing AADT. This was also the case for the heavy vehicle component.

#### Recommendations

The Organisation for Economic Cooperation and Development (OECD) recommends a noise standard of 65 +/-5 dB(A) for existing roads, [119] so taking the maximum value of 70 dB(A) an *Environmental index of noise* was proposed for Mexican highways. The index represents the measured Leq (in Queretaro State where most of the measurements were undertaken) divided by the acceptable OECD value. The roads in Mexico exceeded this value by 8.7% on average using this index.

The Mexican Institute of Transport has recommended imposing an upper limit of 75 Leq dB(A), with a required reduction of 1 dB each year over a 10-year period in order to reach the OECD standard of 65 dB (during daytime) on sections passing through residential areas.

#### For further information

Juan Fernando Mendoza Sánchez, Head of Environment Research Group, Mexican Institute of Transportation (jmendoza@imt.mx)

### 8.5. ASSESSMENT OF POPULATION ANNOYANCE

These criteria are under constant development and discussion amongst the international acoustics professional community. Typically, they set limits on the number or proportion of the community that is either seriously or highly annoyed by the noise from the particular source under assessment. These criteria are based on empirically derived curves that show annoyance increasing with noise level (refer *section 3.2* about noise annoyance).

One benefit of working with population annoyance criteria is that they facilitate the determination of areas or clusters of population that experience either adverse or positive environmental noise impacts from the road being assessed.

Once the noise environment has been estimated (e.g. once noise levels or noise annoyance are known), there is a range of methods to determine the impact of noise. Some methods, such as the German LKZ (*LärmKennZiffer, noise index*) [120], are based on the exceedance of a noise limit value. The LKZ Index is calculated by multiplying the exceedance of a limit value in decibels by the number of people affected. While it does not take the annoyance itself into account, it provides a simple and explainable approach.

Other methods focus on noise annoyance (percentage of population *highly annoyed*) rather than on the compliance to specific limit values. As noise annoyance occurs even with comparably low noise levels, hotspot identification requires a comparison of noise levels for given areas. An absolute indicator is not feasible.

Most methods taking noise annoyance into account, such as the German VDI 3722-2 [121], are based on several earlier reports regarding noise annoyance (such as Miedema and Vos [122] and Guski et al. [123]). In general, two indicators are frequently used to describe noise annoyance: percentage of population *highly annoyed* (% HA) and percentage of population reporting *sleep disturbance* (% SD). The percentage of people affected is calculated based on the noise levels.

Various documents, such as EEA [124] or WHO [11], provide exposure-response relationships that allow for calculating these indicators. The WHO relationship is defined as follows:

$$\% HA = 78.9270 - 3.1162 * L_{den} + 0.0342 * (L_{den})^2$$

Other methods have a more qualitative and holistic approach. For example, a Swedish method defines a *sound quality index* which is based on the fact that the overall sound environment of a dwelling is dependent on a number of factors. These include the indoor sound level, outdoor sound level, whether the home has access to a silent facade, the extent to which the outdoor environment is exposed to noise (refer *case study 7*). The methodology is primarily used in urban planning but is also relevant to other contexts.

## CASE STUDY 7

### Swedish sound quality index method for assessing traffic noise impacts at dwellings

Authorities in Sweden have developed a method for assessing the sound quality of homes. The method is based on an overall assessment of the acoustic environment within and around the dwelling or building complex.

The method is formulated on the basis that a number of factors influence the acoustic environment. These include the indoor and outdoor sound level, whether the home has access to a quiet facade, and the extent to which the outdoor environment is exposed to noise. In this context it may be possible to have houses with a high sound quality even in very noisy situations. For example, a high noise level on the facade facing the road can be compensated by having a quiet facade facing a quiet courtyard and good soundproofing of the dwelling.

The method is based on the factors and the scoring system detailed in the following.

#### Noise on the traffic side

The façade with the highest traffic noise level provides the score used. The following scoring is applied:

Quality	Score
> 65 dB (LAeq,24h)	-3
61-65 dB (LAeq,24h)	-2
56-60 dB (LAeq,24h)	-1
< 55 dB (LAeq,24h)	0

#### Noise at quiet side of the building

The level of the noise on the quiet side of the building, for example the side of the building facing the courtyard is scored as follows.

Quality	Score
56-60 dB (LAeq,24h)	0
51-55 dB (LAeq,24h)	+2
≤ 50 dB (LAeq,24h)	+6

#### Noise at the entrance

The noise level at the entrance, i.e. outside and in the immediate vicinity of the entrance to the dwelling is scored as follows.

Quality	Score
> 60 dB (LAeq,24h)	-2
56-60 dB (LAeq,24h)	-1
51-55 dB (LAeq,24h)	0
≤ 50 dB (LAeq,24h)	+1

#### Noise in the courtyard, patio and balcony

The noise levels outside the building but within the residential property are scored as follows.

Quality	Score
No patio	0
Shared or private patio/balcony, max. 70 dB (Lmax) and 50 dB (LAeq,24h)	+2
Shared or private patio/balcony with maxi 70 dB (Lmax) and 50 dB (LAeq,24h) and greater open space ≤ 55 dB (LAeq,24h)	+4
Shared or private patio/balcony with maxi 70 dB (Lmax) and 50 dB (LAeq,24h) and greater open space ≤ 50 dB (LAeq,24h)	+6

#### Noise indoor

Indoor noise levels are based on the LAeq, 24h-level and the Lmax-level in sleeping and living room areas with closed windows.

Quality	Score
Not more than 30 dB (LAeq,24h) and 45 dB (Lmax)	0
Not more than 26 dB (LAeq,24h) and 41 dB (Lmax)	+7
Not more than 22 dB (LAeq,24h) and 37 dB (Lmax)	+11

#### Multiple traffic types/noise sources

The number of traffic sources (mainly road and rail but may include air and sea traffic) and other noise sources, e.g. industrial or sports determine the score.

Quality	Score
> 3 traffic types/noise sources	-6
2 traffic type/noise sources	-3
One dominant traffic type	0

### Plan solution

The score for the apartment's layout is determined based on the traffic noise level outside the window.

### The neighbourhood

Quality	Score
Apartment > 60 dB (LAeq,24h) at all windows in all living areas	-12
Apartment >35 m2 has at least one living room with side windows with a maximum of 55 dB (LAeq,24h)	-8
At least half the living rooms have windows on a side with a maximum of 55 dB (LAeq,24h), apartments ≤ 35 m2 all sides up to 60 dB	0
All living rooms have at least one window exposed to ≤ 55 dB (LAeq,24h)	+4
At least half the living rooms have windows exposed to max 50 dB (LAeq,24h)	+8

The score for the neighbourhood is determined by how noisy it is in areas within five minutes' walk. The noise is expressed in relation to noise at the current building.

Quality	Score
Very noisy neighbourhood with a noise level no more than 5 dB lower than on the project's traffic side.	0
Moderately noisy neighbourhood where the noise level is 5–10 dB lower than on the project's traffic side.	+1
Quiet neighbourhood where the noise level is 10–15 dB lower than on the project's traffic side	+2
Very quiet neighbourhood with a noise level more than 15 dB lower than on the project's traffic side.	+3

### Calculation of sound quality index

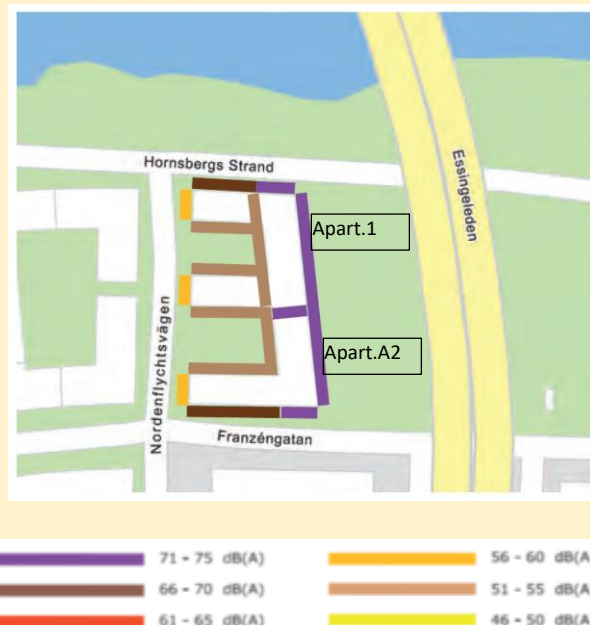
Based on calculated scores, the calculation of the sound quality index is as follows:

Sound quality index = (The average for all apartments + the minimum value for any apartment) /15.

If the sound quality index is  $\geq 1.0$ , the sound environment is acceptable (for new dwellings); if the sound quality index is  $\geq 2.0$  the sound environment is described as very good.

### Worked example

Calculation of facade noise at a residential building was undertaken near a major road (refer diagram below).



Assessment of each factor gave the following score as shown below. The sound quality score is calculated for apartments 1 and 2 as shown in the next column.

Factor	Apart. 1	Apart. 2
Noise traffic side	-3	-3
Noise quiet side	0	0
Noise at entrance	-1	-1
Noise outdoors	+2	+2
Noise indoors	+7	+7
Several noise sources	0	0
Plan solution	0	+4
Surroundings	+1	+1
Total	+8	+12

The sound quality index is 1.2 for this example. The index is higher than the minimum requirement and indicates high sound quality.

### For further information

Hallin et al.[125]

## 8.6. COST-EFFECTIVENESS ANALYSIS

Different assessment methods can be used to prioritise noise mitigation. A particularly useful and common approach is the use of cost-effectiveness analysis to determine the economic merits of potential solutions.

Cost-effectiveness analysis helps to identify the most cost-effective option for achieving a set of predefined objectives. The most cost-effective solution is the option that, for a given output level, minimises the actual value of costs. Alternatively, it can be the option that maximises the output level for a given fixed cost. The efficiency of measures is assessed by dividing costs by units of effectiveness. Units of effectiveness are simply a measure of any quantifiable outcome central to the project's objectives, for example the cost needed to reduce the number of people exposed to noise by one.

Cost-effectiveness analysis seeks to identify and place monetary value on the costs of a programme. It then relates these costs to specific measures of programme effectiveness. Analysts can obtain a programme's cost-effectiveness ratio by dividing costs by what we term units of effectiveness:

$$\text{Cost-effectiveness ratio} = \frac{\text{Total cost}}{\text{Units of effectiveness}}$$

Units of effectiveness are simply a measure of any quantifiable outcome central to the programme's objectives.

For example, a programme for prioritisation of noise control would likely consider the reduced number of dwellings exposed to noise to be the most important outcome. In this situation, using the formula above, the units of noise are divided by the costs of implementing the measure's cost-effectiveness, which is interpreted as the ratio of *cost per noise reduced dwelling*. Then the cost-effectiveness ratios for different kinds of noise mitigation measures are compared, to determine which mitigation measure costs less per unit of outcome (in this case it would be a reduced number of noise exposed dwellings).

The method can be used for a multitude of other outcomes of interest as well. For example, an analyst could also compute cost-effectiveness ratios for which noise exposed residential areas should have the highest priority with regard to noise reduction. In this case, the estimated cost of noise barriers for each residential area in the study is divided by the estimated noise reduction per noise barrier. The project with the smaller cost-effectiveness ratio is the better project.

*Case studies 8 to 10* provide examples of noise impact assessments that have been undertaken to assist in prioritisation and determining the most cost-effective option for noise abatement.

## CASE STUDY 8

### Strategic traffic noise impact assessment in Auckland, New Zealand using noise maps

#### Overview

Exposure to excessive noise levels has been proven to have adverse effects on people's health including sleep disturbance, cardiovascular effects such as hypertension, and mental health effects such as stress and anxiety. Noise maps can be used to identify communities that may be subject to adverse noise effects.

The NZ Transport Agency initiated a strategic noise mapping exercise in 2009 (refined in 2012) for the Auckland state highway network to provide a tool to inform and prioritise areas for noise mitigation. This generated a comprehensive set of noise maps for the Auckland state highway network for the base years 2006 and 2011. The purpose of generating maps for the two years was to enable investigation of changes to road traffic levels over this time period.

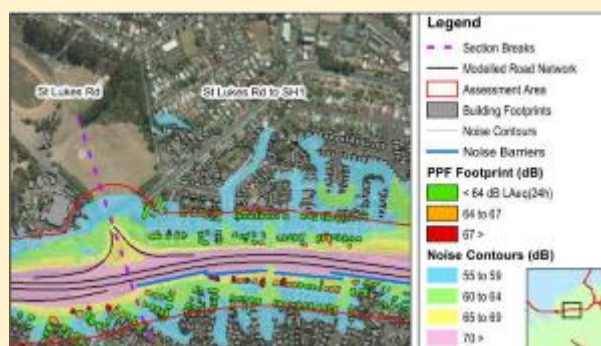
#### Methodology

A collaborate approach to the noise mapping project was undertaken through establishment of a project steering group leading the work supported by external geographic information system (GIS) specialists and acoustic specialists. The GIS specialists focused on the data management aspects as well as the mapping and spatial analysis of acoustic model output data. The acoustic specialists focused on quality assurance activities as well as preparing and running the noise model for the Auckland state highway network.

An important objective for the project was to establish a mapping methodology that was future proofed and could be replicated elsewhere in New Zealand.

#### Results

The figure below is an example of the Auckland noise mapping output. Noise levels are shown for individual noise sensitive buildings in accordance with the categories in the New Zealand road traffic noise standard NZS 6806:2010.



*Auckland noise maps graphical output*

Noise mapping for the entire state highway network has now been completed. The results of the noise mapping indicate that there are around 13,000 people exposed to external noise levels more than 64 dB (category B in NZS 6806:2010) from state highways.

These results have been used to inform the business case for the State Highway National Noise Improvement Initiative. If/once approved, this initiative will support a programme for the installation of noise barriers and low noise pavements to mitigate identified areas of high residential noise exposure. Other uses for the noise mapping have been assisting with complaint management, and informing transport and land-use planning.

#### For further information

Hannaby et al. [126]



## CASE STUDY 9

### Strategic traffic noise impact assessment in Denmark using noise maps

#### Project overview

The Danish Road Directorate has developed a policy and methodology for identifying noisy *hot spots* along the existing road network and prioritising these for funding for noise barriers. The starting point for identification is national noise mapping, which is updated every five years.

#### Methodology

The basis for determining priorities between different noise barrier projects is a cost-effectiveness analysis. This compares the cost of noise mitigation with the change in total noise annoyance in an area.

The method can be summarised as follows:

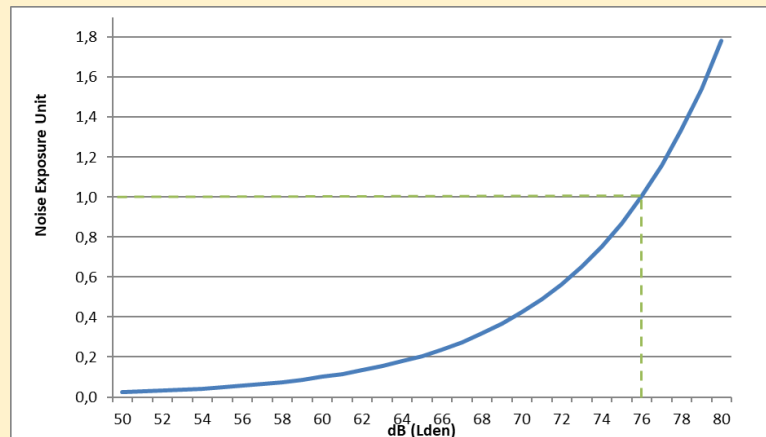
- Hot spot areas are identified using national noise maps. These are defined as residential areas where at least one dwelling is exposed to more than 65 dB ( $L_{den}$ ).
- Benefits of barriers are assessed in terms of feasibility and potential effectiveness in reducing noise levels. The barrier must achieve at least a 3dB noise reduction ( $L_{den}$ ).
- The total noise annoyance (noise exposure score, NES – refer section 5.4) for each *hot spot* area is calculated: for the present situation ( $NES_{present}$ ), as well as for a situation with a proposed noise barrier ( $NES_{after}$ ). For each project area, the noise reduction is calculated as a total NES value  $\Delta NES = NES_{present} - NES_{after}$ .
- Construction costs are estimated for each potential noise barrier project.
- The cost-effectiveness ratio is then calculated for each hotspot area: Cost-effectiveness ratio =  $\Delta NES /$  (construction costs for a noise barrier (EUR)).
- Noise barrier projects with the highest cost-effectiveness ratio are given the highest priority.

#### Noise exposure score

The calculation of the NES is based on noise levels at the façade of the dwelling (calculated as free-field). The NES is based on a dose-response relationship called the noise exposure unit (NEU):

$$NEU = 0.01 \times 4.22^{(L_{den}-C)/10}$$

where: C is a constant = 44 and  $L_{den}$  is the calculated noise level at the façade.



Relationship between NEU and noise level at façade (dB,  $L_{den}$ ).

To calculate the total NES for the hotspot area, each dwelling is multiplied by the corresponding NEU. For example, the NEU for an exposure at 76 dB is 1, and 0.2 for an exposure at 65 dB (see figure above). This means that 10 dwellings exposed to 76 dB will have a total NES of 10 (10 dwellings  $\times$  1 NEU = 10 NES) which is equivalent to 50 dwellings with a noise level of 65 dB (50 dwellings  $\times$  0.2 NEU = 10 NES).

#### A simple example to explain the method

Refer table on the next page. In this example, two different noise barrier projects are evaluated (sites 1 and 2). For each project, calculations of noise levels have been performed on each housing façade. The noise-reducing effect and price of respectively 4 m, 5 m and 6 m high noise barriers are examined for each of the projects – and the most cost-effective project is nominated. Site 1 is much more cost effective than site 2 because the reduction in NES per 1 million euro is significantly greater than for site 2.

The most cost-effective project for site 1 is a 5 m high noise barrier, while the most cost-effective project for site 2 is a 4 m high noise barrier (see green cells on next page).

Site	Noise barrier			Number, dwellings		Noise exposure score (NES)	Reduced $\Delta$ NES/ mio €
	Height	Length	Price mio. €	$\geq 65$ dB	$\geq 55$ dB		
1	Reference – no barrier			23	78	25.9	Reference – no barrier
1	4 m	997 m	1.11	0	42	13.2	11.4
1	5 m	997 m	1.26	0	36	11.4	11.5
1	6 m	997 m	1.41	0	30	10.3	11.1
2	Reference – no barrier			79	156	26.7	Reference – no barrier
2	4 m	2005 m	2.21	3	113	20.3	2.90
2	5 m	2005 m	2.61	3	106	19.2	2.87
2	6 m	2005 m	2.97	0	100	18.2	2.86

*Calculating the most cost-effective approach for noise mitigation using NES – a worked example.*

#### For further information

Danish Road Directorate, e-mail: [vd@vd.dk](mailto:vd@vd.dk)  
att. Jakob Fryd

## CASE STUDY 10

### Strategic traffic noise impact assessment in Hong Kong using noise maps

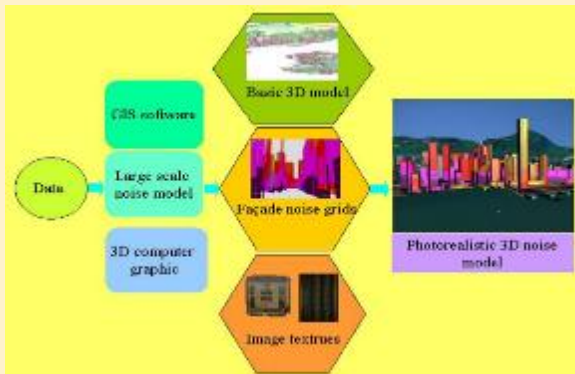
#### Overview

Noise maps are increasingly being recognised internationally as an important tool in noise management. They are useful in identifying potential high noise areas due to road traffic and assessing the impacts of mitigation measures. The Hong Kong Environmental Protection Department developed a traffic noise map for Hong Kong in 2006 – about a year before European states were required to produce their own noise maps.

Most people in Hong Kong live in high-rise buildings and therefore to map the impacts on people living on different floors, a 3-D noise model was needed to supplement the assessment of the road traffic noise impacts. Unlike a 2-D model, the 3-D one shows the noise impacts on every floor of a building, rather than just at ground level.

#### Methodology

A large amount of data was collected to produce the noise map. This included about 100,000 buildings, 1,600 km of busy roads, geographical information (such as terrain, barriers, road surface types) and traffic data (such as traffic flows, composition and speed).



*Schematic of the inputs to derive the photorealistic 3-D noise model*

#### Results

The Hong Kong noise map shows that 1.14 million people are exposed to traffic noise exceeding L10 (1 hour) 70 dB(A). The worst affected district is Yau Tsim Mong, where almost 40% of homes are exposed to elevated levels of traffic noise. Older urban areas like this one generally experience the worst traffic noise problems because they were developed before noise control was considered a priority. They are also the most difficult areas to mitigate noise because of the density of development.



*3D model of Sha Tin Road shows noise levels at different heights*

With the noise map and 3-D noise model, buildings and even individual flats most affected by traffic noise can be identified. This tool has been used to help refine noise mitigation strategies, such as prioritisation of low noise road surfacing and retrofitting of noise barriers. During public consultations on noise barrier projects, sound has been combined with the 3-D noise model so people can hear, as well as see, the effects of barriers. This is helping gain greater public support for the noise management solutions.

#### For further information

Environment Protection Department, Government of the Hong Kong Special Administrative Region.

<https://www.epd.gov.hk/epd/misc/ehk08/en/noise/topicissue.html#top>

## 8.7. VISUALISING AND COMMUNICATING NOISE IMPACTS

As most people affected by noise are not well versed in noise or physics, a noise impact assessment must report and explain clearly the existing and predicted future noise levels, the consequence (effect) of the change in noise level to the receiver and the significance of the noise levels and changes.

It is common to evaluate and present noise impact assessments using noise maps. Noise maps describe spatial distributions of noise levels. They allow an efficient, large scale and detailed visualisation of the noise distributions in areas where the land uses are sensitive to noise. With the graphics from noise modelling software, it is possible to create presentations in 2D or 3D. Below are some examples.

### 8.7.1. Mapping grid noise and façade noise results

Noise assessments are most commonly carried out using grid noise calculations or façade noise calculations. People or homes that are affected by noise can be counted using the results of the noise calculations. These results can also be shown on maps displaying the results of the calculations.

The façade noise map uses estimates of the noise impacts at receivers along the façades of buildings (*figure 35*). Receivers can be placed on every floor with either a fixed number of receivers per façade or a set spacing between them. The type of building, the status of the noise control and the number of inhabitants per building/floor would be known for each receiver location. The façade noise map then shows the highest noise for each façade. The grid noise map is typically a map where all the receivers are at ground level (and follow the terrain) (*figure 36*).

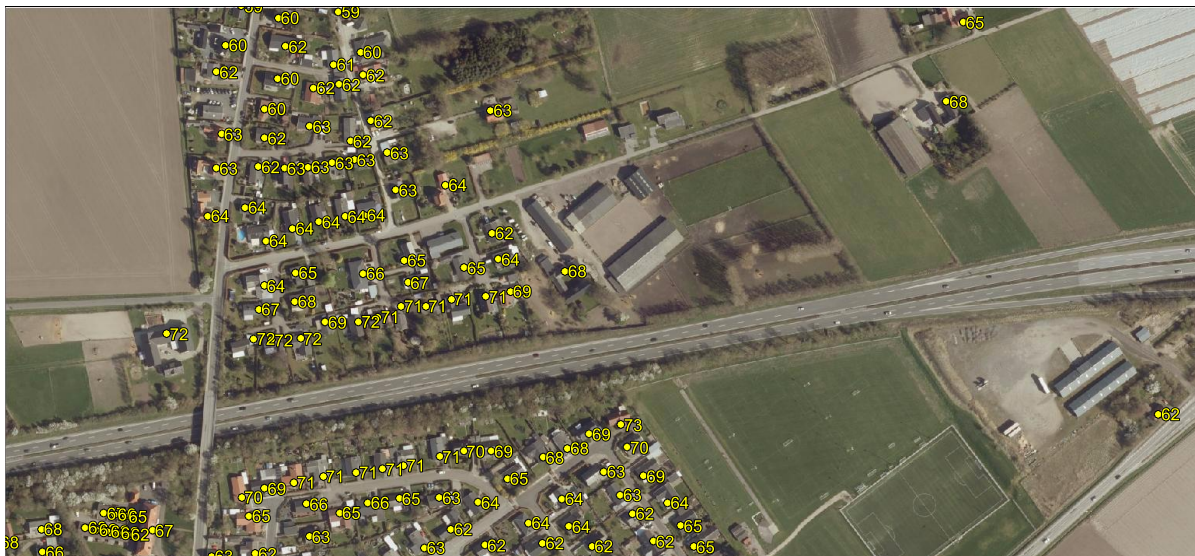


Figure 35: Façade noise map showing the highest calculated facade noise level (dB, Lden) on each dwelling.  
(Source: Jakob Fryd. Danish Road Directorate)



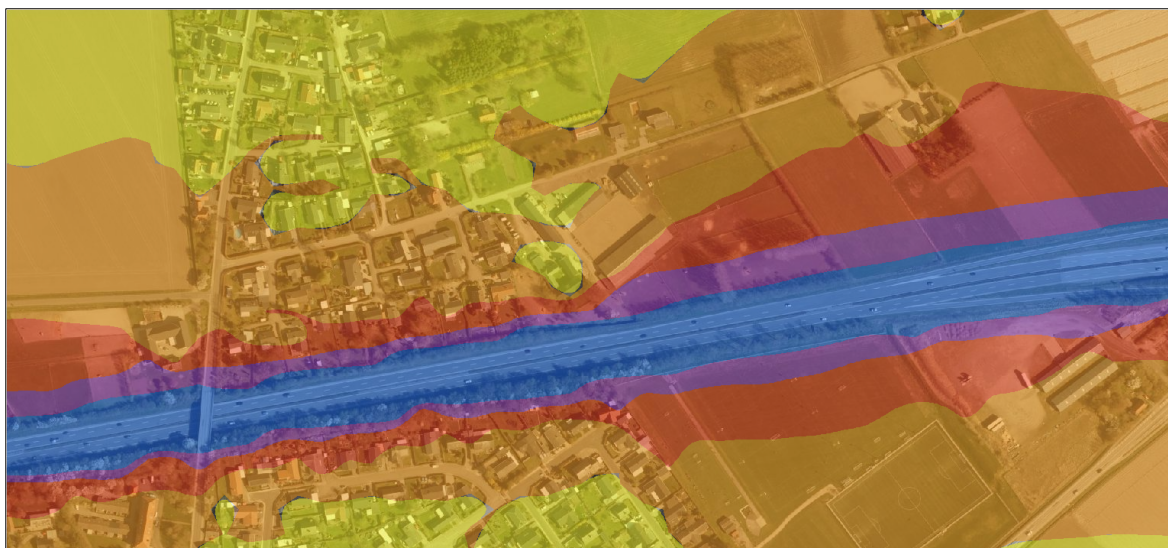


Figure 36: Grid noise map of same area as above showing the noise level 1.5 m over terrain (dB, Lden)  
(Source: Jakob Fryd, Danish Road Directorate)

Grid noise maps can be small or large scale and are used in many different ways. *Figure 37* shows the use of a grid noise map at a local level which highlights the impact of a road in Denmark, whereas *figure 38* shows an overall noise map of Europe which identifies quiet areas unaffected by noise pollution.

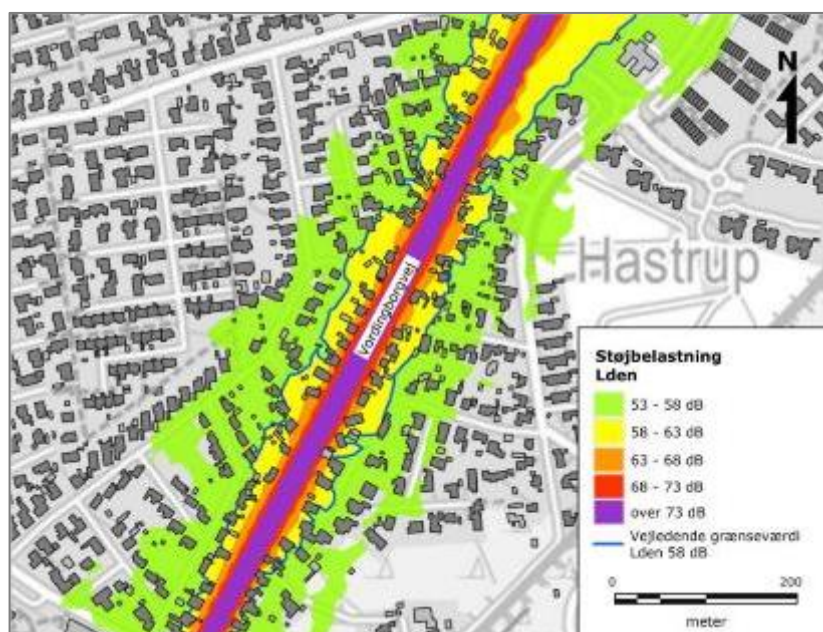


Figure 37: Noise map from Koege in Denmark  
(Source: Ramboll Denmark, 2018)

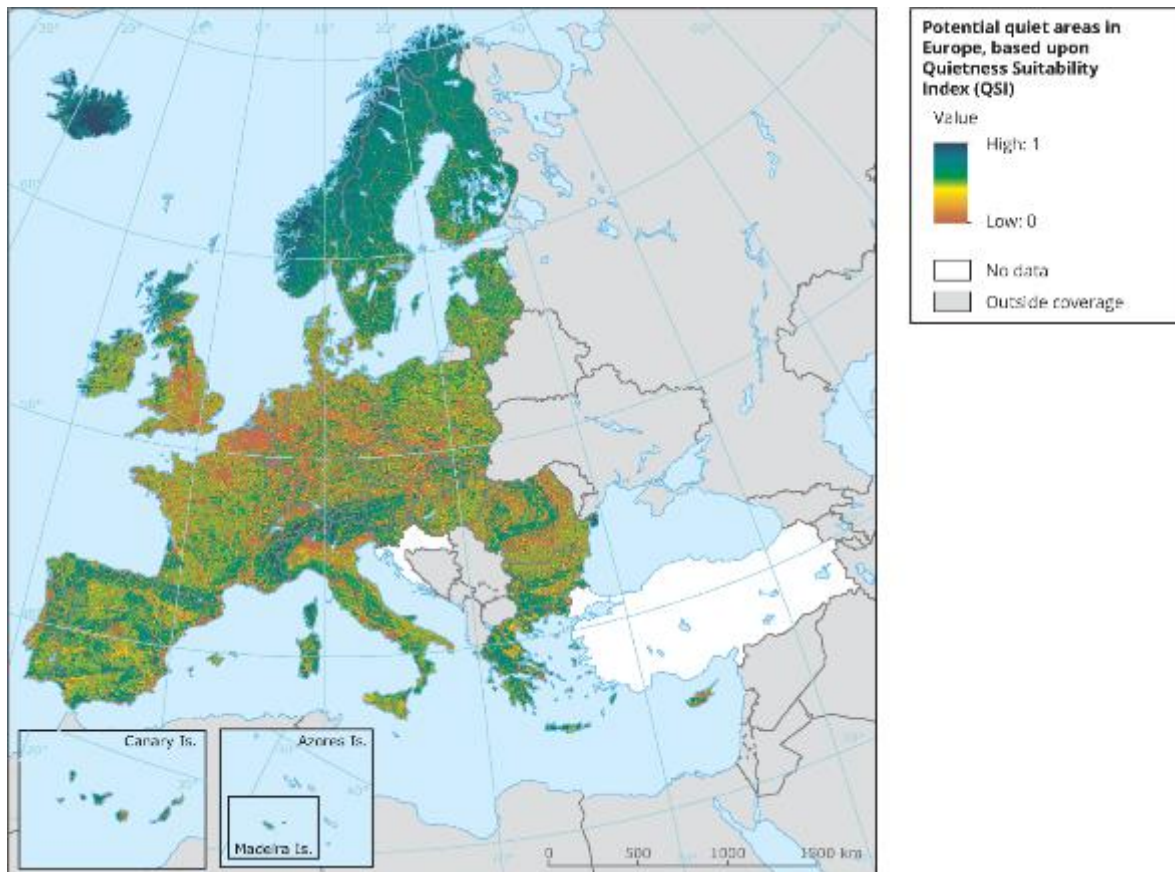


Figure 38: Potential quiet areas in Europe based upon the Quietness Suitability Index (QSI). [127]

### 8.7.2. Mapping the results of noise mitigation solutions

The first step of an assessment is to establish the “reference situation”, which is the predicted future situation for the noise from the existing road if it remains unchanged. The predictions take into consideration the increase of traffic, in the absence of any intervention, for a reference year which is taken as the opening year for the proposed road project. A different reference year can also be used to take increasing traffic over a longer planning horizon into consideration (e.g. for a strategic noise assessment). The existing road network includes the existing major roads (or road network) carrying most traffic, as well as minor roads which might have an influence on the overall noise exposure in the area.

Different alternatives to this reference situation are then investigated in the noise assessment. For a roading development, alternatives may be different alignments of the road and therefore have different noise impacts on the surroundings. They are referred to as the preferred option (the option which is suggested as the best solution), alternative 1, 2, and 3 and so on. For a strategic traffic noise assessment, the alternative options may be different mitigation measures such as traffic management or noise walls. For example, *figure 39* shows the results of traffic interventions following a strategic noise assessment in South Korea.



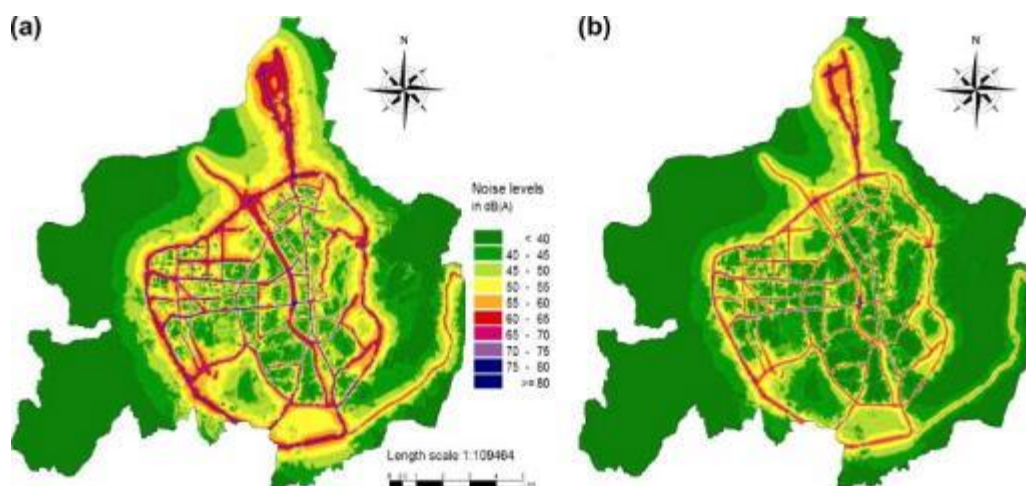


Figure 39: Noise map of Gyengo, South Korea before and after traffic intervention. [128]

In Denmark, the number of dwellings exposed to different noise levels is counted based on the noise mapping, and the total noise annoyance is calculated based on a noise exposure score (NES) for the study area (refer *case study 11*). Counting dwellings and calculating the total noise nuisance as an expression of road noise impact on the surrounding environment can be supplemented by further analyses and descriptions of the noise impact magnitude.

### 8.7.3. Presenting the benefits of noise mitigation options

The results of a noise impact assessment can be displayed in figures and maps that show differences in noise levels. They can also be presented in tables that compile the calculated differences between the noise levels before and after an intervention. *Table 10* gives an example of a noise impact summary for a new bypass road using the methodologies presented in *chapter 8.1*, step 3 (*table 8 and Table 9*). The traffic volumes and associated noise levels in the inner city will be reduced significantly as a result of the project, leading to beneficial effects in sensitive land uses such as dwellings and recreational areas.

		Dwellings	Schools	Recreational areas	Places of interest
Adverse Beneficial ↑ ↓	Substantial effect	23		1.5 km <sup>2</sup>	
	Moderate effect	67		2.5 km <sup>2</sup>	
	Slight effect	117		3.0 km <sup>2</sup>	1
	No effect	12	1	1.0 km <sup>2</sup>	1
	Slight effect	21		2.5 km <sup>2</sup>	1
	Moderate effect	12	1	3.5 km <sup>2</sup>	
	Substantial effect	4		0	
	Severe effect	0		0	

Table 10: Example of how changes in noise impact may be quantified in the EIA In contrast, residential and noise-sensitive areas located near the new road will experience an adverse effect.

If a table is compiled for each scenario, it can be compared with the baseline scenario. This can help describe and assess the noise impacts of each scenario.

In addition to the overall noise assessment for a study area covered by an EIA, it can also be helpful to use this method for counting houses in smaller local areas in order to describe the traffic noise impact in more detail.

The consequences of an intervention can also be illustrated by means of differential noise maps, for example, *figure 40* shows a map with the relative noise reductions. In comparison, *figure 41* shows the benefit in terms of absolute noise levels, of using a noise barrier to reduce traffic noise impacts.



Figure 40: Differential noise maps showing the noise reduction due to increasing a bank of earth from the height of 6 m to 12 m. The map shows the predicted noise reduction.

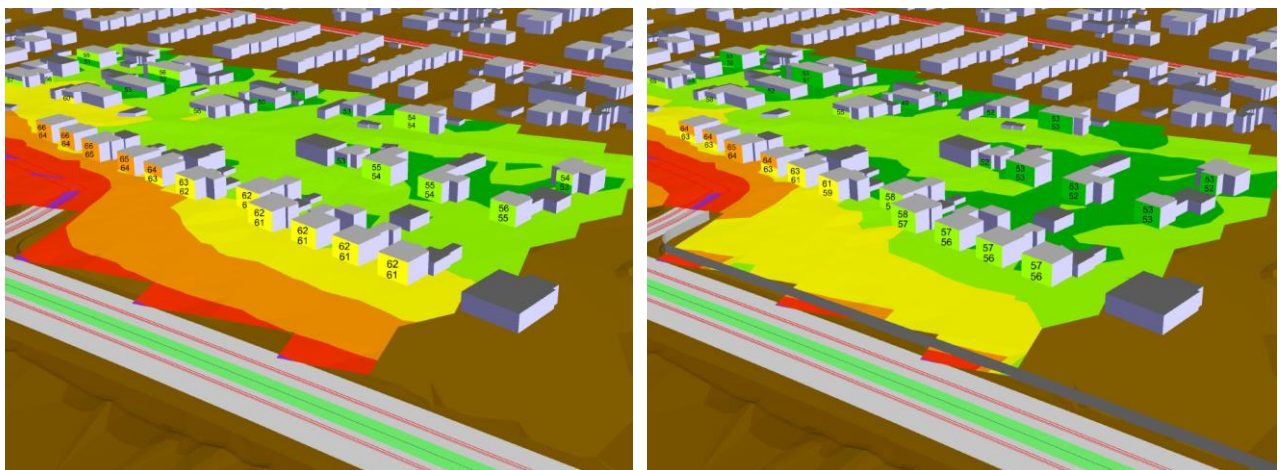


Figure 41: Road noise calculations without (left) and with (right) a noise barrier along the road. The result can be used to show the significance of a noise barrier at a particular location. The grid noise map shows noise 1.5 m above the ground, and façade noise levels at different heights are shown as numbers on buildings. The map shows the predicted noise reduction.



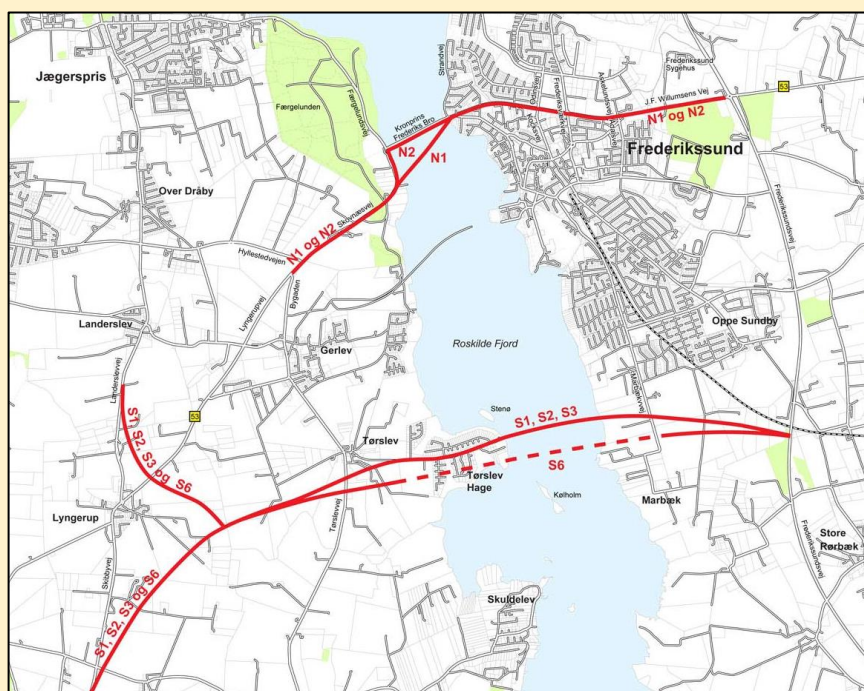
## CASE STUDY 11

### Environmental impact assessment, Roskilde Fjord, Denmark

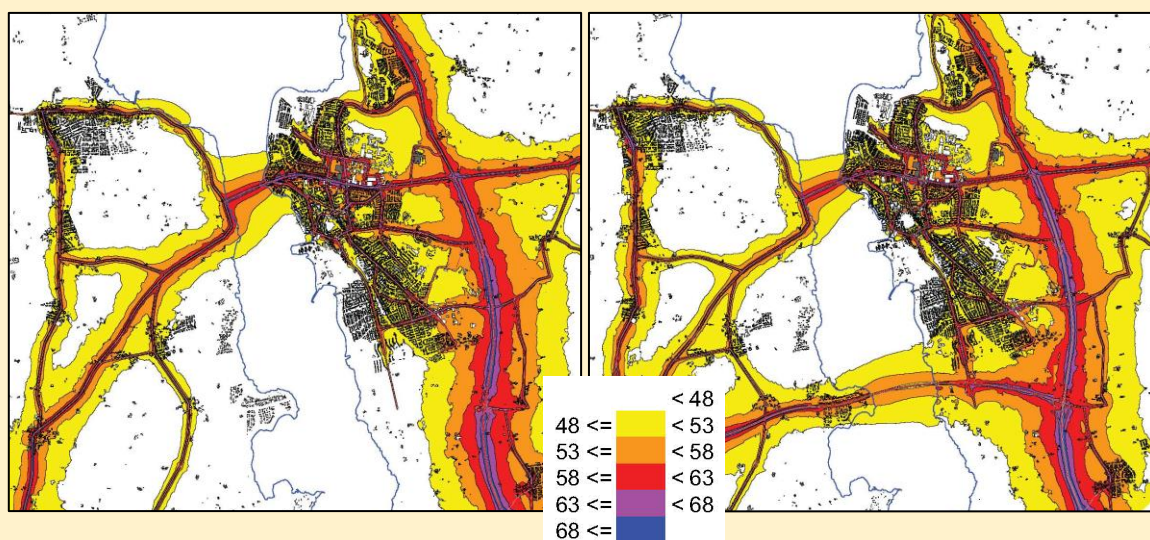
The purpose of the project was to include a new road link and improve the road capacity and connections over the Roskilde Fjord. The existing road passes through the city of Frederikssund.

Several alternative solutions had already been studied in the Environmental Impact Assessment, as follows (see figure below):

- The N-solutions (N1 and N2) included an enlargement of the existing road through Frederikssund, including noise barriers etc.
- The S-solutions (S1, S2, S3 and S6) included a new road link south of Frederikssund.



Northern and southern solutions for a new road link over Roskilde Fjord



Noise maps showing the noise impact ( $L_{den}$ ) of two different solutions – alternative N1 (left) and alternative S1 (right)

In the reference situation, 1,817 dwellings in the area of investigation were exposed to more than 58 dB ( $L_{den}$ ). This represented a NES value of 281. For the S1-solution (main solution) this was reduced to 1,780 dwellings with a reduction of the NES by 13. The other alternatives represented more or less the

same reductions of NES. This shows that the alternative solutions offered less noise exposure for the dwellings in the area of investigation. The NES was included in the economic analyses of the road project.

Situation	Number of noise exposed dwellings				Noise exposure score (NES)
	58–63 dB	63–68 dB	> 68 dB	> 58 dB	
Reference situation	1,272	454	91	1,817	281
N1, enlargement	1,210	481	89	1,780	271
N2, enlargement	1,250	446	89	1,785	267
S1, bridge (main solution)	1,210	481	89	1,780	269
S2, short tunnel	1,236	442	88	1,766	268
S3, long tunnel	1,199	476	88	1,763	268
S6, very long drilled tunnel	1,233	441	88	1,762	268

*Number of dwellings exposed to noise and the noise exposure score (NES) for each solution.*

#### For further information

Danish Road Directorate, e-mail: [vd@vd.dk](mailto:vd@vd.dk)  
att. Jakob Fryd

## CASE STUDY 12

### Using low cost noise sensors in Spain to inform and engage transport users and communities

#### Overview

Santander, in Northern Spain, has a population of 180,000. Some 12,000 electronic sensors, or 'nodes', have been fixed to buses and buildings, to measure a variety of parameters, such as noise, temperature, ambient light levels, carbon monoxide concentration, and the availability and location of parking spaces.



*Aerial view of Santander, Spain*

#### Environmental monitoring

Environmental monitoring is undertaken to obtain an overview of the environmental conditions in Santander such as temperature, CO<sub>2</sub> level, luminosity and noise, among others (see photo below).



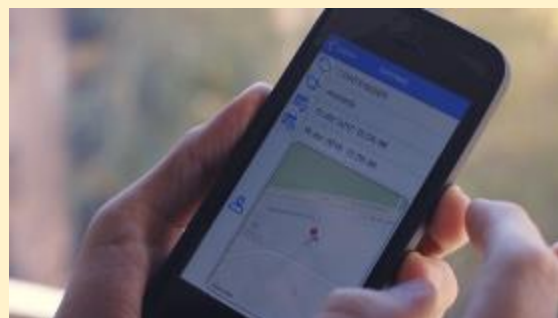
#### Participatory sensing

Participatory sensing involves utilising a mobile phone to send physical sensing information, e.g. GPS coordinates, and environmental data such as noise or temperature. This information is fed to the SmartSantander platform. Users can subscribe to services such as *the pace of the city*, where they get alerts for specific types of events currently occurring in the city. Users can also report the occurrence of such events, which will subsequently be sent to other users who have subscribed to this item.

The users receive notifications of the events via a smartphone application, SMS and emails in the preferred language. All users interested in receiving the notifications must register with the service, completing a personal profile (including for example the preferred language) and selecting the information they are interested in.

This allows active members of environmental and pro-cyclist groups to take part in SmartSantander activities and help report environmental data with their smartphones.

The smartphones are mounted on their bicycles and used to record noise levels, road and traffic condition data. The data is then uploaded to the system through a SmartSantander app. Similarly, other members of the cyclist community can upload their own data to the system and help build a map of the locations with the highest noise in the urban area.



#### For further information

<http://www.smartsantander.eu/>

<http://santander.es/content/proyecto-mapa-estrategico-ruído-del-municipio-santander>

#### 8.7.4. Explaining and experiencing traffic noise levels

To fully appreciate the impact of various noise levels and understand their variations, they must be actually experienced by listening. This is best achieved in either one of two ways. First, road designers, engineers or affected residents can visit a roadside location with a sound level meter and hear the actual noise level. This approach has the advantage that it is real, but it is difficult to experience a chosen noise level – to experience 60 dB, one must find a location with a 60 dB noise level. The alternative approach is to use simulated noise in a purpose-built studio with calibrated acoustics (refer case study 13). Recorded traffic noise can be played at a chosen level and adjusted up and down at will. This approach is quick and easy if the necessary resources are available but suffers somewhat because of the unrealistic visual environment.

The term auralisation was introduced in 1991 [129] where auralisation was defined as:

*the process of rendering audible, by physical or mathematical modelling, the sound field of a source in a space, in such a way as to simulate the binaural listening experience at a given position in the modelled space.*

A more recent definition refers to auralisation as the technique of creating audible sound files from numeric (simulated, measured or synthesised) data [130]. In general, one can say that auralisation describes different techniques that recreate sounds in such a way they represent different acoustic situations either from basic recordings or by the use of information about the sound source and the sound propagation in the surrounding environment [131].

Noise does not disappear just because auralisations are utilised, but the expectations about the noise generated by a future motorway are better balanced if there is the opportunity to hear the consequences beforehand. It also means that the addition of a new noise source, as a result of a new or upgraded project has been explained and presented in a more detailed and accessible way than has been the usual practice in the past.

For road planners, noise consultants and decision makers, auralisations of future traffic noise can be a useful tool for evaluating various noise mitigation solutions from the planning stage. Auralisations are now playing a greater role in decision making and in explaining acoustic phenomena through the use of sound examples. Additionally, under specific circumstances, auralisations can be made with very accurate noise levels in the playback system to precisely model the future soundscape.

The following approach was developed by DELTA Acoustics<sup>12</sup> and the Danish Road Directorate and illustrates the methodology for the creation of auralisations. There are three key components to consider: the sound sources, the acoustic transmission paths and the calibrated soundscape listening situation and system.

The auralisation approach is based on binaural sound recordings of single vehicle pass-bys, which is important for achieving the highest credibility for the final auralisation. The vehicle pass-bys have to sound like real vehicles, not just computer simulated sounds). Each vehicle pass-by is recorded using binaural recordings with head and torso simulations (HATS). Pass-by recordings are made in controlled conditions, ensuring that they do not include background or irrelevant noise. They are

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<sup>12</sup> Now: DELTA a part of FORCE technology



also made under a practically non-existent (or very low) downwind situation, so that subsequent corrections for wind speed are as small as possible. The pass-by recordings typically last up to 30 – 60 seconds corresponding to 750—1,500 m distance at 90 km/h. As a result, the recordings are useful for auralisations of single vehicles as well as for mixed traffic due to a specific traffic flow of a certain auralised road.

*Figure 42* illustrates the set-up for this approach. Recordings are made on straight roads at approximately constant speed with no or very little terrain variation. Recordings were also made close to the road – typically 30 m from the roadside (nearest lane).



*Figure 42: Recording vehicle passing by using HATS. (Source: Per Finne, DELTA Acoustics)*

Each vehicle pass-by is modified using the relevant time-slice transfer functions calculated using the prediction model Nord2000. Generally, the point of auralisation is a different geographical and topographical situation compared with the recording site. Changes in sound propagation are dealt with using the calculated transfer functions from the recording site  $H1(f)$  and the auralisation site  $H2(f)$  (refer *figure 43*).

The method used for auralisation is straightforward and based on corrections to the individual pass-by recordings using precise calculations of sound propagation from the recording situations as well as the point of auralisation. In order to modify the time signal, each correction value refers to approximately 10 m segment of the road. The length of segmentation is not mandatory but should be considered in relation to the auralised situation, i.e. positioning of noise barriers, terrain variations. The segmentation also has a significant influence on the perceived quality of the auralisation sound file.

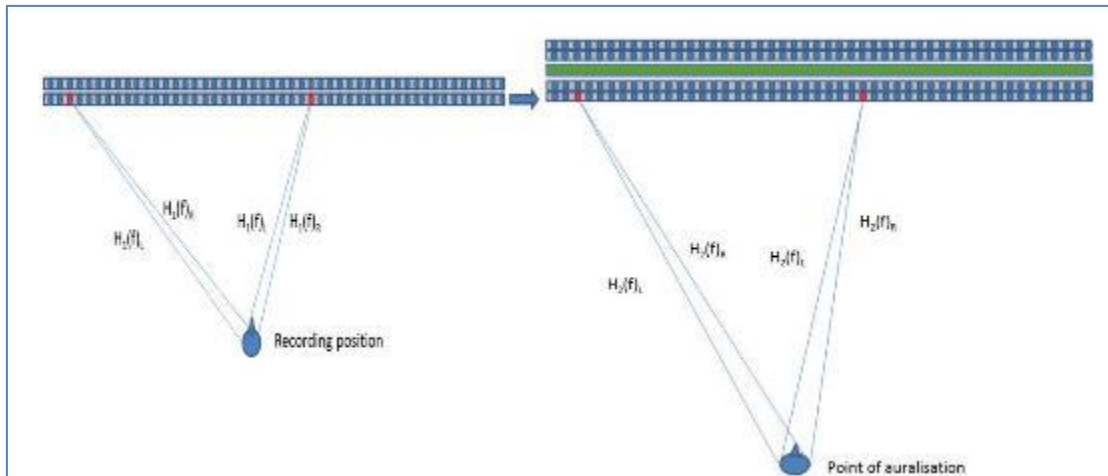


Figure 43: Transfer functions for the left and right ear for two road segments out of a large number of segments representing the road line. Each lane is considered individually. Each recorded vehicle pass-by from the recording position is modified using the relevant time-slice transfer functions calculated with the prediction model NORD2000. [132]

The auralisation process is illustrated in figure 44. A calculation model is used to determine the transfer functions based on data from a sound library. The library contains a large number of vehicle pass-by recordings (e.g. light or heavy vehicles at 80 km/h). Correction for different surface properties (e.g. noise reducing asphalt) can be applied during the post-processing phase. Each vehicle pass-by is then modified using the relevant time-slice transfer functions from the recording site and the auralisation site.

The auralisation LAB software module creates the modified sound file corresponding to the auralisation position. A model is used to calculate the transfer functions after all the vehicle pass-by calculations have been made and they are mixed into one sound file with the specific requirements of speed, traffic intensity and so on. Finally, a particular soundscape is added. This is normally a binaural recording of background noise, which has specified characteristics like “afternoon in the open land” or “birds singing in open land” etc. The soundscape is of great importance and gives the listener a strong awareness of context while listening to the auralisation. Real recordings of the soundscape at the location of the auralisation can provide the listener a better opportunity to understand the context of the listening example when added to the road noise auralisations [132]. For example, allowing recordings of birdsong and other natural sounds that are characteristic of the location will provide an overall better listening experience than just the sounds of road traffic noise.

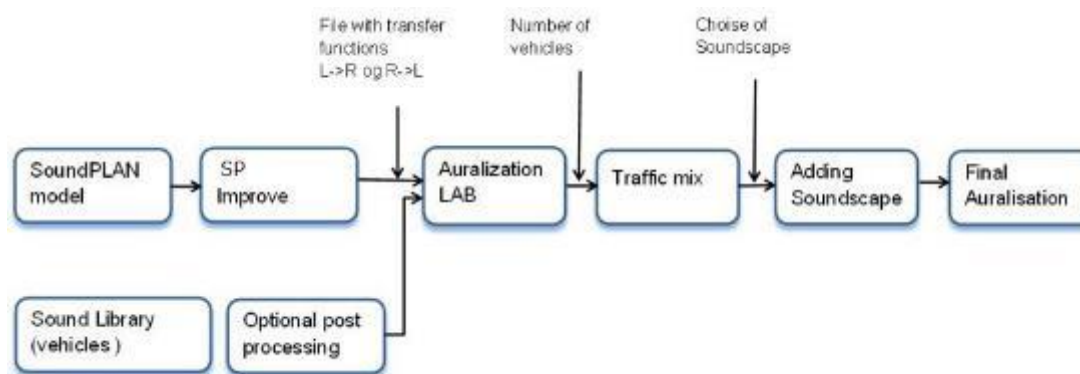


Figure 44: Schematic showing how “pass-by” measurements are made to create a road traffic noise auralisation simulation. [132]

## CHAPTER 8: CONCLUSIONS:

- Noise assessments are undertaken for a range of reasons including for environmental impact assessments and public health impact assessments. They can be done at a project level or a regional or even national level.
- Project noise impact assessments are used to determine the effect of the expected change in the acoustic environment as a result of a proposed road development or intervention.
- A strategic noise impact assessment may be undertaken for an existing situation for new developments. They are generally focused on an area (such as a precinct, a town or a new land development) rather than a specific route or road project, with a view to understanding the overall noise environment and where mitigation may be necessary.
- There are many methods available for undertaking an environmental noise impact assessment. In any given situation, the technique adopted must be tailored to the situation itself so that all relevant factors are included as appropriate in the assessment.
- Modern traffic noise modelling software allows the results of traffic noise impact assessments to be presented in noise maps that describe spatial distributions of noise levels. They allow for detailed visualisation, in 2D or 3D, of the noise distributions in areas where the land uses are sensitive to noise.
- To fully appreciate the impact of various noise levels, they should be experienced and auralisations – either approximations or calibrated in a purpose-built studio – are now considered best practice to demonstrate to the community the level of noise that will be experienced with proposed road changes.

## CASE STUDY 13

### Using auralisations to communicate road project traffic noise impacts to the public in Denmark

#### Overview

The Danish Road Directorate uses auralisations (or sound examples) at public meetings to explain the noise impacts of projects, or to demonstrate the effectiveness of noise mitigation measures such as noise barriers or low noise asphalt surfaces.

For instance, auralisations were used at public meetings in connection with the presentation of results of an EIA for a new motorway between two cities in southern Sealand, Denmark.

Various options were examined for the new motorway. The noise impact was described for each of the options. An overview of proposals examined in the EIA study of Route 54 between Næstved and Rønnede is shown below.



*Overview of proposals examined in the EIA study*

For the public hearing of the EIA study, a number of auralisations were presented at public meetings for the project. The purpose was to give local residents an idea of how the future motorway would affect them in terms of noise. It was also intended as a way of demystifying the noise impact, for example the idea that noise will not be annoying if it stays within recommended limit values.

Examples were presented of how the motorway would sound at three specific sites (positions) along the Route A option. In principle, examples could have been used along the other routes at the same distances from the road if traffic conditions and the propagation of sound were otherwise quite similar.



*One of the receiver points included in the sound examples*

The Danish Road Directorate also arranged an *open house* at a local community centre. People could go there throughout the day to obtain more detailed information about the project. The auralisations were actively used as a starting point to talk about how a motorway would affect the local area.

#### Results

Judging by the interest at the public meetings, the recorded auralisations were a good supplement to the EIA written material. The auralisations were presented to over 200 local citizens, which exceeded all expectations, as there was a limit of a maximum of 25 people per presentation.



*Presentation of auralisations at a public meeting in Toksværd, 12 December 2016.*

#### For further information

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att. Jakob Fryd



## 9. MITIGATION

### 9.1. PLANNING

The impact of traffic noise on the community can be minimised through compatible zoning interfaces and by appropriate urban and site design that locates noise sensitive land uses such as homes and schools well away from busy roads. It is normal practice in Europe, North America and Australasia to locate new freeways away from residential areas to the extent that is feasible, and to discourage new residential development along existing freeways.

However, the ability to earmark large tracts of vacant land for future road development has become increasingly difficult in many cities due to population growth. In an established urban environment, providing a sufficiently wide buffer to separate residential areas from major roads is not always possible, and is generally perceived as an inefficient use of space. Besides, new developments are often sited near transport corridors to facilitate access. Consequently, some noise sensitive land uses will inevitably be developed in high noise locations.

Road traffic noise is most commonly regarded as a problem in residential areas (including open spaces); it is considered less important in commercial and industrial areas. For this reason, locating industrial zones between residential areas and major roads as shown in *figure 45* can be a very effective way of protecting residents from traffic noise, although it should be recognised that it can result in other problems if the industry itself is noisy.



Figure 45: Industry between motorway and housing, Eastlink, Melbourne Australia. (Source: Google Maps)

An alternative approach is to simply maintain a strip of open space either side of the road as shown in *figure 46*. This approach can require a large amount of land to provide adequate noise reduction. Increasing the distance from the road from 20 m to 100 m can reduce noise by about 7 dB (assuming soft ground). Further increasing the distance to 200 m would only yield another 3 dB. Unless an additional use for this land can be found (such as farming) it may be difficult to justify dedicating so much land to noise control.



*Figure 46: Open space between motorway and housing, Stony Trail, Calgary, Canada  
(Source: Google Maps)*

The effectiveness of open space for limiting noise can be enhanced by measures that increase the ability of the intervening ground to absorb sound. This may be achieved by ensuring that the ground is porous (avoiding reflective surfaces such as paved car parks or water). Dense forest of sufficient width (in the order of 100 m) can achieve several dB of additional noise reduction. This is due to the scattering of sound waves by trees, and trees supporting soft, loose, absorptive soil. Where sufficient soil is available, constructing an earth mound in an open space can be very effective at reducing noise even if it is of modest height as shown in *figure 47* (refer also to *chapter 9.7.6* on vegetated noise barriers). A similar benefit can be achieved by locating the road in a cut (refer also *chapter 9.2 on road design*) and having loose soil and protective vegetation on the slope of the cut.



*Figure 47: Buffer and earth mound, Park Rd, Adelaide, Australia.  
(Source: J.McIntosh, Department of Transport, Victoria, Australia)*



Open space alongside major roads in urban and suburban areas is often used for parkland. However, there have been occasions when this has generated community expectation that the open space itself should be protected from traffic noise.

In dense urban settings, particularly cities with high-rise residential zones, separating noise-sensitive land use from noisy roads is not always possible. In this instance, residential buildings should be designed in a way that protects their occupants from noise. Refer to *chapter 9.8* for more information on urban and building design.

## CASE STUDY 14

### Strategic noise mapping in Spain for planning roads

#### Overview

Spain's state road network is over 26,000 kilometres long, making it the longest network of highways and motorways in Europe. It is estimated that the construction, maintenance and operation of this network provide jobs for over 40,000 people in Spain.

Road transport represents the main means of transport chosen by people in Spain, accounting for 90% of all transport, and the main means of freight transport, accounting for 84% of freight transport. Recent years have seen the implementation of new actions to improve the network's performance and quality.

In terms of the regulatory framework, a new Highway Act was approved in 2015, which replaces the old law dating back to 1988. This addresses the need for a fit-for-purpose and modern provision of a public highway service. With respect to noise, the 2015 Highway Act introduces stronger provisions for addressing noise impacts from road traffic.



#### New Highway Act 2015

The Highway Act 2015 introduces a new framework that sets restrictions on residential development adjacent to highways based on road traffic noise. The Act introduces the concept of a *noise protection zone*, which is an area where noise exposure does not meet the required noise quality standards.

These noise protection zones are defined through noise maps or specific noise assessments made by the Ministry of Development. They are designated by the different public administrations – national, regional and local level – and their approval is subject to public consultation.

The Highway Act also establishes *strategic noise mapping* as the main regulatory tool for noise management in the field of planning, building and maintaining roads.



#### Summary

The new Highway Act has introduced stronger noise provisions to protect residential exposure from the impacts of road traffic noise, through designation of noise protection zones. The new legislation will result in improved traffic noise exposure outcomes compared with the old law of 1988.

#### For further information

BOE Legislación Consolidada [133]

<https://www.boe.es/buscar/act.php?id=BOE-A-2003-20976>

BOE Legislación Consolidada (2015) [134]

<https://www.boe.es/buscar/act.php?id=BOE-A-2015-10439>

## 9.2. ROAD DESIGN

### 9.2.1. Gradient

Traffic noise can be reduced by optimal design of road geometry, although there are often constraints on geometry due to a range of other competing objectives. Some potential measures are described below.

Minimising the road gradient reduces the power vehicles require to drive uphill. This can result in substantial noise reduction, particularly where a sizable percentage of the traffic is heavy vehicles. A gradient of 3% will increase the proportion of propulsion noise. Steep gradients have larger effects on noise level when the proportion of heavy vehicles is greater. In some countries where trucks operate with unmuffled engine brakes, reducing gradients may reduce noise from engine brake usage while descending (see *chapter 9.4* for further discussion).

### 9.2.2. Cuttings

Cuttings are generally not designed to address noise issues alone, but they can provide noise benefits. Locating a road within a cutting provides an effective sound barrier on either side of the road, as shown in *figure 48* where the adjacent receivers are completely screened. However, its acoustical effectiveness may be impaired by the reflection of sound as explained below.

### 9.2.3. Cutting walls

Vertical concrete walls as shown in *figure 48* can result in noise reflecting from one side of the cut to the other and diffracting over the top. A more effective design for mitigating noise is to have sloping batters (earth slopes) either side of the road, causing noise to reflect upwards. If the batters are composed of soft soil, protected by vegetation, they will provide enhanced ground absorption, reducing the level of sound that diffracts over the top of them. An example is shown in *figure 49*.



*Figure 48: Road within cutting, A50 Stoke-on-Trent, U.K.*

*(Source: Google Maps)*



Figure 49: Road with sloping batters, A50 Stoke-on-Trent, U.K.

(Source: Google Maps)

The noise benefits of vegetated sloping batters were investigated when constructing a motorway in Geelong, Victoria, Australia. The responsible road agency offered a strip of surplus land approximately 100 m wide along its side, which was then allocated for residential development. Noise measurements were made at a few locations in the area and were found to be significantly lower than previously expected from modelling using the CRTN algorithm (see *chapter 6* and *appendix 1* for further information on traffic noise models). Analysis showed that because the motorway was in a cutting, with porous soil slopes (stabilised by vegetation) there was significantly greater noise reduction than the traffic noise modelling had predicted. Further investigation by the road agency similarly identified other locations where earth mounds or earth cuttings had resulted in greater noise abatement than anticipated due to a combination of ground absorption and the effect of blocking direct sound transmission.

#### 9.2.4. Tunnels

Traffic noise can be rendered virtually inaudible by completely covering a road or enclosing it. In most jurisdictions, the cost of such measures is considered too high to justify them based on noise alone, but examples do exist. *Figure 50* is one such example with a roof over the road covered by soil and vegetation. The roof is accessible and can be walked over, with no awareness that a road exists underneath.

Enclosed roads can be achieved in one of three ways:

- Driven tunnel. This is generally the most expensive tunnelling construction method and usually involves the use of a tunnel boring machine to build longer tunnels under rivers, harbours, sensitive ecological habitats, etc.
- Cut and cover. A trench is excavated, the road is constructed in the trench, and then a roof is constructed over the top of the trench as shown in *case study 15* which is an illustration of a planned enclosure in Hamburg, Germany.
- Elevated tunnel. Walls and a roof are constructed over a road that is on ground level. This option can be visually intrusive and is not common (an example is shown in *case study 16*).

While road tunnels can mitigate traffic noise impacts they can also create adverse noise impacts because of reflections from the road, roof and walls, resulting in elevated levels of noise spilling out at the portals. To prevent this, it is often necessary for the ends of the tunnel to be lined with sound absorptive cladding. A limited number of traffic noise models are capable of modelling the effect of noise at tunnel entrances (see *appendix 1*, which lists the models that can be used to assess the effects of road tunnel portal noise).



*Figure 50: Vegetated motorway cover, A13 Autobahn, Schonberg im Stubaital, Austria.  
(Source: J.McIntosh, Department of Transport, Victoria, Australia)*



## CASE STUDY 15

### Using a road tunnel to reduce traffic noise in Hamburg, Germany

The Hamburger Deckel (Tunnel) is an infrastructure improvement project on one of Germany's busiest and longest motorways, the A7, which runs for 964 km. It links Scandinavia in the north with Southern Europe and carries 152,000 vehicles a day around Hamburg. The A7 motorway was built in the 1970s through the western part of Hamburg.

The new project is expected to be completed in 2022 and is in direct response to the increasing traffic congestion and growing patronage along the motorway. It will result in an expansion from six to eight lanes and will produce 25 new hectares of green space in the city of Hamburg because of enclosing existing surface roads within the tunnel and creating land bridges and open green space over the tunnel structure.



*Example of motorway section before extension*



*Example of motorway section after extension and cover of the motorway*

As traffic became worse, the city realised it had to find a way to keep the noise in the area low enough to meet national laws for noise pollution. According to law in the Hamburg districts noise levels of 59 dB by day and 49 dB by night must be met when new buildings are constructed or major changes to roads are made. Since simple walls would not be enough, they decided to turn sections of the road into covered tunnels. The design can reduce noise in surrounding neighbourhoods to almost nothing.

The *Hamburger Deckel cut and cover* solution consists of three new road tunnels through the city districts of Schnelsen, Stellingen and Bahrenfeld, with a total combined length of 3.5 km. The concrete and parkland canopy for the tunnels spans on average 34 m and has an average structural depth of 2 to 3 m.

Aimed at reconnecting the disconnected districts and stitching together the urban fabric, each tunnel deck is to support new extensive parklands, allotments of community gardens and parcels for new residential developments.



*Green open spaces and new residential areas as a result of the tunnel project*

The Hamburger Deckel project has been community driven from the outset. During the planning process the community was engaged at a number of stages, with regular workshops and public events. These were used as an opportunity to create a design brief for the landscape design competitions, ensuring the needs of the residents were incorporated into the design outcome. Throughout the planning process, consultants and planners were in close contact with residents of the district through public consultations and regular publications of design proposal documentation. This created a transparent planning process with regular community feedback.

The project is expected to cost around AUD\$1 billion and take almost 10 years to complete in the period 2012–2022. The project is financed by the Federal Republic of Germany by 83% and City of Hamburg by 17%. A breakdown of the cost for road improvements (enlargement), noise barriers and tunnels represent respectively approximately 31%, 12% and 57% of total costs.

#### For further information

<http://www.hamburg.de/contentblob/4018374/cc0787aa162bce5efba0cd3adcf6ec47/data/12-08-broschuere-gesamtprojekt-freiraum-und-ruhe-english.pdf>



## CASE STUDY 16

### Innovative multi-function noise barriers in Korea

#### Overview

The Korea Expressway Corporation (KEC) is actively progressing Korea's road noise reduction policy in consultation with government agencies to address high noise exposure in residential areas next to the highways. The target is to meet the noise standard (55 dB(A) night-time limit 10pm to 6am) in roadside areas by 2025. Since 2012, KEC has implemented an extensive noise barrier programme along its highways to reduce noise levels. There are 3,024 noise barriers installed, with a total length of 741 km (2017 figures).

Opportunities, through the SMART Highways project (2007–2014), have been taken to optimise the benefits of these installations by integrating the design with other functions and installing eco-friendly, multi-function noise barriers to achieve more sustainable outcomes. These include aesthetic functions, air pollution mitigation and renewable energy generation (solar modules).

#### Design

Soundproof tunnels have a market share of about 26% and continue to increase as the preferred noise reduction solution for large new city residential development and road expansion projects.

Because these tunnels have an integral structure, they are lightweight compared with general soundproof tunnels and can cost less. The design of the tunnels is flexible, which can also increase the aesthetics of the road.

To verify the effectiveness of solar photovoltaic soundproof tunnels, multi-functional noise barriers were incorporated into the construction of tunnels at the Sungsu Grand Bridge in Sanggye-dong, Nowon-gu, Seoul.



*View of the soundproof tunnels*

The noise reduction effect was estimated to range from about 1 dB to approximately 18 dB depending on the floor height of the surrounding apartments and the distance from the noise source.



*Process of installation effect analysis*

Attachable air pollution mitigation modules have been specifically designed to reduce road traffic emissions of greenhouse gases (CO<sub>2</sub>) and particles (PM<sub>10</sub>) and monitoring has indicated reductions in CO<sub>2</sub> of 6.5% and reductions in PM<sub>10</sub> of 18% respectively. The sound absorption coefficient was determined to be 0.9, higher than the standard noise walls of 0.7. At a frequency of 500 Hz, the acoustic attenuation coefficient is 33.9 dB and the attenuation coefficient at 1000 Hz is 35.3 dB.



*Design of soundproof wall*

#### For further information

<http://www.ex.co.kr/eng/>  
<http://english.molit.go.kr/intro.do>

### 9.3. LOW NOISE PAVEMENTS

It is the authors' experience that noise problems are often best solved by addressing the cause of the noise at its source. The interaction of vehicle tyres on road surfaces is the main cause of most traffic noise. While improvements to tyres are critical for noise abatement, many road agencies only have direct control over road surfaces and not vehicle tyres. This section outlines some opportunities for and experiences with reducing road noise through improved road surfaces. *Case studies 17 to 20*, provide a series of international examples which discuss the acoustic performance of different pavement designs.

Comprehensive information on road surface noise is set out in the PIARC report entitled *Quiet pavement technologies* [8], including detailed descriptions of the specific mechanisms that generate road surface noise. Three key surface properties that affect noise are, in order of decreasing importance: texture, porosity and stiffness. How these all interact with the tyre to generate noise is complex and care is needed when applying simple rules, such as “noise increases as texture size increases”, because there may be other interactions that disrupt these trends.

#### 9.3.1. Texture

Noise heard outside a vehicle is caused mostly by road surface texture that repeats itself every 10 to 150 mm (known as macrotexture). All else being equal, this type of texture should be minimised (flattened). However, negative texture such as formed by gaps or voids below a flat surface can assist in reducing noise with respect to porosity, as discussed in the following section. Therefore, while positive texture protruding from the surface is usually disadvantageous in terms of limiting noise, increasing the amount of negative texture below the surface is usually beneficial. *Figure 51* makes the difference clear. In the positive texture example, the tyre is rolling on single points of contact, unable to find some support between these. The contact forces and therefore the excitation of the tyre structure that causes vibrations and noise are high. In the negative texture example, the road surface carries the tyre on a series of small flat plateaus, thus reducing the local contact forces and the vibration excitation.

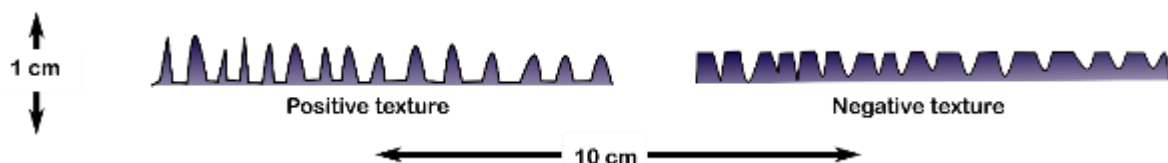


Figure 51: Schematic categories of road surface profiles.

(Source: J. McIntosh, Department of Transport, Victoria, Australia)

*Figure 52* shows the difference between these two categories of road surfaces by means of real road surface textures. The diagram on the left shows the roughness profile of a mastic asphalt gritted with chippings with 8 mm maximum grain size giving a “positive” texture. The diagram on the right represents a stone mastic asphalt with 8 mm maximum grain size giving a “negative” texture. The blue curves uncover the shape of the road surface.

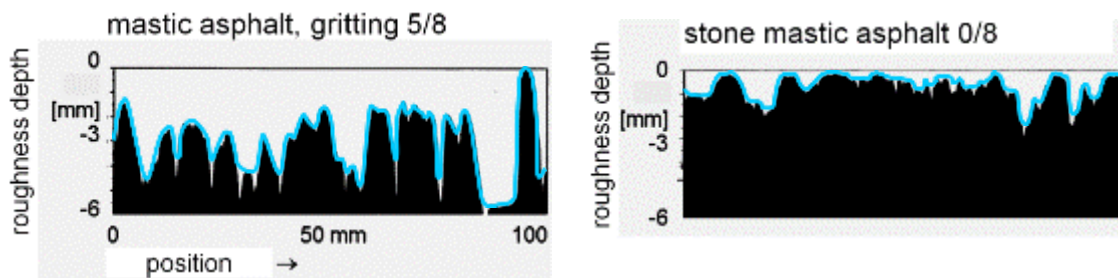


Figure 52: Roughness profiles of real road surfaces. Left: mastic asphalt with gritting, maximum grain size 8 mm; right: stone mastic asphalt, maximum grain size 8 mm. [90].

Figure 53a shows the average rolling noise level for car series production tyres depending on the maximum grain size of the gritting of mastic asphalt (blue) and the maximum grain size of the mix of hot rolled stone mastic asphalt (green). “Coast-by” noise levels are taken when the engine is off and the gearing decoupled, for cars rolling by at a distance of 7.5 m from the microphone, with a speed of 80 km/h. Figure 53b shows prints of the points and areas of contact between a slick tyre without tread profile and the road surface, taken on an area 10 by 15 cm<sup>2</sup>. Figure 53c shows typical roughness profiles of the different road surfaces, each 100 mm long.

The effect of the maximum grain size and the way the asphalt is laid can be clearly seen in figure 53a, b and c. As the maximum grain size becomes increasingly smaller the rolling noise level decreases and reaches its minimum between 3 mm and 5 mm. The contact forces between the tyre and the surface are distributed on a multitude of contact points per square centimetre. The number of contact points rises tremendously with the reduction of the maximum grain size (see figure 53b). This leads to a continuous reduction of the local contact force per contact point between the tyre and the road surface, thus creating a reduction of the vibration excitation and noise production of the tyre. The difference between the rolling noise levels for wearing courses with 8 mm and 3 mm maximum grain size is about 4 dB. When the hot asphalt mix is rolled, the contact point density is increased again. The surface roughness tips are set on the same level which gives a very high contact point density and excellent profile evenness (see figure 53c). This results in an acoustic benefit of 3 to 4 dB compared with asphalt surface treatments that do not need to be rolled.

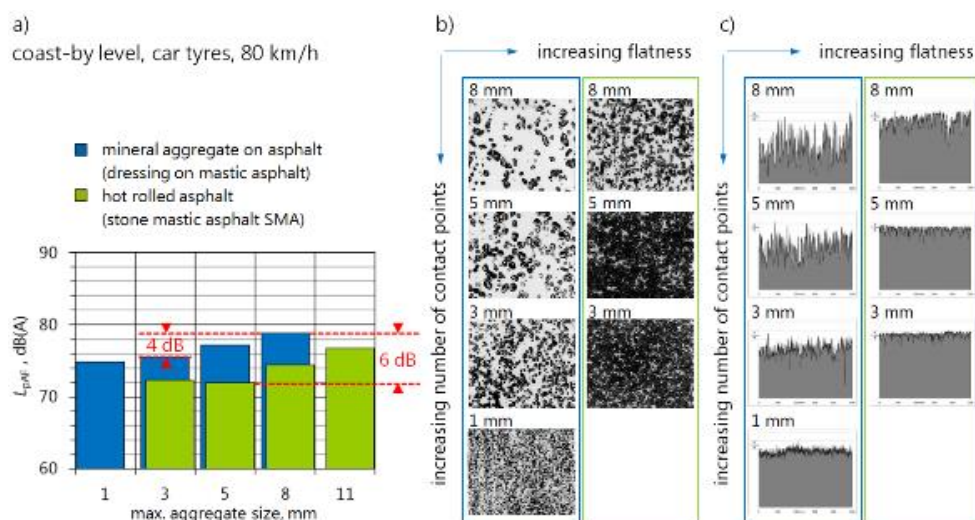


Figure 53: a) Coast-by level  $L_{pAF,R}$  for an average car tyre on road pavements of different makings and maximum grain sizes; b) representation of the contact points between a slick tyre c) typical roughness profiles of the various asphalt wearing courses. [90].

The effect of different road pavements on the rolling noise must be evaluated separately for car and truck tyres. Truck tyres do not necessarily react to the characteristics of the road surface in the same way as car tyres. Trucks and cars respond differently to various road surfaces, as the size, tread profile and mass of truck tyres make them more insensitive to pavement textures (refer *figure 54*).

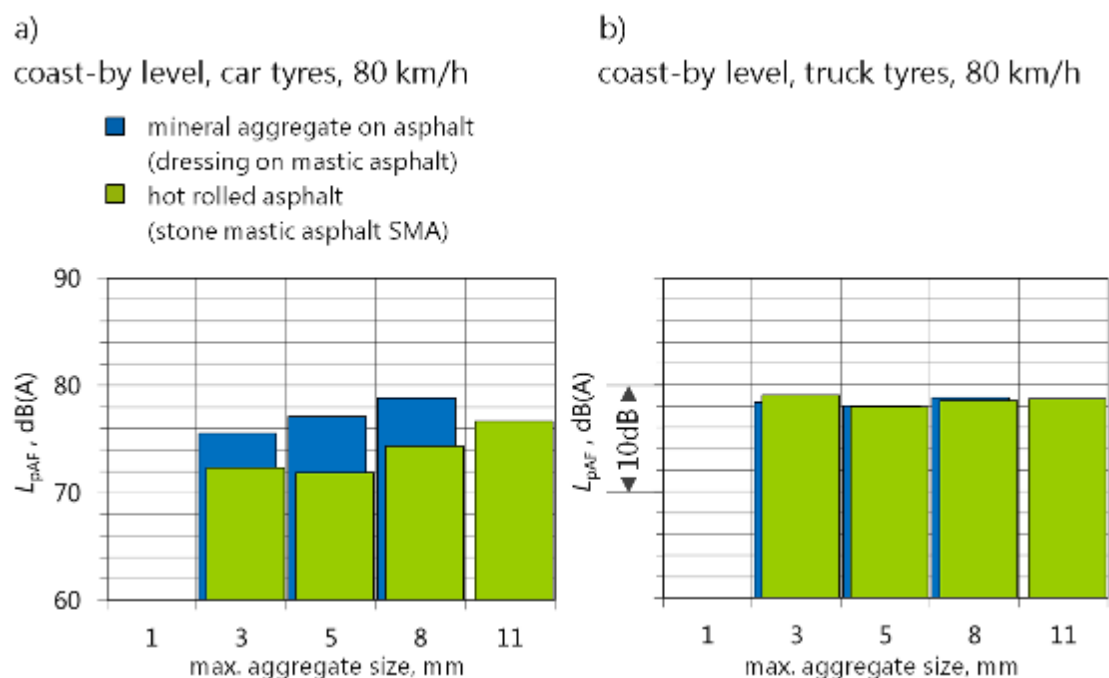


Figure 54: Average coast-by (engine off, distance 7.5 m, 80 km/h) level  $L_{pAF,R}$  for tyres on road pavements of different makings and maximum grain sizes; a) series-production car tyres; b) series-production truck tyres. [90]

Figure 55 shows results from rolling noise measurements in New Zealand for six sections of porous asphalt with three different mix designs, together with a trend line. Two of the mixes used a 10 mm chip size (EPA10 and EPA10HV), with one of them having an increased void content (EPA10HV). The third mix used a larger 14 mm chip size (EPA14). For these examples the graph shows noise increases (LCPX: P1,80) as surface roughness increases (mean profile depth).

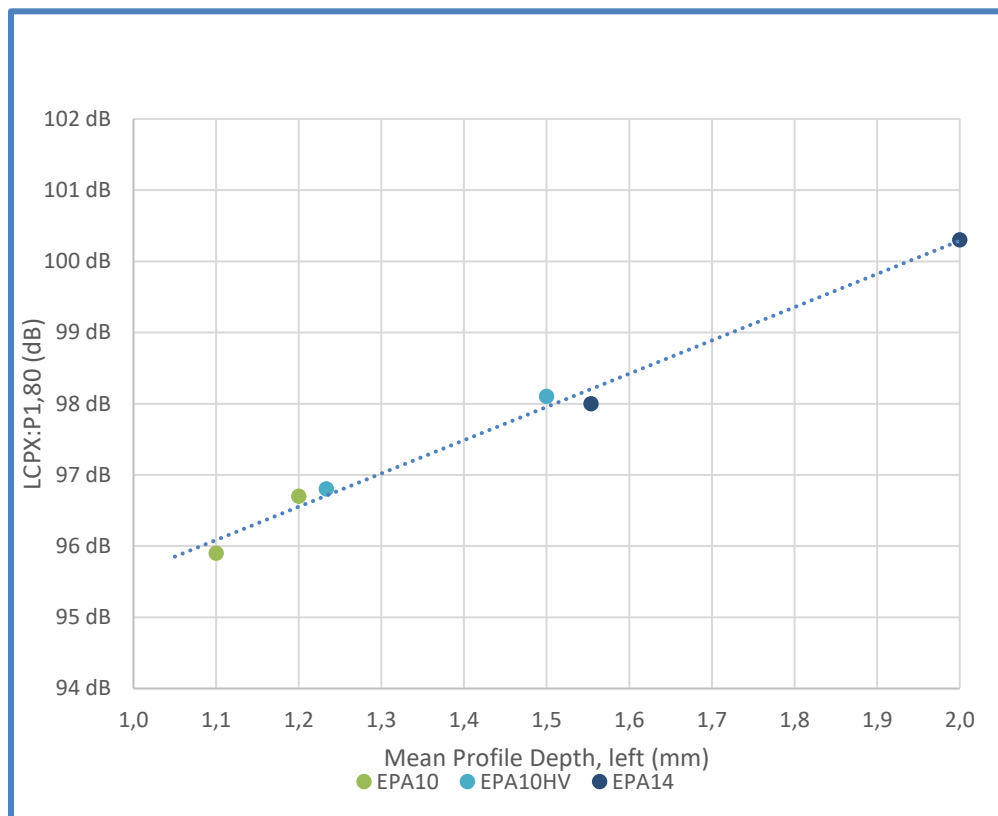


Figure 55: Measured porous asphalt road surface noise and texture.

(Source: unpublished data, NZ Transport Agency)

### 9.3.2. Porosity

The porosity of a road surface is the percentage of the total volume of the surface that consists of air gaps. Materials used in most road surfaces have a porosity of less than 5%. When the porosity increases to approximately 20%, noise reductions are achieved through absorption of noise, decreasing the effect of tyre/road noise generation and amplification mechanisms.

Sound absorption coefficients range from 0 (0% sound absorption) to 1.0 (100% sound absorption). The porosity or void content, expressed as a percentage of total volume (Vol. %), needed to cover this range of sound absorption coefficients is 0 Vol.-% to 30 Vol.-%. Figure 56 shows the rolling noise level reduction that is achievable depending on the sound absorption coefficient in the frequency range from 500 Hz to 2,000 Hz. This frequency range covers the most important frequencies as they relate to rolling noise. The rolling noise level is reduced even at quite low absorption coefficients commencing at 0.1 (10%) which corresponds to a void content of 8 Vol.-%.



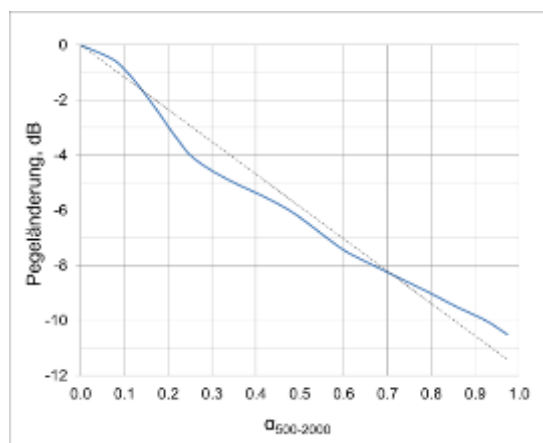


Figure 56: Rolling noise reduction as a function of the sound absorption coefficient  $\alpha_{500-2,000}$  in the frequency range from 500 Hz to 2,000 Hz. (Source: Müller-BBM)

Sound absorption coefficients, however, do not correspond well to the void content. When it comes to sound absorption, the voids within the porous asphalt structure need to be accessible to air and sound waves travelling through the porous layer. Tests performed in a road material testing laboratory do not discriminate between open and closed voids. As a rule, an asphalt pavement with void contents of more than 18 Vol.-% – determined by means of bore cores taken from the completed asphalt layer and use of the dipping and weighing method [135] – provides good to excellent sound absorption coefficients between 0.7 and 0.9 maximum.

### 9.3.3. Stiffness

The road surface is much stiffer than the rubber of the tyre and impact forces arise that can generate noise. A lower impact, and therefore lower noise, can be achieved by using surfaces of reduced stiffness. An example of a surface with lower stiffness is a poro-elastic surface incorporating rubber crumb.

While it is theoretically possible to achieve significant noise reductions by adjusting the stiffness of the road surface, the extent of practical changes often conflicts with other requirements such as safety, engineering and cost. Ongoing research is therefore seeking to optimise these parameters to achieve noise reductions in a cost-effective and practical manner, while at the same time preserving other functional requirements.

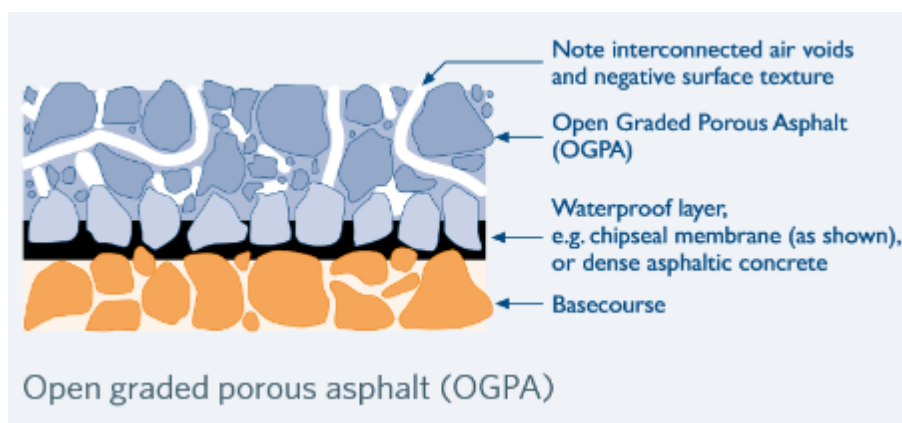


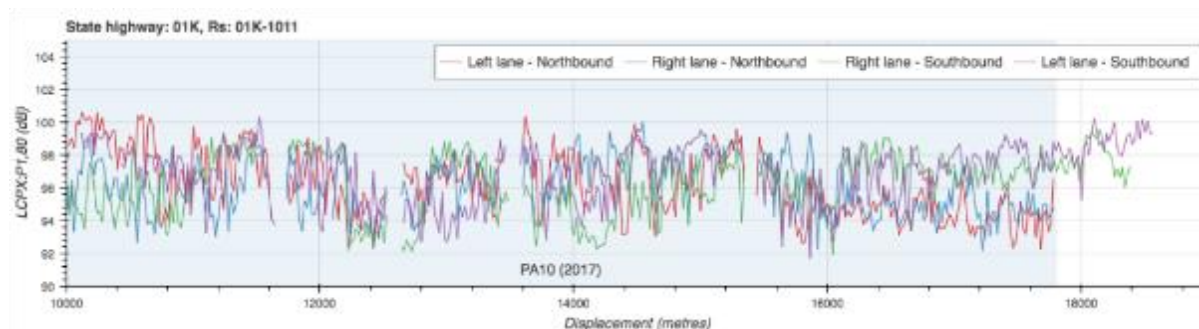
Figure 57: Cross section through a porous asphalt surface. [136]

The most common noise-reducing surfaces currently used internationally are made with porous asphalt. The texture of these surfaces can be minimised by the selection of a small chip size, and the porosity can be adjusted through the mix designs, although this in turn can be limited by the chip size. A standard porous asphalt can provide a practical road surface to achieve modest noise reductions.

Trials have been conducted with thicker or multiple layers of porous asphalt or with rubber crumb in the mix to improve the noise reduction. However, such surfaces are often expensive, sometimes using twice as much material as standard porous asphalt, and in some cases have shorter lifespans or more expensive maintenance regimes.

A development that has potential to assist in the optimisation of road surfaces for noise reduction is the use of epoxy-modified binders in porous asphalt (refer *chapter 9.4* for further discussion on vehicle and tyre regulation for traffic noise). Surfaces have been developed in some countries with epoxy included to substantially extend the surface life and consequently reduce whole-of-life/maintenance costs [137]. Coincidentally, the strength introduced by the epoxy also makes it practical to increase porosity without undue risk of premature failure, and hence creates scope for cost-effective optimisation of porosity for noise reduction.

Measurements of the noise reduction of porous asphalt surfaces in different countries often show significant variations in performance along the length of a road. *Figure 58* is an example from measurements along four lanes of a new expressway in New Zealand opened in 2017. The porous asphalt is the same specification for the entire length of all four lanes, but the measured noise levels vary over a range of 8 dB. While this is a severe example, significant variations are found along most porous asphalt surfaces. Potentially, enhanced quality controls for temperature and thickness regulation during paving may reduce variations.



*Figure 58: Variability in noise from a porous asphalt surface along four lanes of a new expressway*  
(Source: unpublished data, NZ Transport Agency)

The application of the porous asphalt concept on an area of 300,000 m<sup>2</sup> on a motorway in Southern Germany is described in *case study 20* (on double layer porous asphalt). Practical experience in managing large-scale porous asphalt paving projects could be gained through experimenting with different laying strategies.

#### 9.3.4. Tyre and pavement interaction

Tyre/road noise is not merely a matter of road surface characteristics but also of the tyre properties, including tread profile, structure and material composition. In *figure 59* the coast-by levels of 12 car tyres (year 1997) representing different brands, operation purposes (summer and winter) and

widths as well as three different truck tyres for different purposes (trailer, traction, and mud and snow) are plotted for different speeds versus various representative road surfaces. The first group of road surfaces on the left comprises four pavements made from porous mixes with different thickness and void content. The fifth pertains to a surface complying with ISO 10844 [138], which is specified for car and tyre noise approval testing. The following three groups of surfaces comprise pavements that are made from the same type (hot rolled asphalt, surface dressing and mastic asphalt) but with varying maximum aggregate size and thus showing different textures, varying from fine (1 or 3 mm maximum aggregate size) to coarse (8 mm maximum aggregate size).

The level differences of the tyre/road noise caused by different tyres are significant. The noise caused by the tyre ranges up to 8 dB. However, the influence of the road surface design is even greater, with a noise reduction potential up to 13 dB. Except for the porous road surfaces, the ranking of the car tyres is irrespective of the speed. A *noisy/quiet* tyre at low speeds remains a *noisy/quiet* tyre at high speeds. Porous sound-absorbing road surfaces yield the lowest level differences between different tyres, particularly at higher speeds.

Truck tyres of different types also behave in a varying manner. In general, tyres designed to be used on the steering axle of a tractor or trailer have the lowest noise levels. Truck tyres with a pronounced block tread profile, such as tyres for the driving axle or mud and snow tyres, are much noisier, independently of the road surface, except on sound-absorbing pavements.

In general, porous road surfaces represent the most significant noise control measure for road construction that can reduce the tyre/road noise of truck tyres significantly. As this type of road pavement is as effective for car tyres as for truck tyres it is – from an acoustical point of view – the best choice for noise mitigation on roads with a significant percentage of heavy vehicles (at least 10% heavy vehicles). Texture optimised but impervious road pavements can be a good choice when noise from heavy vehicles is not an issue.

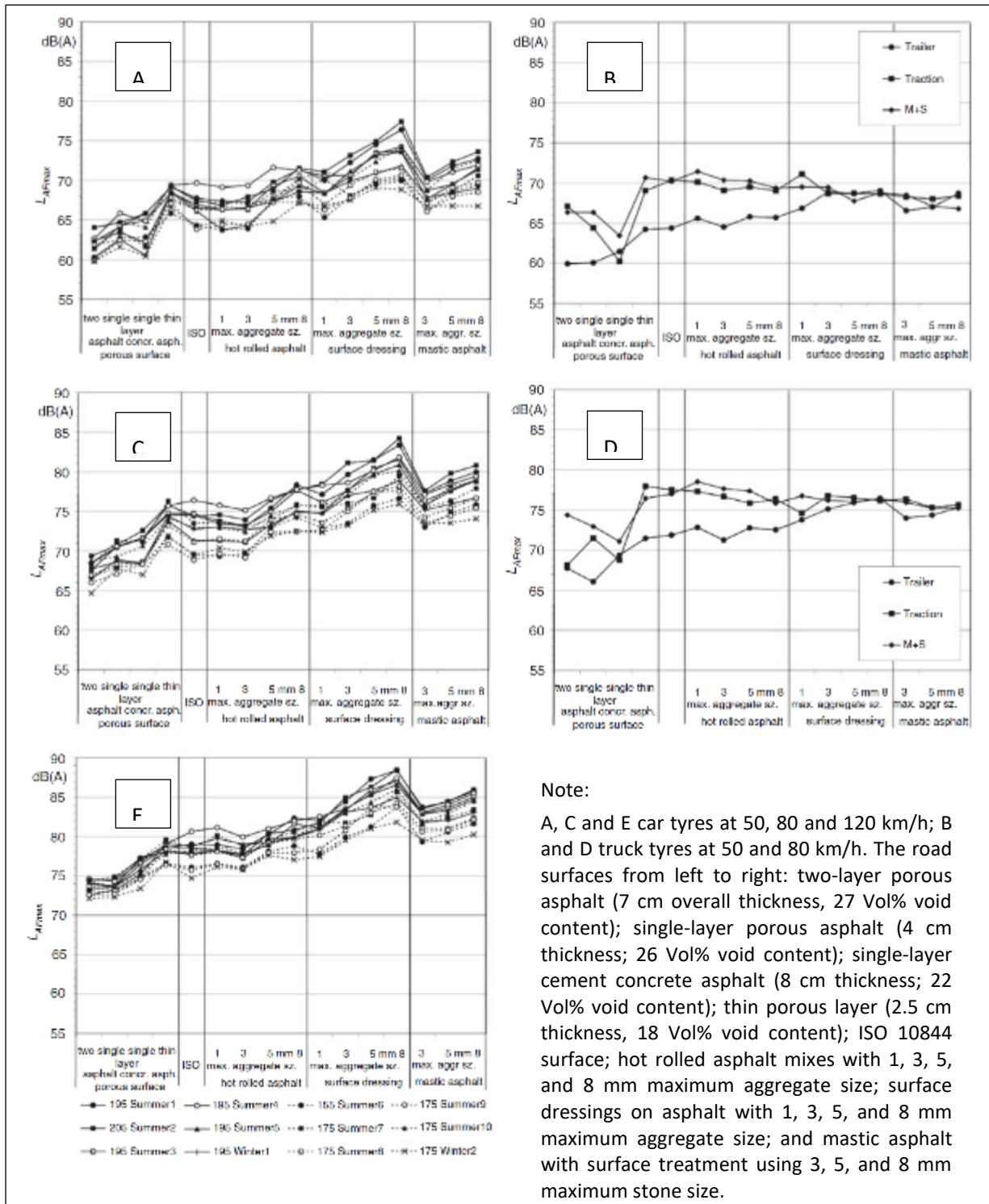


Figure 59: Coast-by levels of 12 car tyres and 3 truck tyres for different speeds and road surfaces. [90]

## CASE STUDY 17

### Australian and Swedish long-term pavement acoustic performance trial

#### Overview

It has long been known that porous asphalt is quieter than dense surface materials. It is also well understood that a smooth road surface is quieter than a rough surface. However, porous asphalt is not smooth.

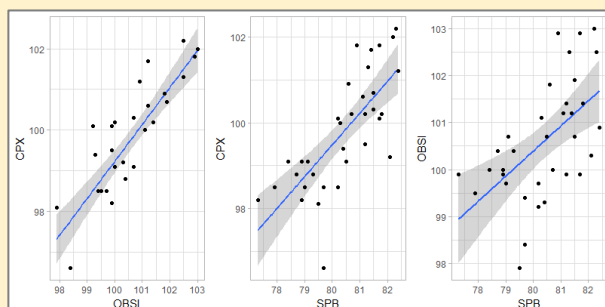
Two trials sought to determine whether the conflict between porosity and smoothness could be avoided by grinding smooth laid porous asphalt. Because pavement trials are expensive and there was confidence that the pavements would be reasonably quiet, sites were chosen where existing high noise levels needed to be treated. The sites were chosen based on practicality (safe roadside access, absence of large reflecting surfaces etc.) and where noise walls had to be avoided to protect high quality views.

The first site chosen was on the E4 Motorway at Husqvarna, Lake Vattern in Sweden [139]. The second was on the Peninsula Freeway at McCrae, Port Phillip Bay in Victoria, Australia. Both trials yielded significant reductions in noise level.

#### Methodology

The Australian trial compared three different methods for measuring tyre/road interaction noise to identify a preferred method. The three methods assessed were: statistical pass-by method (SPB) generally in accordance with ISO 11819-1 [82] (but with a pre-determined speed correction function); close proximity method (CPX) in accordance with a 2012 draft of ISO 11819-2 [140]; and on-board sound intensity (OBSI) in accordance with AASHTO TP 76-12 [141].

#### Results

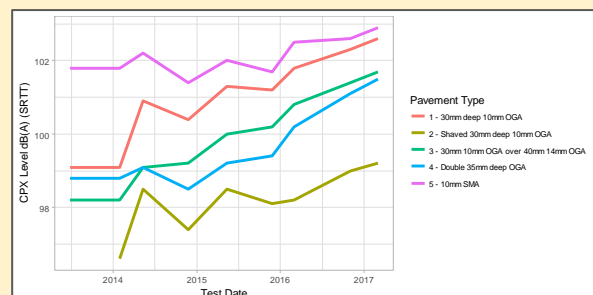


Comparison of test methods

As shown in the left-hand column, the two methods with the closest correlation were the OBSI and CPX, with a coefficient of determination ( $R^2$ ) of 0.8068. The on-board method that most closely correlated with SPB was CPX with an  $R^2$  of 0.4099. Based on this result, CPX was the recommended measurement method.

The trial compared four open-graded asphalts (OGA) against a baseline of stone mastic asphalt (SMA) with maximum aggregate size of 10 mm (most commonly used for low noise pavement in Victoria). It is typically laid in a 30 mm thickness over a non-porous base. The most novel asphalt was standard OGA with approximately 1 mm cut from its top surface using a rotary diamond grinding machine.

The noise levels were measured nine times over a period from May 2013 to March 2017, as shown below for CPX levels with a Standard Reference Test Tyre.



Noise level change over four years

#### Noise level change over four years

As expected, there was a slight increase in noise levels over the four years. All the OGAs were quieter than the SMA but increased in noise level more quickly over the four years. This is consistent with past experience. The noise reducing ability of OGA is dependent on its porosity, which reduces over time due to clogging with dirt – and possibly also with compaction. The pavement with the lowest noise level is the OGA with its upper surface removed as shown by line 2 in the above figure. (Note there was no noise measurement in May 2013 because the grinding was not done until after the first measurements.) This result confirmed the observation at Husqvarna that the removal of the top of OGA does in fact reduce noise. It showed that the noise level increased at a similar rate to the other OGAs but remained under the level of the new SMA.

#### For further information

Buret et al. [142]



## CASE STUDY 18

### Comparison of tyre-pavement noise levels between United States and European pavements

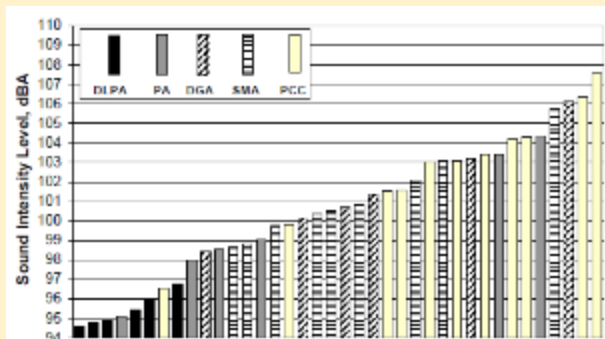
#### Overview

The on-board sound intensity (OBSI) method is the preferred measurement method to quantify the acoustical performance of different highway pavements in the US. Pavement surfaces have been measured in California and Arizona using this method since 2002.

In 2005, pavements in four European countries (Netherlands, Germany, Belgium and France) were measured using the OBSI method and compared with the US measurements, as part of the noise intensity testing in a European study. A total of 68 pavements were measured in Europe and compared with more than 200 pavements in the US.

#### Results

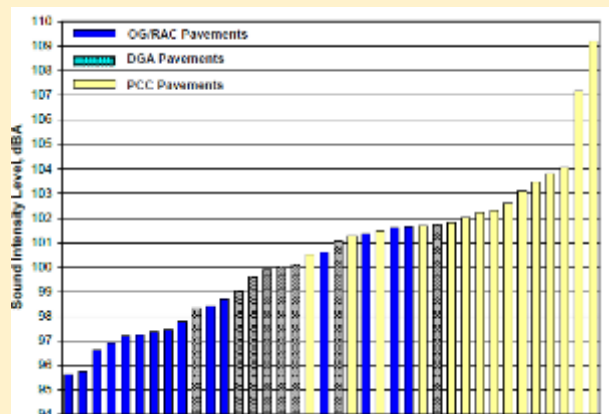
The figure below shows the range of acoustic pavement performance in Europe with the noisiest being rigid pavement in the Netherlands and the quietest being a double layer porous asphalt (DLPA),



also in the Netherlands.

*OBSI measurements for representative pavements in Europe (97 km/h)*

This range was almost identical to that in the California and Arizona database at that time (95.6 to 109.2 dB(A)), although the absolute levels were slightly lower.



*OBSI measurements for representative pavements in US (97 km/h)*

#### Conclusions

The data from the US and Europe indicated that the range of tyre pavement noise levels was similar in both regions, with the quietest European pavements performing slightly better than the best in California or Arizona. DLPA of fine aggregate size, porous rigid pavement, and exposed fine-aggregate rigid pavements, which are not generally found in the US, performed well within their respective pavement category. Pavements common to both Europe and the US produced similar noise levels when pavement textures and aggregate sizes were considered. California and Arizona rubberised asphalt pavements, which were not found in Europe, displayed performance approaching that of the quieter DLPA pavement.

In the US, the OBSI database is used to define the range of acoustic performance that can be expected for different pavement types. It also helps in the early decision-making process for alternatives for noise abatement.

#### For further information

Lodico and Donovan [143]

## CASE STUDY 19

### Acoustic performance of asphalt over time in Denmark

As part of a national project on the optimisation of noise reducing asphalt (so called thin layer asphalt), four different thin layer pavements and a standard asphalt concrete as a reference surface were built in 2003 on an urban road in Copenhagen. A year later four different thin layer pavements and a reference pavement were built on a Danish motorway.

Surface type	Urban road	Motor way	Exp. lifetime
AC 11d	x	x	17 years
AC 8d	x		14 years
AC 8o		x	12 years
AC 6o	x		12 years
UTLAC 8		x	12 years
UTLAC 6	x		12 years
SMA 8		x	12 years
SMA 6+	x	x	12 years

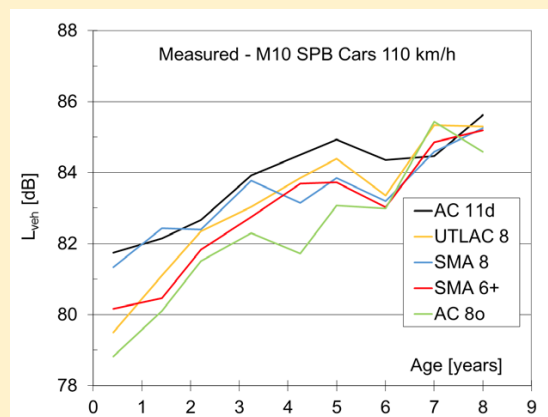
*Surface types built on the urban road in 2003 and on the motorway in 2004 and their expected service life time, in years.*

The surface types are listed in the table above. The surface types are asphaltic concrete (AC), either dense graded (d) or open graded (o), ultra-thin asphalt layers (UTLAC) or stone mastic asphalt (SMA). The numbers shown in connection with the surface type denote the maximum aggregate size, i.e. 6 mm, 8 mm or 11 mm. The OGA concrete, AC 8o or AC 6o, has an open surface which is supposed to lead to a reduction in noise generated by air pumping. The surface denoted SMA 6+ is stone mastic asphalt with 6 mm maximum aggregate size to which a small fraction of 6/8 mm aggregate has been added to obtain a more open structure.

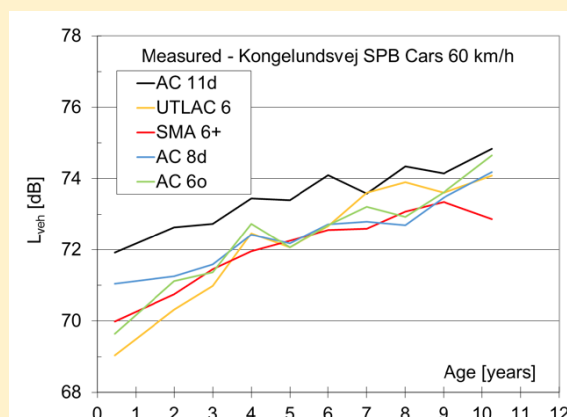
These pavements have been monitored by SPB measurements of noise from vehicles over a period of 10 years. The data has been analysed in order to determine the changes in noise levels during the life of the pavement.

The study shows that pavements seem to become noisier at a faster rate in their initial years than they do over their entire lifetime. Therefore, comparisons of acoustic ageing effects should ideally be based on complete life-cycle time histories of noise levels.

#### Results of measurements



*SPB noise levels as a function of pavement age, from cars on the motorway at a reference speed of 110 km/h.*



*SPB noise levels as a function of the pavement age, from passenger cars on the urban road at a reference speed of 60 km/h.*

The motorway carries much higher traffic loads than the urban road and the pavements seem to age acoustically at a faster rate on the motorway than on the urban road. The difference between the average noise levels measured at all pavements in the first and last measurements of the series shown here are 4.9 dB during eight years on the motorway and 3.8 dB during 10 years on the urban road, corresponding to an average increase in noise level of 0.6–0.7 dB per year on the motorway and 0.4 dB per year on the urban road.

#### For further information

*Danish Road Directorate, report 460, 2013 [101]*

## CASE STUDY 20

### Use of double layer porous asphalt (DLPA) in Germany to reduce road project noise impacts

#### Situation

To the north of Munich in Southern Germany, the motorway A9 passes through some sensitive areas: residential, upmarket office locations and Munich Technical University campus. With 147,000 vehicles passing every 24 hours, 5% of which were heavy vehicles, the road agency planned and built a two-lane extension. It also specified noise mitigation measures to help reduce the road traffic noise levels in the vicinity by more than 6 dB and even more than 10 dB in some sections. The road agency decided to lay a double layer porous asphalt (DLPA) pavement to reduce the traffic noise at source in addition to building noise barriers to further reduce noise at the nearest receivers.

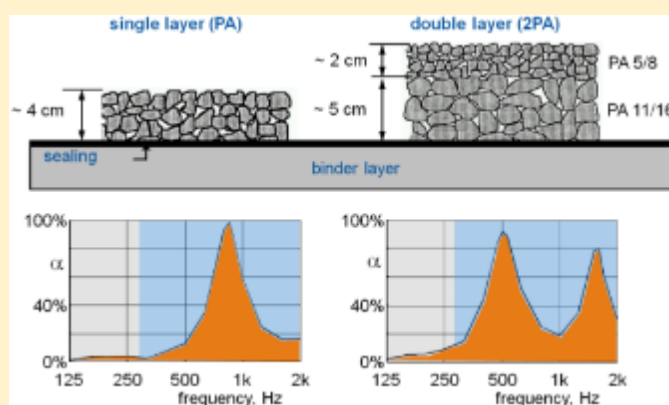


Motorway A9 (red line, length 10 km) and sensitive land use (green areas).

#### Road construction

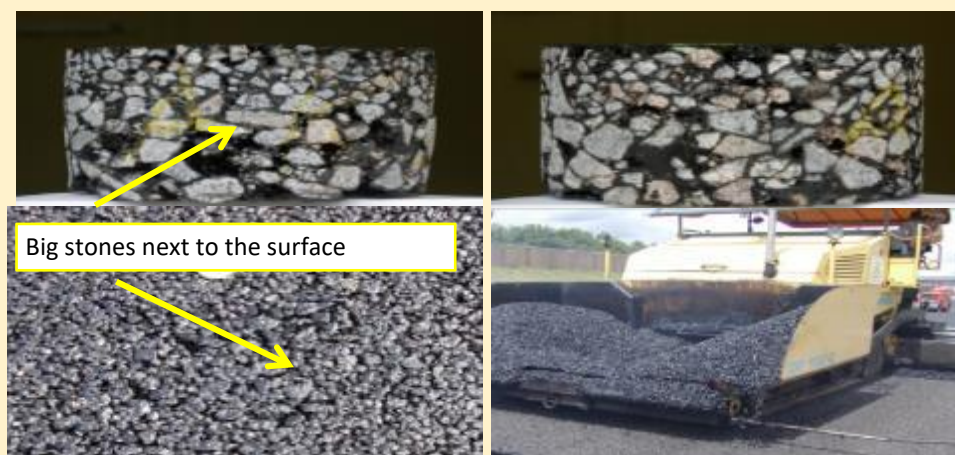
The idea behind the double layer concept is to implement a thicker acoustic absorber on top of the road surface instead of a standard single layer porous asphalt (PA). The thicker the absorber, the lower the noise frequencies to be reduced. This is worthwhile in order to adapt the absorption to the frequency spectrum of the tyre/road noise. In general, single layer PA with 8 mm maximum grain size cannot be applied more thickly than 4 or 5 cm without compromising its structural durability. Applying the double layer concept could resolve this problem. The diagrams below show both structure and acoustic behaviour of the double layer in comparison with the single layer PA.

For the bottom layer a PA mix with 16 mm maximum grain size is used, providing a good working drainage of the entire wearing course. Due to its small grain size the top layer gives a road surface with optimised texture. In the Munich case, a total of 300,000 m<sup>2</sup> of DLPA had to be constructed. Pilot tests helped find the most feasible way to cope with this road construction challenge.



The images below show three concepts for the laying process of the two asphalt layers and the machinery involved were tested: *hot on cold* (two passages: top layer rolled out on the bottom layer that had already cooled down), *hot on hot* (two passages: top layer rolled out on the bottom layer that had hardly cooled

down) and *compact* (rolling out both layers in a single passage using special machinery). *Hot on hot* and *compact* had to be rejected due to big stones being stirred up from the uncompacted bottom layer into the top layer, thus giving a poor surface texture.



Left: drill core and road surface from the hot on hot test, right: drill core and construction work applying hot on cold.

### Acoustic behaviour

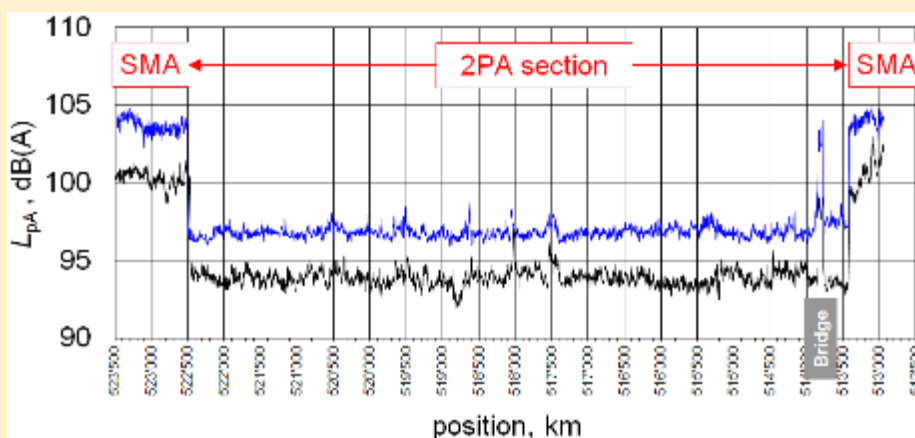
CPX measurements of the tyre/road noise show a reduction by 8 dB (tyre A) and by 6 dB (tyre D) compared with the adjoining SMA 8 sections.

Unfortunately, six years after the construction of the DLPA the porous wearing course failed. In the section point between the bottom of the lower layer and the binder course, stripping occurred due to the pressure of vehicles driving over the road surface.

The porous skeleton lost contact with the subgrade and broke down. As a result, the DLPA road surface had to be replaced by a single layer PA with a thickness of 5 cm.

### For further information

Contact: [Müller-BBM](mailto:info@MBBM.com) at info@MBBM.com



A-weighted sound pressure level  $L_{pA}$  of the tyre/road noise measured in close proximity depending on the position along the road. Speed: 80 km/h. Black: passenger car tyre A; blue: truck tyre D according to ISO/CD 11819-2 (2005).



#### 9.4. VEHICLE, DRIVER AND TYRE NOISE REGULATION

As mentioned earlier, road traffic noise is most effectively mitigated at source. Road agencies generally have the most opportunity and greatest ability to reduce noise at source using low noise pavements. Other options to reduce traffic noise at source include noise created by the vehicles themselves as well as the contribution of tyres to noise from contact with the road. As shown in figure 15, propulsion noise from cars is dominant at speeds up to around 30 km/h and from trucks at speeds up to 75 km/h. At higher speeds, noise caused by the interaction of tyres and pavement surfaces is more dominant (see *chapter 7.1*).

Most countries regulate noise emitted by vehicles with a view to limiting propulsion noise. These regulations typically require well-designed engine air intake and exhaust systems. Some countries also regulate noise from tyres when driven on a defined road surface.

Furthermore, it is important that vehicles are maintained and operated in a way that minimises noise. Consequently, most countries impose *in-service* regulation of exhaust noise, and prohibit the use of horns other than in an emergency. A few jurisdictions also regulate noise from truck engine brakes.

The main regulations are summarised in the following sections.

##### 9.4.1. Vehicle noise emission regulation

The maximum acceptable sound level of cars, truck and buses is stipulated within the United Nations Economic Commission for Europe (UN-ECE) Regulation No 51, Revision 3 [144] which also specifies the method for testing noise emissions. As a total of 63 countries around the world have agreed to apply UN-ECE vehicle regulations [145], they are of international importance.

The regulation specifies two pass-by noise tests and a stationary noise test. The pass-by tests are intended to determine the contribution that a vehicle would make to  $L_{Aeq}$  traffic noise based on normal driving in an urban setting. The stationary test is intended to form the basis of in-service noise compliance testing.

There are several limit levels for the pass-by tests for different types of vehicle. The vehicle manufacturer or importer is responsible for demonstrating compliance with the pass-by noise limits but only needs to report a stationary noise level. This reported level later becomes the basis for an in-service noise limit.

A similar regulation, UN-ECE R41 Revision 2 applies to motor cycles [146].

##### 9.4.2. In service vehicle noise regulation

To ensure that owners maintain their vehicles to prevent them becoming excessively noisy, and to prevent reckless customisation of vehicles, most countries regulate in-service noise levels. This is important because an impaired exhaust system can dramatically increase noise. The stationary noise test reported in regulations UN/ECE R41, R51 and R63 can be conducted reasonably easily on the roadside. The regulations require that the stationary noise of any vehicle must be no more than a few decibel greater than the level at which that vehicle type was certified. Enforcement of such a regulation requires officers to be equipped with tables of individual vehicle type noise level data.

#### 9.4.3. Tyre noise

In Europe, since 2001, tyres have been subject to maximum noise levels under regulation UN-ECE R 117 [147]. Similar regulations have been introduced into Japan and South Korea. Tyres are tested by means of coast-by noise measurements and responsibility for compliance testing rests with the tyre manufacturer or importer. Regulation of noise from tyres, as distinct from vehicles, is important both because of the significance of the tyres to overall noise emissions and also because of the fact that a vehicle will have multiple sets of tyres in its lifetime, not just the original set.

The test procedure to determine compliance is a pass-by test similar to those required by UN-ECE R51. The main differences are that the test vehicle approaches the test site at a higher speed and the engine is switched off, so the vehicle's momentum propels it past the microphones at the specified speed. This speed is 80 km/h for Class C1 (passenger car) and Class C2 (light truck) tyres. The specified speed for class C3 (heavy truck and bus) tyres is 70 km/h.

#### 9.4.4. Regulating driver behaviour

Regulations can also prohibit operating a vehicle in a way that creates excessive or unnecessary noise. Unnecessary noise can include noise generated from actions such as spinning wheels, using noisy truck engine brakes in residential areas or using horns other than in an emergency.

In some countries, truck engine brakes pose a very serious noise problem. There is some debate about whether it should be addressed by influencing driver behaviour or by regulating vehicle condition. As shown in *case study 21*, there has been success in New Zealand where the government has engaged with the trucking industry to discourage engine brake use in built-up areas, but this approach has been unsuccessful in Australia. In contrast, regulating driver behaviour is used in some parts of North America by imposing a prohibition on driving in a way that produces excessive noise (refer *figure 60*).



Figure 60: Engine brake noise sign, British Columbia, Canada.  
(Source: J McIntosh, Department of Transport, Victoria, Australia)



An alternative enforcement approach is currently (2019) being developed in Australia. The intent is to identify excessive engine brake noise automatically using a roadside microphone and sophisticated signal processing that identifies engine brake noise by its characteristic modulation (how the sound level fluctuates). The system will connect to a camera and automatic number plate recognition system to allow a fine to be issued automatically. The use of modulation rather than sound level as the indicator of excessive noise avoids the problem of the level depending on the distance from the vehicle to the microphone. Measurements made using this system are intended to generate the necessary evidence to take legal enforcement against operators of trucks creating excessive noise as a result of inappropriately using their engine brakes.

In general, it is preferable for governments to use non-regulatory approaches to encourage vehicle owners and drivers to minimise noise. A prohibition on driving in a way that causes unnecessary noise is subjective and may be difficult to achieve in some jurisdictions. Conversely, methods of noise enforcement based on objectively measuring the sound of passing vehicles have proved extremely challenging and stopping vehicles for stationary noise tests has associated difficulties. It is better for drivers to understand that the noise they produce can disturb other people and affect their health and lead to community opposition to road freight activity.

## CASE STUDY 21

### Managing disturbance from noisy heavy vehicle engine brakes in New Zealand

#### Overview

Heavy vehicles have supplementary braking systems to assist the primary (wheel) brakes to reduce wear and to avoid brakes overheating on long descents.

Noise from modern supplementary braking systems cannot be distinguished from general engine/exhaust noise. However, older trucks with supplementary engine braking systems can generate a loud distinctive sound, sometimes described as a *machine gun* sound.

Although only a small proportion of older trucks in the New Zealand vehicle fleet have noisy engine brakes, there are frequent complaints from people living near state highways about the disturbance they cause. This can be avoided by truck drivers switching off engine brakes when driving near houses, or by fitting effective silencers. Signs that have been installed requesting drivers not to use engine brakes are often ignored. There is therefore a need to identify the trucks causing disturbance, so action can be taken.

#### Noise camera

Engine brakes create pulses of gases in truck exhausts. Noise cameras have been developed in Australia which detect the resulting “modulated” sound characteristic, and then photograph the number plate of the truck responsible (see block diagram of the noise camera system below).

The NZ Transport Agency has two noise cameras using this system and has deployed them on seven sites during the period 2013 to 2018.



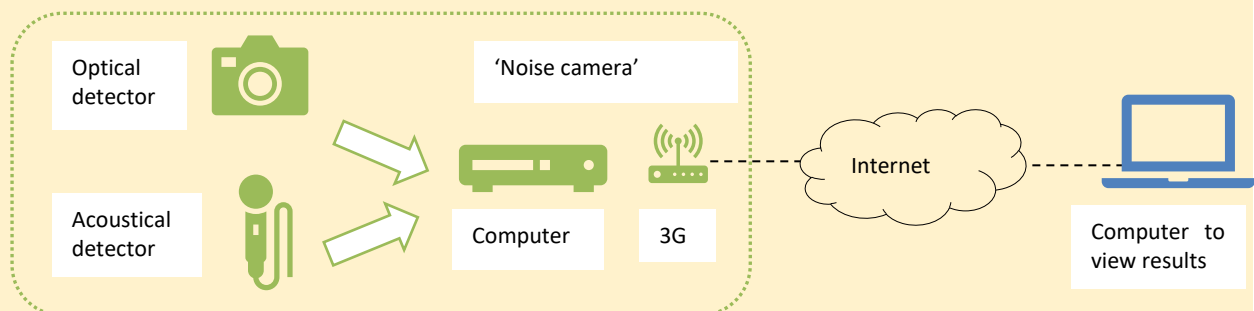
*New Zealand noise camera mounted on a lamp post*

When trucks have been identified by the cameras, the New Zealand Transport Agency has found that operators usually take steps to avoid reoccurrence. Enforcement action has not been required.

Despite receiving numerous complaints, the New Zealand Transport Agency has detected infrequent engine braking using the cameras. This could be due to limitations of the cameras which may be missing some braking events, or the disturbance is being caused by other sources. The majority of modulated sound detected by the cameras relates to noisy motorcycles rather than engine braking. This is being investigated further in 2018.

#### For further information

[environment@nzta.govt.nz](mailto:environment@nzta.govt.nz)



### 9.5. ELECTRIC VEHICLES AND TRAFFIC NOISE

Sales of electric cars have grown remarkably in recent years. Their share of new car sales in major economies grew by a factor of around 100 between 2010 and 2016 [148]. In 2017 and 2018, all major car manufactures indicated their intent to manufacture electric cars in large volumes. After several *false starts* the electric vehicle revolution is now on its way. Electric vehicles are welcome because of their potential to reduce urban air pollution and greenhouse emissions (provided they are powered with low greenhouse gas emitting electricity). Their impact on traffic noise is less clear.

There is a popular view that traffic noise levels will reduce because of a change from petrol and diesel fuelled vehicles to electric vehicles. While this is true to a degree, the effect on noise levels is likely to be small, at least until electric heavy vehicles replace diesel fuelled heavy vehicles.

Noise generated from a petrol or diesel vehicle is predominantly caused by its propulsion system and the interaction of its tyres with the road surface (rolling noise). As a vehicle's speed increases, the propulsion noise typically increases in a linear manner while the rolling noise increases at a logarithmic rate. This means that propulsion noise is dominant at low speeds and rolling noise is dominant at higher speeds. As shown previously in *figure 15*, the crossover speed where rolling noise becomes greater than propulsion noise for light vehicles is approximately 30–40 km/h.

Around 2008, a potential accident risk was identified whereby visually impaired people might be unaware of electric vehicles operating near them as a result of the lack of noise they create when travelling at low speeds. Since that time, considerable research has gone into the ability of people to hear approaching vehicles (internal combustion engine or otherwise) and their ability to estimate the subsequent movement of the vehicles.

In fact, the United States has legislated to impose minimum sound levels on electric and hybrid vehicles travelling at speeds of no more than 30 km/h [149]. The risk remains somewhat controversial, with some arguing that very quiet petrol vehicles have existed for many years without a safety risk being identified, and that evidence of a causal relationship between low vehicle noise and accidents is weak [150] [151].

On balance, it seems likely that the American regulation of minimum sound levels will have only minor effects on traffic noise levels and safety, since:

- The regulation requires only moderately low noise levels and applies only to vehicles travelling at low speed.
- The regulation applies only to vehicles travelling at relatively low speeds and does not apply to petrol vehicles.

Compared to cars (light vehicles), the electrification of trucks is expected to bring significant traffic noise reductions. As previously shown in *figure 15*, the propulsion noise from heavy vehicles is dominant up to substantial speeds (as well as being much higher than propulsion noise from cars). In many parts of the world, freight traffic is increasingly operating at night to avoid daytime traffic congestion, particularly in city areas. This is currently contributing to residents being subjected to high night-time noise levels and consequent sleep disturbance.

There is great potential for the electrification of trucks to reduce sleep disturbance, particularly in city areas and along major highways where trucks run overnight between cities. It is recommended that jurisdictions consider incentives or regulations to encourage freight operators to invest in

electric trucks. These incentives could take the form of curfews that apply to diesel trucks only or the implementation of road use charges that are higher for diesel vehicles.

In addition to electrification, motor vehicles of the future are expected to be increasingly automated and eventually driverless. It is unlikely that automation will have a considerable influence on noise levels (other than possibly reducing horn usage). However, it may accelerate the trend to night-time freight transport operation and increase the urgency of encouraging electric trucks.

## 9.6. MANAGING SPEED AND TRAFFIC OPERATIONS

Traffic speed is one of the key factors contributing to road noise levels, along with other factors such as overall traffic volumes, number of heavy vehicles and type of road surface.

As previously shown (refer *chapter 7.1*), propulsion noise (vehicle noise from engine, exhaust and other components) will dominate the total road noise at low speeds. As speed increases, a crossover speed is reached at which the tyre/road noise becomes an equal source of noise, before becoming the dominant source at higher speeds. As engines have become quieter over time, the crossover speed has decreased, and tyre/road noise has become more important. Only at high speeds will aerodynamic sources begin to dominate.

Noise control measures aimed at reducing speed can therefore lead to noise reductions, in particular from tyre/road noise. Typically, speed management and traffic calming measures are the responsibility of the local authorities rather than that of a national road agency, as localised circumstances need to be considered when setting speed limits and supporting infrastructure to manage speed.

Legal measures, through the setting of speed limits, are primarily intended to safeguard road users from severe accidental damages but are also being implemented for noise control reasons. Typically, the sound power of the tyre/road noise of passenger cars increases by the power of 3.5. For example, a reduction of the driving speed in a ratio of 1:1.25, as is the case for a reduction from 100 km/h to 80 km/h for instance, results in a noise level reduction by 3.4 dB.

Hence, speed management becomes a key tool in noise management. Results of noise analysis carried out on the Spanish National Highways Network in 2017 show that reducing speed limits in urban areas can lead to less noise pollution [152]. A summary of noise reductions potentially achieved through changes in traffic speed is outlined in *table 11*.

Change in speed	Change in noise level
From 130 to 120 km/h	0.9 dB
From 120 to 110 km/h	0.9 dB
From 110 to 100 km/h	0.9 dB
From 100 to 90 km/h	0.9 dB
From 90 to 80 km/h	1.3 dB
From 80 to 70 km/h	1.4 dB
From 70 to 60 km/h	1.4 dB
From 60 to 50 km/h	1.5 dB

Table 11: The effect of a change in speed.

The noise decreasing effect can be added, so that a reduction of speed from e.g. 80 km/h to 50 km/h reduces the noise 4.3 dB. These reductions assume that traffic follow the posted speed limits. It is also assumed that 10% of the traffic is heavy vehicles and the maximum speed limit for heavy vehicles is 90 km/h. The noise reduction increases slightly when the speed reduction also applies to heavy vehicles, i.e. below 90 km/h.

Intelligent Transport Systems (ITS) applications are an important tool for enabling speed management and noise mitigation policies in real time. For instance, controlled motorways in England use active traffic management to automatically regulate traffic speed limits in real-time in response to prevailing traffic levels on the motorway. Drivers perceive that the steady flow of traffic at 50 mph (80 km/h) resulted in overall time savings in comparison with the stop-start of motorways on which people drive at speeds varying from 30 mph to 90 mph (approximately 50–145 km/h). Noise reduction is a co-benefit of such traffic management measures [153].

Another technique to reduce traffic noise is to use “soft speed” management measures which focus on the smart use of technology and education to influence driver behaviour rather than impose legal or financial penalties. A European example involves detecting a vehicle as it approaches from a measured point ahead, which allows the time needed to cover the distance to be calculated to determine whether the vehicle is speeding [154]. This can trigger a dynamic message sign to display a warning message near noise sensitive receivers such as residential areas, schools and hospitals.

## 9.7. NOISE BARRIERS

### 9.7.1. Design of noise barriers

Many factors need to be considered in the detailed design of noise barriers, including their acoustic performance as well as non-acoustic characteristics.

When a low to moderate acoustic performance is required, i.e. less than 10 dB noise reduction, the choice of barrier material is not critical from an acoustics perspective and therefore non-acoustic factors can have more influence on the outcome. For a noise reduction greater than 10 dB, or where the barrier height is over 2 m, the acoustic performance of the material selection becomes more important.



The following aspects determine the effectiveness of a noise barrier:

- positioning  
(where should the noise barrier be placed between road and receiver?)
- dimensioning  
(what is the appropriate height and length of the barrier?)
- conditioning  
(do sound reflections at the barrier have to be suppressed?)
- materialisation  
(what is the adequate material to meet acoustic and structural requirements?)

The noise maps shown in figure 61, figure 62, Figure 63 and Figures 64 allow for an easy understanding of several design scenarios that outline noise barrier design considerations.

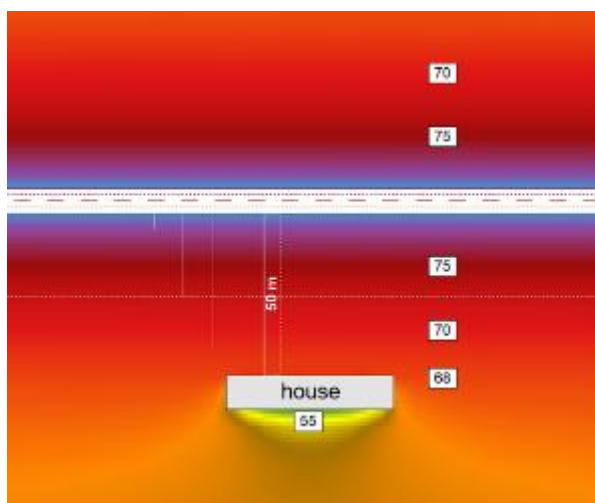
The area-wide sound propagation calculations underpinning the design scenarios presented in these figures are based on the following assumptions:

- flat ground between the road and the house (receiver)
- traffic volume of approximately 1,500 vehicles/h, of which 20% are heavy vehicles
- speed of 120 km/h for cars and of 80 km/h for trucks
- noise barrier of height 6 m above ground
- area-wide noise levels determined in dB(A) at a height of 2 m above ground.

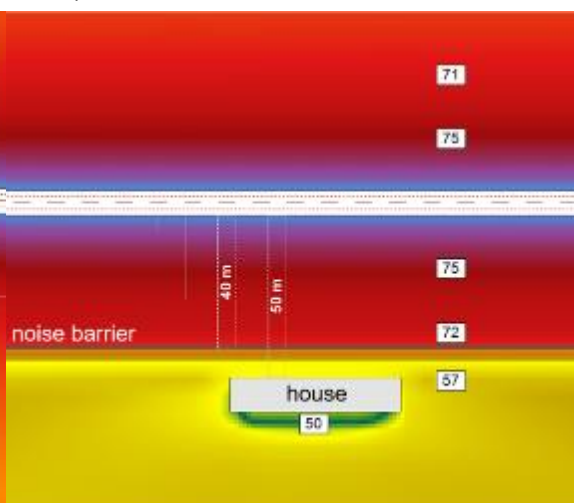
### Positioning

Based on the modelled assumptions in *figure 61*, a noise barrier positioned closer to the house is the most effective. In this example, the noise barrier is sound reflecting on both sides (reflection loss: 1 dB).

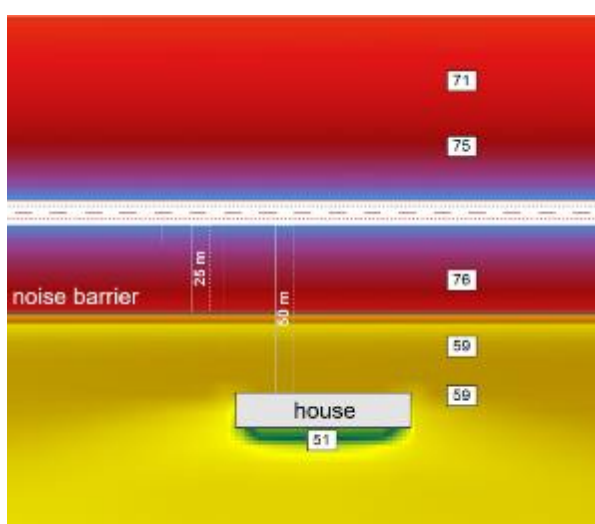
61a) No noise barrier



61b) Noise barrier is close to the house (distance: 10 m)



61c) Noise barrier is in the middle between the road and the house



61d) Noise barrier is close to the road (distance: 5 m).

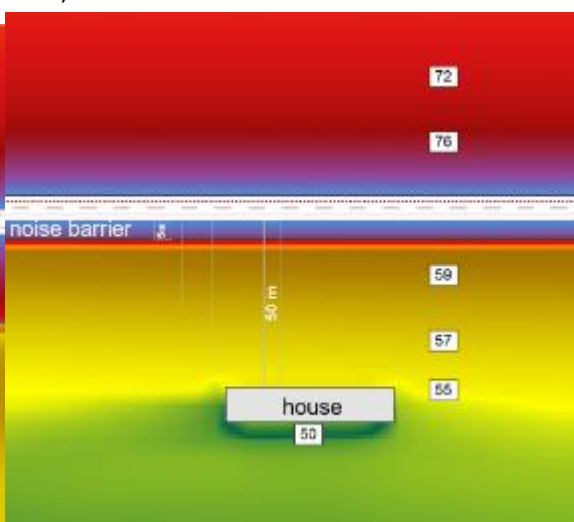


Figure 61: Positioning the noise barrier. (Source: Müller-BBM)

### Dimensioning-length

As shown in *figure 62* and *Figure 63*, dimensioning the barrier inappropriately costs a great deal of money without having a significant and positive acoustic effect. In this example, the noise barrier is close to the road (distance 5 m) and sound reflecting on both sides (reflection loss: 1 dB).

- The shorter noise barrier severely reduces the effect of the noise mitigation. The noise levels at the roadfront of the house escalate by 11 dB compared with the “infinite” length noise barrier.
- The length of the noise barrier needs to be dimensioned carefully by taking into account the physical structure of the roadway, the distance between the road and the noise barrier and the required noise level reduction. The excess length of the barrier  $dl$ , i.e. the length which is needed at both ends of the noise barrier in addition to the length of the roadfront of a house (receiver) should be:

$$dl = \left( \frac{34 + 3 \cdot dL}{\sqrt{100 + s}} \right) \cdot b \text{ in m}$$

where

- $dL$  required noise level reduction in dB
- $s$  right angle distance between the road centreline and the road front of the house in metres
- note: for multilane roads the  $dl$  values should be determined for the nearest and the furthest lane with respect to the receiver. The result is the average of both  $dl$  values.
- $b$  right angle distance between the axis of the noise barrier and the road front of the house in metres.

In figure 62  $dl$  is 265 m with  $dL = 13$  dB,  $s = 54$  m,  $b = 45$  m.

Length of the noise barrier

62a) Noise barrier with *infinite* length (similar to figure 62b) Noise barrier with *finite* length being 40 m longer than the front of the house.

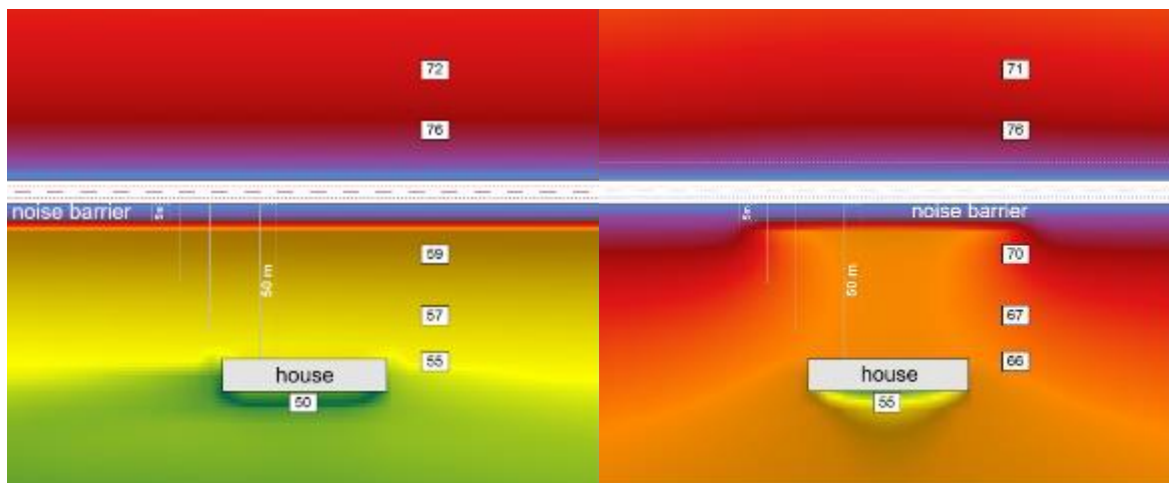


Figure 62: Dimensioning the noise barrier length. (Source: Müller-BBM)

### Dimensioning- height

In this example, the noise barrier is close to the road (distance: 5 m) with infinite length and sound reflecting on both sides (reflection loss: 1 dB). In figure 63a, the noise barrier is 6 m high, while in figure 63b, the noise barrier is 3 m high. Figure 63a and figure 63b noise maps are in the horizontal plane; figure 63c and figure 63d noise maps are in the vertical plane.

The lower noise barrier severely reduces the effect of the noise mitigation. The noise levels at the road front of the house escalate by 6 dB compared with the 6 m high noise barrier example. The height of the noise barrier needs to be dimensioned carefully by taking into account the physical structure of the roadway, the distance between the road and the noise barrier, and the required noise level reduction. Other factors such as visual impact, constructability and costs also need to be considered.

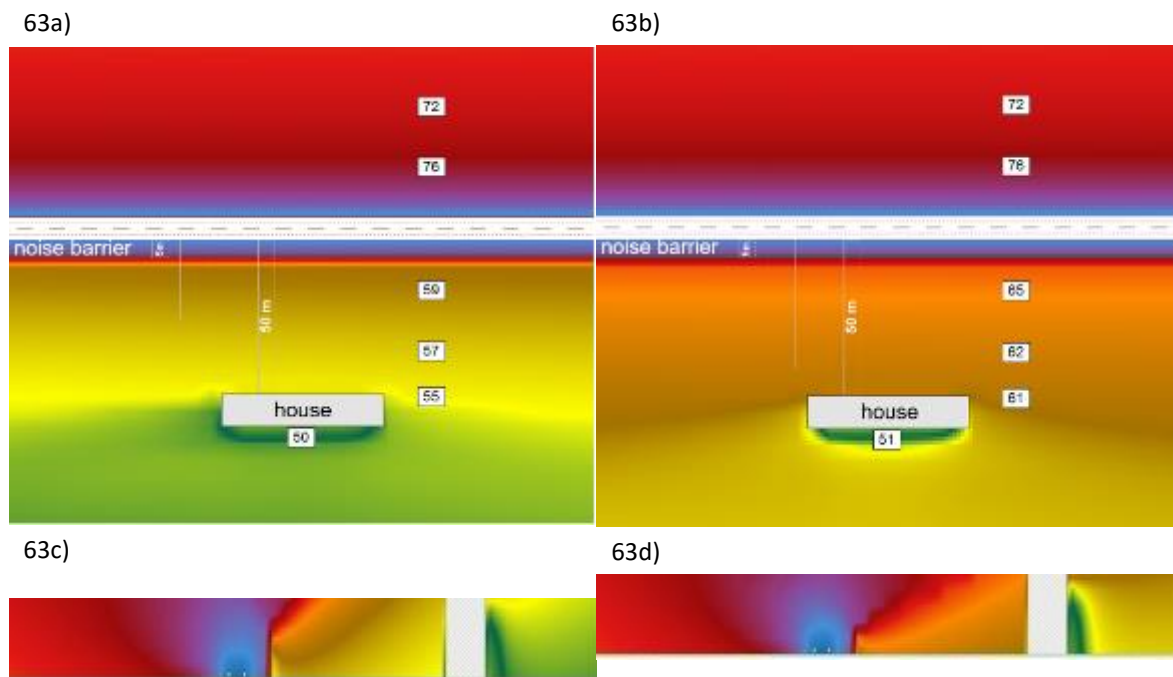
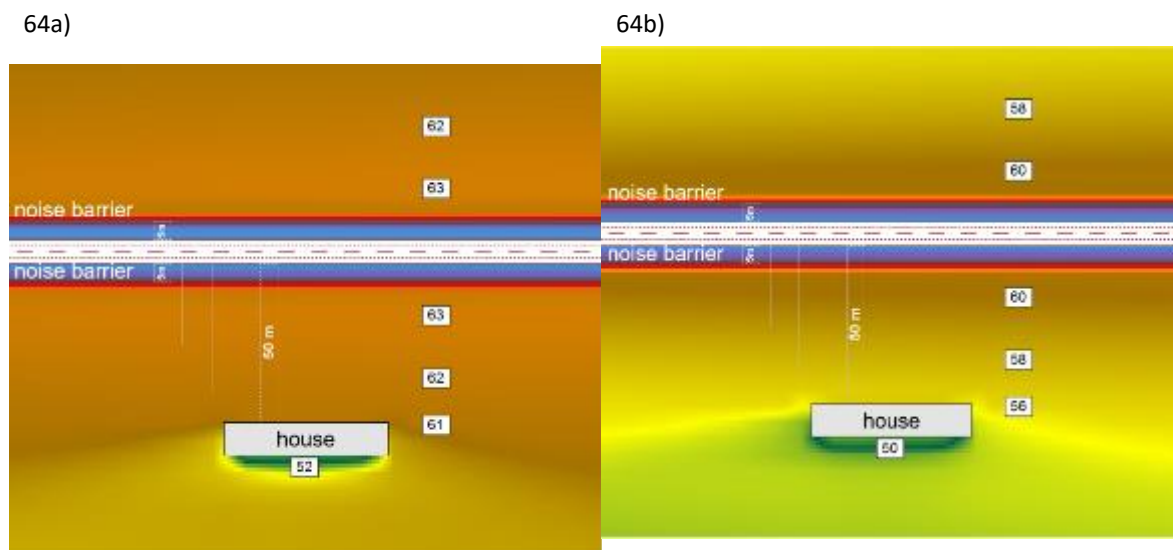


Figure 63: Dimensioning the noise barrier. (Source: Müller-BBM)

### Conditioning

The sound reflecting noise barrier on the opposite side of the road severely reduces the noise mitigation effect.

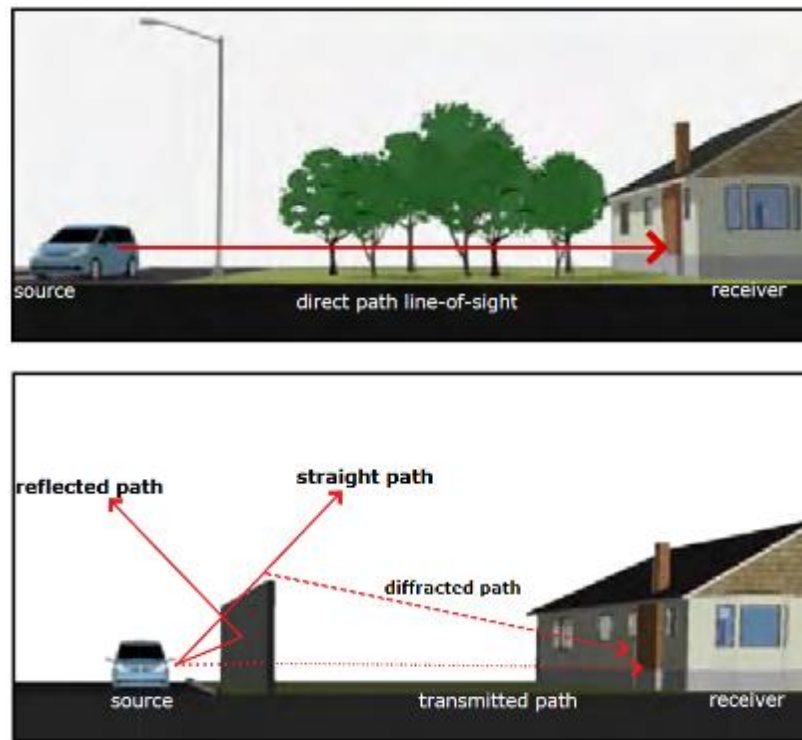
Figure 64 shows that furnishing the noise barriers with sound absorbing material on the sides facing the road helps to bring the noise levels back to the original values on the opposite side. In this example, noise barriers are on both sides of the road at close distance. In figures 64a, both noise barriers are sound reflecting on both sides (reflection loss: 1 dB); while in figures 64b both noise barriers are highly sound absorbing on the sides facing the road (reflection loss: 8 dB).



Figures 64a and 64b: Conditioning the noise barrier with sound absorbing material. (Source: Müller-BBM)

### 9.7.2. Conventional noise barriers

Noise barriers are the most widely recognised form of noise mitigation on major roads, providing an obstacle to noise propagating from vehicles to nearby residences. The following two diagrams (refer *figure 65*) show a scenario without a noise barrier (top image), where noise travels directly from a vehicle to a house, and a scenario with a noise barrier (bottom image), where that direct line of sight path is partly obstructed.



**FIGURE 65: PROPAGATION PATHS WITHOUT (TOP) AND WITH (BOTTOM) A NOISE BARRIER [155]**

The bottom diagram shows how noise barriers do not provide perfect mitigation as a significant amount of noise can still diffract over the top of the barrier (refer *chapter 2*) and a smaller amount can be transmitted through the barrier. Nevertheless, topography or high buildings often result in houses and apartments looking over the top of a potential barrier, impairing its effectiveness.

The factors involved in the design, performance, construction and maintenance of noise barriers have been well researched, tested and reviewed over several decades. This body of knowledge is comprehensively set out in the CEDR report: *State of the art in managing road traffic noise: noise barriers* [7], which provides background and detailed information on noise barriers.

Several road authorities have also published helpful guidance on noise barriers, for example:

- *Noise wall design guideline*, NSW Roads and Maritime Services, 2018 [156]
- *State highway noise barrier design guide*, NZ Transport Agency, 2010 [155]
- *Noise barrier design handbook*, US Federal Highway Administration, February 2000 [157]

Noise barriers can be formed by any object blocking the straight-line path between vehicles and houses. Often buildings themselves act as noise barriers, along with topographic features and road features such as cuttings that have been discussed earlier (refer *chapter 9.2*). However, when referring to a “noise barrier” it generally means a specific “noise wall”, “noise bund” or a

combination of the two. Internationally, various terms are used for noise bunds including “earth bunds”, “earth berms” and “earth mounds”. For consistency, “earth mounds” is used throughout this report.

Both noise walls and earth mounds can be effective as noise barriers, with the performance generally dictated by the height and positioning of the top edge of the barrier (refer *figure 66* for examples of noise barriers). There are often practical considerations as to the type of noise barrier used. For example, earth mounds are only being feasible where there is space available for their wide footprint.



*Figure 66: Two types of noise barrier – a planted earth mound (left) and a noise wall (right). [158]*

In some residential settings, to achieve sufficient height from a noise barrier without building an oppressively high wall or using up an excessively wide space for an earth mound, a combination of an earth mound with a wall on top can be effective, as shown in *figure 67*.



*Figure 67: A low height noise wall (timber fence) on top of an earth mound. [158]*

In urban environments, the verge areas at the sides of major roads must meet numerous functional requirements often in a highly constrained space. Commonly there are safety barriers, retaining walls, stormwater systems, lighting and signage, landscaping and security or access fencing. Where noise barriers are also required there are opportunities for integrated design solutions, but also design constraints.

In New Zealand, safety and noise walls by urban motorways have sometimes been constructed as separate parallel structures, often around 1 m apart. Not only is this an inefficient use of limited space, but also the resulting gap between the noise and safety barriers can become a litter and weed trap that is difficult to maintain. A better alternative in such circumstances is to design combined barriers.



For combined noise and safety barriers, in addition to engineering/structural requirements a key factor to consider is that the noise wall element must not create snagging hazards for vehicles should they hit the safety barrier. If a vehicle snags on a barrier it can lead to more severe crash outcomes. To avoid snagging the following design guidance has been used in New Zealand:

- Combined noise and safety barriers should not have protrusions or patterning greater than 20 mm deep.
- The noise walls element of a combined barrier should taper into position vertically and/or horizontally at an angle of less than 1:15.
- The road-side face of a barrier should stay behind a plane sloping at a vertical angle of at least 6° away from the road.

One approach in New Zealand has been to add a concrete noise barrier on the rear side of a standard concrete safety barrier as shown in *figure 68*. However, a better alternative is to fully integrate the noise and safety barriers into a single structure as shown on the right image.



*Figure 68: A combined noise and safety barrier (left) and a fully integrated noise and safety barrier (right)*  
(Source: R Hannaby, NZ Transport Agency)

A basic design principle for all noise barriers is that they are most effective when tall enough to break the line of sight from the road to the receiver. After they break the line of sight, the noise barrier can achieve approximately 1.5 dB of additional noise level reduction for each metre of barrier height. Hence, there is a diminishing return as the barrier height increases and this is shown in *figure 69*, where the gradient of the noise reduction flattens out as the height of the noise barrier increases.

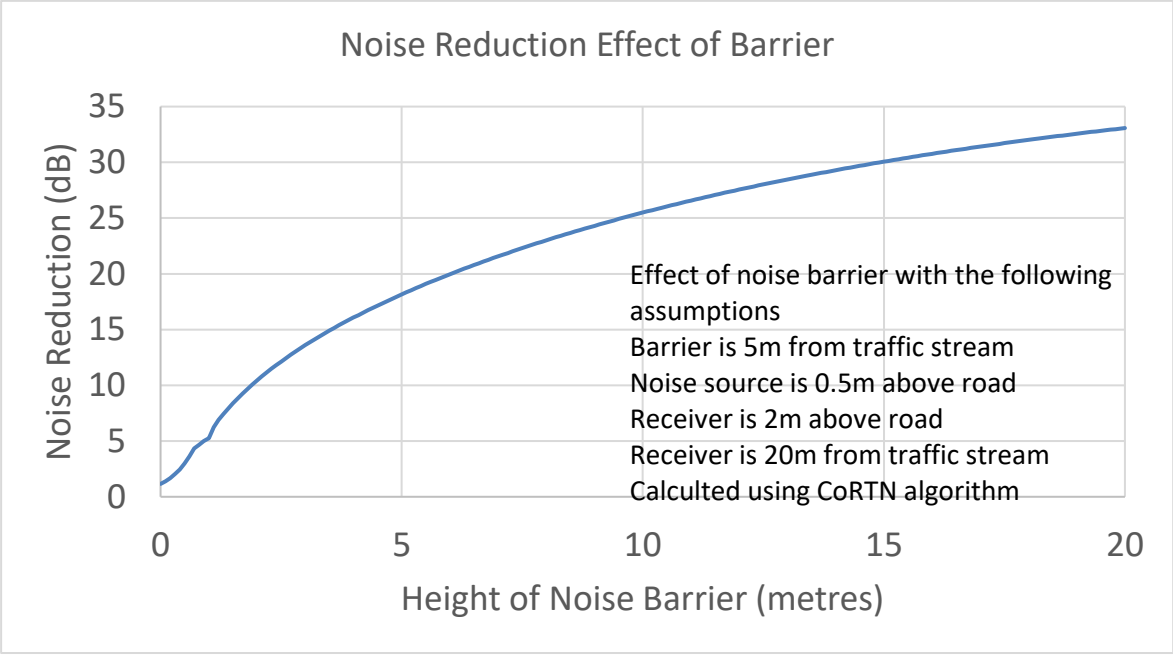


Figure 69: Relationship between height of noise barrier and noise reduction.  
(Source: J McIntosh, Department of Transport, Victoria, Australia)

## CASE STUDY 22

### Architecturally designed high-curved noise barriers in Munich, Germany.

#### Situation

As described in *case study 21*, the noise barriers formed part of a mitigation package to address traffic noise from the upgraded A9 motorway in the north of Munich agglomeration, Southern Germany. In addition to the low noise surfacing described in *case study 21* the administration also decided to reduce traffic noise through the construction of noise barriers.

#### Noise barrier design

The noise barriers, in order to meet the noise limit values at the receivers, had to be 8 m in height. In addition to this there was not much space for the construction because of densely populated areas next to the motorway. The architectural design had to meet static acoustic as well as aesthetic requirements.



*The curved walls seen from the motorway.*

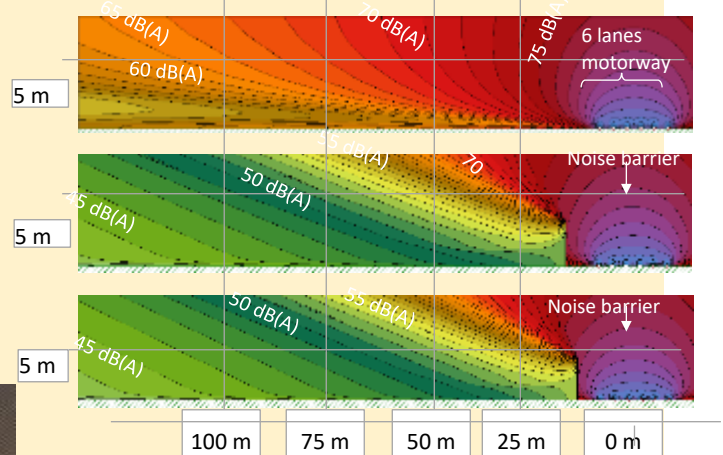
To enhance the screening effect, the design engineers decided to give the wall a curved shape which brought the screening top edge of the wall 3 m closer to the road without being at odds with safety clearance requirements. The figure above shows the perspective from a driver's point of view.

#### Acoustic effect

Noise calculations demonstrated that without noise barriers the road traffic would cause noise levels (equivalent sound pressure levels for the daytime from 6 am until 10 pm) of 67 dB(A) to 73 dB(A) at distances of 60 m to 20 m from the roadside and at a height of 5 m above ground which corresponds to the height of the windows on the first floor of the houses. The results shown

in the figure below are based on calculations without taking into account the houses next to the motorway. The noise barriers are assumed to be sound absorbing on the road side. The road surface is a SMA 8.

Erecting a conventional noise barrier brought the noise levels down by 18 dB to 20 dB at close proximity (5 m–25 m distance) to the wall and by 15 dB further from the wall. Comparing the curved noise barrier with a conventional one it turned out that the architectural design of the curved wall helped reduce the noise levels by another 1 dB.



*Road traffic noise impact ( $L_{Aeq,6-22h}$ ). Top: without noise barrier; middle: conventional noise barrier without curve; bottom: architectural curved noise barrier. Straight line intervals: 1 dB.*

#### Visual effect

The architectural design of the curved wall has a secondary effect which adds to its appeal. Due to its curved shape the top edge of the wall seems to flee from the houses and to widen the space between the houses and the wall. The lower half of the wall is vegetated which augments the impression that the wall is not as high and vast as it really is. The figure below shows the situation from a resident's point of view.



#### For further information

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### 9.7.3. Noise barrier material selection

The choice of barrier materials is influenced by a range of non-acoustic factors including the physical dimensions of the barrier, the location of the barrier and local environmental conditions, structural strength, fire-resistance and resistance to impacts, aesthetic quality requirements including local architectural considerations, the perception and acceptance of the structure by the general public and, finally the cost (including construction and maintenance).

In many practical situations, the road side of a noise barrier needs to be covered with sound absorbing elements to keep traffic noise from being reflected at the barrier and increasing the noise levels at receivers on the opposite side of the road. In principle the whole range of sound absorption coefficients between 0.0 (0% sound absorption, total reflection) and 1.0 (100% sound absorption, no reflection) can be realised, subject to space and cost.

Moreover, sound absorption can be achieved irrespective of the type of material used for the construction of the barrier. Mineral wool behind a thin protective foil and a perforated or slotted covering made of wood, metal or plastics can be sufficient. Even glass panels can be sound absorbing which is managed by micro perforation. Higher maintenance is needed for sound absorbing noise barriers where, due to the open covering, moisture, dust and vegetation can penetrate the construction and corrode it. For a satisfactory lifetime the construction must be frequently inspected and maintained.

The following section describes the materials that are available for the construction of noise barriers together with their advantages and disadvantages.

## CASE STUDY 23

### UK research into the use of recycled tyres in noise barriers

#### Project overview

In 2014, the UK Transport Research Laboratory (TRL) was commissioned by the Scottish Road Research Board to investigate the potential for incorporating tyre derived rubber material (TDRM) from recycled tyres within noise barriers. The study aim was to determine the potential of tyre noise barriers for reducing noise emissions from major roads in Scotland.

#### Methodology

The research was undertaken over four phases. Phase 1 involved a desk top study of current barrier designs that could incorporate TDRM. The review considered regulatory requirements, practicalities, and environmental and safety factors associated with the use of TDRM. Phase 2 involved refinement and agreement of the two-concept tyre noise barrier designs from phase 1. These were: 1) barrier constructed from gabion baskets with 100% unbound (loose) TDRM fill; 2) barrier constructed from gabion baskets with unbound TDRM as an acoustic core and an outer fill of stone.



(a) Sound absorption test

*TDRM barrier tests at Heriot-Watt University*

Phase 3 involved a more detailed assessment of the feasibility of the two concept designs, including: regulatory and contract requirements, and pros and cons of different grades of unbound TDRM. Phase 4 involved preliminary investigation of acoustic performance and non-acoustic properties of TDRM to determine feasibility. This included laboratory testing of acoustic performance of TDRM chip.

#### Conclusions

The research concluded that:

- TDRM chip size should be no more than 50 mm (preferable maximum is 20 mm). There should be a mix of different chips.
- TDRM could be used as an acoustic absorber within barriers but the performance may not meet or exceed that of other materials.
- Additional regulatory requirements may be triggered for use of TDRM.
- Detailed design will need to ensure stability and minimise deformation due to settlement of TDRM.
- Use of gabion baskets is feasible, if reinforced, but potential issues are aesthetics and protecting the geosynthetic bag used for the fill.
- The stone barrier with TDRM core design is preferable as it is more robust and durable. Also, TDRM should ideally not be exposed to reduce fire risk (use of fire retardants is essential).
- TDRM is generally viable from an environmental perspective but should be deployed only at roadsides where surface water contamination is likely to be minimal.
- Unless there is an overwhelming requirement to use TDRM, there are too many factors in favour of using other materials.

#### For further information

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### Timber noise barriers

Timber noise barriers may be fully reflective or sound absorptive and be either single-leaf or double-leaf construction. The manner in which timber noise barriers are constructed varies. They may, for example, be constructed planks secured to cross members where the joints between the planks on the opposite side to the cross members are typically covered with additional timber strips. Sound absorptive materials (if used) typically sit between the cross members. Alternatively, they may be constructed from interlocking elements using, for example, a tongue and groove construction. Panels may be prefabricated or constructed in situ from their component parts and are typically supported between or up against either metal or timber posts.

Timber noise barriers (refer *figure 70*) may provide a better solution in a rural landscape context because they can fit into the landscape more naturally. However, they have a more limited lifespan than other barrier materials and therefore higher maintenance costs.



Figure 70: Example of a timber noise barriers A22 Autostrada del Brennero, Rovereto, Italy.  
(Source: G. Magaro' ANAS SpA)

### Metal acoustic barriers

Metal acoustic barriers are typically cartridge/cassette-type panels constructed from aluminium or steel and can be sound reflective or sound absorptive (when sound absorptive, the metal surface in front of the absorptive material is perforated) (refer *figure 71*). These panels are usually supported between metal posts and offer aesthetic benefits as they can be manufactured in different colours. Recent developments<sup>13</sup>, have involved graphics or photographs being digitally printed onto the surfaces of the barriers, thereby offering the scope to completely change the appearance of the barrier and the perception for both drivers and the properties protected by the noise barrier. Metal barrier materials will always be pre-fabricated, allowing a high degree of quality control and conformity of production and the modular nature of the components offers potential ease of installation and replacement.

<sup>13</sup> e.g. Hebel Manufacturers – <https://hebel.com.au/segment/civil-and-utilities/#segment-applicationsleast>),





Figure 71: Example of metal noise barriers. Source: A57 Tangenziale di Mestre, Villabona, Italy.  
(Source: G. Magaro' ANAS SpA).

### Concrete noise barriers

While noise barriers cast *in situ* may be used or constructed to be self-supporting, more commonly concrete is used for manufacturing precast panels (refer figure 72). These may be a combination of reinforced concrete with a porous concrete face or manufactured as a wood-fibre/cement composite. Such panels are usually supported between metal posts. The visual impact of concrete panels can be improved using colour and texture. Concrete is impervious and dense, and therefore has a high acoustic performance. It is also durable with a long life span (of up to 100 years) and requires little or no maintenance during this time.



Figure 72: Example of a concrete noise barrier (with transparent panels at the top). A33 Asti-Cuneo, Magliano Alpi, Italy. (Source: G. Magaro' ANAS SpA)

### Transparent noise barriers

Transparent noise barriers may be constructed from glass, acrylics, plexiglass, polymethyl methacrylate, etc. (refer figure 73). They are used to either provide a fully transparent barrier or are incorporated as components within an opaque barrier constructed from other materials. As such, their primary benefit is to reduce the visual impact that would result from the use of a conventional opaque barrier. They may allow drivers to view the surroundings beyond the road

environment, allow residents a view across the road and reduce unwanted shading on the residents' side. When they are used as the upper acoustic elements on an opaque barrier, they can reduce the perception of being enclosed. Conversely, privacy of residential areas can potentially be compromised (frothing lower sections of transparent barriers may be an effective way to allow both privacy and light). The use of transparent materials usually comes with high capital and maintenance costs and designs need to ensure that light reflectivity (glare to drivers) is reduced.



Figure 73: Example of a transparent noise barrier. A31 Valdastico, Vicenza, Italy.

(Source: G.Magaro' ANAS SpA).

#### Plastic/composite noise barriers

These are typically cartridge type panels manufactured from plastics or recycled plastics, reinforced with glass fibre (refer figure 74). They can be sound reflective or sound absorptive. When sound absorptive, the surface in front of the absorptive material is perforated. These panels are typically supported between metal posts. As with metal panels, they offer aesthetic benefits as they can be manufactured in different colours, but the materials also mean the surface of the acoustic elements can be textured so that the barrier appears to be constructed from other materials. Similarly, they also offer benefits in terms of ease of installation and replacement.



Figure 74: Example of a composite noise barrier. A10 Autostrada dei Fiori, Savona, Italy.

(Source: G.Magaro' ANAS SpA).

### Natural stone

Natural stone is used to fill so-called gabions and to construct noise barriers by stacking them. Gabion (from Italian *gabbione* meaning *big cage*) is a cage or box made of thick metal wires. Typically, the grain size of the natural material used for noise barrier gabions is 25–38 mm. The mass of the walls is high. However, the wall, first of all, is not impervious, thus providing some sound absorption but poor sound insulation values. Sound is transmitted quite easily through a gabion. Therefore, additional measures must be taken. The gabions get a sound insulating core that is made of steel panels or sand. The joints between the wire cages are filled with sealing gaskets. *Figure 75* shows a gabion along an urban ring road in Ingolstadt, Southern Germany.



*Figure 75: Gabion noise barrier, Westliche Ringstrasse, Ingolstadt, Germany, 2005.  
(Source: Müller-BBM)*

#### 9.7.4. European standards on noise barriers

The European Standard EN 14388 [159] sets requirements for acoustic performance, non-acoustic performance and long-term performance characteristics for noise barriers, claddings, covers and added devices. The standard also includes guidance on the certification and marking of road traffic noise reducing devices which serve as the backbone for noise barrier specifications and to help create a fair and reliable market for barrier products across the continent.

For product conformity, that is for a noise barrier to be considered for the European highways market this standard requires that the barrier product has been assessed and categorised in accordance with the required parts of the European standards series EN 1793 for acoustic performance [160] and the required parts of series EN 1794 for non-acoustic performance (mechanical, structural, environmental and safety) [161].

In this framework, long term performance is assessed following the procedures of EN 14389 [162].

explains how the various European standards relate to each other.

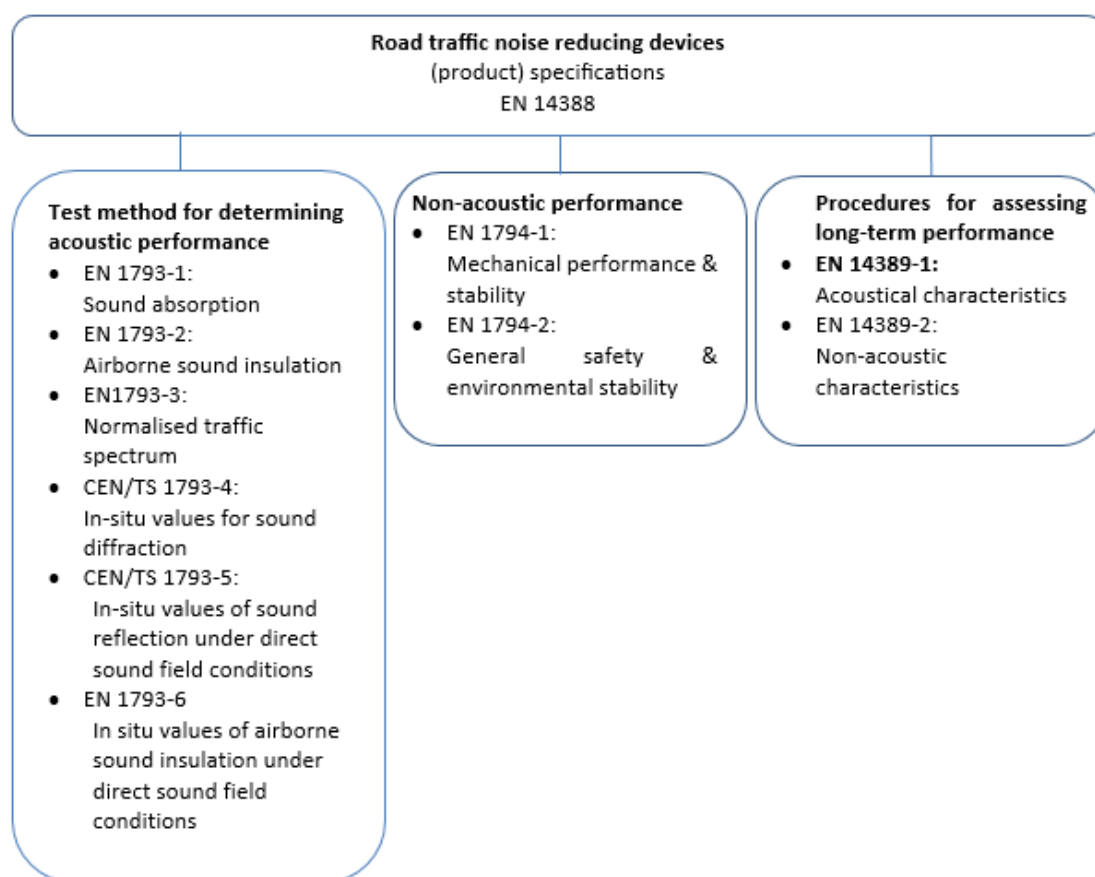


Figure 76: Overview of the European standards for performance characteristics.

(Source Jakob Fryd Danish Road Directorate derived from EN14388)

The standards enable project managers to make specific demands on the contractor for the acoustical performance of noise barrier projects. As shown in *table 12*, EN 1793-1 provides a test method to categorise the sound absorptive performance of a noise barrier as a single number rating in categories ranging from A0 to A4 and covering a  $DL\alpha$ <sup>14</sup> range from *not determined* to greater than 15 dB. In contrast, and as shown in *table 13*, EN 1793-2 provides a test method to categorise the airborne sound insulation performance of a noise barrier as a single number rating. These categories range from B0 to B4 covering a  $DL_R$  range from *not determined* to greater than 34 dB.

<sup>14</sup>  $DL\alpha$  is the single number rating of sound absorption.  $DL_R$  is the single number rating of airborne sound insulation.

Category	DL $\alpha$ dB
A0	Not determined
A1	> 4
A2	4–7
A3	8–11
A4	12–15
A5	> 15

Table 12: Categories of absorptive performance in EN 1793-1. [160]  
The value DL $\alpha$  is an expression of how much noise is reflected from the barrier.

Category	DL $_R$ dB
B0	Not determined
B1	> 15
B2	15–24
B3	24–33
B4	> 34

Table 13: Categories of airborne sound insulation, EN 1793-2. [160]

The sound transmission and absorption characteristics of a noise barrier are commonly determined using laboratory-based tests (EN 1793-1 and 2). It is noted that the laboratory-based tests will be restricted to the assessment of devices used only “under reverberant conditions”. The in-situ tests (EN 1793-5 and 6) will be the reference in the future.

A noise barrier with a sufficient sound insulation abates the sound energy propagating directly through the noise barrier. Their contribution to the overall sound level will therefore be reduced to a minimum. The sound insulation properties of a noise barrier are especially determined by its mass and the thickness of the barrier. Densities of the order of 15–20 kg/m<sup>2</sup> will generally provide sufficient insulation.

Currently, the sound transmission characteristics of a noise barrier are commonly referred to in terms of DL<sup>R</sup>, the single number rating of airborne sound insulation, although the development of new test methods has resulted in a similar index, DLSI, based on in-situ rather than laboratory testing.

#### 9.7.5. Low height noise barriers

Low height barriers can be utilised in the following situations: [163]

- To provide shielding between two traffic lanes (or two tramway tracks). Investigations into this approach have shown its potential to create a *quiet* road infrastructure, allowing shielding of adjoining cycle paths or recreational areas from traffic noise. Low height barriers can also assist in shielding noise for adjoining residential buildings in the lowest floors (up to 5 m high).



- To provide shielding between bridges and walkways or cycle paths beneath the bridge (refer *figure 77*). This approach can be very effective from an asset management and environmental perspective. Careful design can enable such low height barriers to act as both a safety and noise barrier. In particular by reducing noise transmitted to the side and below the bridge such barriers can improve the amenity value of any walking and cycling infrastructure (as well as urban parks and other recreational areas) situated below the bridge.

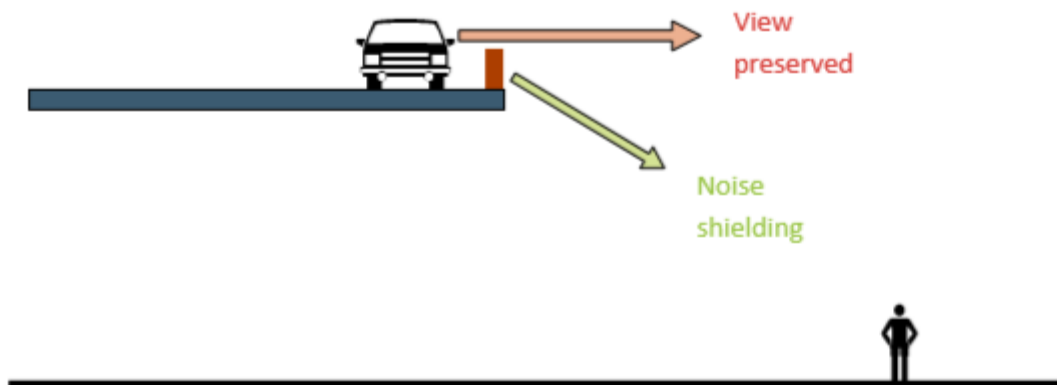


Figure 77: Shielding of walkways and cycle paths beneath bridge. [163]

- To provide shielding from two lanes of traffic (refer *figure 78*). The benefit of installing 1 m by 1 m stone (gabion) walls was modelled based on a two-lane urban road with 100% light vehicles (50 km/h). The geometry of the gabion structure appeared to make no difference ( $\pm 1$  dB). Because of the ease of installation of these structures, they may be an efficient solution but only for low receivers and only when they are not too close to the barrier (i.e. at least 1 m between the gabion and the walkway or cycling path).

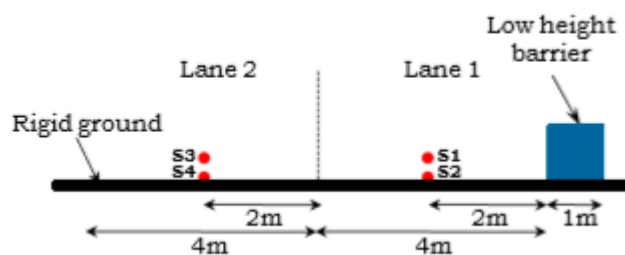


Figure 78: Urban road configuration with gabions. [163]

- To provide shielding between major roads or train routes where there is significant open flat space with no or minimal buildings in between the transport corridor and any sensitive receiver (refer *figure 79*). Numerical simulations for such situations have shown that a basic low height grassy earth mound (1 m in height and up to 1 m in width) can be effective in shielding receivers up to 5 m high. For high-speed roads (such as motorways) or rail, they would be most effective when the transport corridors are embanked (at least a few metres

high) or when the height of the receiver area is lower by a few metres than the infrastructure reference plane.

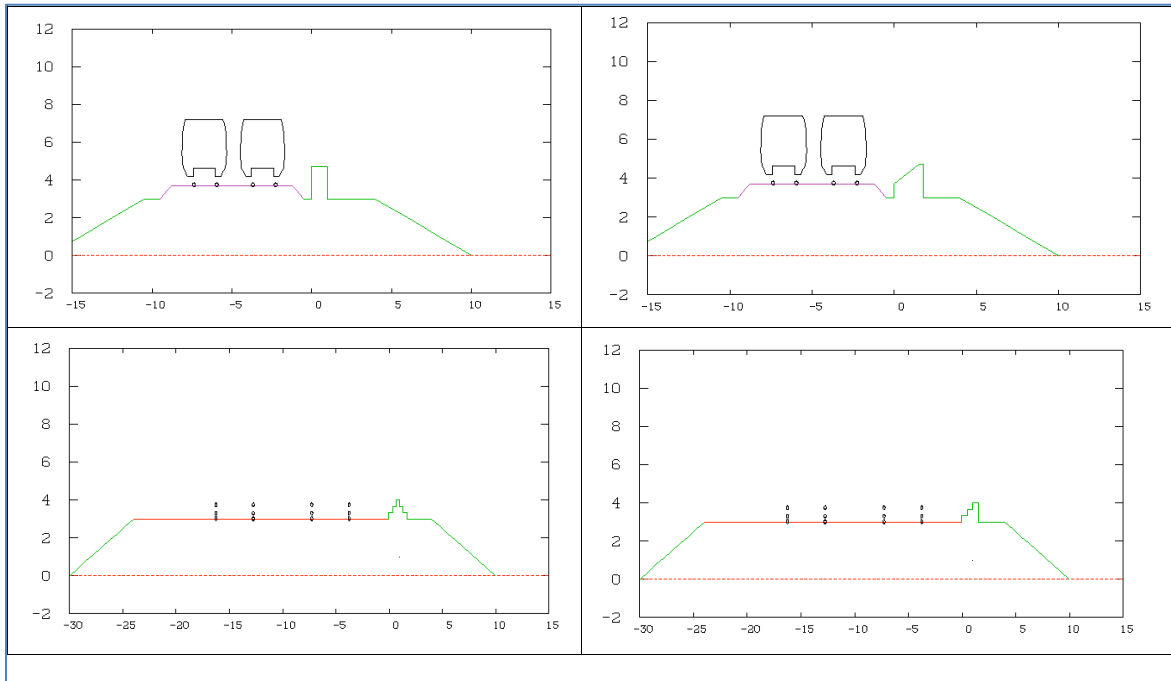


Figure 79: General overview of low height earth mounds configured for railways and motorways. [163]

To improve the sound environment along a popular esplanade in Lyon, France, a 1 m high, 14 m long and 40 cm thick bio barrier was erected as a barrier against noise from an adjacent road (refer figure 80). The barrier was a metallic structure, filled with a substrate on which 40 plants per square metre were grown on both sides. Noise measurements were taken at sitting height (1.2 m), 3.5 m from the roadside. A questionnaire was also completed by pedestrians at the same location.



Figure 80: Questionnaire respondents and acoustic measurement equipment behind the low height barrier (left) and at the side of the barrier right). [164]

Noise measurements showed that the barrier reduced noise levels from about 67 to 62 dB ( $L_{Aeq}$ ). This outcome was consistent with results from acoustic simulations which estimated a noise attenuation of 4 dB. The noise variability was also reduced by the barrier, as it reduced high frequency more than low frequency sounds.

Responses to the questionnaire showed that the overall quality of the sound environment improved by making it slightly more restful. However, the perception of benefit was less than expected and it was observed that the reduction in variability did not strongly influence the perceived annoyance. In addition, the relative level of low frequency sounds, measured as the

difference between C- and A- weighted noise levels (LC–LA) had increased due to the effects of the barrier. This supported the conclusions of previous experimental research, which suggested as a rule of thumb to compensate for the change in spectral balance of the noise, each increase of 1 dB in LC–LA would result in a decrease in LA of approximately 0.4 dB due to the presence of the barrier.

#### 9.7.6. Vegetated noise barriers

Vegetated areas and surfaces are beneficial in both urban and rural environment, even without considering the benefit of noise reduction.

Historically, the role of vegetation in noise barriers has been debatable. Its role in reducing noise has been viewed as mostly psychological on the basis that measured noise reductions were minimal and hence, theoretically, would be barely perceptible. Nonetheless, vegetative barriers are still viewed positively by the community. This is supported by anecdotal evidence of complaints generated with the removal of scattered vegetation between houses and the road in the process of constructing a new noise wall, with residents experiencing a perceived increase in noise, rather than any actual increase.

Measuring the effectiveness of vegetative barriers is difficult. Barriers would need to be assessed through different seasons (full leaves, without leaf, falling leaves), different plant types (tree, shrub, size of leaf, leaf angle) type of soil, as well as different heights of trees and shrubs as well as density of planting.

There are also some disadvantages in using vegetation versus traditional concrete or timber noise walls [165]:

- [It is perceived that] more maintenance is required for vegetated noise barriers.
- Vegetation could decrease the accessibility and therefore effectiveness of inspections.
- Vegetation is a source of humidity which could affect sound absorbing materials or even concrete barriers.
- Trees just in front or behind a barrier with the crest of the trees higher than the top of the screen reduce the efficiency of the barrier caused by reflections against the underside of the crest and the leaves so the sound waves reflect over the top of the barrier. The height of vegetation near the barrier should therefore be limited to the top of the barrier, which reinforces the notion of increased maintenance.

To obtain a demonstrable noise reducing effect (approximately 3 to 5 dB), it has long been estimated that a dense forest close to the road and with a depth of at least 100 m is needed [166]. Given this space is generally not available in urban environments, more conventional high noise barriers of timber or concrete have become the norm. However, as the aesthetic requirements of the landscape are becoming more of a concern, it means that the visual quality of a noise barrier needs to be considered on an equal footing with that of noise abatement. This applies whether the noise barrier is a solid wall, an earthen mound, or a planted barrier.

The European Union funded research project – *Holistic and Sustainable Abatement of Noise by optimized combinations of Natural and Artificial means* (the HOSANNA project) undertaken between 2009 and 2013, has studied a number of green abatement strategies including new barrier designs, planting of trees, shrubs or bushes, ground and road surface treatment and greening of building facades and roofs [167]. Investigations conducted as part of this project are based on advanced theoretical methods rather than measured in real situations. While the estimation

methods have been validated and are applied in situations that are as realistic as possible, a non-negligible uncertainty should be expected [168]. Recommendations that resulted from the project highlight the value of making use of the acoustic properties of vegetation when seeking to optimise noise mitigation. These properties relate to three mechanisms:

- sound absorption
- sound diffusion, which occurs when a sound wave impinges on the vegetation and is then reflected back
- sound transmission when a sound wave is passing through the vegetation.

The project demonstrates the value of a more holistic approach to urban design (refer *chapter 9.8* on soundscapes and *figure 81*), where the creation of quiet(er) spaces can be achieved through a combination of treatments including use of vegetative barriers (low and high), ground treatments such as soft ground or roughness-based noise reduction, building treatments, as well as traditional traffic noise walls. While some treatments may have limited benefits in terms of noise reduction when applied individually, they can contribute to significant improvements when used in conjunction with other measures. Wherever possible, consideration should be given to accommodating existing vegetation in the design process.

Details on the findings of the project, including recommendations for implementation and the economic analysis of the costs and benefits of the various measures considered have been compiled in *Environmental methods for transport noise reduction* [168].

Some of the different approaches to incorporating vegetation within noise barriers are described in more detail in the following sections.

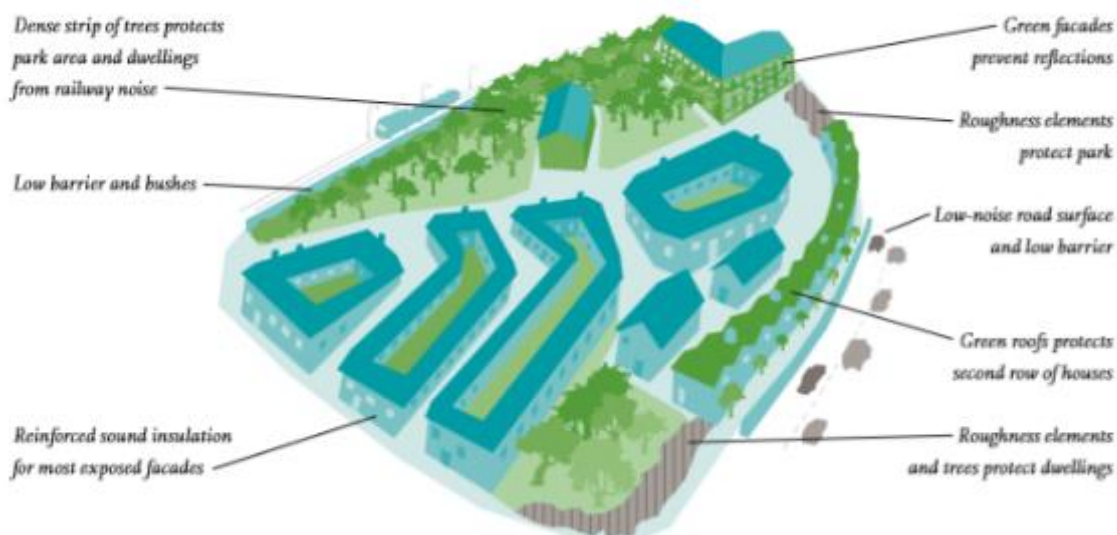


Figure 81: Combining solutions to protect the quiet sides of noise-exposed buildings. [167]

### Earth mounds

Earth mounds are typically used instead of concrete or timber acoustic noise walls. They are a good solution to reduce traffic noise in rural areas, because they fit into the landscape more naturally than any vertical structure, especially where they support planting which improves its appearance in rural contexts. They also have advantages compared to conventional screens including:

- They have a natural appearance and may not be perceived as noise barriers.
- They create a more open area feeling compared to noise barriers.
- They do not require extra security fencing.
- Costs are typically lower for construction and maintenance.
- They have a higher perceived effectiveness.
- They virtually have an unlimited lifespan.

The major constraint of using earth mounds is that they need space. To build an earth mound of 4 m high, there must be at least 13 m of available space.

In the course of a few years, a man-made earth embankment with vegetation will appear to blend in with nature and enhance the natural character of the landscape. And, in the course of time, a planted earth embankment will become a small ecological system, in which various animal species and plants flourish. The advantages of earth embankments are that they have a very long lifetime, limited maintenance cost, and almost no graffiti problems. Furthermore, excess material from other locations, such as soil and stones from construction work, can be recycled for noise reducing purposes.

To address the land space requirements of an earth mound, an alternative arrangement is to use trapezoidal-shaped soil embankments (refer *figure 82*). In the majority of cases the embankment is made of reinforced soil, which has the advantage of keeping the embankment face almost vertical, with a consequent saving in construction material and reduction of overall size. The supported earth embankment still provides for the possibility of effective revegetation. Also, in these constructions, many materials can be used (metal, synthetic and/or organic fibres). In the rural context, they will appear more natural than concrete, but may not be as durable.

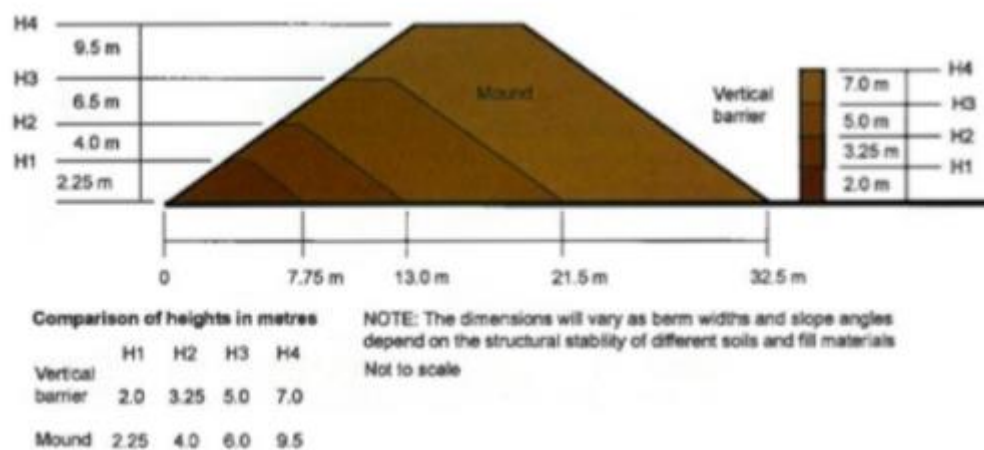


Figure 82: Comparison of the acoustic performance of a vertical noise barrier and an earth mound. A 4 m high earth mound is equivalent, acoustically speaking, to a 3.25 m high screen. [165].

Investigations comparing the performance of earth mounds with that of conventional noise walls by means of scale model measurements have concluded that the optimal choice is dependent on the acoustical properties of the mound [169]. In the case of downwind propagation, numerical modelling showed that the geometry of the mound also influenced its efficiency [170].

In a still atmosphere, the performance of a 4 m high wall would perform better than a packed earth mound of the same height, in particular, if it can be placed at the foot of the mound (the diffracting

edge of the wall is then closer to the noise source). However, for the same diffracting edge location, an acoustically soft earth mound was found to provide at least a similar noise reduction to a wall and can outperform the wall by approximately 2 dB(A).

If wind blows towards the receiver, the top of a vertically erected wall can present large wind velocity gradients that lead to a downward bending of the sound rays and impair the shielding efficiency of the barrier. Numerical predictions have highlighted that while strong winds could almost completely negate the performance of a wall; mounds with a smoother (non-steep) profile presented lower wind gradients, and their acoustic performance was observed to be more resilient to wind effects. For mounds with a slope of 1:3, or for steeper slopes but with a flat top, the average negative effect could be smaller than 1 dB(A) in many cases [165].

This is consistent with acoustically soft mounds outperforming walls in long-term assessments. It should also be noted that non-steep soft mounds will limit reflection of sound on the source side.

### Bio barriers

Bio barriers are used where there are space limitations and are designed to incorporate planting within their structures. They are specifically used where there is too little space to incorporate planted earth mounds. Examples of bio barriers are provided in *figure 83*, *figure 84* and *figure 85*. A 4 m high bio barrier can be positioned in a space 2.5 m wide. In these designs the structural spaces are filled with inert material and vegetation that allow for an effective sound insulation barrier height of up to 5 m, with a need for space at the base of 2 to 3 m.

Reinforcement of support structures can be in various materials: wood, concrete, steel or recycled plastic. Almost always, they require anchoring to the ground and the success of the vegetation is closely connected to a number of conditions that allow vegetation to grow including drip irrigation, ground substrate, use of fertiliser and the choice of plant type which should preferably be indigenous bush species.

Applications of over 20 years throughout Europe have identified the following design issues:

- The wooden structures have the advantage of using a material that does not radiate heat and provides open niches that allow a good development of the plants. However, the nature of the wooden material, means that it has a limited lifespan.
- Concrete structures are optimal from an engineering point of view but have some issues with the use of vegetation due to the heating of the material. This problem can be overcome when the plants have developed providing coverage to the structure itself.
- Structures in metal supports are valid both from an engineering point of view and for the support of the growing plants.



- Other examples of bio-barriers are constructed wholly from recycled materials or use recycled materials as a constituent material. While most of these are still prototype systems or undergoing on-road trials, some are already commercially available. This type of barrier is constructed from panels or elements with hollow sections which can be filled with earth/gravel or planted to allow vegetation to establish itself on the barrier façade.



Figure 83: Bio barrier with wooden structure. [165]



Figure 84: Bio barrier with concrete structure (after construction and fully vegetated). [165].



*Figure 85: Bio barrier with metal structure (after construction and fully vegetated). [165]*

Results from the EU-funded Hosanna project indicated that noise abatement obtained with a vegetation substrate on rigid barriers could be close to that observed with classical absorptive materials currently used for conventional barriers [168],[171]. If the road is in a trench or cutting, the noise reduction may be quite large; the narrower the trench the higher the gains. Numerical modelling for a full covering of the two walls of a 6 m deep trench predicted a noise reduction (compared with the same situation with rigid walls) of 7 to 12 dB within an area 40 m long and 5 m above ground, located 1 m behind the edge of the trench. However, at a location closer to the trench (1 m), the reduction would only be about 2–3 dB since the noise sources would then be in direct sight.

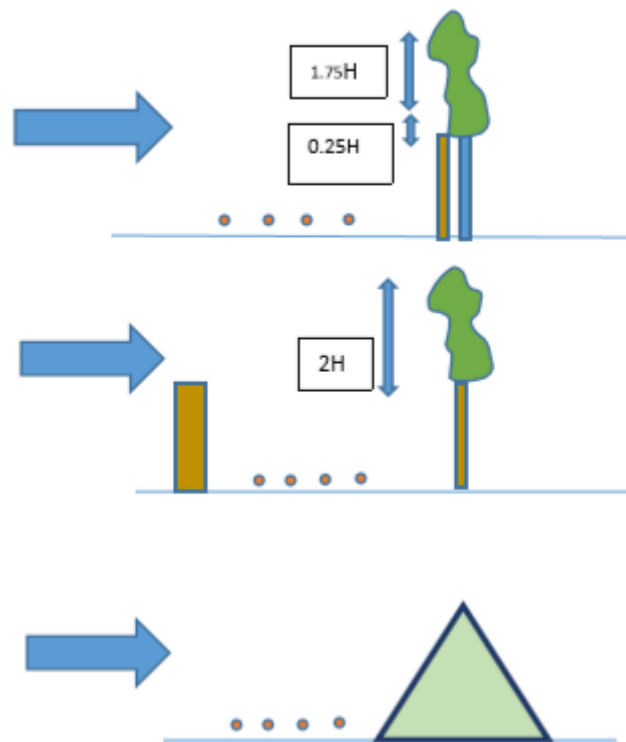
Existing noise barriers can be improved by planting vegetation along their top edge, which increases noise attenuation. Most conventional barriers have caps made of solid structural material. Replacing these with caps of planted growing medium (made of natural fibres and mineral materials) can substantially improve the acoustic performance. For a pedestrian or a cyclist 1 m behind the barrier, the acoustical noise reduction due to a 1 m wide vegetated T-shaped element with a rigid base is predicted to be approximately 7 dB(A) compared with an uncapped 4 m rigid barrier [168]. A fully soft cap would provide even higher attenuation.

The closer the receiver is to the barrier, the more effective the vegetated cap. It is ideally suited to situations where:

- pedestrians and cyclists are moving close behind the barrier (at most a few metres away) to create a sufficiently quiet path
- there are small recreational areas, or building entrances situated no more than 20 m behind the barrier.

### 9.7.7. Acoustical benefits of trees and shrubs

The use of trees as a wind break behind a noise wall can help prevent wind effects that impair noise barrier performance (refer *figure 86*). For low wind speeds a statistically significant (but small) increase has been observed. With increasing wind velocity, this effect increases. For wind speeds between 6 m/s and 7 m/s, an increase of more than 2 dB in the noise reduction performance of the wall is obtained. For wind speeds between 11 m/s and 12 m/s, the use of trees behind a barrier results in an improvement of almost 4 dB [172].



*Figure 86: Optimum canopy design to reduce downwind effects near a single noise wall, a steep earth mound and noise walls position at both sides of a four lane highway.  $H$  indicates the noise wall height. [168]*

Conversely, the presence of a row of trees behind a noise barrier can result in increased sound pressure levels at high frequencies due to noise scattering on the canopy of the trees. However, typically, traffic noise produces only a small amount of acoustic energy in the high frequency range relative to low frequency bands. For highways with dense traffic, wind-induced vegetation noise has been found to be of minor significance.

The noise reduction potential of shrubs is limited, accounting for less than 1.5 dB(A) at 70 km/h but can enhance noise abatement if combined with trees. Hedges, if designed to contribute to noise reduction, should be sufficiently thick and very dense internally. In addition, there should be sufficient biomass close to the group to prevent sound propagating underneath the hedge.

The effect of a tree's trunk diameter is an important factor in noise abatement. With increasing trunk diameter, noise abatement is also increased. However, with increasing distance between the trees, the abatement is reduced, and the importance of trunk diameter is similarly reduced. The effect of trunk height is less important; a difference of about 1 dB is observed for a trunk height of

1 m compared with 2.5 m for a trunk diameter of 22 cm) [173]. A tree spacing of 3 m and a trunk diameter of 11 cm is the starting point for positive abatement.

The planting of trees behind a noise barrier, can also increase shielding at higher frequencies (refer *figure 87*). Traditionally used as wind breaks, a row of trees is especially useful in a highway configuration with open fields behind the noise barrier. In the absence of wind, tall rows of trees will lead to increased downward scattering of sound [173]. However, depending on the canopy design, strong improvements at short distances may be offset by adverse effects at greater distances downwind.

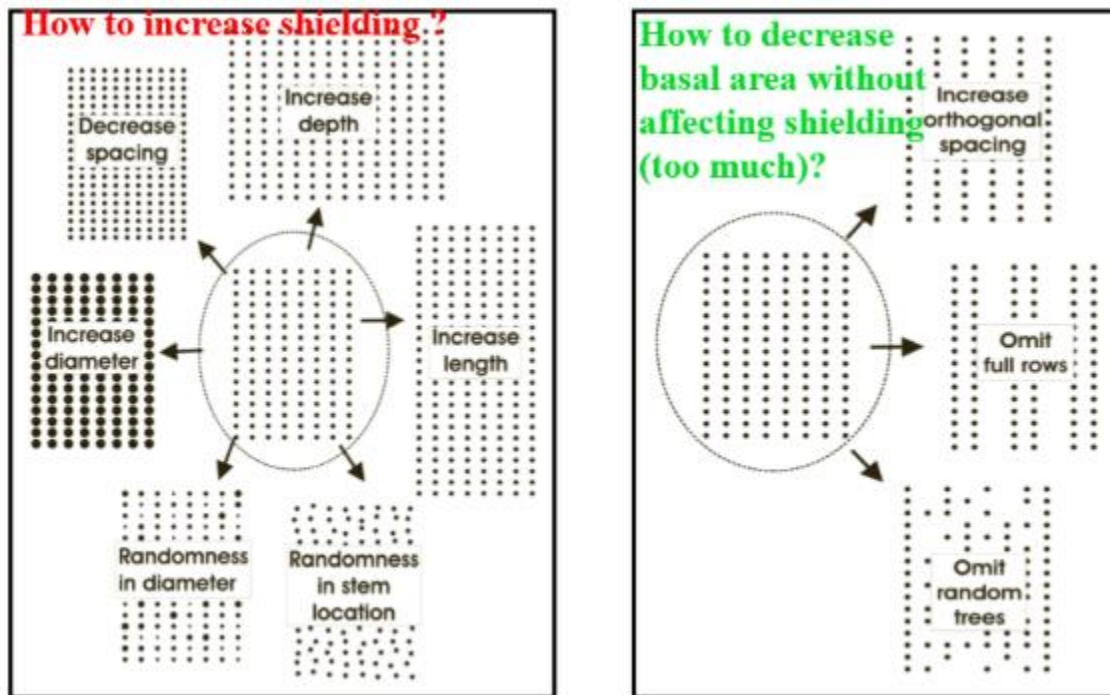


Figure 87: Tree belts along roads: guidelines. [173]

#### 9.7.8. Acoustical benefits of grass and soil

It is also important to appreciate that the typical soil under vegetation has been as important in reducing noise as the actual vegetation and accounts for about half the dB of traffic noise reduction predicted [173]. Compared with sound propagation over grassland, for a light vehicle travelling at a speed of 70 km/h, 3 dB(A) reduction has been estimated by the action of the soil alone.

The introduction of a 45 m wide area of soft surface to replace hard ground starting 5 m from the nearest traffic land will reduce noise levels by at least 5 dB(A) and up to 9 dB(A) for a 1.5 m receiver 50 m from the road. The type of grass can also influence the ground effect. Ground that is compacted because of frequent mowing, rolling of passage of wheeled equipment is likely to have a higher flow resistivity and thereby reduce noise to a lesser degree (see *figure 88*).

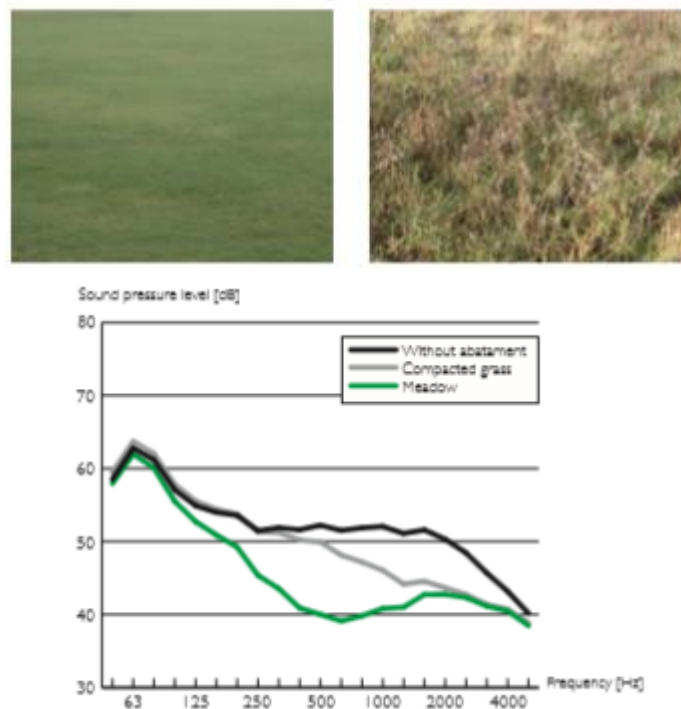


Figure 88: Influence of two different grass types on the propagation of traffic noise. Sound-pressure level spectra predicted for a 1.5 m high receiver located 50 m from the nearest traffic land (5% heavy and 95% light vehicles, travelling at 50 km/h) for compacted grass (grey), meadow (green) and hard ground (black) between road edge and receiver. Predicted insertion loss: 5 dB(A) for compacted grass and 8 dB(A) for meadow. [173].

## 9.8. URBAN AND BUILDING DESIGN

Major roads can be deliberately located away from noise sensitive land uses, only to have sensitive uses subsequently encroach nearby. This can result in “reverse sensitivity” which means the vulnerability of an established activity (e.g. a road) to objection from new sensitive land uses located nearby [174]. The existing use may then be subject to legal or political pressure to modify or cease its operation. In the context of traffic noise, people may choose to live on low cost land near a major road, and then complain about the noise. They may then demand measures to reduce noise or may object to future upgrading of the road.

Reverse sensitivity risks due to traffic noise can be minimised by land use planning that seeks to either prevent encroachment of noise sensitive land uses or to ensure that the encroaching sensitive land uses implement measures to protect themselves. In a rural setting, reverse sensitivity can be avoided by discouraging the construction of new dwellings within a specified buffer distance from major roads. However, in an urban setting, this is unlikely to be practical, in which case new sensitive uses should be developed with adequate noise protection. This may consist of noise walls funded by the developer of the new land use or may consist of buildings designed to protect their occupants from noise.

In order to minimise risks of reverse sensitivity, it is recommended that road agencies publish maps that inform future land users of current and future noise levels such as that shown in *figure 89*. At the very least, this information should be provided to local planning authorities. This will allow the authorities to take steps to minimise reverse sensitivity.



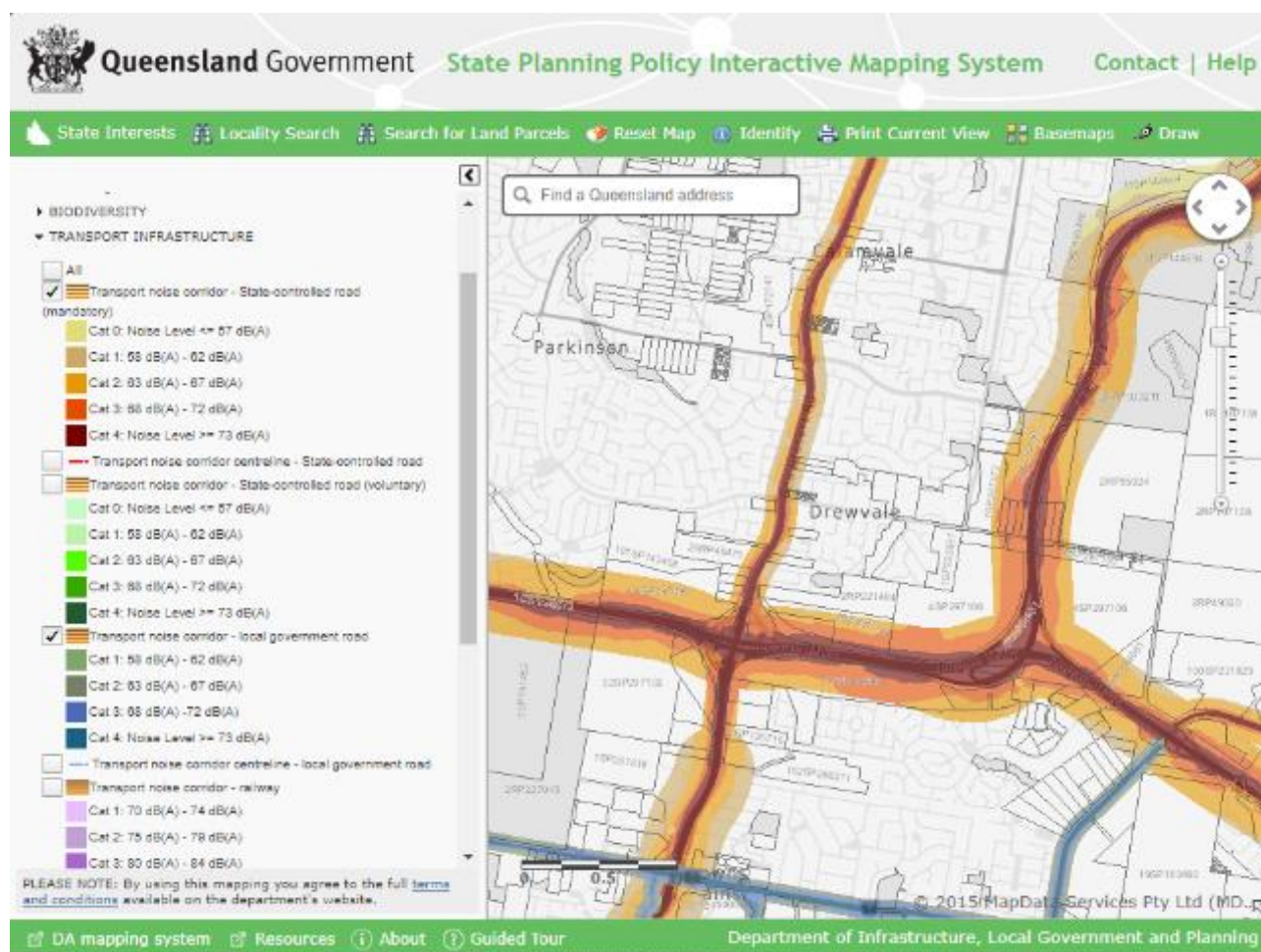


Figure 89: Traffic volume map, Brisbane, Australia. [175]

Many jurisdictions have planning or building regulations which require dwellings and other noise sensitive buildings in noisy locations to meet certain acoustical requirements. Often these are based on acoustical standards which specify maximum acceptable or desirable indoor noise levels. The rationale for these regulations is that new land uses should be designed to respond to the existing land use.

Where a noise sensitive building faces directly onto an already existing noisy road, there is often little that the developer of the new building can do to reduce the noise emitted from the traffic on the road. However, the developer can implement noise walls or acoustic structures into the building fabric and design the layout to reduce disturbance. In effect, this means that rather than aiming to achieve a particular noise level outside the building, the intent should be to achieve a target interior noise level.

The WHO has proposed the following interior noise levels in its Guidelines for community noise [13]:

- Residential living rooms (day and evening time) 35 dB  $L_{Aeq}$
- Bedrooms (at night) 30 dB  $L_{Aeq}$ , 45 dB  $L_{Amax}$
- Hospital ward rooms 30 dB  $L_{Aeq}$  at any time, 40 dB  $L_{Amax}$  at night

These levels are challenging to achieve, so some jurisdictions accept levels as much as 10 dB higher.



The design of building insulation depends on knowledge of the noise level that a building will be exposed to in the future. For this reason, it is common for planning authorities or road agencies to provide information on future noise levels, or at least provide information on traffic volumes that can be used to calculate noise levels. For example, *figure 89* shows on-line mapping that specifies noise levels new dwellings must be designed to in order to tolerate the impact of traffic noise in Queensland, Australia.

Some road or planning authorities publish guidelines or standards that recommend specific building features based on categories of noise level. For the highest noise levels, they may strongly discourage any noise sensitive land use. The New Zealand Transport Agency has comprehensive guidelines to help minimise the potential for adverse traffic noise impacts arising from plans to build new noise-sensitive buildings near major roads.<sup>15</sup>

It is inevitable that some homes will be built near noisy roads and these should be planned, designed and constructed in a way that protects the future occupants from noise. Provided noise levels are not extreme, the acoustical design of detached houses may be specified by reference to suitable acoustical standards [176]. However, for major building contracts, or where noise levels are very high, this should preferably be undertaken by a competent acoustic practitioner.

#### **9.8.1. Building design and layout**

The outline of a building should be designed to minimise the extent to which it is affected by reflected sound. *Figure 90* shows an undesirable condition where a front courtyard receives excessive noise because of noise being reflected from the sides of the courtyard. Reflection of noise is also a common situation where continuous rows of buildings on either side of a street reflect noise back and forth.

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<sup>15</sup> refer <https://www.nzta.govt.nz/resources/effects-on-noise-sensitive-land>

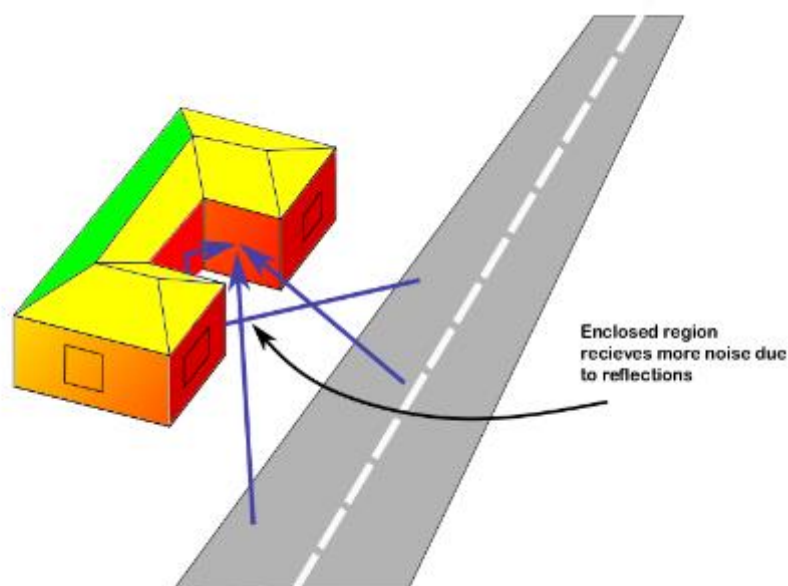


Figure 90: Internal reflections in front of house.

(Source: J McIntosh, Department of Transport, Victoria, Australia).

Mitigating noise in a high-rise apartment can be particularly challenging. One approach is to design the building with a podium – a lower section of the building that extends closer to the road and contains noise tolerant uses such as shops or car parking. The podium protects a few floors above it, while the higher floors get a degree of protection because of their greater distance from the road as shown in *figure 91*. The higher floors may still require some form of acoustic treatment such as double glazing or the enclosing of balconies.

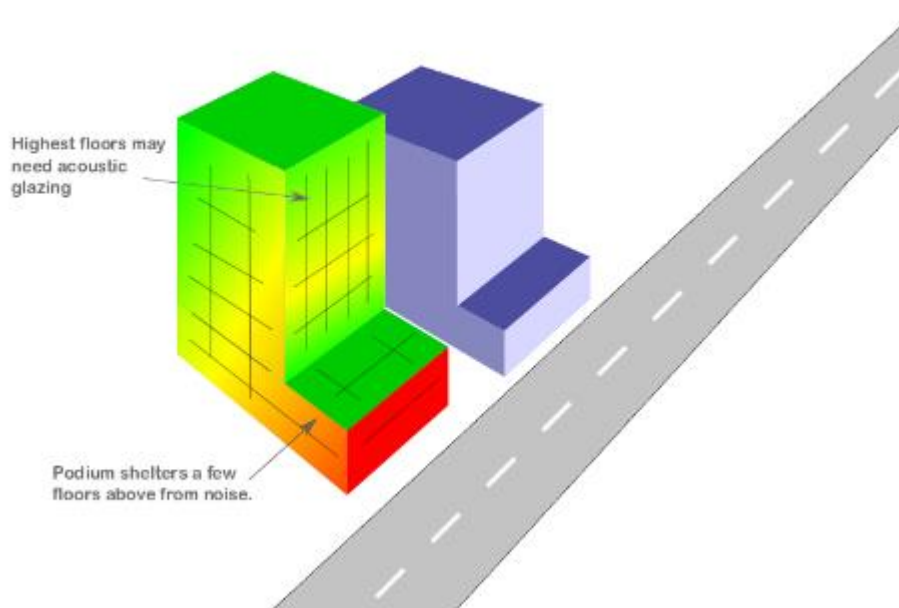


Figure 91: Use of podium to protect high rise dwellings from traffic.

(Source: J McIntosh, Department of Transport, Victoria, Australia).

The interior floor plan of a building should also be designed with noise in mind. Usually this will mean deciding which rooms are more sensitive to noise (bedrooms and possibly living rooms) and which are less sensitive (garage, bathrooms, utility rooms, possibly kitchens). The least sensitive rooms should be located closest to the noise source. This may compromise other considerations in the design of a building. For example, it is common for detached houses to have kitchens and living rooms facing a rear garden, which results in bedrooms facing the road.

The interior design of apartments can be particularly challenging where entire apartments are on the side of a building facing a road.

Once options to control noise by building layout are exhausted (or where the building already existed prior to construction of the road) it may be necessary to change the design of the building envelope and its ventilation (refer *case study 26*). Obviously, the specification of the building envelope depends on the level of traffic noise and the use of the affected rooms. Some potential specifications are presented in *table 14*.

In locations with adverse climates, there is a degree of alignment between building energy efficiency objectives and acoustical objectives [177]. Walls that insulate heat well tend to also be efficient in insulating sound, and gaps around doors and windows are undesirable on both fronts. However, there is a conflict in the design of double glazing – the optimum separation of the panes for thermal efficiency is about 12 mm but a much wider gap is preferred for acoustical purposes [178].

Effective sealing of all exterior gaps in a building create the need for mechanical ventilation to provide fresh air for the occupants. In situations where mechanical ventilation is used, it should be designed in a way that ensures it does not create a noise pathway into the building. This may be done by designing ducts between the inside and outside so they are indirect (e.g. elbows or U- or Z-shaped ducts) and are lined with sound absorptive material. Suitable ventilation systems are available commercially. Alternatively, they can be designed to collect air from the side of the building away from the road. This has the possible advantage of introducing air with a lower concentration of air pollutants.

Another option is to design windows that can be opened for ventilation, but in a way that provides a degree of noise mitigation as shown in *figure 92*. This works by providing an indirect path for the noise to travel along, with sound absorbing material that prevents noise reflecting around corners in the path.

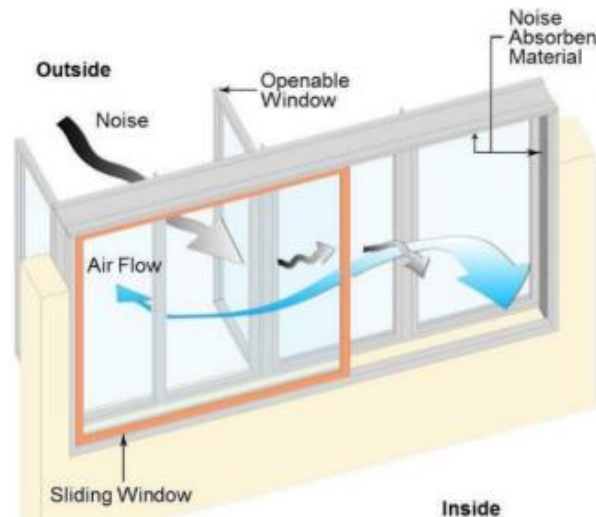


Figure 92: Acoustic window. [179]

A further improvement to interior noise levels can be achieved by furnishing the interior of the building with sound absorbing materials as much as possible – heavy drapes can help.

#### 9.8.2. Building acoustic treatment

Sometimes it is necessary to improve the sound insulation performance of the envelope of an existing building. This may occur when a new road is constructed near an isolated dwelling in a rural setting and the length of noise wall that would otherwise be needed to protect the dwelling is excessive. It may also be the case for elevated or tall buildings that are difficult to protect with noise walls, or where there are requirements for the buildings to have direct access to the road.

Regardless, it is common for road agencies to take responsibility for modifications to existing buildings for acoustical purposes. This poses several challenges. First, many road management authorities lack specialist housing construction expertise. Second, variations in the pre-existing acoustical properties of buildings can make it difficult to achieve predetermined interior noise levels without a specific design of the modifications for each individual building. These challenges are multiplied if many buildings must be modified.

There are two common approaches to dealing with these two challenges. The first may be addressed by engaging building acoustics specialists to manage the entire process. The second challenge may be addressed by specifying pre-determined “packages” of noise reduction measures. These packages can be specified on the basis of the expected outdoor noise levels. A range of possible packages is presented in *table 14*. This approach can be outsourced to a building firm.

Difference between external and desired internal noise levels	Design features
10 – 15 dB	Acoustical sealing of doors and windows, closing eaves
15 – 20 dB	As above plus: <ul style="list-style-type: none"> <li>external doors have solid cores</li> <li>windows of 6.38 mm laminated glass or similar</li> <li>mechanical ventilation to allow windows to be kept closed</li> </ul>
20 – 25 dB	As above but: <ul style="list-style-type: none"> <li>windows of 10.38 mm laminated glass</li> </ul>
25 – 30 dB	As above but: <ul style="list-style-type: none"> <li>double glazed windows with: <ul style="list-style-type: none"> <li>one pane of 6.38 mm laminated glass</li> <li>other pane of 8 mm float glass</li> <li>50 mm air gap</li> </ul> </li> </ul>
30 – 35 dB	As above plus: <ul style="list-style-type: none"> <li>100 mm thick high-density ceiling insulation for upper floor</li> </ul>

*Table 14: Australian example of building acoustic requirements to reduce traffic noise impacts. Note: performance quoted in table 14 is indicative only and is a function of the initial construction to which those treatments were applied. (Source: unpublished data, Department of Transport, Victoria, Australia).*

The acoustic specialist approach will generally provide more consistent outcomes than the package-based approach but will do so at greater expense. Some acoustic consultants have nevertheless developed efficient processes to minimise the cost of the specialist-based approach [180].

## CASE STUDY 24

### Quiet facades, Copenhagen

A highly traffic-congested street in the central part of Copenhagen housing went through an extensive renovation. In this context, the 'Green Noise' project was carried out, with the aim of finding a relatively simple, non-space consuming, technical solution to reduce traffic noise indoors and provide a fresh clean air supply for the dwellings. The main elements of the project are as follows:

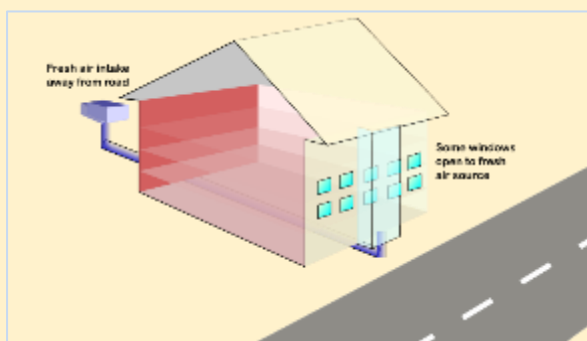
- façade noise screen in the form of glass columns and fresh air supply towards the street
- solar panels for an additional power supply for fans
- heat recovery.

Residents can get fresh air by opening the window, and the soundproof glass columns in front of windows contributes to passive solar heating when the sun is shining.

The air in the glass columns comes from the courtyard where the air is cleaner than the air from the street. It uses a mechanical system to draw air in from behind the building, passing under the building via a duct, and releasing it into glass columns outside the front windows. The system is shown in the figure below.

One criterion was that the traffic noise indoors in the renovated house needed to meet requirements in the Building Regulations, at a maximum of 33 dB Lden indoors with the windows closed.

Pre- and post-measurements of the façade insulation were carried out in two apartments. On the ground floor, the indoor noise level was reduced by 11 dB with closed windows and by 17 dB with open windows (behind the glass column). On the second floor, the indoor noise level was improved by 7 dB with closed windows and 15 dB with open windows (behind the glass column).



*Noise insulation with fresh air supply, Fredensgade,*



*Copenhagen.*

*Source: Danish Road Directorate*

### For further information

Ministry for Children and Social Affairs (2005), Grøn støj – bygningsrenovering i støjbelastede boliger, Denmark

<https://byfornyelsesdatabasen.dk/file/552684/dok.pdf>



## CASE STUDY 25

### The use of integrated planning, urban design and building design to reduce traffic noise impacts in Munich, Germany

#### Situation

Munich city is made accessible by several arterial roads heading from the outskirts to the city centre and by three arterial ring roads: the outer motorway ring, the so-called middle ring and the inner old town ring. Up to 145,000 vehicles are using the middle ring every 24 hours. Concurrently the most densely populated areas are found along the middle ring. The equivalent noise levels in front of the houses exceed 70 dB(A) during the day and 60 dB(A) at night-time. In July 2000, Munich city council resolved to implement the Middle Ring action programme which sets out the urban road planning measures and actions, the timeline for their realisation and the parties involved. In addition, a Middle Ring financial support programme was also established to promote public as well as private initiatives.



*The Munich ring roads.*

#### Action and financial support

The action plan includes three main measures which are intended to reduce the road traffic noise levels to tolerable values in residential areas:

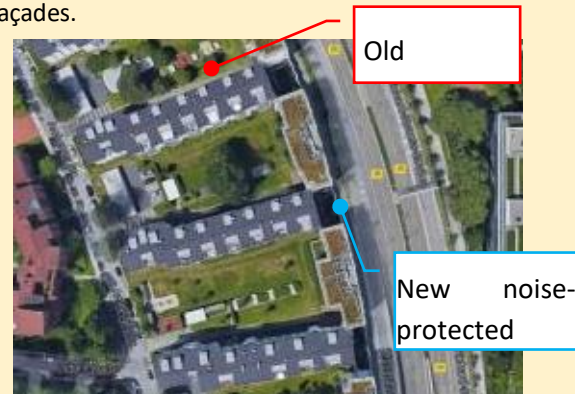
- separation of through traffic and residential district traffic
- construction of tunnels for the through traffic
- structural measures for existing buildings along the middle ring.

The commitment of the public authorities to restructure the road network, to build tunnels and to fund the efforts of private house owners in connection with the redevelopment and renovation of existing estates and housing complexes gave an effective push for an integral and extensive

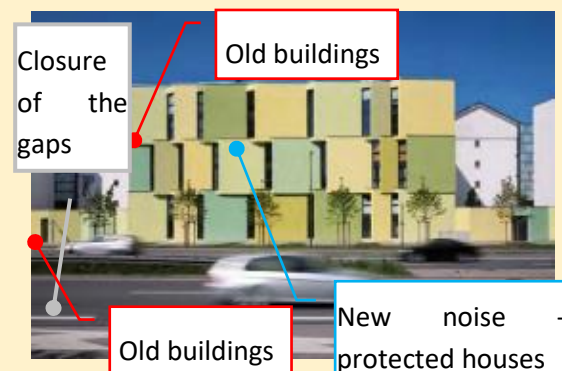
improvement of the noise situation along the ring road.

#### Structural measures – an example

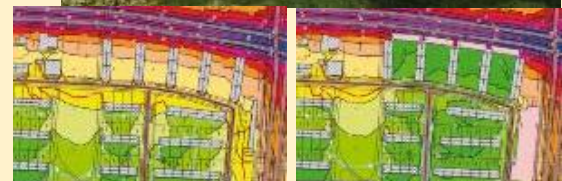
In the 1850s, many residential houses were built in Munich along existing roads. No one addressed the noise protection issue. Many buildings were built adjacent to major roads, thus forming perfect gateways for the road traffic noise impact on their façades.



*The housing situation seen from above.*



*The housing situation seen from the roadside*



*The housing situation seen from the rear side.*

*Equivalent sound pressure levels for the night-time.*

*Left: without noise protecting houses; right: with noise protection houses.*

### 9.8.3. Green walls in building design

To date, green walls have been recognised more for their climatic benefits – helping to conserve energy, improving air quality and mitigating the urban heat island effect, along with bringing about a sense of well-being. However, their acoustic properties have now raised the increasing possibility of green walls being used as a potential alternative to conventional walls in public spaces, commercial construction and traffic routes, particularly to address noise in the low and high-frequency ranges.

Not to be confused with bio barriers which are used along road corridors (refer section 9.7.6), green walls are a building design option – for both interior and exterior walls. The key concept is to have vertical panels consisting of small modules which are attached using a light aluminium frame and organic membranes richly filled with nutrients and favourable micro-organisms. The system is highly efficient in terms of irrigation, meaning it does not require excessive care. The plants reach their visual impact within a few weeks after installation.

A Spanish study, carried out under the EU-funded SILENTVEG project, conducted laboratory tests on the acoustic properties of green walls [181]. Its aim was to help predict their sound insulation performance in the real world. The modular systems in this study comprised recycled plastic boxes filled with coconut fibre acting as the *soil*. They were all planted with *Helichrysum thianschanicum* (common name curry plant), a popular shrub for gardening in the Mediterranean region, with an average height of 40 cm.

The researchers placed 10 of the boxes, totalling 2.4 m<sup>2</sup> in area, onto a wall which separated two rooms. They emitted noise in one room at frequencies ranging between 100 Hz and 5,000 Hz, and then measured the reduction in noise levels in the room on the other side of the green wall. The green wall reduced noise levels in the neighbouring room by an average of 15 dB. By comparison, thermal double glazing can reduce noise by 30 dB, and a sound barrier made from two layers of plasterboard, separated by a wool-filled cavity, can reduce noise by 70 dB. Furthermore, the sound absorption coefficient of the green wall was calculated to be 0.40, i.e. it absorbed 40% of the sound.

Hence, although green wall systems can provide passive acoustic insulation, maintenance costs can be prohibitive with estimates in the order of approximately 20% of its installation cost per year<sup>16</sup>. Nonetheless, they remain an important option for consideration in building acoustic treatments.

### 9.8.4. Soundscapes

Sound or noise in the environment has traditionally been considered in negative terms as both intrusive and undesirable as described in *chapter 4*. The EEA in its *Good practice guide on quiet areas* [182] notes:

*what we learn from two rounds of noise mapping assessment implemented in accordance with the Environmental Noise Directive (END) is that road traffic noise, both inside and outside urban areas, is the most dominant source affecting human exposure above the action levels defined by the END.*

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<sup>16</sup> <https://sourceable.net/green-walls-support-interior-acoustics/>

Consequently, much of the work to date has been oriented towards engineering noise control and determining what attenuation or amelioration measures would be employed to limit the impact of traffic noise to below defined guideline levels. However, there is increasing interest in environmental noise and its mitigation as a result of the broader issue of urbanisation [6], recognising that reducing the sound levels from certain sources may not necessarily result in an acoustic environment of high quality, because the character of the sound is equally important and greater emphasis is required on the way the acoustic environment is perceived and understood [183].

The sound environment in our cities is one of those aspects that typically appears on the project agenda only very late and often only when discovering that a project might not meet relevant regulatory requirements with respect to noise. In these situations, regulations are seen as hindering the project. This perspective that lacks the awareness of the importance that an adequate sound environment has for the functioning of the urban space [184]. Hence, the notion of “soundscape” has many positive aspects. For example, traffic noise can be annoying, but the sound from individual vehicles can provide positive information; a warning, for example to pedestrians about their presence [185].

The term “soundscape” gained prominence in the 1970s (e.g. Schafer, 1977 [186]). Schafer and his colleagues defined soundscape as *[a]n environment of sound (or sonic environment) with emphasis on the way it is perceived and understood by the individual, or by a society* [187]. Ever since this concept emerged, researchers have wondered how the acoustic environments would affect the perceived quality of cities and how sounds could be used in urban planning and design.

In 2014, the International Organisation for Standardisation (ISO) published Part 1 of a new International Standard, ISO 12913 [188], on soundscape, which defines the term as *[the] acoustic environment as perceived or experienced and/or understood by a person or people, in context*. Thus, soundscape is different from “acoustic environment” in that it is a construct of human perception, which is influenced by one’s social–cultural background as well as by the acoustic environment in context. It is more about how people experience the acoustic environment as opposed to the physical measurement of sound [183].

There are four key influences on the perception of a soundscape: demographics, activity, time and space. These factors all influence the perception of soundscapes but few of them are directly related to the sounds themselves [189]. The concept of soundscape is represented in *figure 93*, where “sound” represents traditional objective measures of the sound signal and “scape” represents the concept that a soundscape is a dynamically changing entity. It is made up of various sound sources, the perception of which also depends on the variety, mix, direction and how they interplay.

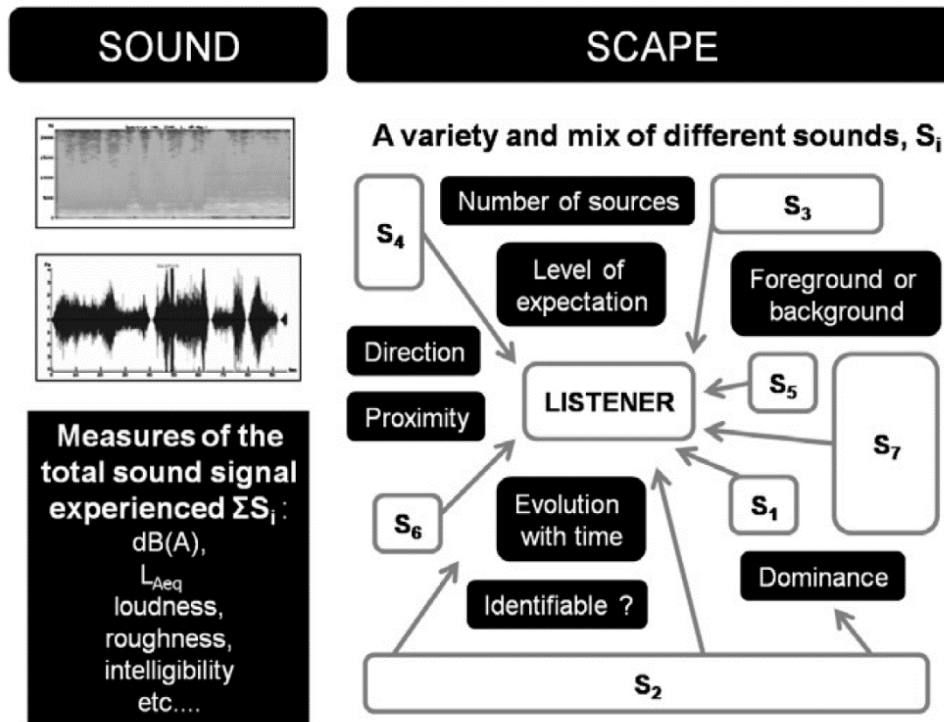


Figure 93: Concept of a soundscape. [185]

Soundscape recognises that human perception of the urban environment is multi-sensorial, with the visual sense related to the auditory sense, and such interactions can have an important effect on people's perception of noise. As an example, the effect of the noise barriers is not only a noise reduction at the ear of the resident. It also partially hides the source of the sound from sight, and visual design of the barrier may help to improve the overall perception of the environment. This demonstrates that noise control in the context of soundscape design should not only consider reducing levels of unwanted sounds, but also improve the audio-visual perception of the urban environment [184].

Ultimately, the intent is to provide the public with more meaningful sound maps based on perception of soundscapes by taking into account the relationship between the acoustic environment, human responses and the behavioural characteristics of people living in the environment [189].

The integration of soundscape design in the planning of outdoor spaces is key to creating enjoyable public spaces. Brown and Muhar [190] introduce a pragmatic approach to the acoustic design of outdoor spaces. In recognition of the diversity of stakeholders involved in place making (planners, landscape architects, engineers, acousticians, as well as engaged members of the public), they highlight the interest of setting clear and unambiguous acoustic objectives, formulated using plain language that is understood by all (see *table 15*). These objectives are derived after identification of the activities intended for the place considered and allow documenting of wanted and unwanted sounds. While these initial stages do not necessarily require specific acoustic expertise, the intervention of a specialist is instrumental to the rest of the design. It indeed involves assessing the relevant acoustic characteristics (such as magnitude, time variation) of the various components of the soundscape, by measurement or other methods, such as making use of recordings of the wanted and unwanted sounds. Strategies and design options are then investigated to manage unwanted sounds, for example by mitigation or masking, and enhance wanted sounds.

An examination of current practices shows that approaches, methods and indicators used for the identification of quiet areas vary widely, as do the physical and effect-oriented definitions or selection criteria.

A	Moving water should be the <i>dominant</i> sound level
B	A particular (iconic) sound should be clearly audible over some area
C	Hear, <i>mostly</i> , (non-mechanical, non-amplified) sounds made by people
D	<i>Not</i> be able to hear the sounds of people
E	The sounds of nature should be the <i>dominant</i> sound heard
F	<i>Only</i> the sounds of nature should be heard
G	Suitable to hear <i>unamplified</i> speech (or music)
H	Suitable to hear <i>amplified</i> speech (or music)
I	Acoustic sculpture installation sounds should be clearly <i>audible</i>
J	Sounds conveying a city's vitality should be the <i>dominant</i> sounds heard
K	Sounds that convey the identify of place should be the <i>dominant</i> sounds heard

Table 15: Examples of acoustic objectives for outdoor spaces. [190]

Figure 94 outlines the steps in an acoustic design for outdoor space and table 16 provides the EEA guidance for noise levels.

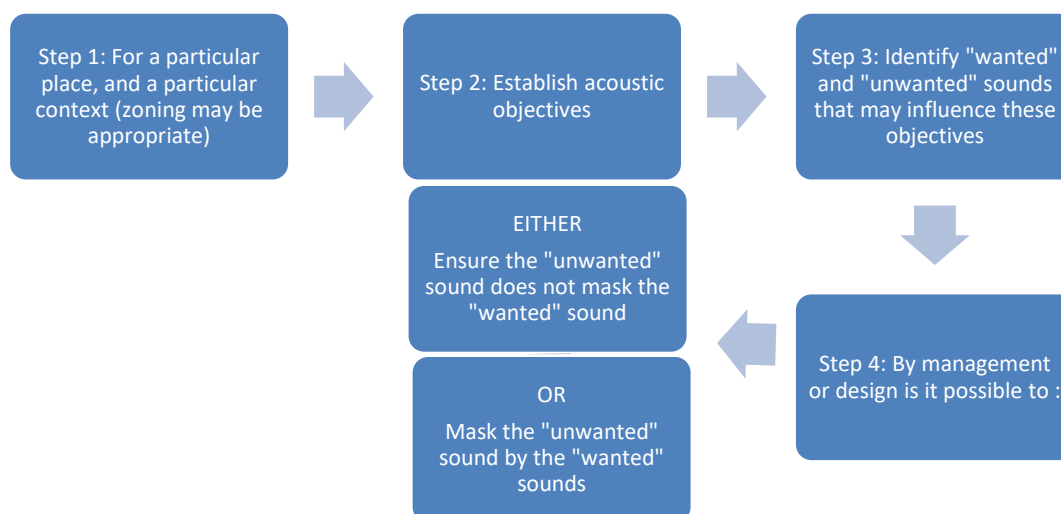


Figure 94: Steps in an acoustic design process for outdoor space.[191]

Type	Indicator	Range criteria Urban (dB)	Range criteria Open country (dB)
Acoustic indicator	L <sub>eq24h</sub>	40	25–45
	L <sub>den</sub>	50–55	–
	L <sub>50</sub>	-	35–45
	L <sub>90</sub>	-	30
	L <sub>95</sub>	30	–
	L <sub>day</sub>	45–55	30–40
Functional	Recreation	Moderate intensive activity	Passive activity
Distance	From motorway	-	4–15 km
	From agglomeration	-	1–4 km
Soundscape	Perceived acoustic quality/appreciation	-	-
Size	-	100–100000m <sup>2</sup>	0.1–100km <sup>2</sup>
Visual	Areas with established values in official documents, e.g. land use plans or nature conservation plans	-	-

Table 16: Indicators and criteria for quiet areas. [182]



## CASE STUDY 26

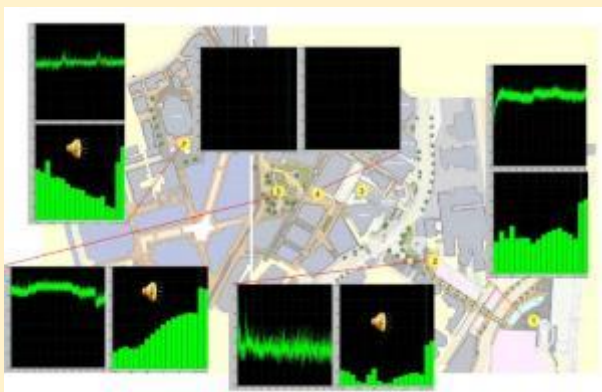
### Integration of soundscapes concept into urban design in Sheffield, England

#### Gold Route

An example of the integration of soundscape into urban design is the Gold Route in Sheffield, UK. The Gold Route links the two universities in the city through a network of public spaces and streets redeveloped from the mid-1990s to 2010. The city's historical identity is commemorated by a place design focusing on crafted steel, Pennine sandstone and flowing water. Each of the spaces of the Gold Route was designed to have its own character. This is enhanced by making use of different water features, providing each place with a specific soundscape as illustrated in the figure below. The lower figure shows changes of the waterscape sound levels with their frequency and time at different locations of the Gold Route, measured at 1 m from each water feature.



*Waterscapes across the Sheffield Gold Route*



*Changes of waterscape sound levels*

#### Sheaf Square

Sheaf Square fronts the Sheffield railway station and marks the start of the Gold Route. It received the 2010 *Great Place* award from the UK Academy of Urbanism.

Previously a carpark adjacent to major thoroughfares, Sheaf Square was transformed in 2006 as part of the refurbishment of the railway station. Access to the city, which was previously via a subway, is now through the pedestrianised square. A 90 m long stainless steel sculpture, *The Cutting Edge* provides visual separation from the adjacent main road, and effectively acts as a noise barrier, as illustrated in the figure below. The acoustic environment is further enhanced by the sound of water flowing along the surface of the structure. A number of water features, including fountains and cascades complete the soundscape of the square.



*Sheaf Square*

#### For further information

Kand and Hao (2011) [192], Kang (2012) [193]

## CHAPTER 9: CONCLUSIONS

- Planning measures including separation of sensitive uses from the noise source remains the single most significant opportunity for mitigation.
- At a regional or national level, collaboration between road agencies and other key stakeholders is required, including those responsible for urban design and planning, building design, manufacturers of vehicles and tyres, as well the construction industry responsible to ensure low noise pavements and noise barriers are constructed to meet performance requirements.
- The concept of “soundscapes” shows the need to consider the relationship between the acoustic environment, human responses and the behavioural characteristics of people living in the environment.
- Noise barriers are typically constructed from wood, metal, natural stone or concrete and need to be carefully located and constructed to ensure they deliver maximum noise mitigation.
- Vegetation barriers, such as tree belts, are unlikely to provide a demonstrable reduction in noise.
- As the aesthetic requirements of the landscape are becoming more of a concern to the community, the visual quality of a noise barrier needs to be considered on an equal footing with that of noise abatement.
- Speed management using intelligent traffic systems (ITS) can be an effective tool in traffic noise management.
- The change in traffic noise due to changes in the vehicle fleet associated with the update of electric vehicles is likely to be small, at least until electric heavy vehicles replace diesel fuelled heavy vehicles.
- Traffic noise can be reduced by construction of roads that have a smooth surface and use porous asphalt to absorb noise.

## 10. ROAD CONSTRUCTION AND MAINTENANCE

### 10.1. CONSTRUCTION NOISE

Road construction activities can produce significant levels of noise and vibration at neighbouring sites. Adverse effects from high levels of noise and vibration include annoyance and interference with daytime activities such as work, study and domestic living. Other effects include potential sleep disturbance, and long-term impacts on health, such as increased stress and hypertension. Building damage (both cosmetic and structural) may result from construction vibration. It is therefore essential that effective management of noise and vibration effects is integral to all road construction projects, particularly in built-up areas.

Construction noise mitigation measures should be properly planned and implemented in a structured hierarchy depending on the extent of predicted effects. In general, the hierarchy of mitigation should be in the order of:

- managing times of activities to avoid night works and other sensitive times
- liaising with neighbours so they can work around specific activities
- selecting equipment and methodologies to restrict noise
- installing screening/enclosure/barriers (refer
- 
- 
- figure 95 which shows the use of shipping containers as temporary noise walls)
- offering neighbours temporary relocation
- for long duration of works, treating neighbouring buildings.

Effective stakeholder engagement is a critical part of managing construction and maintenance noise and vibration. Stakeholder engagement can have a greater bearing on acceptance of the works and complaints than the actual noise and vibration levels. Neighbours who understand what, when and why the works are happening are often able to adjust their activities accordingly and are generally more tolerant of construction noise and vibration. For larger projects, stakeholder engagement should commence during the planning stages. Residents can be informed about the work through a variety of means, including personal visits, letter drops, community meetings, newspaper and radio advertising, site signboards, posters and notices on websites. Where work continues for long periods, regular updates are important.

Where practicable, works should also be scheduled to avoid noisy or vibration producing activities at any specific times identified as particularly sensitive through stakeholder engagement, accepting there is a balance between avoidance of sensitive times and the overall duration of the works. Examples include school exams or community events.



Figure 95: Temporary shipping container noise wall, Monash Freeway, Mulgrave, Australia  
(Source: J.McIntosh, Department of Transport, Victoria, Australia).

## CASE STUDY 27

### New Zealand online construction noise calculator

#### Overview

To promote good practice in construction noise management, the NZ Transport Agency has developed a free online web-based calculator to make estimations of construction noise for specific activities using a standard equipment library.

The calculator is in a simple format requiring minimal input and is intended to empower the contractor's site staff to regularly check likely noise from upcoming activities, rather than relying on advice from external noise specialists.

Type	Distance	Quantity	Time	Site length	Speed
Excavator (>20t) - 82dB	50 m	1	100%	20 m	km/h
Generator (50 KVA) - 73dB	80 m	1	100%	m	km/h
Truck (10 tonne) - 70dB	50 m	40	100%	m	30 km/h
- Select item -	m	1	100%	m	km/h

Summary	
Excavator (>20t)	70dB
Generator (50 KVA)	58dB
Truck (10 tonne)	52dB
Façade level ( $L_{Aeq(T)}$ )	
	71dB

#### Web-based construction noise calculator

<https://nzta.govt.nz/roads-and-rail/highways-information-portal/tools/construction-noise-calculator/>

#### Evaluation

The tool has provided contractors on major road construction projects with a more efficient way of managing construction noise. However, predictions using the calculator have been found to be consistently higher than measured levels. Part of the reason for this is that the standard equipment library in the tool often does not match the actual equipment used on site which may be quieter. This can be addressed by entering noise levels of custom equipment into the tool-based on-site measurements.

Another reason for over-prediction of noise levels is that a simplified algorithm is used which does not consider all factors affecting noise, such as screening and air absorption. However, this degree of conservatism is considered appropriate for screening purposes to identify areas requiring noise mitigation measures.

A possible future development of this calculator may be a simple GIS-based tool for input of equipment and receiver locations.

#### For further information

[environment@nzta.govt.nz](mailto:environment@nzta.govt.nz)

## CASE STUDY 28

### Replacement of reversing beepers on construction vehicles with broadband alarms to minimise noise disturbance

#### Overview

Communities are often more sensitive to construction noise with a disturbing characteristic, than they are to construction noise at high levels. An example of a frequent cause of complaints in New Zealand is tonal reversing *beepers* on construction vehicles.

Traditionally, most construction vehicles have been fitted with a tonal alarm that makes a loud beeping noise as the vehicle reverses. The noise from these alarms is distinctive due to the single frequency (tone) of noise being produced. Consequently, as well as achieving the goal of attracting the attention of construction workers behind the vehicle, the alarms can be disturbing for nearby residents, particularly at night.

Now a practical and cost-effective solution is to replace the tonal beepers on construction vehicles with broadband alarms.

#### Broadband alarms

Broadband reversing alarms generate noise across a range of frequencies, which creates a less harsh characteristic than tonal beepers. The broadband alarms have a fluctuating sound and are sometimes described as *squawkers* or *quackers*.

Close to a vehicle, broadband alarms can be as loud as tonal beepers, but at a distance the noise does not have the same distinctive characteristics and causes significantly less disturbance. Residents living near construction projects in New Zealand have expressed a clear preference for the broadband alarms.

Broadband alarms generally produce a *beam* of noise, which means they are louder in one direction than in others. When correctly fitted with the beam facing backwards, the alarm will be loud behind the vehicle where workers need to be made aware of the vehicle reversing, but less noise will be *spilled* in other directions towards residents. In addition to the less disturbing noise characteristic, the noise level in neighbouring areas is reduced while safety of workers is maintained.



*Broadband reversing alarm unit*

For construction projects using broadband alarms the biggest challenge in New Zealand has been ensuring that all subcontractors, as well as trucks visiting the site on a one-off basis, have the right alarms fitted. Tight controls are required to ensure all subcontractors adhere to broadband reversing alarm requirements.

#### For further information

[environment@nzta.govt.nz](mailto:environment@nzta.govt.nz)



## 10.2. ROAD SURFACE MAINTENANCE AND NOISE

The surface texture, or roughness, is an important parameter in the design and maintenance of a road. Defects and other surface features can contribute to increased noise from roads.

Maintenance techniques can be effective at prolonging the service life of surfaces. It is also important to maintain roads in good working order to minimise noise. Aspects of poorly maintained roads that contribute to noise include:

- potholes which result in impact noise between vehicle tyres and the edge of the hole, and cause truck loads to rattle
- loose inspection pit covers that rattle when driven over
- ravelling of asphalt (aggregate becoming loose) increasing tyre/pavement rolling noise (see *figure 96*)
- uneven expansion joints in cement concrete roads which result in tyre impact (see *figure 97*).



Figure 96: Example of severe ravelling. (Source: Rijkswaterstaat, Netherlands)

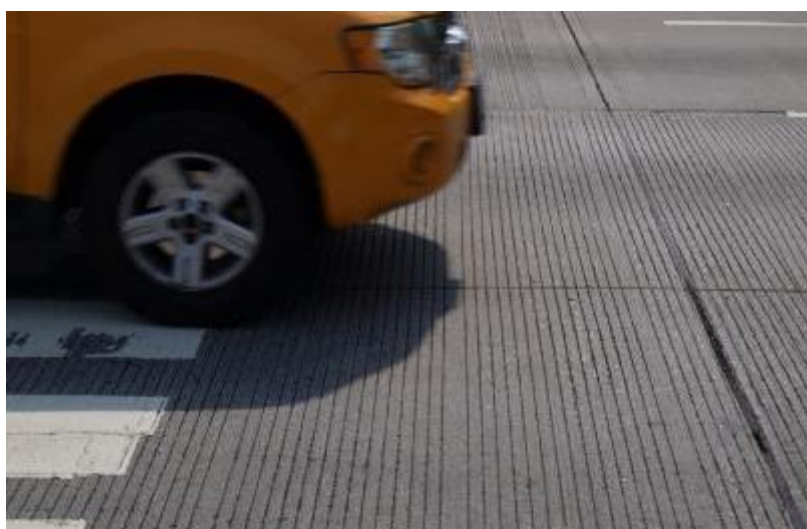


Figure 97: Transversely grooved concrete road, New York City, USA.  
(Source: J McIntosh, Department of Transport, Victoria, Australia).

Poor construction of surfaces can cause defects that contribute to noise impacts. In a similar manner to patches, joints in road surfaces (including ramps and bridges) can produce a mechanical noise from vehicles, which can result in disturbance to neighbouring residents. All road surfaces are at least the

thickness of the aggregate (e.g. 10 mm), which makes it difficult to create a perfect joint. A key factor is to position joints between different road surface types as far from residential properties as practical.

Another example is the installation of audio tactile profiles (ATPs). Otherwise known as a rumble strips, they are designed for safety reasons to generate noise inside a vehicle as a warning to the driver. However, they also cause significant noise outside the vehicle (refer *figure 98*). The noise produced by vehicles travelling on an ATP is typically increased by over 5 dB and has a distinctive low frequency tonal character (rumble) [194].



*Figure 98: Audio tactile profile (ATP) line marking.  
(Source: NZ Transport Agency)*

Consideration should therefore be made to laying an ATP at a reasonable distance from residential properties. For example, an ATP can be laid at least 200 m from residences or other noise sensitive properties, although this may be reduced to 100 m where vehicles are unlikely to drive frequently over ATP markings<sup>17</sup>.

Other maintenance factors that can influence noise generated by the tyre-road interface include:

- Patches: Maintenance work to repair pot-holes and localised defects can cause a change to the surface of the road, with the patch creating a joint. Even a small step-change in the road surface height at the joint can cause *body slap* noise to be generated, especially from empty trucks. The increased noise from the trucks running over the uneven surface can be the cause of noise disturbance, particularly if this is located outside a residential property.
- Prevention and repair of ravelling: If surface aggregate starts to ravel (become loose), tyre/surface noise can increase. To minimise the potential for this effect, surfaces should be sealed. Surfaces can be sealed before ravelling starts using an emulsion with a rejuvenator which is spread over the porous asphalt surface (preventative maintenance method). If the ravelling process has already started, an open emulsion sand asphalt mixture can be applied in the upper part of porous asphalt. Open emulsion sand asphalt is visually not attractive as it has an uneven appearance, but it has been shown to reduce the noise effects of ravelling and is cost effective. Towards the end of service life of the surface, ravelling can be remedied

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<sup>17</sup> For further information on ATPs, refer to TRB presentation – Highway rumble strips: approaches to balancing public safety and community noise. <http://www.trb.org/Main/Blurbs/175712.aspx>

through the inlay of a new porous asphalt layer. Care should be taken to avoid ravelling on old porous asphalt sections during inlay of new porous asphalt.

- **Cleaning:** The noise performance of porous road surfaces reduces over time due to clogging of the voids by dirt and oily materials. Clogging can occur after two or three years of the surface being laid. High-pressure water cleaning (as shown in *figure 99*) has been shown to effectively clean the surface without damage to the structure and can help re-establish the surface's noise performance. It is important to schedule cleaning operations as early as possible to prevent dirt from building up in the pore structure. Studies have indicated that surfaces cleaned preventively once or twice each year may re-establish their long-term noise performance.
- **Resurfacing:** Re-surfacing can alter road-traffic noise levels, particularly if the surface type is changed. Generally, re-surfacing with the same road surface type (including the chip size) will result in similar road traffic noise. Re-surfacing with a significantly noisier surface may have a large impact on nearby residents. When an existing road is re-surfaced it is therefore important to consider the noise implications.



*Figure 99: Road surface cleaning truck  
(Source: NZ Transport Agency.)*

## CHAPTER 10: CONCLUSIONS

- Effective stakeholder engagement is a critical part of managing construction and maintenance noise and vibration.
- Poor construction of road surfaces can cause defects that contribute to noise impacts.
- The noise performance of porous road surfaces reduces over time due to clogging of the voids by dirt and oily materials.
- Road surfaces cleaned preventively once or twice each year may re-establish their long-term noise performance.

## CASE STUDY 29









### Testing the noise impact of different road marking profiles in Denmark

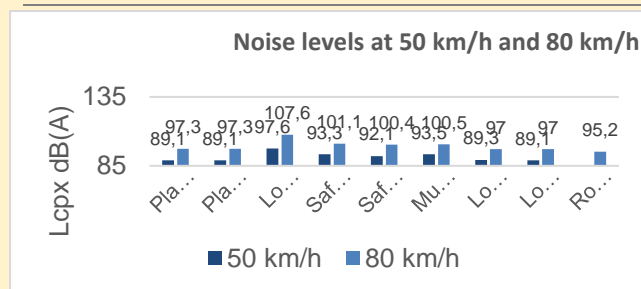
The Danish Road Directorate has tested different variants of road markings to examine whether they are less noisy than the main types of road markings when driving over, while at the same time having acceptable lighting characteristics.

Two of the road markings are horizontal plane with widths of 15 and 30 cm, while six are profiled. The table below shows the geometric conditions of the profiled road markings. Longflex 30 cm is of the type usually used for profiled roadblocks in Denmark.

Type	Length of mark	Gap between marks	No. of rows	Displacement between rows
Longflex 30 cm	20 cm	5 cm	1	
Safeflex 15 cm	17 cm	7 cm	3	5 cm
Safeflex 30 cm	37 cm	24 cm	6	5 cm
Multidot 30 cm	6 cm	3 cm	12	3 cm
Longdot 15 cm	10 cm	2 cm	6	5 cm
Longdot 30 cm	8 cm	2 cm	12	4 cm

*The geometrical conditions of the profiled roadbars*

Plane 15 cm	Plane 30 cm	Longflex 30 cm
		
Safeflex 15 cm	Safeflex 30 cm	Multidot 30 cm
		
Longdot 15 cm	Longdot 30 cm	For further information
		Danish Road Directorate, Jakob Fryd, e-mail: jaf@vd.dk



Noise measurements were performed for each type of road markings according to ISO/DIS 11819-2 Acoustics – Method for measuring the influence of road surfaces on traffic noise: part 2: Close-proximity method at speeds of

50 km/h and 80 km/h. The above figure shows the results of CPX-measurements of the different types of road markings.

It was concluded that the two Longdot markings are promising because of low noise levels and good lighting characteristics. Compared to plane road markings, Longdot markings have approximately the same noise values. Compared to Longflex 30 cm which is the type usually used for profiled roadblocks in Denmark, the Longdot markings resulted in significantly lower noise levels.

## CASE STUDY 30

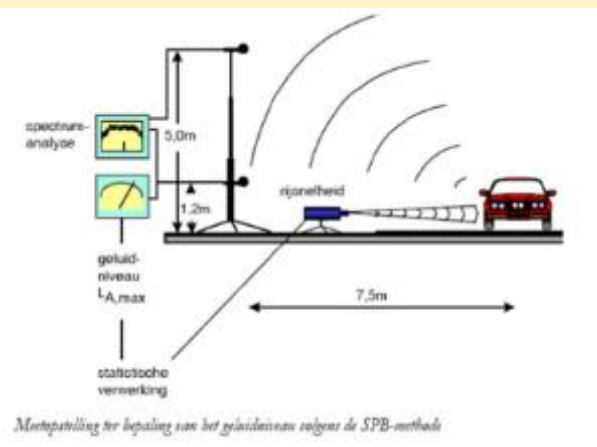
### SPB measurements to investigate acoustic aging in Netherlands porous asphalt road surfacing

#### Overview

Since 1990, Rijkswaterstaat (the Ministry of Infrastructure and the Environment in the Netherlands) has implemented low noise road surfacing porous asphalt concrete 16 (PA16) (particle size 6/16, layer depth 50 mm) to reduce road traffic noise from the highway network.

In 2012, a new noise law entered into force in the Netherlands which set a minimal acoustic standard for road surfacing for major roads. Since 2012, PA16 has become the standard road surface in the Netherlands due to its acoustic performance (able to achieve an average sound level over the lifetime of the surface of around 3dB). There are however constraints, such as higher costs and limited lifetime (e.g. on tight curves) when compared with some other surfacing alternatives.

The determination of the acoustic properties of the low noise road surface is through statistical pass-by (SPB) measurements (based on ISO 11819-1).



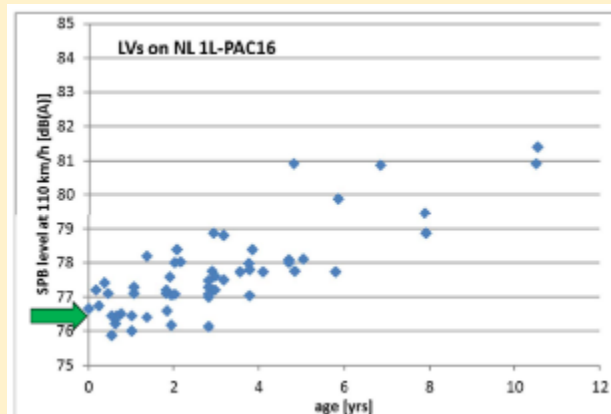
Showing the SPB methodology

In 2014, research was undertaken to investigate the acoustic aging of porous asphalt. The effects of aging porous asphalt include ravelling (affecting texture) and reduced void content. SPB measurements were used to assess the acoustic performance of the aging surfaces.

#### Results

The results of the 2014 research study (including 60 porous asphalt measurements across different test sites) indicated that the SPB level for passenger cars is a function of the age of the surface, with SPB levels generally increasing with time.

SPB levels as a function of age for cars



The end of lifetime/replacement of the porous asphalt road surface ranged from 8–18 years.

The noise reduction properties of PA16 were found to increase with the average speed of traffic for passenger cars but remained the same across all speeds recorded for trucks.

The results of the study indicated that the average sound level over the lifetime of the surface of PA16 for the traffic mix on the highway network was 2.7 dB.

#### For further information

<https://www.rijkswaterstaat.nl/english>



## 11. CONCLUSIONS AND RECOMMENDATIONS

Noise from road transport is a growing concern amongst policy makers, road agencies and the general public. Unfortunately, many road agencies are yet to evaluate the environmental noise exposure of their affected population and consequently do not fully appreciate the health and economic burden that traffic noise represents. In comparison to many other pollutants, the management and mitigation of traffic noise is hampered by this lack of knowledge, as well as the lack of consistent metrics and criteria for assessment and evaluation.

Traffic noise exposure is also a social equity issue. With lower housing costs near busy, noisy roads, the effect of noise is not uniformly distributed throughout the population, with vulnerable groups such as children, the elderly, the sick and lower socio-economic groups suffering most.

A further factor is that as urbanisation increases so will congestion, leading to commercial vehicles shifting journeys to night-time hours, resulting in increased sleep disturbance.

In contrast to air pollutant emission standards for vehicles, noise emission limits have not been enforced and have lagged behind vehicle advancements. The most cost-effective noise mitigation measures are those addressing the noise at source. This includes noise from the engine, exhaust, mechanical systems and contact between tyres and the road. However, there has been no evidence that population exposure to traffic noise has reduced as vehicle fleets have modernised and automated. There is a clear need for motor vehicle manufacturers and policy makers to collaborate on improving test conditions and standardising vehicle noise emission requirements to achieve cost-effective reductions in ambient noise levels.

The impact of traffic noise on the community can be minimised through greater integrated transport and land-use planning and appropriate urban design that locates noise sensitive land uses, such as homes and schools, away from busy roads. Strategic transport and land-use planning is also critical in limiting traffic noise by reducing traffic volumes; minimising distances that people need to travel and reducing car dependency by providing alternative modes of transport, such as public transport or active transport modes. Integrated land use and transport planning is essential in delivering the best possible environmental outcomes, avoiding mitigation that might otherwise need to be implemented. Road agencies need to take a stronger role in influencing land-use planning as the single most important step in avoiding and/or preventing further increases in the environmental burden on current populations and future generations due to traffic noise.

Although often criticised by the community for the level of disturbance associated with traffic noise, road agencies are only one part of the solution. Effective traffic noise management must be seen as a shared responsibility including:

- vehicle and tyre manufacturers for their role in reducing the source of noise from propulsion systems and the tyre-road interface
- government and policy makers for their role in introducing legislation to regulate noise from vehicles and the determining acceptable levels for sensitive receivers
- vehicle owners and drivers for their role in vehicle maintenance and operation of the vehicle to reduce unnecessary use of horns and engine brakes which in some countries or major cities, may be more important than a new high performing low noise road surface
- planning authorities for their role in appropriate buffers and land use



- property developers and building designers for their role in designing and building housing stock with appropriate noise insulation.

This best practice guide provides an overview of the range of mitigation measures available to road agencies, however, the technological solutions must be supported by:

1. Partnerships – inside and outside of a road agency, with the right stakeholders at the right time to collaborate on new technologies and to affect an improved understanding of the importance of noise mitigation.
2. Systems thinking – to emphasise the need for holistic solutions and to understand the complex interactions between transport and the environment to enable effective interventions.
3. Economic evaluation – it is often difficult to fully cost the impact of transport externalities such as noise, especially at a project level. Benefits are often assessed as incidental relative to the value of travel time and costs do not fully reflect the indirect impact on the community. There is a need to better understand the full economic value associated with transport-related environmental interventions and incorporate these into cost benefit assessments, particularly given the recent guidelines released by the World Health Organization [11]. To do so, requires road agencies to undertake a systematic assessment of the noise exposure across the network and to recognise that short term profits need to be balanced against long term benefits particularly as retro-fitting noise mitigation is often far more expensive than avoidance or early mitigation.
4. Capability development – raising capability within road agencies is an important step in ensuring that designers, planners, engineers and environmental staff fully appreciate the implications associated with network design, maintenance and development. Simple communication tools, such as case studies, access to auralisation files and infographics are key to disseminating information and raising awareness.

Whilst the need for collaboration across planning, transport and environmental agencies has been noted, it is equally important that road agencies continue to share their understanding and knowledge. The road noise database (**Road Noise dB**) developed by Technical Committee E2 and maintained by PIARC, remains a key tool in highlighting the current range of policies, metrics and criteria used in the assessment and evaluation of noise. Continuation of this database will assist PIARC members in developing a consistent evaluation framework.

Finally, new technologies such as ITS, autonomous vehicles and electric vehicles may partially address traffic noise problems, but are unlikely to provide a complete solution. In the short term, they may lead to increased noise levels, if they facilitate increased mobility of more vehicles. As a result, quiet pavement technology and traffic noise barriers, remain key mitigation tools available to road agencies. Further work is required to provide more support to agencies and their contractors to ensure that these are constructed and maintained for optimal acoustic performance, in addition to safety and durability, during their life.

In conclusion, it is interesting to review the development of road agencies. Historically, road agencies were established to provide a consistent standard of road infrastructure, directly managing state or national roads or highways. This responsibility included authorisation to use the roads, with road agencies tasked with licensing of drivers and registration of motor vehicles. Road

safety matters were not a major consideration in the early days of an emerging new transport technology. However, the growth in vehicle ownership resulted in increased vehicle fatalities, requiring road agencies to enter a second phase which focussed on reducing road fatalities. More recently, although fatalities have fallen, injuries requiring hospitalisation continue to increase, contributing both directly and indirectly to significant costs to the community. Hence, road safety remains a core priority for road agencies worldwide.

A third and future phase for road agencies, is likely to focus on the *health* of the population which would include reducing road trauma, increasing active transport and public transport and reducing or eliminating road transport emissions such as traffic noise. For those road agencies that are currently moving in this direction, it signals the clear need to give greater prioritisation to environmental issues and take the next evolutionary step in addressing one of the most important environmental risks to health today from the transport industry – road traffic noise.

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### 13. GLOSSARY

AADT	Annual average daily traffic
Aspiration	With respect to traffic noise policy, it is a statement of what would be desirable “in an ideal world”. [In decreasing order of enforcement – law, requirement, guideline, goal, <i>aspiration</i> ].
Angle of diffraction	Angle of diffraction is the angle that the path of noise must bend to get around an obstruction in order to get from the source to the receptor.
A-weighting	The most common weighting that is used in noise measurement is A-weighting. Like the human ear, this effectively cuts off the lower and higher frequencies that the average person cannot hear. A-weighted measurements are expressed as dBA or dB(A).
Binaural	Relating to sound recorded using two microphones and usually transmitted separately to the two ears of the listener.
CEDR	Conference of European Directors of Road
CI	Confidence interval
Conditioning	Used in determining the effectiveness of a noise barrier, conditioning refers to the need to assess whether sound reflections at the barrier need to be suppressed.
Coast-by noise levels	Coast-by noise levels are taken when the engine is off and the gearing decoupled, for cars rolling by at a distance of 7.5 m from the microphone, with a speed of 80 km/h.
CPB	Controlled pass-by
CPX	Close proximity (road surface noise measurement)
C- weighting	In comparison to the A-weighting, the “C” weighted sound level does not discriminate against low frequencies and measures uniformly over the frequency range of 30 to 10,000 Hz. C-weighted measurements are expressed as dBC or dB(C).
DALYs	Disability-adjusted life years
dB	Decibels
DEFRA	UK Department of Environment, Food and Rural Affairs
Dimensioning	Used in determining the effectiveness of a noise barrier, dimensioning refers to the need to assess the most appropriate height and length of the barrier.
EEA	European Environment Agency
EIA	Environmental impact assessment

END	Environmental Noise Directive (Directive 2002/49/EC relating to the assessment and management of environmental noise)
EU	European Union
EPA	Environment Protection Agency/Authority
Façade noise level	A noise level measured or predicted at the façade of a building, typically at a distance of 1 m, containing a contribution made up of reflections from the façade itself. In general, a façade level will be three dB higher than a free-field level.
Far field	Distribution of acoustic energy at a much greater distance from a source than the linear dimensions of the source itself; the region of acoustic radiation used to the source and in which the sound waves can be considered planar. See also near field
FHWA	United States Federal Highways Administration
Free field noise level	Noise levels that have been measured or predicted in the absence of any influence of reflections from nearby surfaces, other than the ground. In practice, a noise level is considered to be free field if it is at a distance greater than 3.5m from any reflecting surfaces, other than the ground.
GDG	Guideline Development Group (for the 2018 WHO Environmental Noise Guidelines for the European Region [11])
GIS	Geographic information system
Goal	With respect to traffic noise policy, is a statement of what an organisation aims to achieve. [In decreasing order of enforcement – law, requirement, guideline, <i>goal</i> , aspiration].
Grid noise calculations	A grid noise calculation is the calculation that produces a map of noise levels at a grid of points completely covering an area of interest.
Guideline	With respect to traffic noise policy, it is a specification that an organisation will seriously strive to achieve, but may not achieve in some circumstances. [In decreasing order of enforcement – law, requirement, <i>guideline</i> , goal, aspiration].
IEMA	Institute of Environmental Management & Assessment
I-INCE	The International Institute of Noise Control Engineering – a worldwide consortium of organisations concerned with noise control, acoustics and vibration. The primary focus of the institute is on unwanted sounds and on vibrations producing such sounds when transduced. I-INCE is the sponsor of the INTER-NOISE Series of International Congresses on Noise Control Engineering held annually in leading cities of the world.
Indicator	With respect to traffic noise criteria, it is a chosen measure used to describe a noise level. Also called, descriptor, index or metric.

IRR	Incidence rate ratio
ISO	International Organisation for Standardisation
ITS	Intelligent transport systems
Law	With respect to traffic noise policy, it is a legal requirement. [In decreasing order of enforcement – <i>Law</i> , requirement, guideline, goal, aspiration]
LAeq	A-weighted, equivalent sound level. LAeq is the equivalent steady A-weighted noise level which contains the same acoustic energy as the actual fluctuating noise.
Ldn	Ldn (day-night average sound level) is the LAeq level for the 24-hour day calculated after adding a 10 dB penalty to the night-time period. This penalty reflects that noise is more disturbing at night when people are trying to sleep.
Lden	Lden ( <i>day, evening, night sound level</i> ) is similar to Ldn, but with a penalty of 5 dB that applies for the evening period, as well as the 10 dB penalty for the night period. The hours that define the daytime, evening and night-time period vary between jurisdictions.
LKZ	LärmKennZiffer, a German noise index to determine the impact of noise
Materialisation	Used in determining the effectiveness of a noise barrier, materialisation refers to the need to determine the most appropriate material to meet acoustic and structural requirements.
n.d.	No date
Nearfield	Nearfield of the sound source, which (in the context of this report) is the tyre/road contact point. Within this region the sound field includes characteristics that are not measured when observations are made further away from the source, in the far field. Typically, the near field is limited to a distance from the source equal to approximately one wavelength of sound or equal to three times the largest dimension of the sound source - whichever is the larger.
NEF	Noise exposure factor
NES	Noise exposure score
NEU	Noise exposure unit
Noise immission	Noise immission is created by noise sources (noise emission) of various types which are propagating noise into the environment.
OBSI	On-board sound intensity
OGA	Open graded asphalt

PA	Porous asphalt
Positioning	Used in determining the effectiveness of a noise barrier, positioning refers to the need to assess where should the noise barrier be placed between road and receiver.
Requirement	With respect to traffic noise policy, is a specification that is regarded as mandatory but has no legal force. [In decreasing order of enforcement – law, <i>requirement</i> , guideline, goal, aspiration].
Road Agency	Any organisation with responsibility for national and/or local roads including planning, construction and operation. The term is used interchangeably with road administration or national road authority.
SANS	Southern African National Standard
SEK	Swedish krona
SPB	Statistical pass-by (method)
SMA	Stone mastic asphalt
Thermic	Pertaining to, or caused by heat or temperature: e.g. thermal energy
WHO	World Health Organization
YLL	Years of life lost due to premature mortality in the population where $DALY = YLL + YLD$ .
YLD	Years lost due to disability (YLD) for people living with the health condition or its consequences where $DALY = YLL + YLD$



## APPENDIX 1: COMPARISON OF MAJOR TRAFFIC NOISE MODELS

Technical attributes	TNM Model	CRTN Model	RLS 90 Model	ASJ-RTN Model	SonRoad Model	Nord2000 Model	NMPB Routes Model	CNOSSOS	KHTN
Application	Highway and networks	Highway, single traffic stream	Highways, car parks, simple streams only	Highway constant speed in different traffic conditions	Highway, road networks	Source model for road and rail traffic	Highway, road networks	Road and railway traffic	Highway, road networks
Predicts traffic volumes	No	No	Yes	No	No	No	No	No	No
Traffic conditions	Constant speed, acceleration, grade and interruption	Constant speed, grades	Constant speed, grades, quasi-intersections, interruptions	Constant speed, acceleration/deceleration mode, junctions, signalised intersections, road tunnels, depressed and semi-underground roads, flat/overhead roads and double-deck viaducts	Constant speed, grades	Motorway, urban motorway, main road, urban road, urban road or feeder road in residential area, residential road	Steady speed, acceleration, deceleration	Constant speed, acceleration/deceleration mode, corrections for slip and acceleration/deceleration defined	Constant speed, grades
Vehicle types	Automobiles, medium trucks, heavy trucks, buses	Light vehicles/ heavy vehicles	Light vehicles/ heavy vehicles/car parks	Light vehicles (passenger cars and small sized vehicles),	Passenger cars and trucks	Light (<3,500kg), medium (3,500-12,000kg) and	Light vehicles <3.5 tonnes and heavy goods vehicles, 3.5	Light vehicles, medium heavy, heavy, other heavy	Passenger car, Light truck, medium

Technical attributes	TNM Model	CRTN Model	RLS 90 Model	ASJ-RTN Model	SonRoad Model	Nord2000 Model	NMPB Routes Model	CNOSSOS	KHTN
	and motorcycles			heavy vehicles (medium sized and large sized) and motorcycles		heavy (>12,000kg) vehicles	tonnes or higher	vehicles and two wheelers	truck, bus, large truck
Propagation	Energy type Propagation in 1/3rd octave band is modelled considering atmospheric absorption, divergence, acoustical characterisation and topography of intervening ground, walls, earth mounds and their combinations, intervening rows of buildings and intervening areas of heavy vegetation.	Energy type	Energy type The calculation is made starting from an average level $L_{m,E}$ measurable at a distance of 25 m from the centre of the road lane. It includes corrections due to presence of obstacles, vegetation, air absorption, reflection and diffraction, ground absorption, etc.	Energy type The model is developed based on geometrical acoustics and contains effects of shielding by barriers or buildings, ground surface, air absorption and meteorological condition. The procedures for application to roads with special cases such as interchange, signalised intersection, double deck viaducts, road	Energy type Propagation model calculates geometrical spreading, air absorption, reflections at vertical surfaces, possible shielding effects and the constructive and destructive interference between direct and ground reflected sound waves.	Energy type Propagation model is based on analytical solution (geometrical ray theory and theory of diffraction) calculates the 1/3rd octave band attenuation from 25 Hz to 10 kHz for a homogeneous atmosphere. Refraction by geometrical modification of rays based on heuristic approach is incorporated. Model is applicable for any terrain	Energy type Propagation model includes calculation of probability of occurrence of downward refraction conditions for each direction, search for propagation trajectories between each source and receiver, calculation of attenuation in downward refraction conditions and homogeneous conditions. Sound levels are weighted	Energy type Reference model employs three propagation models: parabolic equation (PE) model, straight-ray (RAY) and boundary element method (BEM). Atmospheric refraction is taken into account by PE. Outside the source region, a PE model is used. For a flat ground surface, the Crank-Nicholson PE (CNPE) model	Energy type Propagation model calculates geometrical spreading, air absorption, ground absorption, the shielding effect by diffusing wall (diffraction attenuation)

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				tunnel, semi underground road and roads, with built-up areas are also included.		profile assuming that terrain is approx. by a number of straight segments characterised by surface impedance and roughness. Fresnel zone interpolation is preferred for all terrains	by average occurrence pi of downward refraction conditions and homogenous conditions	or the Green's function (GFPE) model is used. For a ground surface with smooth hills, the generalised-terrain PE model (GTPE) is used. BEM and RAY are used for obstacles with complex shapes, while CNPE and GFPE for rectangular obstacles. Point-to point propagation is dependent on speed-sound gradient calculated from the wind speed, wind direction and temperature profile.	

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Basic model	It computes vertical sub source vehicle emissions depending upon vehicle type, pavement type and throttle conditions. Seventeen constants defined depending upon variables for converting A-weighted noise level emissions to 1/3 <sup>rd</sup> octave band spectra. Emission based on vehicles pass-by at 15 m over flat absorptive ground	L10 in terms of total hourly flow is calculated at a reference distance of 10 m and reference hourly mean traffic speed of 75 km/h	Average level LmE at a distance of 25 m from centre of road lane and is a function of amount of vehicles per hour and % of heavy trucks	Sound power level is defined as a function of vehicle speed with change in noise generated due to pavement type, road gradient and noise directivity considered in correction terms. Sound power level is defined for steady and non-steady traffic flow. For signalised intersections and junctions, the coefficient of deceleration and steady flow are the same, while coefficients for acceleration and non-	Sound power level derived from maximum pass-by level of single vehicle at a distance of 7.5 m and at a height of 1.2 m above ground. Effective source height is 0.45 m.	Sound power level is derived from pass-by measurements with result normalised to 10 m and angle of integration of 2.75 rad. Method provides 1/3 <sup>rd</sup> octave band results from 25 Hz to 10 kHz.	Noise emission of traffic lane characterised by its sound power level per metre and per vehicle Lw/m/veh which is the sum of power unit noise component and rolling noise component. Rolling noise component is defined for three road surfaces R1, R2 and R3.	Each vehicle category is represented by two point sources, each having a specified sound power contribution from rolling and propulsion noise. For calculating the sound power from whole vehicle, the sound power between lowest and the highest source is distributed. The effect of speed and acceleration is taken into account in formulation of source strength for rolling and propulsion noise	Pass-by noise and CPX noise are caused by running at 60 km/h for passenger cars, SUVs and buses, 50 to 110 km/h for small trucks, 10 km/h for trailers and dump trucks at 50 to 100 km/h. Measure and analyse.

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				steady flow are the same.					
Geometrical divergence	Adjustment for distance Ad from the elemental roadway segment to receiver defined $Ad = 10 \log_{15} d \sin \alpha$ 180 $\alpha$ is angle subtended by elemental roadway segment in degrees	$\Delta d$ is distance adjustment define	$DS, L$ , is attenuation to distance and air absorption defined in model $Ds = 11.2 - 20 \times \log(s) - (s/200)$ where s is distance between emission and emission point	$LA = LWA - 8 - 20 \log(r) + \Delta L_{cor}$ where LWA is A-weighted sound power level of single running vehicle and $\Delta L_{cor}$ accounts for corrections for diffraction, ground effect and atmospheric absorption	$A_{div}, f = 20 \log \times (d) + 11$	$\Delta L_d = 10 \log(4 \pi R^2 / R_0^2)$ R = propagation distance, $R_0 = 1m$		Point source: $\Delta L_d = 10 \log(4 \pi d^2 / d_0^2)$ d = propagation distance, $d_0 = 1m$ Line source: $\Delta L = 10 \log(\Delta \theta / 4 \pi d)$ $\Delta \theta$ = angle of view from receiver to segment	$L_{wi} = A_i + B_i \log V$ In KHTN, the coefficient is applied to the 1/1 octave band center frequency in the range of 63 to 8,000 Hz
Source characteristics and height of source	Simple stream. Energy apportioned to two source heights: one at pavement level and one at 1.5 m above pavement except for heavy trucks, where the	Single stream. Noise levels are obtained at a reference distance of 10 m from the nearest carriageway edge of highway	Single stream. The starting point of the calculation is $L_{mE}$ measurable at a distance of 25 m from centre of road lane. The model is also able to evaluate the source	Simple straight stream.	Single vehicle with microphone position at a distance of 7.5 m and at height of 1.2 m	Road and railway lines are represented by a number of vertically and horizontally spaced point sources. Vehicle is represented by noise source at	Each source line is broken down into a set of sound point sources placed 0.05 m above roadway. $G_{dBN08}$ describes the pass-by maximum levels in dB(A) measured at	Distributes 80% of tyre road noise on a source 0.01 m above the ground and 20% either on 0.30 m or 0.75 m depending on type of vehicle. For propulsion noise, it is the other way	Simple straight stream.

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	upper height is 3.66 m above the pavement		emissions of the parking lot.			height 0.01 m, 0.30 m and 0.75 m. Heavy vehicles have an extra source height of 3.5 m.	7.5 m horizontal distance and 1.2 m height above the ground surface.	round. For heavy construction equipment, additional point source for exhaust noise at 3.5 m is used.	
Input data	Traffic type, flow, speed, road and emission data, local characteristics	% heavy vehicles, flow, speed, road and environmental data, gradient	Traffic type, flow, park or road data	Traffic type, speed, barrier geometry, road surface and gradient, flow (steady/non-steady), distance from source to prediction point, mean wind speed and density of buildings	Vehicle type, speed, grade of road and surface type	Traffic intensity, speed and composition, number of vehicles per lane per unit time, type of road surface & temperature, local topography (terrain shapes, screen/buildings, road surface type), aerodynamic roughness length of grounds	Average hourly flow rate for each category of vehicle, speed and traffic flow type of each vehicle category, road platform surface category, road gradient	Traffic speed, composition, intensity (flow), flow characteristics viz., acceleration/deceleration	Traffic type, speed, barrier geometry, road surface and gradient, flow, distance from source to prediction point



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Noise descriptor	One hour LAeq DNL and CNEL (community noise equivalent level)	L <sub>10</sub> (1 hour) and L <sub>10</sub> (18 hour)	LAeq Lm,E, Lm (Mean level for each lane)	L <sub>WA</sub> , LA, LAeq,T	A-weighted sound power level, immission level L <sub>f</sub> in 1/3 octave band	LAeq LAeq,T, Lden and Lnight.	LAeq, LT	LAeq, T, Lden and Lnight.	LAeq, Lwi
Type of mapping	Multiple dual → points grid	Line → point	Line → point	Line → point	Line → point	Line → point	Line → point	Incoherent line source → point	Line → point
Gradient effect	Model computes adjusted speeds based on user input speeds, roadway grade and traffic control devices. TNM reduces input speeds depending upon steepness and length of upgrades	Gradient correction: $\Delta G = 0.3G$ dBA	Gradient correction: RRS = 0.6 $ g  - 3$ for $g \geq 5\%$ RRS = 0 for $g \leq 5\%$	Gradient correction: $\Delta L_{grad} = 0.14igrad + 0.05igrad^2$ where $igrad$ is gradient of road (%). It is applied only to heavy vehicles ascending inclined roads	$\Delta s$ , correction for uphill grade $g(\%)$ , where $\Delta s = 0.8g$	Each segment of terrain profile is assumed to be perfectly flat. Ground fluctuations handled by segmented terrain and specifying ground roughness. Four roughness class N,S,M&L defined	Correction term $\Delta L_m$ defined for uphill, downhill and horizontal pavements. Three potential gradients defined: horizontal (gradient less than 2%), upwards (gradient of 2% to 6%) and downwards (gradient of 2% to 6%)	The effect of the gradient is described as $a = a_1 + g \sin(\alpha)$ where $a_1$ is acceleration of vehicle	Not mentioned

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Directivity	Sub source-split ratio for vehicle emission, $r_i$ defined in terms of five constants	Angle of view adjustment defined	Not mentioned	Directivity function defined	Not mentioned	Directivity function defined	Not mentioned	Directivity functions defined for rolling and propulsion noise	Not mentioned
Ground effect	TNM model for reflection coefficients based on approach of Chessell incorporating the single parameter ground impedance model	Not defined	Level difference caused by ground absorption and meteorological influences in free field, DBM defined in model.	Correction for ground effect $\Delta L_{grad}$ for excess attenuation defined. Ground reflection coefficient $R_m$ defined in terms of complex error function and admittance $\beta$ and coefficient of finiteness of reflecting surface $G_m$ defined in model.	Correction $A_{gr}$ defined. Coherence loss factor (K) defined in model for signifying summation is completely phase sensitive ( $K = 1$ ) or purely energetic ( $K = 0$ ). Sound pressure of ground reflected wave is calculated using Chessell's approach	Use of geometric ray in their Chien and Soroka model. Coherence factor defined for effects from frequency band averaging and turbulence, fluctuating refraction, surface roughness and scattering zones	Attenuation due to ground Chien and Soroka model. Coherence factor defined for effects from frequency band averaging and turbulence, fluctuating refraction, surface roughness and scattering zones	Analytical formula established by Chien and Soroka. Additional correction factor of coherence due to presence of turbulent eddies near ground surface defined. Each impedance discontinuity is modelled through a Fresnel weighting approach	Sound absorbing effect by the ground and shielding effect (diffraction attenuation) by the soundproof wall conform to ISO 9613-2.
Atmospheric absorption	Atmospheric absorption defined in		DS, L, attenuation due to	Correction term $\Delta L_{air}$ is calculated	Air absorption in third octave band f	Refraction modelled by using curved	Atmospheric rarefaction in downward	Uses straight rays and curves the	Atmospheric absorbing and rarefaction is

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and rarefaction	terms of ambient air temperature, reference air temperature 20 C and oxygen relaxation frequency $f_{r0}$		distance & air absorption defined	considering standard state of atmosphere (20 C, 60% R.H & 101.325 kPa) as a function of distance from source to prediction point	according to ISO9613-1 for temperature + 8 C and RH 76%	sound rays. The curvature depends upon vertical sound speed profile and is determined by semi-analytical approach. Air absorption calculated in accordance with ISO9613-1	conditions taken into account by means of height correction terms. Turbulence also taken into account. Attenuation due to atmospheric absorption $A_{atm}$ defined	ground to simulate refraction; radius of curvature determined from maximum height of curve. Effect of air absorption is calculated with ISO 9613-1. Curved ground analogy is adopted by inverse curving of the terrain rather than curving sound rays	in conformity with ISO 9613-1.
Meteorological effects	TNM does not account for atmospheric effects such as varying wind speed or direction or temperature gradient. TNM		DBM is attenuation due to ground and atmospheric effect	Change in $LA_{eq}$ due to effect of wind defined $\Delta L_m$ , line	Meteorological effects on sound propagation are ignored	Wind and temperature gradient used to approx. the vertical effective sound speed profile by $\ln$ -log relations	Two classes of meteorological conditions. Homogenous and downward propagation defined	A excess, $j$ is excess attenuation representing the effect of ground, meteorology, barrier and air absorption.	Not mentioned

Technical attributes	TNM Model	CRTN Model	RLS 90 Model	ASJ-RTN Model	SonRoad Model	Nord2000 Model	NMPB Routes Model	CNOSSOS	KHTN
	assumes neutral atmospheric conditions							Standard P2P model for homogenous atmosphere is used. Sound speed profile is approximated by means of Lin-Log function	
Correction for road surfaces	TNM defines energy average emission levels depending upon road	Correction for concrete and bituminous surface; impervious bituminous and pervious road surface	Correction for road surface DStro defined	Frequency characteristics of road vehicle noise on dense asphalt and drainage asphalt pavement defined	Correction for road surface ΔBG defined	Correction for type of road surfaces, air temperature, ageing, max aggregate size and country. DK; FI, NO & SE have additional correction	Road pavement influence addressed by grouping pavement into 3 categories (R1, R2 & R3) correction for ageing effect. Correction for air temperature included	Correction for road temperature, tyres with and without studs, road surface wetness and ageing defined	The noise level is measured by correcting the noise coefficient according to the type of the vehicle.
Noise at intersections and roundabouts	Two accepted methods for modelling intersections: 1) modelling roadways that stop short of and restart	Not mentioned	Correction term for increased effect of traffic light controlled intersections	Four calculation methods defined viz., precise, semi-precise, simplified model and	Not mentioned	Correction on vehicle noise emission for continuous acceleration (after crossing) and continuous	Not mentioned	Micro-simulation based correction factor Cs applied to emission level. Cs is	Not mentioned

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	after an intersection and 2) modelling a complex series of intersecting roadway segments			summing the contributions from two intersecting roads under non-steady flow conditions		deceleration (before a crossing). Model recommends using cruising vehicle emission value		evaluated as average of correction function $C(x)$ over length of segment estimated by simulated noise emission profiles. Curve $C(x)$ fitted to noise emission profiles using least squares method	
Impedance effects	TNM allows users to enter various ground types based on effective flow resistivity (cgstrays) measured by Embelton. The ground type and associated effective flow resistivity (EFR) are	Not mentioned	Not mentioned	Complex sound pressure reflection coefficient $R_m$ defined in terms of complex error function or Faddeeva function and admittance $\beta$ calculated as $1 \beta \propto 1 \rho \propto 5:50 \propto e f \% \& 0:632 ! " \rho$	Ground impedance is described by one parameter model of Delany and Bazley; the error function is calculated by algorithm from Gautschi	Ground surface classified into seven classes A to H based on flow resistivity. Impedance calculated by Delany and Bazley model. Road surface represented by ground type G ( $\sigma =$	Acoustic absorption of ground is represented by a frequency independent dimensionless coefficient $G$ between 0 and 1. $G$ trajet is defined as the fraction of absorbent ground present in the	For porous road surface: Hamet model; ISO road surface: One parameter model with flow resistivity $2 \text{MPa s/m}^2$ , surface with cluster: one parameter model with flow resistivity $200 \text{MPa s/m}^2$	Not mentioned

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	defined. TNM averages the ground impedance in vicinity of reflection point using Boulanger's approach			$i8:43 \sigma e f \% \& 0:632 !"$ Where $\sigma e$ is effective flow resistivity in kPa s/m		20,000 kPa s/m 2)	whole of the path covered. $G = \text{Min } 300 \sigma$ $\# \$ 0:57 ;1 \text{ hi}$ $\sigma \text{cgs rays}$		
Diffraction effect	Multiple reflections between parallel barriers computed in two dimensions; double diffraction included; in case of three or more perturbable barrier, TNM chooses most effective pair of barriers based on their input heights in accordance with Foss selection algorithm	Reflection adjustment defined	DB is attenuation due to topography and building dimension defined in model. DE is correction for absorption characteristic of building surfaces	The fundamental correction term for diffraction is calculated as a function of path length. Empirical formulation for simple barrier, finite length barrier, thick barrier, multiple barrier with overhang, edge modified, low height and transmission through barrier defined	Correction Agr/bar/refl,(f ) included in propagation attenuation to take care of ground effect and barrier attenuation including effect of reflecting objects in third octave band	Hadden–Pierce ray solution for a wedge with finite impedance faces is used for single screens and Salomons approach for multiple. The Jonasson image method is used with diffraction by Hadden–Pierce and ground effect by Chien and Soroka for screen on ground surfaces	Correction term defined in model in terms of Fresnel number(N) and corrective term Ch. Barrier diffractions are calculated using Maekawa's approximated formulation considering barrier as a hard surface	BEM & RAY can be used for obstacles of complex shapes. CNPE & GFPE can also be used for rectangular obstacles; GTPE is used for propagation over smooth hills. Degouts approximation of Fresnel integrals gives attenuation as a function of path length difference and wavelength. Reflections	Diffraction effect (diffraction attenuation) by the soundproof wall conforms to ISO 9613-2.



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								from the faces of wedges/ thick barriers are taken into account as ground effect	
Tyre type Correction	No	No	No	No	No	No	No	Yes	No
Bridges tunnels, viaducts, defined	No Rows of buildings as optional element included	No	No RLS considers parking lot emissions	Yes	No	No Nord2000 handles only tunnel openings	No Special elements, eg trenches, tunnels and partial covers included	No GTPE is used for ground surface with smooth hills	No
Vegetation effect	Attenuation through dense foliage and tree zones incorporated in propagation path. Earth mounds can be selected with user selectable heights, top widths and side slope	Not mentioned	DB is attenuation coefficient due to topography and building dimensions	Not mentioned	Correction A <sub>fol,f</sub> according to ISO9613-2	Statistical scattering model influenced by reflection, scattering and absorption due to trunks, branches and foliage	Roughness parameter defined for sparse habitat (farms, villages, trees and hedges)	Rough terrain with vegetation can be described by terrain roughness and ground impedance. Diffraction effects of earth mounds taken into account by Deygout approx. The attenuation as	Not mentioned

Technical attributes	TNM Model	CRTN Model	RLS 90 Model	ASJ-RTN Model	SonRoad Model	Nord2000 Model	NMPB Routes Model	CNOSSOS	KHTN
								a result from propagation through tress Ascat,i defined	





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