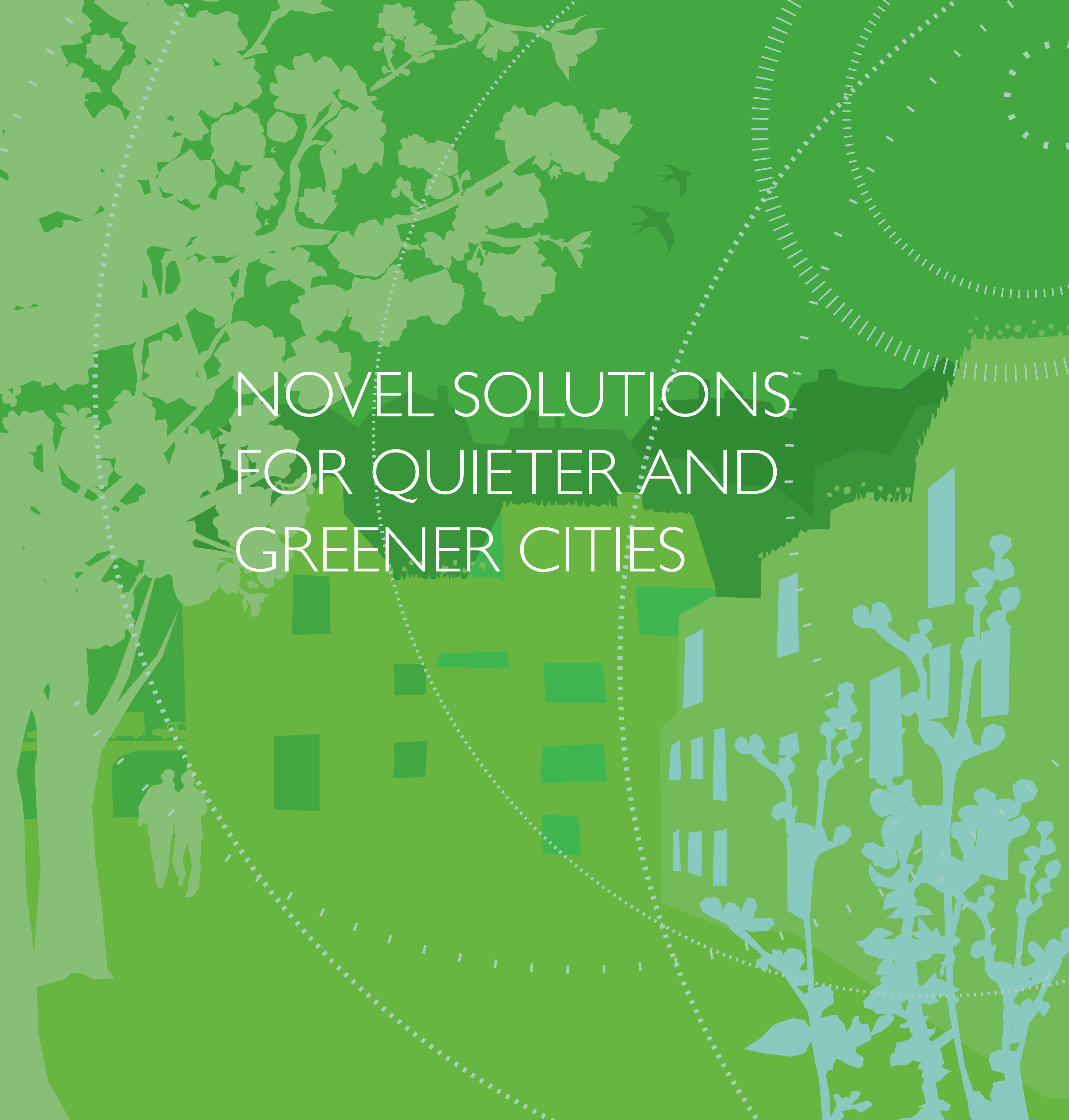

NOVEL SOLUTIONS FOR QUIETER AND GREENER CITIES

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COOPERATION

NOVEL SOLUTIONS FOR QUIETER AND GREENER CITIES

Foreword

Vegetated areas and surfaces are greatly appreciated in both urban and rural environments. The beneficial effects of greening mean that the costs of new greening or of maintaining existing green surfaces are often easy to justify – even without considering the benefit of environmental noise reduction. The thrust of the project presented in this brochure was to find better ways of using vegetated surfaces and recycled materials to reduce road and rail traffic noise and improve the perceived sound environment.

We present a toolbox containing a large variety of measures. Traffic noise situations are often complex and a single noise mitigation measure is seldom sufficient. Some of the tools we propose each lead to 2–3 dB(A) in noise reduction, so an appropriate combination of measures is needed to obtain a larger effect. Other noise abatements from our toolbox individually reduce noise by 10 dB(A) or more. It should be noted that most of the estimated noise reductions have been calculated using advanced numerical methods, rather than measured in real situations, so a non-negligible uncertainty is expected in real situations. To minimize this uncertainty, the estimation methods have all been validated and are applied in situations that are as realistic as possible. In addition, the impairment in performance due to meteorological effects has been estimated for selected cases by modelling the effects of mean wind and turbulence.

With this brochure, we would like to encourage the implementation, testing, and further evaluation of the suggested green noise abatement methods. Detailed information on the project results will be made available in a handbook to be published in 2013.

Content

PARTNERS

Chalmers University of Technology (Sweden), CSTB (France), Canevaflor (France), IBBT Gent University (Belgium), Müller BBM (Germany), Open University (UK), City of Stockholm (Sweden), TOI (Norway), University of Sheffield (UK), University of Bradford (UK), Stockholm University (Sweden), Acoucité (France), and Hanyang University (South Korea).

The HOSANNA project

This brochure summarizes the main findings of the research project "HOlistic and Sustainable Abatement of Noise by optimized combinations of Natural and Artificial means" (HOSANNA). The project aimed to develop a toolbox for reducing road and rail traffic noise in outdoor environments by the optimal use of vegetation, soil, other natural materials and recycled materials in combination with artificial elements.

The project studied a number of green abatement strategies that might achieve cost-effective improvements using new barrier designs, planting of trees, shrubs, or bushes, ground and road surface treatments, and greening of building facades and roofs. The noise reduction was assessed in terms of sound level reductions, perceptual effects, and cost–benefit analyses.

The project was coordinated by Chalmers University of Technology (coordinator: Jens Forssén) and involved 13 partners from seven countries. The research received funding from the European Union Seventh Framework Programme (FP7/2007–2013) under grant agreement n° 234306, collaborative project HOSANNA.

Introduction

Noise from roads and railways is a widespread environmental exposure that adversely affects human health and well-being and is associated with considerable costs to society. More than half of the residents of large European cities live in areas where it is likely that noise levels adversely affect their well-being and health. In addition, many public spaces, such as city parks, esplanades, and green open spaces, are noise exposed, which reduces these areas' potential to provide rest and relaxation.

Traffic noise causes annoyance and sleep disturbance, it interferes with rest, concentration, and speech communication and negatively affects children's learning and school performance. There is also increasingly strong support for a causal link between long-term exposure to road-traffic noise and cardiovascular disease, including hypertension and myocardial infarction.

The World Health Organization (WHO) has estimated the yearly burden of transport noise-related disease in the EU to correspond to a loss per inhabitant of two days per year and, of environmental factors, only air pollution is estimated to have a larger disease burden. For traffic noise, the main disease burden is related to annoyance and sleep disturbance. The social costs of traffic noise have been estimated at 0.4% of total GDP, or about one third of the costs of road accidents.

Successful noise reduction will therefore lead to substantial economic gains and positive effects on public health and well-being. The most effective noise-mitigation method is to reduce noise emissions at the source, for example, by means of regulations demanding quieter engines, tires, or road surfaces, or by limiting traffic flow volumes and introducing stricter speed limits. However, such methods are often difficult to implement for economic, city planning, or political reasons. Therefore, at-source noise reduction must be complemented with methods that act on the noise during its path to the receiver. The aim of the project presented here was to develop new and environmentally friendly methods of this kind.

Principles of noise reduction

As sound propagates outdoors from a source, the factors determining the sound level at the receiver relate to the distance between source and receiver, properties of the medium, air, in which sound propagates, and properties of the boundary, that is, the ground material and profile, including noise barriers and other obstacles.

DISTANCE

In free space, sound from a point source spreads spherically and decays by 6 dB with each doubling of the distance from the source, whereas sound from a line source spreads cylindrically and decays by 3 dB with each doubling of distance. Predictions of the maximum sound levels of road traffic noise are based on a single vehicle as the noise source, whereas predictions of the average, or equivalent, sound level (e.g., Lden and LAeq,24h, where time-averaged energy is used) assume the whole length of the road to be the source. Therefore, the maximum noise level decays by 6 dB per doubling of distance from the road, whereas the equivalent level decays by 3 dB per distance doubling, assuming a long straight road and insignificant influence of ground, wind, and other environmental factors. A similar principle applies to railway noise. In general, when making noise mapping calculations, the whole traffic network has to be considered along with the existing propagation conditions.

MEDIUM

The acoustic properties of the medium of propagation, air, relate to meteorological conditions, such as wind speed and temperature. The largest effects of such factors occur when they lead to refraction, that is, the curving of sound paths. The degree of refraction is determined by the wind speed profile and the temperature variation with height. As a result of downward curving, which may occur in the case of downwind sound propagation (i.e., wind blowing from the direction of the sound source and toward the receiver) or temperature inversion (i.e., increasing temperature with height), the noise levels may increase substantially. Conversely, upward curving, for example, in headwind conditions, may greatly reduce levels compared with situations without such refraction. Refraction effects usually increase with propagation distance.

Temperature, humidity, and, to a smaller extent, static pressure influence the degree of air attenuation, that is, the molecular absorption of sound during its propagation. Air attenuation effects are of importance mainly at high frequencies.

Atmospheric turbulence, in the form of random fluctuations in wind velocity and temperature, distorts the sound waves. The effects can be seen as scattering of sound into shadow regions and reduction of the strength of both positive and negative interference. These effects are of importance mainly at high frequencies.

The project has studied several methods that act on the medium of sound propagation, for example, planting trees behind barriers to improve barrier performance in downward refraction situations, planting a strip of trees along a road or artificially creating upward refraction with sonic crystal-like barriers.

BOUNDARY

In flat terrain, both direct sound from the source and ground-reflected sound can reach the receiver. The effect of the interaction between direct and reflected sound is called the ground effect. At some frequencies, direct and reflected sound partly cancel each other out, which causes the sound level to be lower than if the ground were not present. At some other frequencies, the two sound waves reinforce each other, making the level higher than it would be if the ground were not present. For traffic noise propagating above an acoustically hard ground, such as asphalt, the two sound waves added together will normally lead to an increased noise level. However, above an acoustically soft ground, such as a lawn, the two waves may cancel each other out over a relatively broad frequency range, resulting in a lower level than if no ground were present.

For shielding structures on the ground, for example, noise barriers, height is the most important property, assuming negligible sound transmission through or around the sides of the barrier. Widening the top of the barrier improves the acoustic effect. Better performance is generally achieved if the barrier is placed near the source or near the receiver. In an inner city environment, it may therefore be preferable to use a noise barrier relatively low in height if it can be located near the traffic sources. To improve the performance of such barriers, the width can be increased and the materials on the top and faces of the barrier should be carefully chosen. The materials should be acoustically soft, and in urban environments, with many sound reflections, it is crucial to choose acoustically absorbent materials. In general, important sound reflection can occur from the facades of the urban canyon, from the surfaces of noise barriers, and from the surfaces of vehicle bodies, primarily in the case of large heavy road vehicles and rail vehicles.

The project has examined several methods that act on the boundary, including softening hard ground, roughening flat ground, barrier design, and using absorbent materials on barriers, facades, and roofs.

Innovative noise barriers, using natural and recycled materials

An efficient way to reduce ground transport noise is to block the noise by erecting barriers or other elements near the source. For example, high noise barriers or earth berms are often constructed along motorways and railways to protect noise-exposed residents. Such solutions may not work in dense urban settings because of space limitations, traffic safety considerations, or aesthetic reasons. However, small barriers, less than 1 m high, can be useful in such situations if properly designed.

Conventional barriers are made of wood, metal, or concrete. However, alternative materials may be more cost-effective, provide better noise reduction, and improve aesthetic values. Examples include recycled materials from industries and local communities and natural materials such as stones, soil and vegetation.

The project developed and evaluated several innovative noise barrier solutions, including low-height barriers, lightweight barriers at bridges, vegetated barrier caps, and earth berms of various designs. The project also tested a new type of barrier, called the sonic crystal barrier, which consists of a set of cylinders structured in a way that optimizes noise reduction in specific frequency regions.

USE OF RECYCLED MATERIALS IN NOISE BARRIERS

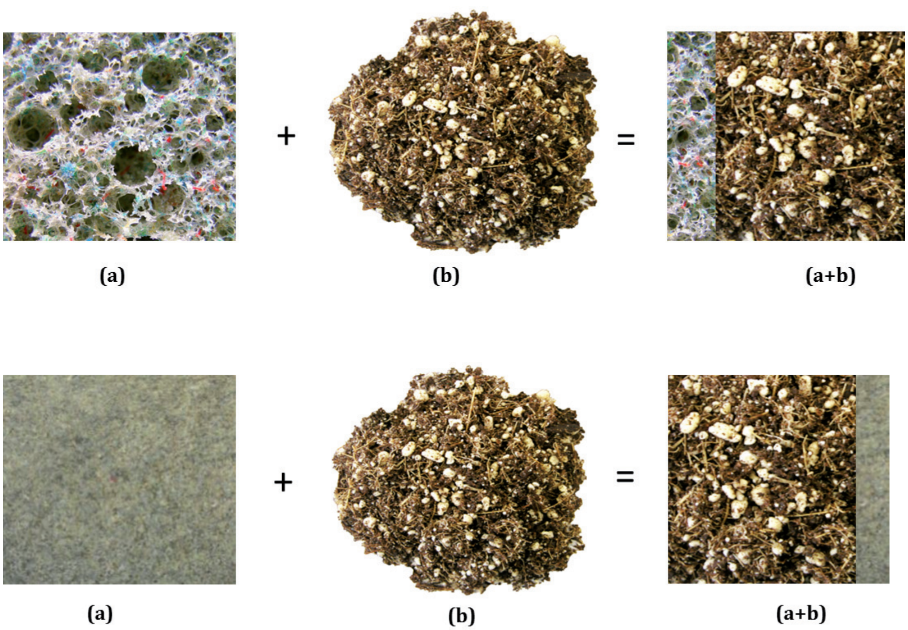
Although the technology for manufacturing noise-absorbing barriers from recycled materials has been available for many years, road noise barriers continue to be produced largely from virgin materials, including concrete, masonry, timber, metal, and acrylic glass.

The most common noise barrier systems that include recycled materials use wood-fibre-reinforced concrete, granulated rubber tyre infill, recycled plastic lumber, or a combination of a retaining recycled shell manufactured from PVC waste with a porous mineral wool core.

To improve on existing technologies, the project has developed a new cold process to produce highly porous media with a controlled pore size distribution and a controlled proportion of open, interconnected pores in a range of pore size distributions. These materials are based on granulated polymeric and elastomeric waste, which can be sourced from the construction industry, manufacturing industry, and local community in the form of post-consumer waste.

The acoustical performance of reconstituted granulated waste depends on several factors related to the ratio of grains to fibres, type of adhesive, and other chemical additives used in the consolidation process. Common characteristics of recycled polymeric waste that can be acoustically optimized include open porosity, flow resistivity, and stiffness. For sound insulation applications, we recommend material with a relatively low open porosity, a relatively high density, and a relatively high damping ratio. Below are examples of how recycled waste may be used: (1) to increase sound absorption and soil retention in vegetated noise barriers, and (2) for the construction and vegetation of a high-density barrier.

A major drawback of conventional porous absorbers is their poor performance in the low-



Top row – Recycled material used for sound absorption and soil retention applications: (a) low-density consolidated material made from recycled waste, (b) low-density soil, and (a + b) combination of low-density consolidated material and low-density soil. Bottom row – Recycled material used in sound transmission applications: (a) high-density barrier material made from recycled waste, (b) low-density soil, and (a + b) high-density panel placed behind low density soil.

frequency range where the acoustic wavelength is greater than the thickness of the porous layer. To improve the low-frequency noise absorption of porous layers, it is common to combine several layers of materials homogeneous in pore structure.

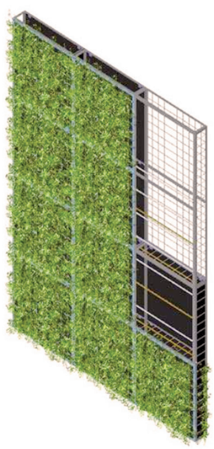
Ideally, a porous noise-absorbing material should have an impedance close to that of air to prevent reflections, while offering high internal acoustic attenuation. These two requirements are difficult to achieve in homogeneous materials, and can be more easily achieved in stratified materials. Samples of recycled polymeric material with a stratified pore structure were produced in the project to improve the noise absorption capability of conventional homogeneous porous layered materials by 20–40%.

USE OF SOIL AND PLANT SYSTEMS IN NOISE BARRIERS

The project's research into the noise absorption capability of soil and plant systems suggests that the acoustic absorption of soil is controlled largely by the type of soil and the amount of moisture. A layer of low-density soil developed in the project displays a frequency-dependent acoustic absorption coefficient close to that of a layer of glass wool of the same thickness.

The presence of leaves with a large surface area can noticeably improve the acoustic absorption of hard soils across a broad frequency range. The enhancement of the acoustic absorption depends on the type of plant, leaf angle, amount of foliage on the plant, and total leaf area in a unit volume; the absorption coefficient of a plant with a larger leaf area exhibits less frequency dependence in the case of a soil with a lower density.

A green wall containing low-density soil provides an alternative to more conventional types of acoustic treatment, particularly in the low- and high-frequency ranges. The key concept is to provide a panel containing a stable porous granular medium, manufactured from waste materials (from the textile, construction, and manufacturing industries), that supports plants that can provide acoustic absorption, water retention, and local climate modification via plant transpiration. Below is an image of the construction principle and an application in the vicinity of a historical building.



A vegetative wall: composition (left); installation (right).

Low-height noise barrier

LOW-HEIGHT NOISE BARRIERS

Low-height noise barriers are small barriers whose width and height do not exceed 1 m, erected to reduce rolling noise from cars or trams. Such barriers can be used in dense urban areas to protect pavements and benches near roads or rails from noise.

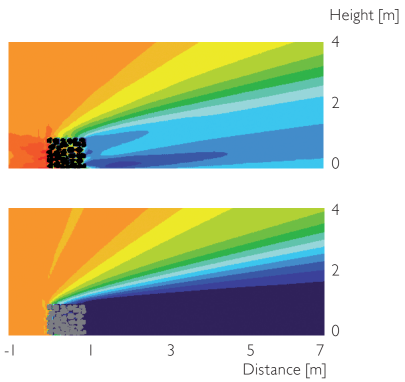
Several configurations of low-height barriers (e.g., using stone gabions or vegetation) have been studied in the project. We demonstrated that low-height barriers can protect pedestrians, cyclists, and nearby residents from noise, provided that the barriers are well designed and located near the sound source. This is possible in situations with limited traffic speed, such as in city centres.

In an open space, a 1-m-high straight barrier made of a 40-cm-wide mixture of natural fibres and mineral materials, with a rigid core, installed along a two-lane road can potentially reduce road traffic noise by about 9 dB(A) compared with an untreated situation, in a region 2–50 m behind the barrier, the height of the receiver being 1–5 m. The noise reduction can decrease by a few decibels in the case of a canyon street, but increase by a few decibels if a second similar low-height barrier is constructed between the two lanes of the road. For trams, the extra noise reduction obtained by adding a second central barrier is approximately 8 dB(A) compared with a single barrier beside the rail, which reduces the noise by approximately 12 dB(A).

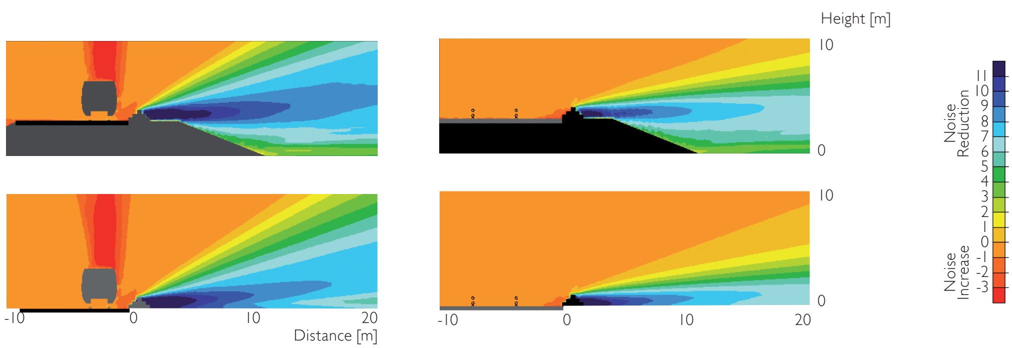
In the case of a 1-m-high standard gabion made of 15–20-cm-dimension stones along a two-lane urban road, the acoustical noise reduction is 3–8 dB(A) compared with an untreated situation, for a receiver located 2–50 m behind the barrier and 1–5 m above ground. Replacing stones with porous clay will attenuate the sound by an extra few dB(A).

If we consider rigid sonic crystals combined with a low-height straight barrier installed along a two-track tramway, the noise reduction is up to 10 dB(A) compared with an untreated situation, for a receiver located 2–50 m behind the barrier and 1–5 m above ground. Adding a 2-cm layer of hemp concrete to the surface of the cylinders leads to additional noise reduction of approximately 7 dB(A).

For grass-covered low-height berms (i.e., 1 m high and 1 m wide) with slopes containing large irregularities up to 25 cm in depth, the acoustical noise reduction is up to 8 dB(A) compared with an untreated situation, in the case of both urban roads and tramways, for a receiver located 2–50 m behind the barrier and 1–5 m above ground. Low-height berms function along high-speed railways and motorways as well, provided the infrastructure is significantly embanked. With a 4-m-high embankment, the acoustical noise reduction is up to 7 dB(A) compared with an untreated situation, for a receiver located 2–50 m behind the barrier and 2–10 m above ground for the train and 2–5 m for the motorway.



Overall decibel reduction (dB(A)) compared with the same situation without a barrier, calculated for a 1-m-wide and 1-m-high gabion barrier made of 15–20-cm-dimension stones (top) and porous clay (bottom), in the case of a two-lane urban road.



Overall decibel reduction (dB(A)) compared with the same situation without a berm, calculated for a low-height stair-case shaped earth berm close to a high speed train (left) or motorway (right) at a 4 m high embankment (top) or on flat terrain (bottom).

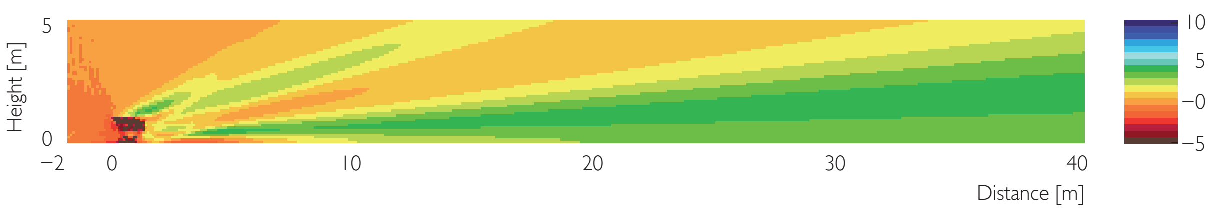
Lightweight vegetated barriers at bridge

LIGHTWEIGHT VEGETATED BARRIERS AT BRIDGES

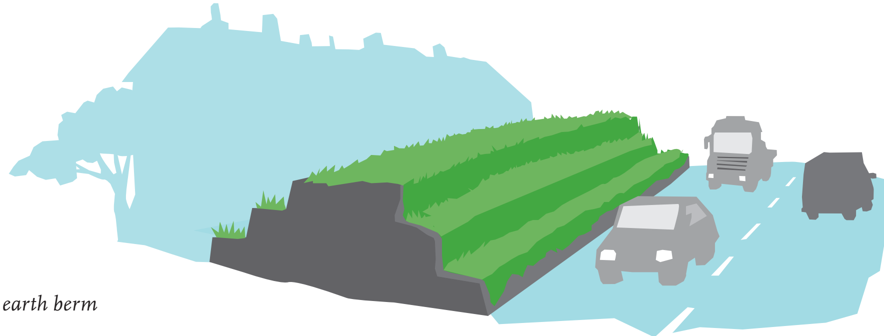
Traffic travelling over bridges in urban areas may expose pedestrians and cyclists in areas below the bridges to noise. Thin rigid 1-m-high noise barriers along the edges of such bridges may reduce noise levels in the receiving areas by up to 4 dB(A) in the case of a four-lane motorway, and by up to 10 dB(A) for a two-track tramway, without disturbing the drivers' view from the bridge. When the low-height barrier is made of a rigid core covered with thick absorptive material of natural fibres and minerals, the noise reduction may reach 5 dB(A) and 15 dB(A) for the motorway and tramway, respectively. The high reduction for the tramway is due mainly to the absorption of multiple-reflected sound energy between the barrier and the tram body. This type of installation can promote walking and bicycling by ensuring acceptable soundscape quality along the travelling path.

REFRACTIVE SONIC CRYSTAL

Refractive graded-index sonic crystal noise barriers (GRIN SC) are a class of sonic crystal barriers with cylinders placed parallel to the ground surface. By spatially varying the properties of the barrier, which in the simplest case consists of air and acoustically hard cylinders, sound waves propagating through the barrier can be redirected upwards (i.e., upward refraction). Parameters such as the cylinder radius, spacing between cylinders, and barrier formation (i.e.,



Overall decibel reduction (dB(A)) compared to the same situation without a graded index sonic crystal barrier. Sound pressure levels are predicted for a 1-m-tall graded-index sonic crystal (GRIN SC) barrier of 1 m² cross sectional area. A two-lane road with lightweight vehicles driving at 50 km/h is modelled. The green regions extending horizontally behind the structure shows where significant noise reduction takes place.



Staircase shaped earth berm

the outer shape of the structure) influence the barrier's performance. A beneficial aspect of GRIN SC noise barriers, within the targeted frequency range, is their lower reflectance (i.e., reflected energy in the direction of the source) than that of traditional noise barriers. GRIN SC noise barriers only function as refractive structures up to certain frequencies, above which other physical properties of the barrier exert a noise-mitigation effect for the receiver. The net noise reduction, expressed in dB(A), thus comprises the effect of a combination of noise-controlling mechanisms.

A 1-m-tall GRIN SC, installed along a two-lane road, can reduce noise by 4 dB(A) at ear height, at a minimum horizontal distance of 15 m from the barrier.

VEGETATED BARRIER CAPS

Existing noise barriers can be improved by planting vegetation along the top edge, which increases sound attenuation during noise propagation. Most conventional barriers have "caps" (or crowns) made of porous wood cement. 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 cyclist moving 1 m behind the barrier, the acoustical noise reduction due to a 1-m-wide element is 8–12 dB(A), compared with an uncapped straight barrier of the same overall height.

EARTH BERMS

Although berms require more space than do barriers, they offer many non-acoustic benefits. The sense of openness is preserved and berms can also be planted, which can improve visual attractiveness and increase their sound absorption. Other advantages are a very long lifetime, limited maintenance cost, and few or no graffiti problems. Furthermore, excess material from other locations, such as soil and stones from construction work, can be recycled by constructing berms for noise-protection purposes.

While a conventional noise barrier's efficiency decreases considerably in downwind conditions (i.e., blowing from source to receiver), berms are less sensitive to the action of such winds. With decreasing berm slope angle, the negative action of the wind decreases significantly. It has been estimated that, in many cases, the average wind effect can be under 1–2 dB(A) for berms with a slope of 18 degrees, or for steeper slopes with a flat top. Although noise barriers can be placed closer to a source than berms of the same height and may be preferred for this reason, it should be borne in mind that this may be at the expense of greater wind-induced deterioration in acoustical performance. When berms are sufficiently acoustically soft, similar shielding can be obtained by a wall and a berm if the elevation of the top of the wall and of the berm are the same.

Predictions indicate that earth berms with non-flat surfaces on their slopes and top can reduce noise more than can conventional, smooth trapezoidal berms. On flat rural terrain, this change in berm geometry from flat to stepped in profile can reduce noise by 4 dB(A) compared with a conventional 4-m-high berm.

Multiple rows of trees in an open field

Trees, shrubs, and bushes

Assigning sufficient space for vegetation is important in urban planning. At the same time, sound waves can be influenced when propagating through vegetation. The well-planned use of vegetation can achieve useful road traffic noise reduction.

The interaction between noise and vegetation includes direct effects such as reflection, diffraction, scattering, and absorption by plant elements such as stems, branches, twigs, and leaves. In addition, developing acoustically soft soil underneath vegetation (by means of plant root action and humus layer formation) and the changed micro-climatology provided by canopies can also lead to noise reduction.

Sound levels are reduced by interacting with plant material in two main ways: sound can be redirected by means of reflection, diffraction, or scattering, or sound can be effectively absorbed by the plant material. Part of the absorption is caused by the damped vibrations of leaves.

In vegetation, multiple scattering occurs. Sound incident on a twig or leaf will change its propagation direction, and is then scattered again by nearby plant elements. As a result, part of the sound energy will leave the direct path between source and receiver, yielding lower sound pressure levels at that receiver. Numerical models with different degrees of complexity have been developed in the project to simulate this effect.

Leaves typically vibrate at sound frequencies near 2–4 kHz. At these frequencies, large sound pressure level differences over a leaf can be measured. Measurements in controlled laboratory conditions indicate more noise reduction with increasing leaf area density, leaf size and leaf weight. Also the orientation of the leaves relative to the incident sound waves plays an important role.

TREES IN STREET CANYONS

Along urban roads flanked by tall buildings there are multiple reflections between building facades and these greatly increase street noise levels, for example, during the passage of a car. Planting trees near the road might contribute to multiple scattering of sound by branches, twigs, and leaves in tree canopies. The longer this reverberation inside the tree canopy, the less energy will remain in the sound wave as a result of the increasing distance travelled and sound energy absorbed. Importantly, part of the sound energy will be redirected and will leave the street in an upward direction, which contributes to noise reduction at the street level.

Results of field measurements indicate that tree reverberation exerts an influence only on frequencies above 1 kHz. At 4 kHz the reverberation time can be as long as 0.34 s. If the tree canopy is sufficiently large, the internal reverberation can be longer still. Measurements made near the same deciduous tree with and without leaves indicate that leaves increase reverberation mainly at frequencies above 2 kHz, though reverberation is still present in the absence of leaves.

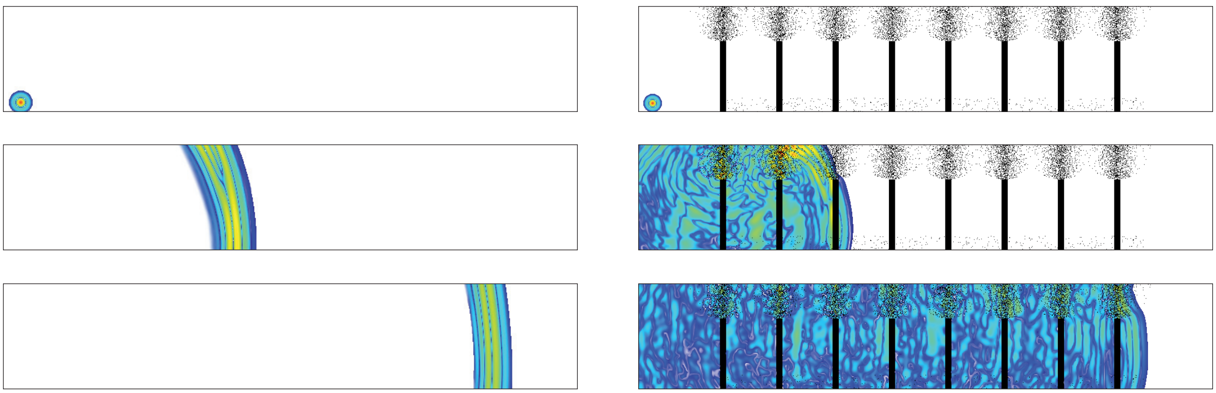
Scale-model experiments suggest that trees may reduce sound propagation along streets, provided that the receiver is sufficiently far from the source. The effect will be most noticeable at higher storeys, where noise reduction is expected in the high frequency part of the sound spectrum. On the other hand, increased downward scattering may be observed for receivers present below the bottom of the canopy. Overall, the reduction in noise levels due to trees in street canyons is expected to be small and no more than 2 dBA.

MULTIPLE ROWS OF TREES IN OPEN FIELDS

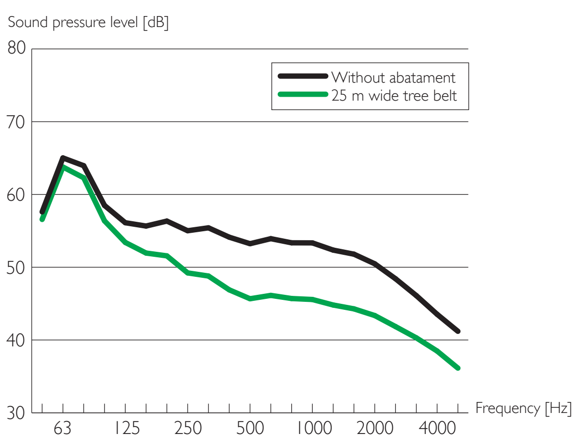
A single row of trees along a road beside an open field will not significantly affect traffic noise levels, though positive effects can be expected when there are multiple rows. The presence of above-ground biomass and the

In-situ transmission measurements of a hedge (top left), absorption measurements of leaves and substrate in a reverberant chamber (top right), absorption measurements of leaves in an impedance tube (bottom left), vibration measurements with a doppler-vibrometer of a single leaf under acoustic load in an anechoic chamber (bottom right).

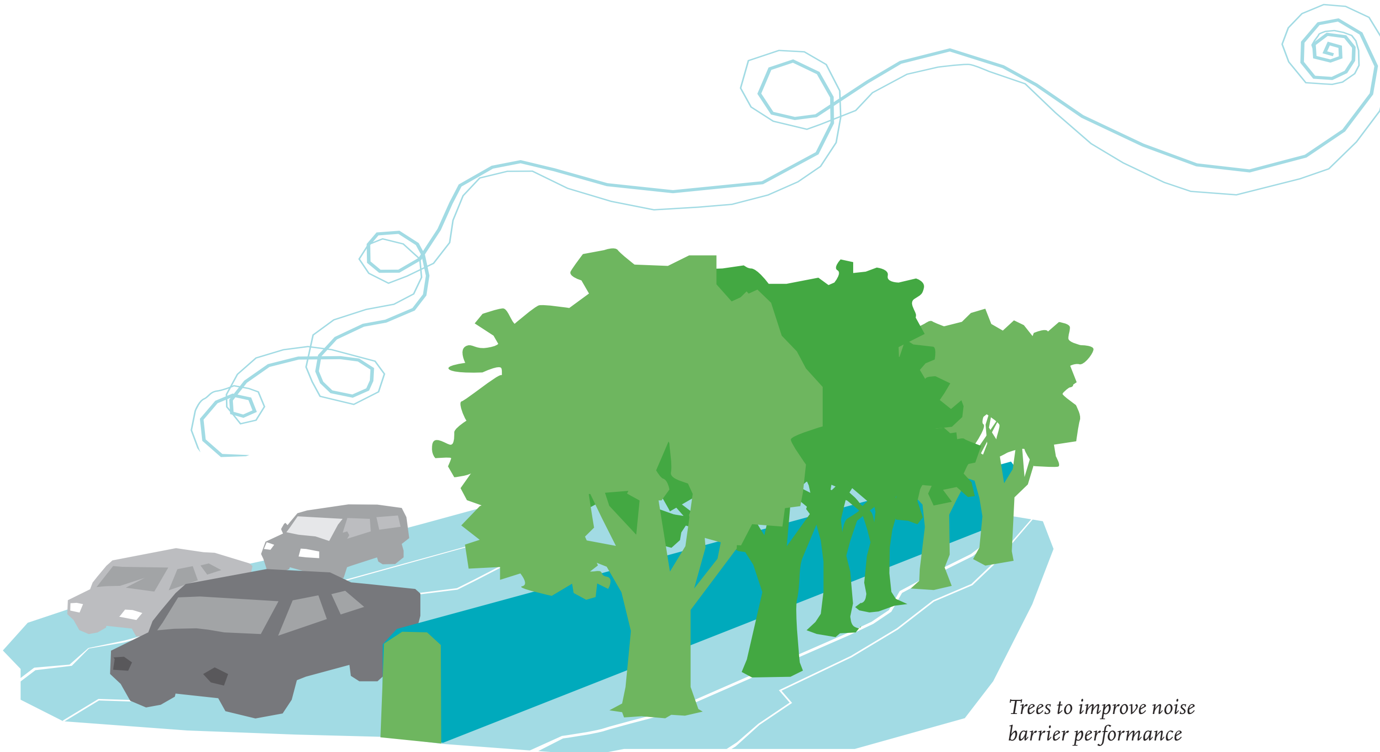
soft soil developing under vegetation together reduce road traffic noise. Both the trunks and low-growing vegetation contribute to the noise reduction effect of a green belt. The canopy layer, on the other hand, could have a small negative effect when both source and receiver are located underneath because of downward scattering by the canopy and downward reflection at the bottom of the canopy. This effect becomes important at very high frequencies, however, only slightly influencing total A-weighted road traffic noise levels. Important design parameters in vegetation belts are tree spacing, trunk diameter, length and depth of the belt, the choice of planting scheme, and shrub biomass density. Above 2 m, tree height is usually not a relevant parameter in typical traffic noise situations.



Snapshots of sound field distribution at three moments during propagation through an open field (left) and a tree belt (right). An acoustic pulse is initially excited (upper row) and the sound field development during propagation is shown (middle and bottom row). The colour scale is arbitrary: orange and yellow indicate zones of high sound pressure levels, green intermediate levels, and blue low levels. The multiple scattering processes in the different layers of the tree belt are clearly visible in the right-hand diagrams.



Sound-pressure-level spectra at 40 m distance from a two-lane road (5% heavy and 95% light vehicles, travelling at 50 km/h) predicted for a 1.5-m-high receiver located behind a 25-m-wide and 75-m-long tree belt, equidistant from the belt ends (green), or at the same position with grassland between road and receiver (black). The tree belt starts near the border of the road. A slightly disordered planting grid is modelled, starting from a regular grid with a spacing of 1 m along the road length axis, and 2 m normal to it. The diameter of the trees modelled was 16 cm, leading to a trunk cover fraction of 1%. Predicted insertion loss of tree belt: 7 dB(A).



Trees to improve noise barrier performance

Tree spacing along the length of the road is a key parameter, and should be as close as practically possible. Pseudo-random planting schemes should be encouraged, that is, the trees are planted following a regular grid, but with small and random deviations. Variations in trunk diameter are also positive when it comes to reducing road traffic noise levels. Tree species should be selected that can develop high stand densities and large trunk diameters. Introducing open zones (not near the borders) does not significantly reduce the performance of the tree belt. Increasing the spacing normal to the length axis of the road, and introducing open zones, is a practical way to achieve a realistic (averaged) trunk volume, without negatively affecting the noise shielding. Calculations reveal that a narrow (approximately 15 m wide) but optimized vegetation belt along a road is equivalent to the shielding of a 1–1.5-m-high conventional concrete noise wall placed directly near the road, that is, about 5–6 dB(A).

PLANTING TREES TO IMPROVE NOISE BARRIER PERFORMANCE

Vegetation influences the local micrometeorology, which in turn influences sound propagation. Of particular interest for sound propagation are changes in temperature profiles, relative humidity, and wind speed profiles.

A 50 m wide vegetation zone significantly limits the build-up of a ground-based temperature inversion layer at night compared to an open field. The presence of a temperature inversion layer at low heights in the atmosphere can otherwise strongly increase sound pressure levels from a road due to downwardly bent sound. During daytime, the typical temperature profiles as found inside a strip of a forest results in a slightly worse shielding compared to sound propagation above an open field. The gain in noise shielding at night is expected to outweigh the reduced performance during daytime.

Vegetation can be designed to improve the micrometeorological conditions near noise walls in wind. Wind negatively affects noise shielding behind nonaerodynamically designed obstacles, such as a row of houses or a vertically erected noise wall. Such refraction effects can be quite dramatic, especially in the case of high wind speeds for downwind receivers. This effect occurs immediately behind a barrier, in the zone where we would expect high shielding.

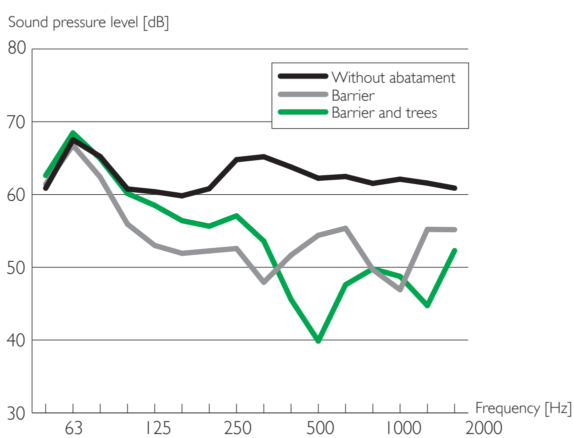
The canopy of trees provides wind shelter, so placing a row of trees behind a noise barrier will help to reduce these wind effects. Specific canopy designs should be applied based on the zone downwind where optimal improvement is wanted and on the type of barrier (i.e., a single noise wall or noise walls on either side of the road). Ideally, canopies should be dense, making coniferous trees particularly suitable. At a short distance downwind, the shielding that was lost by wind action can be largely recovered when the bottom of the canopy starts near the barrier top. Leaving a gap between the canopy and a single barrier leads to maximum improvements further downwind.

Near steeply sloping berms, trees do not improve shielding in wind. Gradually sloped berms, which are more aerodynamic in shape than are vertical noise walls, strongly limit negative wind effects compared to noise walls of the same height. The use of trees near berms is therefore not advised.

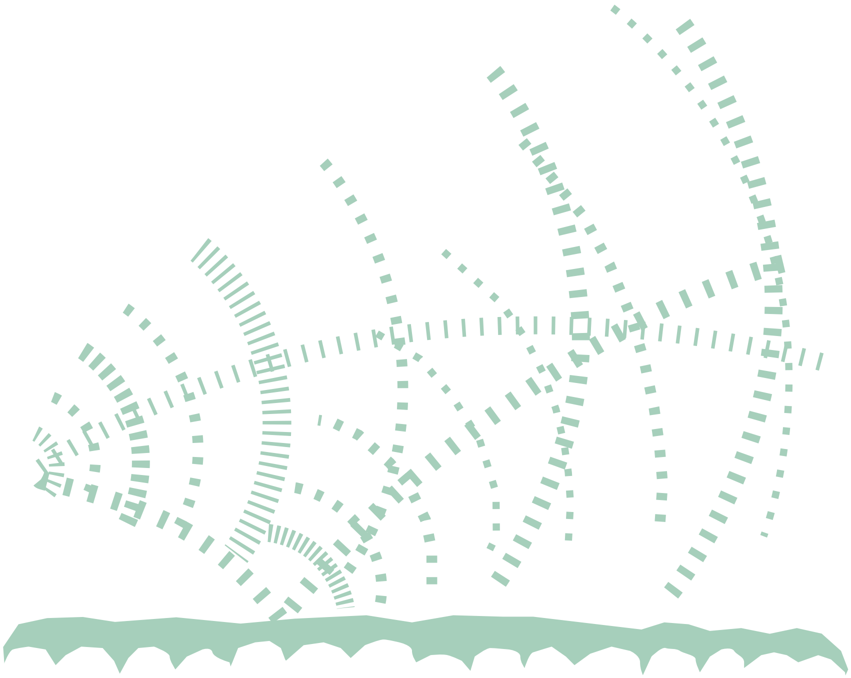
SHRUBS, BUSHES, AND HEDGES

Significant noise reduction by planting shrubs, bushes, and hedges, requires high above-ground biomass densities. The presence of the shrubs themselves is expected to be responsible for a maximum of a few dB(A) of noise reduction in typical road traffic applications. Note, however, that this effect can complement the other effects operating in a vegetation belt, such as the presence of tree trunks and the soil effect. The soil effect is expected to play a major part in the noise reduction caused by a belt of shrubs.

Hedges yield road traffic noise shielding between 1 dB(A) up to a maximum of 2–3 dB(A). Hedges should be sufficiently thick and very dense (internally). In addition, there should be sufficient biomass close to the ground. This is needed to prevent sound propagating underneath the hedge. This is especially important for rolling noise, which is generated close to the ground.



Sound-pressure-level spectra at 100 m distance from a four lane highway (15% heavy and 85% light vehicles, travelling at 100 km/h) predicted for a 1.5-m-high receiver in strong downwind for situations without noise barrier (black), with a 4-m-high barrier near the highway (grey), and with a dense row of trees positioned directly behind the 4-m-high barrier (green). The canopies extend 8 m above the top of the noise wall. A gap of 1 m between barrier top and the bottom of the crown of the trees is reserved to improve the positive effect. Due to the complex shifts in interferences in the acoustic shadow zone, caused by changing the wind fields, a slightly worse situation is possible in some frequency intervals. Note that in the current simulation, downward scattering by the tree crowns has not been accounted for. Predicted insertion loss: 9 dB(A) for barrier alone and 13 dB(A) for barrier combined with trees.



Noise reduction by means of ground treatments

Ground treatments aim to reduce noise at the receiver by exploiting the ground effect, that is, the effect of destructive and constructive reflections of sound from the ground. Such treatments include creating artificial ground roughness by using small hard blocks or by making grooves or pits, burying resonant cavities in the ground or road surface, introducing soft strips or patches (e.g., gravel-filled trenches), or changing the type of ground or groundcover (e.g., planting vegetation with favourable acoustic properties).

Over acoustically hard ground, such as a non-porous concrete or asphalt, destructive interference generally occurs at frequencies that are too high to reduce the overall sound level. For example, at 1.5 m height and distances of 10 m or more from a road, the presence of acoustically hard ground more or less doubles the sound pressure of road-traffic noise, compared with no ground, which corresponds to an increase of 6 dBA. However, over acoustically soft ground, such as grassland, destructive interference generally attenuates the sound more than would be expected by simply increasing the distance and from atmospheric sound absorption.

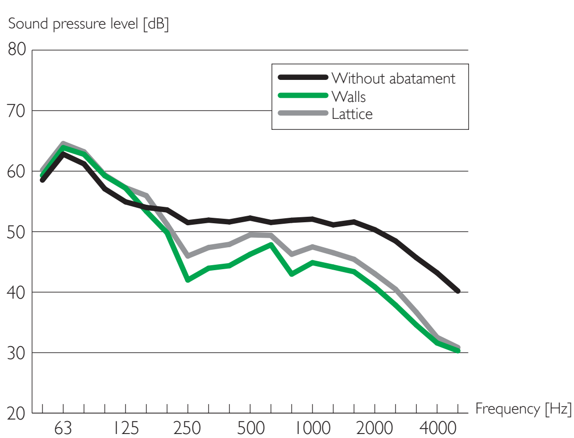
ROUGHNESS ELEMENT CONFIGURATIONS ON HARD GROUND

Introducing small objects on smooth, acoustically hard surfaces changes the sound reflection, thereby reducing the frequencies at which there is destructive interference. The acoustical effects of an array of such roughness elements depend on their mean height, mean spacing, cross-sectional shape, total array width, and whether the configuration is random or periodic. One can design a roughness configuration 0.3 m high and 2 m wide that can help reduce traffic noise by at least 3 dB, compared with smooth, acoustically hard ground, at 10 m from the road, while a 3-m-wide configuration of the same height reduces the noise by at least 7 dB(A) at 50 m from the road.

If the roughness elements are distributed randomly, the ground-effect spectrum displays a single destructive interference pattern resulting in excess sound attenuation over a broad range of frequencies. If the spacing is regular, then there can be additional destructive interference, but affecting narrower ranges of frequencies, than is produced by random roughness of the same height and mean spacing. As far as the overall reduction of traffic noise is concerned, there is no clear advantage to using periodically rather than randomly spaced roughness elements. However, periodic arrangements may be preferred for their appearance and ease of construction or sound perceptual reasons.

Below are two examples of roughness configurations made from ordinary household bricks. The con-

An array of nine parallel walls made from 1440 household bricks loosely stacked on edge (left). The same number of bricks made into a square-cell lattice (right).



Sound-pressure-level spectra from a two-lane urban road (5% heavy and 95% light vehicles, travelling at 50 km/h) predicted for a 1.5-m-high receiver located 50 m from the nearest traffic lane: (i) without treatment (black), (ii) with a 3.05-m-wide parallel-wall array consisting of 16 identical 0.05-m-thick and 0.3-m-high acoustically hard walls with centre-to-centre spacing of 0.2 m (green), and (iii) with a 0.3-m-high, 1.53-m-wide acoustically hard square lattice arrangement (grey). The receiver is assumed to be located along the centre line of the arrays, and both arrays are assumed to start 2.5 m from the nearest traffic lane. Predicted insertion loss: 7 dB(A) for walls and 6 dB(A) for lattice.

figurations were constructed from the same number of bricks, but the parallel-wall configuration (left) is nearly twice as wide as is the lattice configuration (right).

Lattice configurations half the width of parallel-wall arrays of the same height are predicted to produce comparable noise reduction. If there are no adverse meteorological effects and the array length is sufficient, then, for a given receiver height, the noise reduction produced by roughness arrays is predicted to decrease only slightly with increased distance from the road beyond 50 m. For example, the insertion loss predicted for a 3.05-m-wide, 0.3-m-high lattice is predicted to decrease by less than 1 dB(A) (i.e., from 7.1 dB(A) to 6.2 dB(A)) at 50–250 m from the road. Another advantage of a lattice configuration is that its acoustical efficacy is less dependent on the azimuthal source–receiver angle than is that of the parallel-wall array.

The predicted noise reduction is lower if the proportion of heavy vehicles (whose engine noise sources are positioned higher than in cars and produce more low-frequency energy) is greater and if there are traffic lanes farther from the roughness configuration. Nevertheless, 45 m from the edge of a four-lane motorway, carrying 15% heavy and 85% light vehicles travelling at 70 km/h, a 15-m-wide array of 26, 0.247-m-high parallel walls with equilateral triangular cross-sections (i.e., wedges) starting 1 m from the nearside road edge is predicted to reduce noise by 8.5 dB(A) and 3 dB(A) for receivers at heights of 1.5 m and 4 m, respectively. Although the cross-sectional shape of the roughness elements has an effect, the predicted increase in noise reduction that would result from using wedges rather than a 0.3-m-high rectangular low wall of the same cross-sectional area in this motorway case is less than 1 dB.

Greater noise reduction than obtained using regularly spaced identical parallel low walls is achievable using clusters of walls of varying heights. However, such profiles require that the roughness array be wider than it would be without clusters and therefore occupy a larger land area. Compared with hard smooth ground, a 16-m-wide series of wall clusters of varying heights arranged in a fractal pattern is predicted to reduce the sound level that would occur over smooth hard ground by 11 dB(A) for a 1.5 m receiver 50 m from a two-lane urban road (5% heavy and 95% light vehicles, travelling at 50 km/h). This is 2.5 dB(A) more than would be obtained using a 16-m-wide array of regularly spaced identical 0.05-m-thick walls of the same height.

Sometimes bunds or berms rather than fence-type barriers are used for noise control. If the berms are constructed with compacted soil surfaces, the deliberate introduction of roughness in the form of parallel walls or grooves can improve their acoustical performance. For example, a 15-m-wide trapezoidal berm (4 m high with a 3-m-wide top) located next to a four-lane motorway can reduce the average noise by a substantial 18 dB(A) in a region extending up to 20 m behind the receiver-side edge of the berm. Nevertheless, constructing closely spaced, narrow deep parallel grooves (0.2 m deep, 1.25 cm wide, 2.5 cm centre-to-centre spacing) on the top of the berm is predicted to reduce noise by a further 7 dB(A). This is equivalent to the noise reduction resulting from a 1-m increase in the height of the smooth berm. A further noise reduction of up to 3 dB(A) is predicted if all sides of the berm are roughened in the same manner.

Experiments and simulations have demonstrated that the noise insertion loss due to low parallel wall and lattice configurations would be unaffected and, indeed, enhanced by placing small amounts (up to 10 cm deep) of gravel, sand, or soil in the gaps. In principle, it would be possible to grow plants between the elements. In addition, creating a 0.5-m-wide pathway through a roughness configuration would not significantly reduce its noise reduction performance.

Roughness-based noise reduction is also appropriate for mitigating railway noise. As in the case of road traffic noise, the noise reductions caused by the

Roughness-based noise reduction using low parallel walls close to a tramway

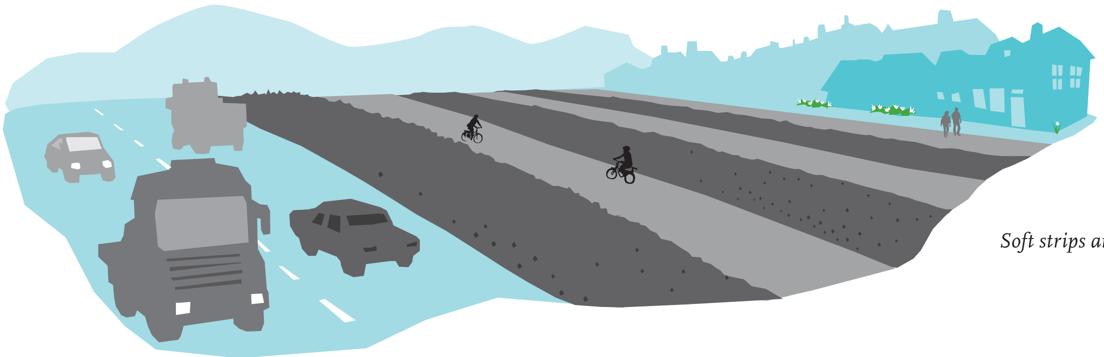
wall systems are predicted to decrease as the receiver height increases. For example, a 3.05-m-wide configuration of 16 parallel walls starting 1 m from the nearest track is predicted to reduce railway noise by more than 6 dB(A) at a 1.5-m-high receiver 50 m from the edge of the track. A configuration of two, four-wall clusters near the rails is predicted to reduce railway noise by 6–7 dB(A) if the configuration consists of acoustically hard walls and by 7–8 dB(A) if the configuration consists of slightly soft walls. Any of the proposed roughness-based treatments can be recessed in trenches or drainage gullies up to 0.3 m deep but their insertion loss is thereby reduced typically by 3 dB.

GRAVEL STRIPS AND PATCHES

Introducing a single strip or multiple strips of an acoustically soft material such as gravel can also reduce traffic noise in cases where otherwise there is hard ground, such as non-porous asphalt or concrete. Predictions suggest a reduction potential of 3–9 dB(A) at a height of 1.5 m, 50 m from a two-lane urban road with either a single wide strip or several narrow strips of gravel alternating with equally wide "hard" strips between the road and a receiver. Similar reductions of between 2 and 6 dB(A) will occur if up to 50% of hard ground is replaced with gravel near to a railway.

Although multiple relatively narrow strips may be preferred for aesthetic or practical reasons, they do not achieve any greater noise reduction than does a single strip of the same total width. Moreover the number of strips within a given area of ground is not predicted to have much influence on the noise reduction. For the considered geometry and the use of gravel, no increase in the noise insertion loss is predicted if the width of a single strip is increased beyond 25 m. On the other hand, the creation of hard strips in otherwise acoustically soft ground offers the added functionality of providing footpaths and cycle paths, albeit necessitating a wider treatment strip to achieve the same reduction as a single soft strip of a given width.

Some improvement in performance can be expected if the strips are distributed in patches, for example, in a "chequerboard" arrangement, since this would reduce the dependence of the noise reduction on the azimuthal angle.



Soft strips and patches

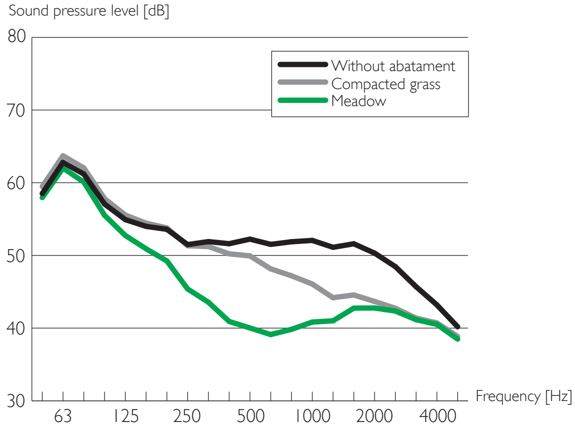
GROUND AND GROUND COVER

Softening the ground between a source and a receiver, for example, replacing asphalt with grass, can substantially reduce the noise from a road. The introduction of a 45-m-wide area of any type of soft ground to replace hard ground starting 5 m from the nearest traffic lane will reduce noise levels by at least 5 dB(A), and up to 9 dB, for a 1.5-m-high receiver 50 m from the road. Similar reductions, 3–5 dB(A), will occur at the 1.5 m high receiver at 50 m if soft ground is introduced in place of hard ground near to a railway.

The type of groundcover, for example, type of grass, can also influence the ground effect. An important parameter when selecting grass is the ease with which air can penetrate the ground surface, that is, flow resistivity. For grounds of comparable porosity, higher noise reduction is expected with lower flow resistivity. Ground that is compacted as a result of frequent mowing, rolling, or passage of wheeled equipment is likely to have a higher flow resistivity and thereby reduce noise to a lesser degree.

The difference between types of soft ground shown in the photos below is predicted to result in up to a 3 dB(A) difference in the sound levels for a 1.5-m-high receiver 50 m from a road as long as the soft ground extends from near (i.e. 5 m) the road edge to the receiver.

Two types of grass-covered ground. Sound-pressure-level spectra predicted for a 1.5-m-high receiver located 50 m from the nearest traffic lane (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.



CROPS

Crops may yield extra attenuation of traffic noise in addition to that due to the soft ground effect. Crops are characterized by the leaf area per unit volume (canopy index) and by the mean leaf size. For dense maize, the leaf area per unit volume is 6.3/m and the mean leaf width is 0.0784 m. For winter wheat, the corresponding values are 30/m and 0.012 m, that is, although the winter wheat is assumed to have higher foliage area per unit volume, it has smaller leaves. The overall sound attenuation can be calculated from the sum of that due to the ground effect and that occurring along those parts of the direct paths from the vehicle sources to the receivers passing through the crop. Example results of such calculations indicate that the combination of high-flow-resistivity ground and a small-leaf crop has little merit with respect to noise reduction. On the other hand, combinations of low-flow-resistivity ground and dense, large-leaf crops are predicted to attenuate the sound by 9–13 dB(A) for a 1.5-m-high receiver 50 m from the road, of which 1–5 dB(A) is contributed by the crops. The corresponding predicted total attenuations for a 4-m-high higher receiver are 2.5–7 dB, of which 0.3–4.5 dB(A) are contributed by the crops.

BURIED RESONATORS

A resonator consists of a hollow container with a neck, rather like a bottle. The resonance frequency can be tuned and depends on the neck's cross-sectional area and length and on the container's volume. An array of buried resonators in an otherwise acoustically hard area can reduce noise levels. For example, a 4-m-wide strip, perhaps of hard shoulder, containing a square array of resonators with centre-to-centre spacing of 6 cm and neck openings of 1 cm tuned to 350 Hz is predicted to reduce the noise level for a 1.5-m-high receiver 40 m from a two-lane urban road (5% heavy and 95% light vehicles, travelling at 50 km/h) by 2–3 dB(A).

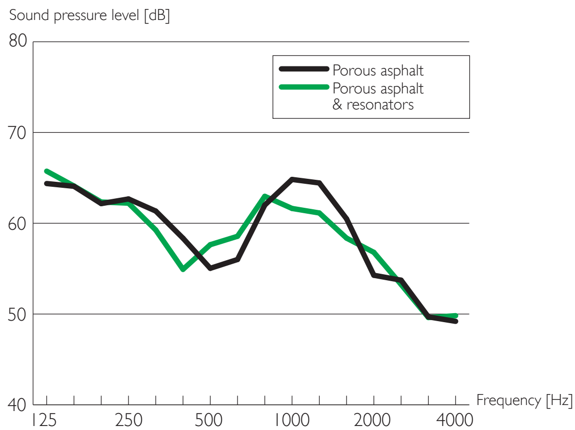
It is possible to combine acoustic resonators with porous road surfaces. Buried resonators affect the acoustical properties of a porous asphalt road in two ways: (a) they attenuate sound during propagation over the road surface, and (b) they reduce the sound amplification associated with the geometry of the tyre–road contact (i.e., the "horn effect").

The sound absorption coefficient measured perpendicular to the surface of twin-layer porous asphalt with a layer thickness of approximately 7 cm has pronounced maxima at approximately 600 Hz

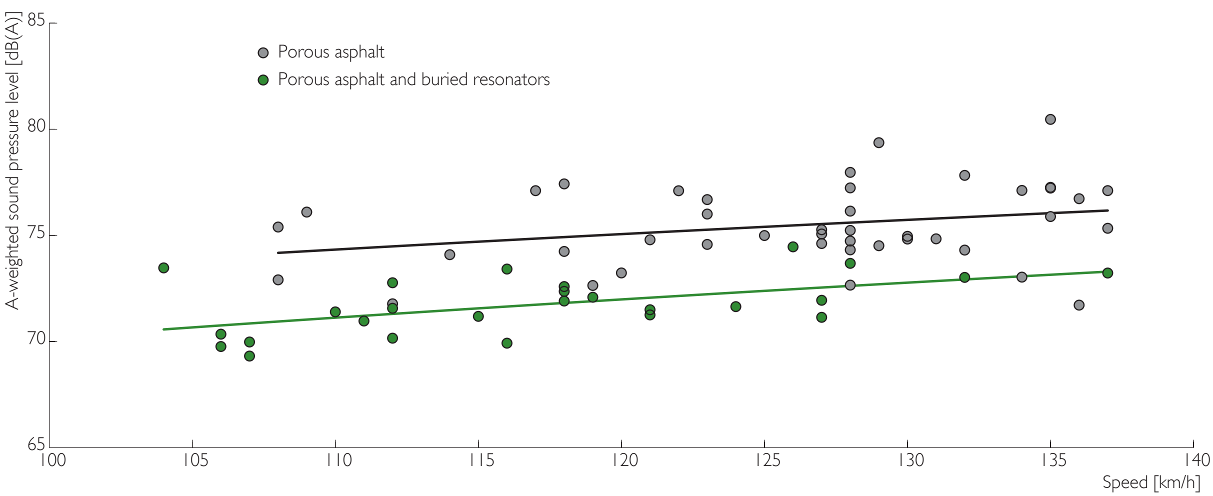
A resonator covered with porous asphalt (left) and the construction of a resonator-improved porous asphalt (right).

and 1800 Hz. Although the maxima decrease in amplitude with decreasing angle of incidence, the frequency dependence of the absorption coefficient could still be improved by inserting resonators tuned to 1 kHz. In this way, buried resonators can improve the noise reduction capability of new twin-layer porous asphalt by approximately 3 dB(A).

Pass-by measurements made on a test section of a highway containing buried resonators after three years under traffic have indicated that the resonators reduce the sound pressure level by the original amount (versus without resonators) of approximately 3–4 dB(A) for passenger cars and approximately 2 dB(A) for heavy trucks for a 1.2-m-high receiver at 7.5 m distance. This means that resonator-improved porous asphalt can yield useful traffic noise reduction not only immediately after construction but for at least three years.



Sound-pressure-level spectra (left) and maximum A-weighted sound pressure levels (below) from pass-by measurements over porous asphalt with and without buried resonators (light vehicle rolling noise at 100 km/h, for a 1.2-m-high receiver located 7.5 m from the road). The addition of resonators increases the insertion loss with approximately 3 dB(A).



Vegetation in urban streets and courtyards

Vegetation in urban streets, squares, and court yards

Vegetation can potentially reduce noise levels in situations in which multiple reflections from facades lead to increased sound levels, for example, in street canyons, courtyards and urban squares. The acoustic effects of vegetation in such situations are related to three mechanisms: (1) sound absorption, (2) sound diffusion, which occurs when a sound wave impinges on the vegetation and is then reflected back, and (3) sound transmission when a sound wave is passing through the vegetation.

Increasing boundary absorption can substantially attenuate noise. Vegetation with soil applied on building facades can have such effect, and this could be greatly enhanced in urban areas since there are multiple reflections. Compared with boundaries reflecting sound in one direction, boundaries reflecting sound diffusely in many directions, such as caused by vegetation, may affect the total sound field. When there are multiple reflections as typically for urban areas, the diffusion effect of vegetation will be greater, even when the diffusion capability is relatively low. In addition, the absorption and diffusion effects are useful for reducing the negative effects of ground reflections that often occur in outdoor sound propagation above hard ground.

VEGETATED ROADSIDE FACADES

In urban canyons vegetation can be placed on the building facades. Climbing plants or green walls

Vegetation in street canyon

that consist of plants, growing medium packed into geotextiles or pots and a supporting structure may be applied. The noise reduction potential of vegetation including substrate placed on street canyon facades is affected by canyon width, vegetation and substrate placement, and receiver position. The noise absorption effect is more efficient in narrower canyons and the extra attenuation provided by placing vegetation with substrate or other absorbing surfaces on facades increases with greater source–receiver distance. Adding vegetation to facades in traffic-bearing streets is more effective for higher receiver positions. Vegetation absorbs and scatters sound mainly at mid and high frequencies, so the acoustic effectiveness of greening facades will be lower at low frequencies.

To illustrate the effect of facade vegetation, noise reduction was calculated for a single street with 19-m-high facades on both sides, assuming non-vegetated facades with very low noise absorption. The acoustic treatment consisted of a supporting system, soil, and vegetation. The calculated predictions suggested that a noise reduction of 2–3 dB(A) may be obtained at a height of 1.5–4 m if all facades are covered with vegetation, compared with non-vegetated facades. If only the upper halves of the facades are covered with vegetation, the reduction is approximately 1 dB(A), whereas vegetation covering the lower halves of the facades may reduce noise by approximately 2 dB(A). Predictions also suggest that inserting a vegetated low barrier between lanes in the street may reduce noise by up to an additional 2 dB(A).

Vegetated facades in urban squares

VEGETATED FACADES IN URBAN SQUARES

As in the case of urban streets, the noise reduction potential of vegetated facades is greater for narrower squares and for receivers situated further from traffic sources. Note that if traffic runs through the square itself, the vegetation will reduce the noise by less than if the traffic runs on a side street.

The effect of green wall treatments on facades was predicted for a square with a street on one side, assuming non-vegetated facades with very low noise absorption. Averaged over 1.5-m-high receivers, a reduction of 3 dB(A) is achieved with vegetation covering all facades in the square and the adjoining street. If vegetation is applied only to the upper parts of the facades, the noise reduction is only 1 dB(A), while if vegetation is applied only to the lower parts, the reduction is 2 dB(A). Inserting a 1-m-high vegetated barrier between the square and the adjacent street can reduce the noise by up to 4 dB(A).

Vegetated courtyard facades

VEGETATED COURTYARD FACADES

Having a quiet side bordering a dwelling would be useful to reduce the adverse effects of noise, such as annoyance and sleep disturbance. Methods that reduce noise in courtyards can therefore be valuable as a complement to noise reduction on the most noise-exposed facades of buildings.

Noise levels in courtyards are lower with higher facade absorption coefficients. Vegetated facades in courtyards reduce noise from all sources situated outside the courtyard, and vegetated facades are also beneficial for noises originating from inside the courtyard.

The effect of vegetated courtyard facades is greatest at the highest frequencies and for lower receiver positions, with an average reduction of 4 dB(A), assuming non-vegetated facades with very low noise absorption. In an elongated courtyard abutting on a trafficked street, the longer side exposed to the traffic means that vegetated facades reduce the noise only slightly, by not more than 0.5 dB(A). Higher noise reduction is obtained when halving street and courtyard geometries, but the reduction is still under 1 dB(A).

VEGETATED OPENINGS TO COURTYARDS

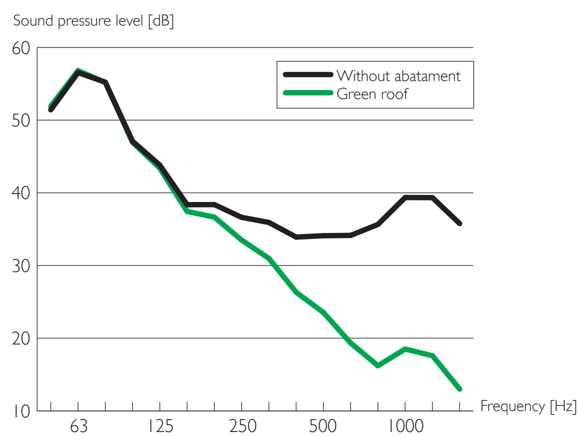
Openings to courtyards can transmit noise, reducing the relative quietness of the non-exposed sides of dwellings. Compared with an enclosed courtyard, an opening facing a busy street can increase the average noise level in the courtyard by up to 15 dB(A) for a 3-m-high opening and 18 dB(A) for a building-height opening of 19 m. In the case of an opening facing a non-trafficked street crossing a busy street, the noise level increases by approximately 6 dB(A) and 10 dB(A) for opening heights of 3 and 19 m, respectively. The noise level differences are relative to road traffic noise originating from the main street only, considering that no noise is coming from side roads.

Vegetating openings leading to courtyards can reduce noise by approximately 4 dB(A) for both an opening directly facing a busy street and one facing a non-trafficked side street. In all cases, the largest decrease in noise levels is found at the highest frequencies and for receiver positions near the opening, although attention needs to be paid to growing vegetation at dark places like courtyards opening (see also page 44).

GREEN ROOFS

Green roof systems absorb sound propagating from streets into courtyards. In street canyons and courtyards, the amount of sound energy propagating over rooftops from noisy to quiet sides is determined mainly by building height, width, and shape. The amount of noise reduction caused by roof vegetation also depends on the roof shape. In the absence of vegetation, angled roofs may perform worse than flat roofs assuming an equal building volume.

Predictions for a 10 cm thick substrate, which is a 'semi-extensive' treatment, on building roofs surrounding a courtyard indicate a noise reduction of approximately 2 dB(A) for vegetated flat roofs and of up to 8 dB(A) for vegetated angled roofs. Some angled roof shapes with vegetation outperform flat rigid roofs by almost 5 dB(A).



Sound-pressure-level spectra at courtyard with and without vegetation on angled roofs. For a two-lane urban road (5% heavy and 95% light vehicles, travelling at 50 km/h) averaged over receiver positions in courtyard. Predicted insertion loss of vegetated roof: 8 dB(A).

Green roofs with short vegetated roof-edge barriers

ROOF BARRIERS

A vegetated roof barrier positively affects the sound field in the courtyard by the presence of absorption at the diffraction edges. For example, a vegetated low-height barrier can be installed along the edges of flat roofs nearest the courtyard, nearest the street canyon, or along both edges. When a barrier is placed along the roof edge nearest the canyon or the courtyard, the average noise reduction is approximately 1 dB(A) for a 0.6-m-high barrier. Placing low barriers along both sides of the central building reduces the noise by an average of 3 dB(A). For a narrow configuration with a street width of 10 m, the noise is reduced slightly more, by an additional approximately 1 dB(A). Note that low-height barriers without vegetation have an insignificant effect in terms of noise reduction.

Combining solutions

Noise engineers may select noise mitigation measures based on noise policies and design objectives, taking into account site-specific constraints, while optimizing cost, benefits, or both. However, this often leads to the selection of a single solution. Commonly, to protect buildings against noise from a nearby road, either a low-noise road surface or a sufficiently high barrier will be selected; if neither of these solutions works, reinforced facade insulation may be prescribed.

The project adds innovative and alternative solutions to the catalogue of possible mitigations. It has demonstrated that vegetated barriers, berms, and embankments with or without added roughness, as well as dense strips of trees, not only perform similarly to traditional noise barriers, but may offer additional benefits. For example, vegetated barriers are noise absorbing, lightweight, easy to install (even in the case of complex terrain), aesthetically pleasing, easy to integrate into landscape architecture, and require little or no maintenance.

The project also proposes solutions that, when applied individually, may perform less well than traditional ones but, when combined, offer alternatives that are cheaper, easier to integrate, and less subject to site-specific constraints and conflicts. For example, low barriers and roughness elements have limited visual impact and do not divide communities in the same way as do conventional noise barriers.

In dense urban areas, conventional noise barriers or porous road surfaces are impractical. Reduction or moderation of traffic is usually considered the only workable solution for action planning, both for reducing noise and improving air quality. Here also, the project offers innovative approaches based on installing low barriers near the source, treating the ground, greening walls and roofs, and providing additional noise absorption with trees, hedges, and plants. Although the effects of such measures may be limited in narrow street canyons, their combined effects allow for the creation of relatively calm areas and quiet facades inside building blocks.

60 + 60 = 63 dB(A)

Noise levels don't add up the way usual numbers do. If a particular spot is exposed to two noise sources, each producing a noise level of 60 dB(A), the resulting noise level will be 63 dB(A). Implementing a highly efficient mitigation measure for one of the sources can reduce the overall noise level by no more than 3 dB(A). Alternatively, adopting a more balanced approach, aiming more modestly to reduce the noise from each source by only 5 dB(A), will result in a global noise reduction of 5 dB(A).

The same holds for road and railway infrastructure. If the infrastructure is entirely visible from a specific location, then installation of a highly efficient noise barrier shielding only half of the infrastructure as seen from that location will reduce the equivalent noise level by 3 dB(A) at best. Installing more modest (and cheaper) noise reduction devices along the full length of the infrastructure, balancing contributions from different parts of the extended source, generally leads to a better cost–benefit ratio.

Combining solutions in areas exposed to road traffic and railway noise

As illustrated above, the project offers a large menu of solutions that can be combined into a balanced design. For example, to create a walking path from the dwellings to the park area, the berm is interrupted and replaced with a protected pedestrian crossing (reduced lane width and limited speed) embedded in roughness elements. Near the crossing, the role of the dense strip of trees along the railway is locally taken over by a low, lightweight vegetated barrier.

In addition, each device may have effects on one or more noise sources or receiver locations, further increasing the overall cost–benefit ratio of the project. For example, the strip of trees protects the housing area from both railway and road noise, shielding up to 50% of its total length; without this strip of trees, barriers would have to be placed all along the road to achieve a similar reduction in noise levels.

5 + 5 < 10 dB(A)

The overall efficiency of a mitigation, expressed in terms of dB(A) levels, depends on the spectrum of the source and may differ from one source to another. Noise levels in different frequency bands add up as if they were produced by independent sources. The optimal design of a single mitigation should therefore focus on reducing noise in these frequency bands in which the A-weighted source levels are highest (i.e., in the 500–1000 Hz range for most traffic-related noise sources). Mitigations with poor performance in this range will have limited effects on overall noise levels, no matter what their performance in other frequency bands.

When considering the combined effects of multiple solutions between one source and one receiver location, the noise reduction can, under some conditions, be added in single frequency bands; once again, the best overall performance is obtained by a balanced approach, that is, exploiting the complementarity of the solutions in the frequency domain.

The acoustical effect of a forest is a typical example: the soft, highly porous forest floor produces high ground effects in the low- and medium-frequency ranges, and scattering by trunks and branches reduces noise in the medium-frequency range, whereas absorption and scattering by leaves is mainly a high-frequency effect. Crops tall enough to block the line of sight have a similar, albeit more limited, effect.

TWO ARE BETTER THAN ONE?

Adding more than one noise-reduction device between the source and the receiver location is generally less efficient than using a single well-designed device. At worst, one device may destroy the other's effect. For example, diffraction by a barrier will destroy most (but not all) of the effects of soft ground. At best, the second device will extend the frequency range over which the first is efficient.

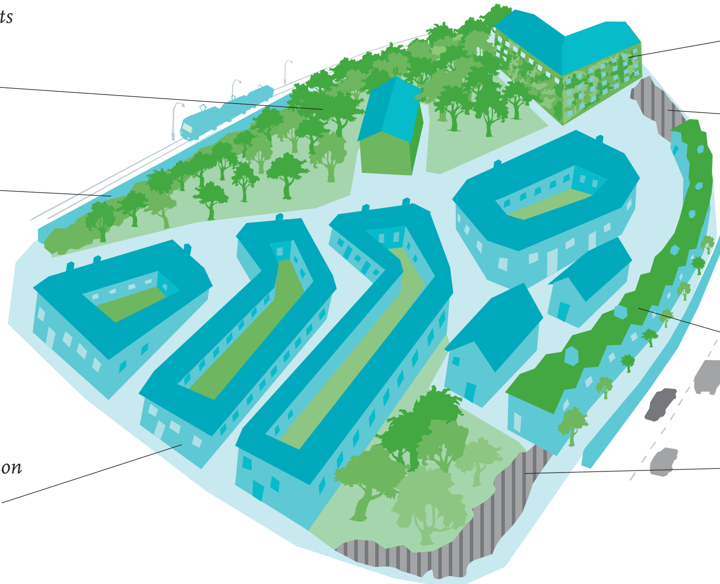
As a general rule, mitigations acting on the noise emissions (e.g., traffic reduction or low-noise road surfaces) and mitigations acting on the propagation path (e.g. through the ground or barrier effect) combine fairly efficiently, although the overall effect may depend on results in individual frequency bands.

In the case of an existing barrier, adding a specifically designed device on top of it may improve its performance more than would be expected from increased height alone. For instance, vegetated caps made of substratum are lightweight, aesthetically pleasing, and efficient at reducing noise. Additional mitigations located near the receiver, such as softening the ground or installing roughness elements, have little or no effect because diffraction over the barrier reduces the ground effect. Hedges may be helpful, partially compensating for the loss of ground effect in the high-frequency range. Densely planted trees behind the barrier have a positive effect.

CREATING RELATIVELY CALM AREAS

In dense urban areas, reducing noise levels at the most exposed facades to below recommended limits may be infeasible because of the short distances between the infrastructure and the dwellings. Low-noise road surfaces or low barriers may help to reduce outdoor noise somewhat, but acceptable indoor levels can be achieved only by means of reinforced facade insulation. The inconvenience of this situation can be partially compensated for by creating relatively calm areas inside building blocks, that is, in interior courtyards. Offering a relatively quiet facade on the shielded side creates opportunities to move bedrooms to the less noisy side, for natural ventilation, and for outdoor activities in private or public gardens, courtyards, and balconies. Recent studies indicate that having access to a quiet side of one's dwelling reduces annoyance equivalently to reducing noise by 5 dB(A) on the most exposed side.

Conventional noise policies for creating relatively calm areas rely on limiting local traffic and discouraging or prohibiting through traffic. The project proposes a large menu of mitigations that, when combined in a balanced approach, may effectively



Combining solutions to protect the quiet sides of noise-exposed dwellings

protect calm areas from surrounding noise sources. For example, greening roofs increases the barrier effect of closed rows of buildings, whereas greening facades reduces the effects of reflection. Trees and plants add absorption, further reducing the (semi) diffuse sound field in the shielded areas.

PREDICTION TOOLS

Innovative mitigation measures are not taken into account by standard prediction methods. For example, methods based on the ISO-standard "Attenuation of sound during propagation outdoors" (ISO 9613-2) simply ignore the effects of low barriers or ground roughness. The project has intensively used numerical calculations in evaluating the effects of innovative solutions in simple configurations. To assess the efficiency of single or combined innovative mitigations in complex situations, the project proposes a holistic tool based on the exploitation of numerical results within the framework of a traditional noise mapping software package. As results are produced on large grids of receivers, the tool allows for the holistic evaluation of noise abatements, for example, by means of global cost–benefit analysis.

Coupled with micro-scale traffic simulations, the tool supports audio simulations, that is, produces results that are directly comparable to measurements, allowing for the prediction of any measurable noise indicator. Audio simulations integrated into virtual reality tools tend to provide a plausible (if not realistic) representation of the planned mitigations, making the link between subjective or objective design goals, implementation decisions, and expected results more understandable to citizens and decision-makers, especially when it comes to promoting innovative solutions whose effects cannot be evaluated from previous experience or good practice.

Perceptual effects

The main perceptual effect of noise mitigation is to reduce the audibility of noise at the point of the receiver, making it less annoying and less likely to interfere with activities such as sleep, rest, and speech. Noise mitigation can also indirectly influence the sonic environment, by making previously masked sounds, such as birdsong or the sound of moving water, more noticeable. In addition to auditory effects, noise mitigation can also improve the scenery of a place; for example, a vegetated noise barrier or earth berm can visually shield the traffic and increase the amount of visible greenery.

The efficiency of noise-mitigation methods is typically assessed in terms of the achieved reduction in A-weighted sound pressure level (dB(A)), which gives a fair indication of the effect on the audibility of noise. However, perceptual studies are also needed, to complement acoustic analyses, because most mitigation methods do not merely reduce the overall level of the noise, but also alter its spectral and time patterns. For example, a noise barrier will reduce high-frequency sounds more than low-frequency sounds and reduce the noise variability on the shielded side of the barrier. These results may affect how annoying the noise is perceived to be, over and above the effects related to the dB(A) reduction. Moreover, the effects of noise mitigation on other sounds, previously masked by the mitigated noise, may not correlate directly with the accomplished dB(A) reduction.

Several methods can be used to study perceptual effects of noise mitigation. In the project, questionnaire studies in the field, listening experiments using field recordings, and experiments using simulated auditory and visual stimuli were conducted. The following sections summarizes results from these evaluations.

PERCEPTUAL EVALUATION OF A VEGETATED BARRIER

The perceptual effects of a low vegetated noise barrier in central Lyon were evaluated in a field questionnaire study, complemented with a listening experiment in the laboratory. The barrier was erected to protect a popular esplanade from road-traffic noise. The purpose of the evaluation was to determine the acoustic and perceptual effects of the barrier.

In the field study, pedestrians were asked to assess the sound environment. Questionnaire responses were collected on two occasions, one before and one after the barrier was erected. Each time, data were collected at two locations, at a place behind the barrier and a place 20 m to the side of the barrier. Acoustic measurements were also made both before and after the barrier was erected; obtaining these measurements entailed making recordings, including binaural recordings used in subsequent listening experiments.

Acoustic measurements made at the same locations where the questionnaire was completed indicated that the sound pressure level behind the barrier was on average 4 dB(A) lower than without the barrier. The noise variability was also reduced by the barrier, whereas the relative level of low-frequency sound increased, because barriers reduce high-frequency sounds more than low-frequency sounds.

The barrier improved the perceived sonic environment. The percentage of annoyed respondents decreased from 59% at places uninfluenced by the barrier to 47% behind the barrier, and ratings of the overall quality of the sound environment indicated that the barrier made the soundscape slightly calmer and less unpleasant. However, traffic was still the dominant sound source and natural sounds, such as birdsong, were not heard more often after the barrier was erected than before.

Listening experiments with traffic noise events simultaneously recorded behind and beside the barrier verified that the barrier reduced the annoyance of the traffic noise, and that this effect was fairly well predicted by the associated dB(A) reduction. However, there was a slight tendency for the annoyance reduction to be a little less than would be expected from the dB(A) reduction. This can partly be explained by the barrier's lower reduction of low-frequency than high-frequency sounds. As a result, the relative level of low-frequency sounds, measured as the difference between C- and A-weighted sound pressure levels (LC–LA), increased due to the barrier. The experimental results verified previous experimental research, which has suggested, as a rule of thumb, that dB(A) reductions can be adjusted down by 0.4 dB(A) per dB-increase in LC–LA caused by the barrier. The barrier also reduced the noise variability, measured as the difference between levels exceeded 10% and 90% of the time. However, statistical analyses suggested that this did not strongly influence the perceived annoyance of the noise.

PERCEPTUAL EFFECTS OF SOFT AND HARD GROUND ALONG TRAMWAYS

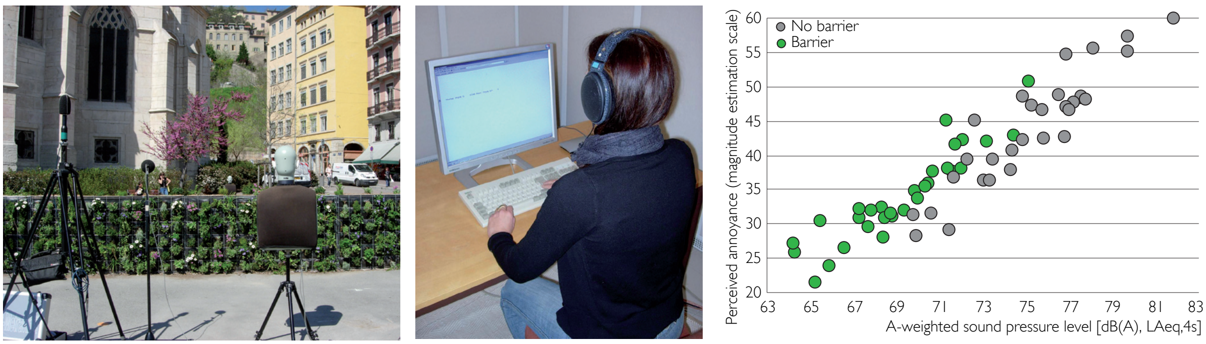
The acoustic and perceptual effects of soft or hard ground between tramways and receivers were evaluated in a study involving measurements, recordings, and a listening experiment. Recordings were made 4 and 7 m from a tramway in Grenoble, France, at a location with soft ground (grass) and at another location with hard ground (asphalt). A large number of tramway passages were recorded, and these were matched to allow comparisons of recordings made in places bordered by different types of ground, but of trams of the same type travelling at the same speed.

At the closer distance, 4 m, sound pressure levels from tram passages were about the same at both the

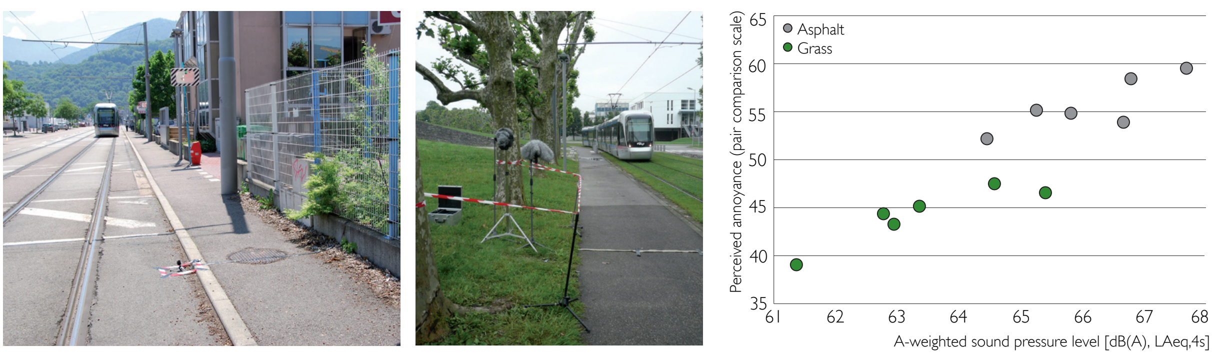
Questionnaire data collection and simultaneous sound level measurements behind (left) or beside (right) a vegetated barrier in central Lyon, France.

grass and asphalt locations. However, at a distance of 7 m, the grass reduced the level of noise by approximately 3 dB(A) compared with the asphalt location.

A listening experiment verified that recordings made near the tramway were about equally annoying, regardless of whether the tramway was bordered by grass or asphalt; for recordings made farther from the tramway, however, the grass margin clearly resulted in less annoyance. The effect at this distance could be predicted fairly well from the associated dB(A) reduction. There was, however, a slight tendency for the annoyance difference between the grass and asphalt recordings to be greater than one would predict from the dB(A) difference alone. Verbal reports from listeners suggest that a main perceptual effect was a reduction of high-frequency sounds in the tram noise, and this observation was supported by acoustic analyses.



Recordings made using "artificial head technology" to obtain high-quality recordings for listening experiments. Diagram: Results of a listening experiment in which 31 listeners assessed the perceived annoyance of traffic noise events recorded at barrier-shielded (green) or non-barrier-shielded (grey) places along the road.



Recordings along a tramway line bordered by hard (left) and soft ground (middle). The diagram shows the results of a listening experiment in which 29 listeners assessed the perceived annoyance of tram passages recorded at a point 7 m from the track, bordered by soft (green) or hard (grey) ground.

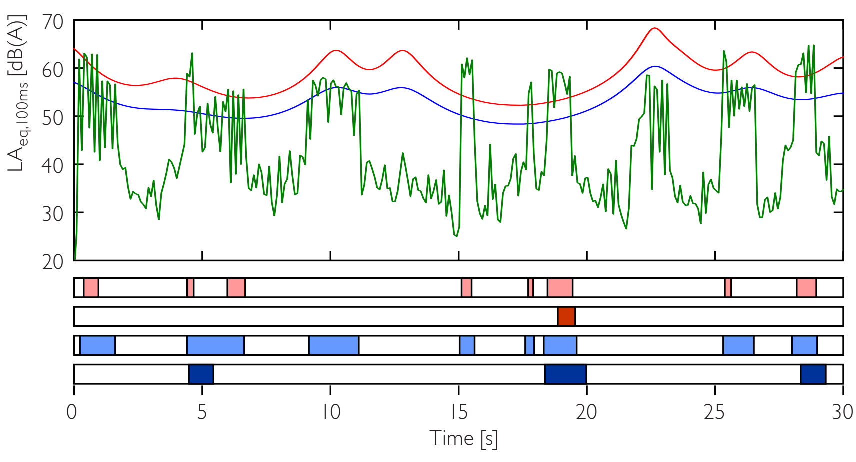
SOUNDSCAPE QUALITY

The overall sonic environment, or soundscape, consists of sounds from many sources. Some of these are wanted and contribute to the overall quality of the soundscape. Others are unwanted and detract from the quality of the soundscape. In urban open spaces, such as city parks, sounds from nature are typically perceived as wanted, whereas traffic noise is not. Noise mitigation can thus improve soundscape quality in two ways, directly by reducing the unwanted sound, and indirectly by making wanted sounds, such as birdsong or the sound of moving water, more noticeable as a consequence of reducing masking noise.

In this context, energetic masking refers to the inability of the human hearing system to detect some of the sounds in a complex mixture. This is caused by the physiological limitations of the inner ear. Increasing the noticeability of a wanted sound – sometimes referred to as perceptual unmasking – is a phenomenon that is determined largely by attention mechanisms. An inattentive visitor to a space will notice some of the sounds without noticing others. A soundscape design aiming to provide a restorative environment for the people using the space may include creating notice-events for wanted sounds. In urban environments, as mechanical sounds often dominate and energetically mask wanted sounds, green noise control can be used to unmask these wanted sounds. Making wanted sounds more noticeable requires a detailed analysis of the spectro–temporal structure of both the wanted and unwanted sounds.

The urban soundscape designer can either use listening panels to evaluate audio fragments containing the envisaged sound mixture or can rely on models such as the Notice-event model to predict the perceived soundscape. One disadvantage of listening experiments is the difficulty of distracting people from noticing the sounds presented in an acoustic laboratory setting; accordingly, such studies are used mainly to assess perceived loudness and sound quality of specific target sounds.

Computer models predicting whether the average visitor will notice a sound are becoming increasingly accurate and powerful. Below is an example of predicted time intervals in which atten-



Fragment of bird sound (green) combined with traffic sound recorded at 15 m distance (red) and traffic noise behind a barrier (blue); the pink and light blue stripes indicate time intervals in which bird sound is not energetically masked; the red and dark blue stripes indicate noticed bird sound.

tion is attracted by a bird sound in the presence of traffic sound with and without a noise barrier. In this 30-second time interval, bird sound is predicted to be noticed three times more often when a noise barrier – reducing the noise level by 6 dB(A) – is introduced

Some of the project's solutions specifically address soundscape quality, for example, as experienced by pedestrians and cyclists in street canyons, urban squares, and parks, and near major roads, railways, and tramways. Moreover, adding vegetation to the urban public space will increase wind sounds and attract wild life with its typical vocalisations. The choice of vegetation is very important in this respect. Seasonal variations are equally important. For instance, the effect of a green noise barrier may be amplified by increased bird activity during spring and summer time.

AUDIOVISUAL INTERACTIONS

Many noise-mitigation methods influence the visual environment as well, and the use of vegetated mitigation elements can improve the visual quality of environments. The extent to which such visual changes also influence auditory perception of noise is debatable. However, the effect on the overall environment is more important, and noise-mitigation methods that, in addition to reducing noise, also improve aesthetic values are obviously better than methods that do not.

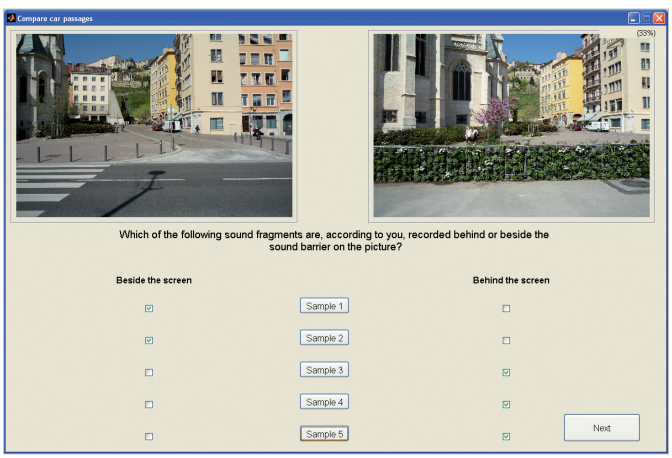
Environments presented in experiments on audio-visual interactions in perception of urban streets.

Aesthetic values are of particular importance in outdoor areas intended for rest and relaxation, such as city parks or recreation grounds. Previous research suggests that the sound environment and scenery independently contribute to the perceived tranquillity of such areas, and that low sound levels combined with a view dominated by vegetation would be associated with a high degree of tranquillity. Many of the methods studied in the project would be suitable for areas intended for rest and relaxation, by simultaneously reducing noise and increasing the amount of greenery.

Experiments with simulated environments conducted in the project suggested that urban streets planted with greenery were perceived as pleasanter and quieter than streets with no greenery. These studies also confirmed that vegetation planted on barriers made the sidewalk more visually attractive.

AURALISATION OF THE EXPECTED EFFECT

Noise control using green and natural materials may take subtler forms than can be expressed simply by the reduction in physical noise levels. By presenting the expected effect of a noise reduction measure to the designer and the public using audio-visual media, the effect can be appreciated in full. However, this requires that the methods used to generate the audio-visual presentation evoke exactly the same perception and appreciation as does the real intervention. From experiments conducted in the project it was concluded that more accurate numerical simulation can produce better audio-visual presentations only if the details and statistical variability of the mitigation measure are also taken into account. The latter is obviously more important for green and natural materials since they display higher variability.



- A significant majority of people can identify which sounds were recorded behind the noise barrier.
- Simulated (auralised) sounds are categorized as occurring behind the barrier as easily as are recorded ones.
- A significant majority of people can nevertheless distinguish between recorded sound and simulated (auralised) sound when the barrier is artificially added.
- People can distinguish between different models used for predicting the effect of the barrier and display a clear preference, the physically more accurate models not necessarily being those perceived as better resembling reality.

Evaluation of audiovisual presentation of noise mitigation; left: screen used to perceptually categorize sounds as occurring behind or not behind the barrier; right: summary of main results.

Economic analyses

Investments in noise reduction methods are often guided by economic considerations. How do we choose between an efficient but expensive method and an inexpensive but less efficient method? When does the additional cost exceed the acoustic benefits of adding extra elements, using higher quality components, or increasing the size of a noise-reducing structure?

To answer such questions, we may employ cost–benefit analyses (CBA) or, to some extent, cost-effectiveness analyses (CEA). CBA converts different streams of monetary values to a common format. This enables us to compare measures having different time profiles, such as pitting lower-quality solutions needing frequent and costly maintenance against higher-quality alternatives that cost more up front, but promise less frequent and less costly maintenance efforts.

COST-EFFECTIVENESS ANALYSIS

Cost-effectiveness analysis (CEA) takes only the acoustic environment into account, and favours the least costly measure or group of measures achieving a predefined acoustic goal, for example, a 10 dB(A) noise reduction. Measures that have a more efficient design and employ fewer or cheaper materials come out on top. An advantage of CEA is that there is no need to put a monetary value on the acoustic target, so CEA can be used in situations in which the monetary value of the benefits has not yet been assessed through research studies. This is currently the case for acoustic improvements in most non-residential settings, such as city parks, where we lack knowledge of the relationship between noise exposure and effects on human well-being and health. CEA is often sufficient in situations in which a predefined environmental limit needs to be reached or in which a political decision is needed to attain a given acoustical improvement.

COST–BENEFIT ANALYSIS

Cost–benefit analysis (CBA) takes a more holistic approach than does CEA, by expanding the scope of analysis to all impacts for which those affected in various ways by the measure are willing to pay. For example, noise reduction methods may also provide aesthetic benefits, reduce local air pollution, and provide thermal insulation, benefits that are included in the CBA.

The expanded scope of CBA may favour more expensive noise reduction methods or methods that provide less noise reduction than do competing alternatives. Noise control and soundscape improvement measures that are aesthetically pleasing can obtain a partly "free" ride by being subsidized by the aesthetic improvements or other additional benefits.

The CBA approach is more demanding than is CEA because all relevant effects need to be assigned a monetary value. When this is possible, the cost-efficiency of a noise reduction method can be calculated. If the benefits exceed the costs, the benefit–cost ratio (BCR) exceeds one (BCR > 1). To be competitive relative to other projects awaiting public funding, a noise reduction project should preferably be robustly efficient, that is, the benefits should outweigh the costs by a factor of two or more (BCR > 2).

Uncertainties are usually associated with both the cost and benefit estimates, which are in part addressed by assigning probability distributions to them. We also try at least to describe and assess factors and aspects that have not been assigned a

Two projects employing vegetated walls to reduce noise on the courtyard of an apartment complex

monetary value, or for which the monetary value is deemed uncertain. We should keep in mind that the costs of the measures are often dependent on the local availability of materials, scarcity of labour, and strength of the competition. Consequently, larger uncertainties can be associated with the "hard" cost estimates than the "soft" benefit estimates.

APPLICATION TO TWO VEGETATED WALL ALTERNATIVES

To illustrate CBA, we compared two alternatives in a project involving vegetated walls, installed to reduce noise while providing aesthetic value. The first alternative involved 3-m-high vegetated walls and the second alternative involved 19-m-high vegetated walls (see illustration above).

We adopted the EC-wide HEATCO recommendations to use an annual discount rate of 3% and a project horizon of 40 years. We also use the HEATCO results to derive a 2011 value for noise reduction of EUR 12.45 per dB(A)-person-year.

Since unit values for the aesthetic and amenity values of green walls were lacking, we estimated them in a separate study. We post-processed the published results in a number of international valuation studies. In our calculations (presented below), we used an estimate of EUR 2.42 per person-year-m^2, which is a relatively conservative estimate of the value of aesthetic and amenity benefits.

We considered two projects employing vegetated walls to reduce noise in the courtyard of a 48-unit apartment complex. A few residents living directly opposite the green walls also benefit aesthetically from the facade treatment.

The total areas covered by the facade improvements are $(2 \times 3 \times 9.6) = 58$ m^2 for the 3-m alternative and $(2 \times 19.2 \times 9.6) = 369$ m^2 for the 19-m alternative. The cost of the vegetated facades is set to EUR 500/m^2, with a lifetime of 10 years. This yields an equivalent annual cost (in 2011) of EUR 56.91/m^2. The annual maintenance cost is EUR 25/m^2.

For the 48-unit apartment complex, the 19-m-high green walls reduce the mean noise level by 4.1 dB(A), while the 3-m-high green walls reduce it by 4.5 dB(A). We assume an average of 2.4 people per apartment, so 115 people in total benefit from the acoustic improvements.

Since the improvement affects only the courtyard, the impact with respect to annoyance reduction is assumed to be 30% of that of reducing the noise level on the most exposed facade.

When taking aesthetic benefits into account, both noise abatement alternatives prove to be robustly efficient, providing benefits four times greater than the costs (BCR > 4). The aesthetic benefits, which are proportional to the costs, dominate the calculations and the two alternatives consequently prove to be about equally efficient.

When we ignore aesthetic benefits, neither of the alternatives is cost efficient, as both cost more than the benefits they produce (BCR < 1). Since the 3-m vegetated facade alternative provides a somewhat higher noise reduction for a substantially lower investment, it is about six times more cost effective than is the 19-m alternative.

ASSESSING THE UNCERTAINTY OF THE CALCULATIONS

To assess the uncertainty of the CBA, Monte-Carlo simulations were conducted. In such simulations, a large number of CBAs are conducted using different input values chosen from a large set of possible values. For the vegetated wall example, it was assumed that actual investment costs were normally distributed around the cost estimate, with a standard error of 30% of the size. We used a standard error of 15% for the number of beneficiaries, and assigned a relatively high uncertainty of 50% to the aesthetic benefits. We conducted 10,000 analyses to obtain a set of 10,000 benefit–cost ratios (BCRs) for each alternative.

Even allowing for substantial uncertainty in all estimated costs and benefits, the benefit–cost ratios are in the area of robust efficiency when aesthetic and amenity benefits are included.

When we ignore the benefits accruing from aesthetic and amenity improvement, there is virtually no chance that the studied measures will ever prove cost efficient. Given the available estimates and their uncertainties, the measures are almost certain to cost more than they are worth in terms of acoustic improvement alone.

In summary, cost–benefit analyses are applicable when we wish to determine whether the total benefits exceed the cost of implementing a measure. The two examples of green measures indicate that including non-acoustic benefits can have a crucial effect on the result. Expanding the scope of analysis and adding aesthetic and amenity values distinguishes between measures that do not seem to be economically viable and those that seem to be robustly so.

Summary of noise reduction methods

The project developed and tested a number of new noise-mitigation methods.
This summary table lists the methods and their potential impact described in detail above.

CATEGORY	MITIGATION METHOD	PROTECTED AREA	NOISE REDUCTION*	COSTS AND BENEFITS
Innovative barriers	Low-height barrier (maximum 1 m high)	Pavements and cycle paths, for a receiver at least 1 m from the barrier; dwellings and open spaces, such as parks, in the barrier's shadow zone	3 –12 dB(A) for an urban road and 9–15 dB(A) for a tramway at a distance of 2–50 m	+ Improves appearance + Contributes to pedestrian and cyclist security – May take up some space
	Light vegetated barrier along bridges (maximum 1 m high)	Pavements, cycle paths, and open spaces below urban roads and tramways; dwellings at the same level or below	Up to 5 dB(A) below a road traffic bridge, up to 15 dB(A) below a tramway bridge	+ Improves appearance + Contributes to biodiversity
	Graded index sonic crystal barrier (maximum 1 m high)	Large open spaces behind the barrier, e.g. parking lots or parks	4 dB(A) at a distance of 15 m from the barrier (for light vehicles only)	+ Sculptural design + High attenuation at certain frequencies, despite pervious structure – Non-uniform attenuation across frequencies
	Vegetated barrier caps (maximum cap size 1.20 m, minimum barrier height 4 m)	Parks, playgrounds, gardens, pedestrian/cycle paths along motorways, for receivers in the barrier's shadow zone	6–14 dB(A) at a distance of 1–20 m, compared with a straight rigid uncapped barrier	+ Improves appearance + Contributes to biodiversity – May need strong barrier foundations
	Earth berms with strongly non-flat surfaces	Open spaces and houses along motorways and railways	Up to 5 dB(A) compared with a smooth trapezoidal berm at a distance of 1–50 m	+ Improves appearance + Less graffiti than for a barrier + Contributes to biodiversity – Takes up more space than a barrier
Trees, shrubs, and bushes	Trees in street canyons and courtyards	Walkways and facades inside streets and courtyards	No more than 2 dB(A) for close positioning of trees in the street	+ Fully green solution (e.g., CO_2 uptake, increases biodiversity) + Improves appearance
	Tree belts (multiple rows of trees)	Open spaces near urban roads and highways; borders of parks near urban roads	Up to 6 dB(A) at a distance of 50 m for a 15-m-deep tree belt; up to 10 dB(A) for a 30-m-deep belt	+ Fully green solution (e.g., CO_2 uptake, increases biodiversity) + Improves appearance + Air pollution reduction – Takes many years to exert its maximum noise-reducing effect – Species allowing dense planting should be selected
	Trees behind barriers	Areas behind noise barriers in downwind sound propagation	Up to 5 dB(A) at a distance of 100 m in strong downwinds near highways	+ Strongly reduces negative visual impact of noise walls – Need for dense canopies to maximize effects – Complex, distance-dependent effect – Negative effects could appear at some distance

CATEGORY	MITIGATION METHOD	PROTECTED AREA	NOISE REDUCTION*	COSTS AND BENEFITS
Ground treatments	Roughness element configurations on hard ground	Pavements and open spaces near urban roads, railways, and tramways	Up to 3 dB(A) at a distance of 10 m; up to 12 dB(A) at a distance of 50 m	+ Visually nonintrusive + Allows access – Takes up more space than a barrier
	Soft strips and patches	Hard shoulders and open spaces such as car parks	3–9 dB(A) at a distance of 50 m	+ Improves appearance
	Ground and groundcover	Rural open spaces along motorways	Up to 9 dB(A) at a distance of 50 m	+ Improves appearance + Increases green space
	Crops	Rural open spaces along motorways	Up to 5 dB(A)	+ Contributes to food security – Seasonal effect
	Buried resonators	Hard shoulders and roads	Up to 3 dB(A) at a distance of 7.5 m	+ May be used to improve the effect of porous asphalt
Vegetated facades and roofs	Vegetated roadside facades	Vegetated roadside facades	2–3 dB(A) at a height of 1.5–4 m on the facade	+ Improves appearance + Reduces air pollution
	Vegetated facades in urban squares	Building facades inside squares	3 dB(A) at a height of 1.5 m throughout the square	+ Improves appearance + Improves thermal insulation of buildings – May make squares appear darker due to reduced light reflectance – High costs of installation and maintenance – Short life-cycle: 10 yr
	Vegetated courtyard facades	Building facades inside courtyards	4 dB(A) at a height of 1.5 m throughout the courtyard and on facades along the whole height of the building	+ Improves appearance + Reduces air pollution + Improves thermal insulation of buildings – May make courtyards appear darker due to reduced light reflectance – High costs of installation and maintenance – Short life-cycle: 10 yr
	Vegetated courtyard openings	3-m-high opening running from front to back through the building	4.5 dB(A) at a height of 1.5 m throughout the courtyard and on facades along the whole height of the building	+ Improves appearance + Improves thermal insulation of facades – May make courtyard openings appear darker due to reduced light reflectance – High costs of installation and maintenance – Short life-cycle: 10 yr
	Vegetated roofs	Semi-extensive installation (10 cm thick substrate) on the roofs surrounding the courtyard	2.5 dB(A) for flat roofs and 8 dB(A) for angled roofs at a height of 1.5 m through-out the courtyard and on facades along the whole height of the building	+ Improves appearance + Reduces heat loss and incoming heat flux into the building + Ameliorates storm water runoff + Low costs of installation and maintenance + Long life-cycle: 50 yr
	Roof barrier	0.64 × 0.96 m (width × height) barrier at edges of the building surrounding the courtyard	3 dB(A) when barriers are placed along both sides of the central building at a height of 1.5 m throughout the courtyard and on facades along the whole height of the building	+ Improves appearance + Improves roof safety

**) Unless otherwise indicated, the quoted noise reduction values are predicted for a receiver 1.5 m above ground at the specified distance from the roadside of a two-lane urban road, with 95% light and 5% heavy vehicles travelling at a speed of 50 km/h. The stated ground treatment reductions are with respect to continuous acoustically hard ground.*

Glossary

TERM	DEFINITION
absorbent materials	Sound absorbents or absorbing materials reduce the reflection of sound as a result of being porous so that air particle motion associated with sound is able to penetrate and its energy is converted into heat by friction with the walls of the pores.
absorption of sound	The process by which sound energy is converted to heat. This can happen in the atmosphere through air absorption, non-porous boundary-friction or interaction with a porous boundary.
acoustically hard/soft	A surface that reflects all of the sound that arrives at it is described as acoustically-hard, whereas a surface that absorbs some or all of the sound that arrives at it is called acoustically-soft.
atmospheric turbulence	Random irregular motion or fluctuation in temperature of fluid (e.g. air) induced by wind friction with the ground or by uneven surface heating. It scatters sound to an extent that increases with frequency. In the atmosphere it reduces ground effects and the acoustical performance of barriers.
auralisation	A method of simulating a real (for example an outdoor) hearing experience in a laboratory or through a virtual environment.
benefit–cost ratio	The ratio between the cash value of benefits accruing from a (noise reduction) action and the costs of implementing the action.
berm	An earthen barrier or bank of earth which may be used for noise control. Frequently berms are made from soil removed during associated construction activities and planted to improve appearance.
damping ratio	A dimensionless measure of how rapidly oscillations decay.
diffraction	The physical phenomenon by which sound bends around the edges of an obstacle, for example the top of a noise barrier.
diffuse	A sound field is diffuse at a receiver if it contains components travelling in all directions.
geometric spreading	The physical phenomenon by which sounds spread from a source after generation. This means that sound levels will reduce from distance alone. Spherical spreading and cylindrical spreading are special cases giving rise to 6 dB and 3 dB reduction per doubling of distance respectively.
ground effect	The physical phenomenon (interference) through which sound reflected from the ground and travelling to a receiver along the reflection path either reinforces or cancels sound that arrives at the receiver directly.
insertion loss	The insertion loss due to a mitigation measure is the difference between the sound levels at a given location without and with a mitigation measure. Usually stated in dB.
open porosity	Volume fraction of interconnecting pores that open to the surface of a material.
porous asphalt	An asphalt mix of stones and binder in which a gap in the stone size distribution is deliberately created so as to result in air-filled voids.
reflection	The process by which the sound incident on a surface is directed away from the surface. During specular reflection the sound is directed away from the surface at the same angle from the surface as the incident sound. Reflection represents a special form of scattering when the scattering object is very large compared with the incident wavelength.
refraction	The process by which the direction of sound penetrating a surface or region is changed.
resonator	A structure that resonates. If an undamped structure is vibrated at the frequency of resonance (resonant frequency) the amplitude of vibration grows arbitrarily large. Typical resonators include damping and can be used to absorb sound near the resonance frequency.
scattering	The process by which an obstacle influences incident sound. It depends on the relative size of the obstacle compared to an incident wavelength. If the obstacle is very small compared with the wavelength its influence is small but the combined influence of multiple scattering may be significant if there is large number of small obstacles per unit volume.
sonic crystal	A regularly-spaced array of (usually acoustically-hard) scattering objects giving rise to stop and pass bands in acoustic transmission at frequencies that depend on the centre-to-centre spacing.