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Toolbox from the EC FP7 HOSANNA project for the reduction of road and rail traffic noise in the outdoor environment

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Abstract

This paper offers a brief overview of innovative methods for road and rail traffic noise reduction between source and receiver. These include using new barrier designs, planting of trees, treatments of ground and road surfaces and greening of building façades and roofs using natural materials, like vegetation, soil and other substrates in combination with recycled materials and artificial elements. The abatements are assessed in terms of numerically predicted sound level reductions, perceptual effects and cost–benefit analysis. Useful reductions of noise from urban roads and tramways are predicted for 1-m-high urban noise barriers and these are increased by adding inter-lane barriers. A 3 m wide 0.3 m high lattice ground treatment, a carefully planted 15-m-wide tree belt and replacing 50 m of paved areas by grassland are predicted to give similar reductions. Tree belts are shown to be very cost-effective and combining tall barriers with a row of trees reduces the negative impact of wind. Green roofs may significantly reduce the noise at the quiet side of buildings.

Keywords: noise; abatement; outdoor; road; rail; prediction; barriers; trees; ground; green roofs; green façades; cost benefit; indicators; listening tests; questionnaires; numerical methods; measurements.

Résumé

Ce papier présente un aperçu de solutions innovantes de réduction du bruit de trafics routier et ferroviaire. Il s'agit notamment d'écrans antibruit novateurs, de plantation d'arbres, de traitements particuliers du sol et des routes, ainsi que de la végétalisation des façades et des toitures, avec des matériaux recyclés et éléments artificiels. Les performances sont évaluées par prévisions de diminution des niveaux sonores, d'effets perceptifs et d'analyses coût-bénéfice. Des réductions significatives du bruit sont observées pour des écrans urbains de 1 m de hauteur, pouvant être inter-voies. Un traitement du sol par l'utilisation d'un réseau de 30 cm de hauteur sur une largeur de 3 m, une bande d'arbres de 15 m d'épaisseur et le remplacement de 50 m de sol pavé par une zone herbeuse permet d'obtenir théoriquement des atténuations similaires. Les bandes boisées offrent un très bon rapport coût-efficacité, et combiner rangée d'arbres et écran antibruit permet de réduire l'effet négatif du vent. Enfin, les toitures végétalisées permettraient de réduire efficacement le bruit de trafic pour les façades calmes.

Mots-clé: bruit; atténuation; extérieur; route; ferroviaire; prévision; mur antibruit; arbres; sol; toitures végétalisées; façades végétalisées; coût-bénéfice; indicateurs; perception; méthodes numériques; mesures.

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1. Introduction

The World Health Organization (WHO) has estimated the yearly burden of transport noise-related disease and annoyance to correspond to the loss of more than 1 million healthy life years every year in the western European countries, including the EU Member States. This corresponds to an individual loss of 1–2 days per year and, of the environmental factors identified, only air pollution is estimated to have a larger disease burden (WHO, 2011). The main disease burden due to traffic noise 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 (den Boer & Schroten 2007). Successful noise reduction will therefore lead to substantial economic gains and positive effects on public health and wellbeing. In short, a majority of the EU population is estimated to be exposed to outdoor road traffic noise levels above the threshold suggested by WHO for onset of negative health effects. At the same time, road and rail traffic are expected to steadily increase, and the source strength is not expected to significantly decrease within the nearest decades. Although indoor noise reduction can be achieved using conventional façade insulation and closed windows, it is a challenge to protect the outdoor sound environment from excessive surface transport noise. If both the outdoor sound environment and the access to green areas are poor, public health may be threatened in the long-term. Hence, methods of reduction are needed during the propagation of sound from source to receiver.
The central project outcomes, which are substantiated by real life field cases, are being presented in the form of a brochure[†], a handbook[‡], scientific reports[†] and publications as well as tables[†] for engineering use. Some of the findings are briefly presented here. The noise reducing methods of the project aim at an increased use of vegetation, through greening roofs, façades and other urban and rural surfaces, innovative vegetated barriers, recycled materials and new treatments of the ground surface. Thereby we suggest extending the current toolbox of traffic noise reducing measures. Furthermore, the perceived improvement of the sonic environment and reduced noise annoyance is demonstrated and cost benefit analyses are made.
Since many of the noise reducing tools presented here are not yet represented by products or implemented in permanent installations, we would like to encourage the implementation, testing, and further evaluation of the suggested tools, for instance by city authorities. The estimation methods have all been validated and situations as realistic as possible have been modelled. 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. Nevertheless, the results from calculations and laboratory measurements should be treated with care, as, in reality, a non-negligible uncertainty is to be expected. The default specification of the traffic noise source is a two-lane urban road (50 km/h, 5% heavy vehicles) modelled with sources at 3 heights (Nota et al., 2005) and a receiver at 1.5 m height. Unless otherwise stated, noise reduction in dB means a lowering of the A-weighted equivalent sound pressure level for the default case. The project HOSANNA was coordinated by Chalmers University of Technology and involved 13 partners from seven countries, receiving funding from the European Union Seventh Framework Programme (FP7/2007–2013).

2. Innovative noise barriers, using natural and recycled materials

2.1. Innovative noise barriers

2.1.1. 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 (Defrance & Jean, 2013). Such barriers can be used in dense urban areas to protect areas near roads or rails from noise. Several configurations of low-height barriers (e.g., using gabions, sonic crystals or vegetation) have been studied in the project (Koussa et al., 2013a). Using a Boundary Element Method code (Jean, 1998) 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 40-cm-wide and 1-m-high straight barrier, made of a rigid core and a mixture of natural fibres and mineral materials, installed along a two-lane road, can potentially reduce road traffic noise by about 9 dB 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 street canyon, but increase by a

[†] Available on www.greener-cities.eu
[‡] To be published in 2014.

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 compared with a single barrier beside the rail, which reduces the noise by approximately 12 dB. Measurements using a prototype barrier, recently carried out in another project (Jolibois, 2013), support this amount of achievable insertion losses. In the case of a 1-m-high standard gabion made of large stones (typical dimensions between 15 and 20 cm) along a two-lane urban road, the acoustical noise reduction is 3–8 dB compared with an untreated situation, for a receiver located 2–50 m behind the barrier and 1–5 m above ground (Koussa et al., 2013b). Replacing stones with porous clay will attenuate the sound by an extra few dB.

2.1.2. 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 in the case of a four-lane motorway, and by up to 10 dB 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 for growth of vegetation, the noise reduction may reach 5 dB and 15 dB 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 below the bridge.

2.1.3. Vegetated barrier caps

Existing noise barriers can be improved by planting vegetation along the top edge, which increases sound attenuation during noise propagation (Defrance & Jean, 2013). 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 noise reduction due to a 1-m-wide element is 8–12 dB, compared with an uncapped straight barrier of the same overall height.

2.1.4. Earth berms

Although berms require more space than barriers do, 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 (Van Renterghem et al., 2012). 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 less than 1–2 dB 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, a wall and a berm can obtain similar shielding 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 (Jean et al., 2013). On flat rural terrain, this change in berm geometry from flat to stepped in profile can reduce noise by 4 dB compared with a conventional 4-m-high berm.

2.2. New recycled materials for acoustic treatment of noise barriers

Although the technology for manufacturing absorbing noise barriers from recycled polymeric and elastomeric waste has been available for many years, road noise barriers continue to be produced largely from virgin materials that include concrete, masonry, timber, metal and acrylic glass. This trend is slowly changing and more types of noise barrier systems that include recycled materials begin to appear on the market. Most common types of these are noise barriers with wood-fibre concrete finish, noise barriers with granulated rubber tyres infill and barriers which are made from recovered plastic often mixed with other recovered materials (Hag-Elsafi et al., 1999). In order to improve on the existing technologies, a new cold extrusion process has been developed as a part of the project. In the process, we blend polyurethane binder and recycled fibres and grains to produce highly porous media with controlled pore size distributions and proportions of open, interconnected pores with a range of sizes, where the residues are transformed into acoustic and thermal insulation materials, in a low-energy production process (Benkreira et al., 2011). A majority of these materials are provided in the form of granulated waste which can be sourced abundantly from the construction industry, manufacturing industry and local community 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 material production process. The knowledge generated as a part of this project can be used to acoustically optimize recycled polymeric waste by controlling the material porosity, permeability, density and stiffness. Some of these materials can be made highly porous and pervious to sound, in which case they can be applied either to the existing or new noise barrier systems in the form of the acoustically absorbing treatment. Alternatively, these materials can be compacted to form a dense, low-permeability barrier layer which can be used to enhance the transmission loss in a noise barrier system. A majority of conventional porous absorbers exhibit a poor performance in the low frequency range where the acoustic wavelength is greater than the thickness of the porous layer. Previously, in order to improve the low-frequency absorption of porous layers, it has been common to combine several discrete layers with homogeneous pore structure. Recycled polymeric material samples with continuously stratified pore structure were produced as a part of the project to provide 20–40 % improvement to conventional homogeneous porous layers designed to increase noise absorption. This enables to reduce the overall thickness of the acoustic absorption treatment proportionally, to achieve the same performance as that expected from the conventional porous absorbers or their combinations.

3. Trees, shrubs and hedges

3.1. Sound interacting with vegetation: direct and indirect effects

The direct interaction between sound waves and vegetation involves two main processes, namely redistribution and absorption of sound energy. Redistribution of sound occurs by reflection, diffraction and scattering when incident on trunks, branches, twigs and leaves. Although only absorption leads to effective loss of acoustic energy, redistribution of sound energy can be effective to achieve noise reduction at a single receiver as well.

In addition, there are some important indirect effects. The acoustically soft soil underneath vegetation (the so-called "forest floor") leads to pronounced ground effects, reducing low-frequency noise (Huisman & Attenborough, 1991). Also the change in microclimatology by canopies, in turn influencing the properties of the sound propagation medium, can be positively employed. Besides these direct and indirect physical effects, positive psycho-acoustic effects related to green measures are also observed (Yang et al., 2011).

3.2. Tree belts of limited depth can be effective noise barriers

Noise shielding by tree belts is the result of a combination of multiple scattering in between the tree trunks and by the presence of a forest floor. In order to obtain useful road traffic noise shielding by planting tree belts, specific guidelines must be followed, since common practice is usually not efficient (Van Renterghem et al., 2012).

The total area taken by the tree trunks in plan view is the basic parameter influencing the acoustic shielding. With increasing stem cover fraction (by either limiting the spacing in between trunks, or by achieving high trunk diameters), the acoustical shielding increases. However, stem cover fraction is practically limited, since sufficient access to water, nutrients and light must be guaranteed.

The choice of a specific planting scheme will make a tree belt efficient or not; a large spread is observed when simulating different planting schemes at a fixed stem cover fraction (Van Renterghem et al., 2012). Of special interest are rectangular planting schemes, where the spacing along the road length axis is limited, while the spacing normal to the road can be relaxed. In addition, allowing for small deviations from a perfectly ordered positioning of trees could lead to an increase in noise shielding. Randomness in tree stem diameter gives a similar effect. Randomly removing trees or even full rows inside the tree belt was shown to influence its noise shielding to a limited extent only, however, strongly relaxing the demand for high biomass density.

Trunk height was shown to be rather unimportant for typical road traffic noise applications. Also, receiver distance relative to the belt does not influence noise belt shielding, in contrast to a common noise wall. The noise level shielding shows a linear behaviour with tree belt depth (normal to the road), while shielding converges when increasing length of the belt (along the road length axis). Optimized 15-m deep tree belts were shown to be equivalent to thin, rigid noise walls of 2 m height, positioned directly at the border of a multilane highway. Belts with a depth of 30 m could even compete with noise walls of 4 m height in case of a rigid reference ground.

3.3. Improving micro-climatology with vegetation

The occurrence of a temperature inversion layer leads to downward bending of sound and pronounced increases in sound pressure levels near roads. This typically occurs during the night, where sufficiently low noise exposure levels should be present. Strips of forests prevent the development of such a ground-based nightly temperature inversion layer, leading to significantly lower noise exposure levels.

Another practical problem with noise walls is the strong reduction in performance under downwind sound propagation conditions (due to wind refraction), easily resulting in a loss of half of its efficiency compared to windlessness (e.g. DeJong & Stusnick, 1976). Also here, vegetation can provide a solution. A row of trees behind a noise wall is an efficient windbreak, leading to the recovery of a significant part of the shielding lost by the action of wind, as shown from an earlier measurement campaign (Van Renterghem & Botteldooren, 2002). Optimal canopy designs were identified in the current project and showed to be dependent on the type of barrier and the location of the dwellings (Van Renterghem & Botteldooren, 2013). Downward scattering by leaves is a potentially negative side effect of tree rows behind noise walls. However, this high-frequency effect does not affect the dominant part of a highway noise spectrum.

4. Noise reduction by means of ground treatments

4.1. Exploiting ground effect

It is possible to reduce noise from surface transport by exploiting the interference between sound travelling directly to listeners and sound reflected from the intervening ground. This is known as ground effect. Attenuation due to ground effect is included in many transport noise prediction schemes, but little attention has been paid to enhancing or exploiting it. Attenuation over hard ground is increased by artificial roughness (Bougdah et al., 2006). Other hard ground treatments involve the introduction of strips or patches of softer ground, gravel-filled trenches, or buried resonant cavities. Resonators can be used to enhance the performance of the porous asphalt used extensively for traffic noise reduction. The attenuation due to soft ground can be increased by changing the type of ground and/or ground cover.

4.2. Roughness-based treatments

Roughness with a height of 0.3 m or less on a hard smooth surface causes a change in the reflection of sound and thereby a reduction in the frequencies at which there is destructive interference. The acoustical effects depend not only on the mean height but also on mean spacing, cross-sectional shape and whether the roughness is random or periodic. If the roughness elements are distributed randomly, the ground effect spectrum shows a single destructive interference, resulting in excess attenuation over a broad range of frequencies. If the spacing is regular, there can be additional destructive interferences associated with the diffraction grating effect but these influence narrower ranges of frequencies than random roughness of the same height and mean spacing (Bashir et al., 2013a). At a 1.5 m high receiver 50 m from a two lane urban road, the creation of a 3 m wide 0.3 m high lattice starting 2.5 m from the nearside lane is predicted to yield an insertion loss of 6 dB compared to smooth hard ground. Roughness in the form of a lattice is particularly useful since the predicted noise reduction has less dependence on azimuthal angle (Bashir et al., 2013b). Roughness can be recessed but is about 3 dB less effective than an equivalent raised array for the same source-receiver geometry. A path through a roughness array, having much less width than the array, has an insignificant effect on its acoustical performance. If berms are constructed with compacted soil surfaces, the deliberate introduction of roughness can improve their acoustical performance (Jean et al., 2013).

4.3. Soft ground and vegetation

A single strip or multiple strips of an acoustically-soft material can also reduce traffic noise in cases where the ground would otherwise be smooth and acoustically-hard. Predictions have been made of the reductions in noise levels at a distance of 50 m from a two lane urban road that would result from replacing acoustically-hard ground surfaces between road and receivers by a variety of porous grass-covered surfaces with surface impedance modelled by slit pore layers (Attenborough et al., 2013). It is predicted that replacing a 45 m wide strip of acoustically-hard ground by any acoustically-soft ground will decrease levels by at least 5 dB at a 1.5 m high receiver and by between 1 and 3.5 dB at a 4 m high receiver. Higher noise reductions are predicted if the ground has relatively low flow resistivity. Ground surfaces that have been compacted, for example by frequent mowing, rolling, or heavy wheeling are likely to have higher flow resistivity. At a 1.5 m high receiver 50 m from the road, use of the lowest flow resistivity grass is predicted to yield up to 3 dB greater noise reductions than if the highest flow resistivity grass is used. The presence of 1 m high dense crops over 50 m range of soft ground is predicted to yield up to 5 dB additional insertion loss.

4.4. Buried resonators

Buried resonators in an acoustically hard area can reduce noise. For example a 4 m wide strip, perhaps a hard shoulder, containing a square array of resonators with centre-to-centre spacing of 6 cm and neck opening of 2 cm tuned to 380 Hz is predicted to reduce the noise level at a 1.5 m high receiver 50 m from a two lane urban road by 3 dB (Forssén & van der Aa, 2013). Buried resonators have been found to improve the acoustical performance of a porous asphalt road (Maennel et al., 2013).

5. Vegetation in urban streets, squares, and courtyards

5.1. Advantage of vegetation to mitigate noise in build-up areas

The acoustic effects of vegetation in build-up areas, such as street canyons, courtyards and urban squares, may relate 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 (e.g. Attenborough, et al., 2007). Increasing boundary absorption can substantially attenuate noise and placing vegetation with soil on building envelope can have such an effect. 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 (e.g. Kang, 2002). 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 the case of sound from a nearby trafficked street canyon being diffracted over the buildings thus entering the courtyard, a green roof on the building may reduce the diffracted sound and decrease noise in the courtyard.

5.2. Vegetated roadside façades

Vegetation placed on building façades may include climbing plants or green walls that consist of plants, growing medium packed into geotextiles or pots and a supporting structure. The noise reduction potential of vegetation including green walls placed on street canyon façades 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 façades increases with greater source–receiver distance along road. As vegetation absorbs and scatters sound mainly at mid and high frequencies (Yang et al., 2013), the acoustic effectiveness of greening facades will be lower at low frequencies. Considering a single street with 19-m-high facades on both sides, and assuming non-vegetated facades with a broadband absorption coefficient of 0.1, placing green wall on all façades may yield noise reduction of 2–3 dB at a height of 1.5–4m, limited due to the existence of the direct sound. The effect is similar for un urban square with a road.

5.3. Vegetated courtyard façades

Having a quiet side bordering a dwelling would be useful to reduce the adverse effects of noise, such as annoyance and sleep disturbance (e.g. Öhrström et al., 2006). Methods that reduce noise in courtyards can therefore be valuable as a complement to noise reduction on the most noise-exposed façades of the buildings. In a situation where noise is entering a courtyard from a nearby trafficked street, an average noise reduction of 4 dB may be obtained by applying green wall on all courtyard façades, compared to a case with non-vegetated facades with a broadband absorption coefficient of 0.1. The effect of vegetated courtyard façades is greatest at the highest frequencies and for lower receiver positions.

5.4. Green roofs to increase quietness at shielded building façades and in courtyards

In-situ measurements (Van Renterghem et al., 2011) and detailed sound propagation calculations in various, realistic building configurations (Van Renterghem et al., 2013) showed the large potential of green roofs in mitigating noise, and could hence be of importance for achieving a quiet side. The application of green roofs was shown to be the most promising building envelope greening measure. When the dominant sound path is diffraction over the roof, sound levels can be efficiently reduced. In case of tilted roofs, improvements exceeding

7 dB (relative to a common rigid roof covering) were predicted, as an average over many potential receiver locations in a courtyard and over various road traffic conditions.

5.5. Vegetated openings to courtyards

Roadside courtyards are not always completely closed and façade openings for convenient accessibility may be encountered. By transmitting too much noise from road traffic, such façade openings may prevent the use of these courtyards as quiet areas. Vegetating openings to courtyards – or covering with other acoustically absorbing material, e.g. from recycled waste – can lead to a reduction of the noise level in the courtyard of about 4 dB for a 3 m wide opening, facing either a smaller cross-street or a trafficked street. This mitigation measure is efficient, as it needs a limited amount of vegetated surface area.

6. Perceptual effects

The main perceptual effect of noise mitigation is that it reduces the audibility of noise at the location 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 acoustic 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 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. In the project, such perceptual effects were evaluated using different methods, as described below.

6.1. Perceptual evaluation of a vegetated barrier

The perceptual effects of a low vegetated noise barrier in central Lyon, France, 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. In the field study, pedestrians were asked to assess the sound environment and data were collected both before and after the barrier was erected. The percentage of annoyed respondents and ratings of the overall quality of the sound environment indicated that the barrier made the soundscape slightly calmer and less unpleasant (Rådsten-Ekman et al., 2011). Listening experiments with traffic noise events simultaneously recorded behind and beside the barrier verified that the barrier reduced the annoyance caused by the traffic noise, and that this effect was fairly well predicted by the associated A-weighted sound level reduction. However, there was a tendency for the annoyance reduction to be a little less than would be expected from the A-weighted sound level reduction. This can partly be explained by the barrier's lower reduction of low-frequency than high-frequency sounds, as found in previous research (Nilsson et al., 2008).

6.2. 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 at 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). At the closer distance, 4 m, sound pressure levels from tram passages were about the same at both the grass and asphalt locations. However, at a distance of 7 m, the grass reduced the level of noise by approximately 3 dB 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 A-weighted sound level reduction. There was, however, a tendency for the annoyance difference between the grass and asphalt recordings to be greater than one would predict from the sound level 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.

6.3. Noticeability of wanted sounds

In listening studies, as those described above, participants are instructed to assess specific sounds in various ways. These methods direct the listener's auditory attention and are therefore ill-suited for studies on how often specific sounds are noticed (noticeability). An alternative approach is to model the relevant perceptual phenomena and use these models to compute a sound's noticeability. A notice-event model has been implemented in computer models predicting whether the average person will notice a sound in a given sound environment (De Coensel et al., 2009). The model was further developed in the project (Oldoni et al., 2013). To illustrate its applicability, the noticeability of pleasant birdsong was described as a function of birdsong-to-road-traffic-noise ratio. Such a relationship may be useful for acoustic designers with an interest to improve the overall quality of the acoustic environment, including all its sources, unwanted as well as wanted.

6.4. 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 unclear. 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. 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 tranquility of such areas, and that low sound levels combined with a view dominated by vegetation would be associated with a high degree of tranquility (Pheasant et al., 2010). Many of the methods studied in the project involve vegetation, and would be suitable for design of 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 (Hong & Jeon, 2013). Studies also confirmed that vegetation planted on barriers made the sidewalk more visually attractive (Hong et al., 2012).

7. Economic analyses

7.1. Web-based tool to assist in the economic analysis of toolbox measures

The economic rationale for implementing noise abatement and environmental improvement measures is not only dependent on the measure under consideration but also on context. The specifics of location, number of affected people, population growth, future traffic increases and decreases and local factors such as access to raw materials etc. play a role. Hard-to-obtain information on appropriate unit prices and valuations needs thus to be collected, harmonized and catalogued. To demonstrate the potential economic utility of the toolbox, an interactive web-based application for cost-benefit (CBA) and cost-effectiveness analyses (CEA) was constructed. An innovation is the integrated Monte Carlo framework, allowing the impact of every uncertainty on economic result indicators to be simulated. An additional improvement is the incorporation of growth functions allowing the dynamics of e.g. tree growth, traffic increase, population increase and changes in risk over time.

7.2. Pioneering valuations

Non-acoustic effects of green roofs and façades and tree canopies are often ignored in acoustic research. However, several international studies have assessed the impact of visual/aesthetic and amenity effects of green façades, roofs and trees on the purchase price of apartments and houses. A literature review was undertaken to extract the relevant information, convert it into a common format, and relate changes in equivalent yearly rent to the size of the area covered by the green roofs, green façades and the tree canopies (Veisten et al., 2013; Veisten et al., 2012). The results were post-processed using meta-analytic techniques and initial estimates of the value of one square metre green façade/roof and one square metre tree canopy obtained. Whereas the initial unit values could be considered crude, they are noteworthy attempts to improve on today's practice of ignoring aesthetic and amenity effects of acoustic measures – effectively assigning them the value nil.

7.3. Several promising measures

Among the acoustic measures subjected to economic analyses are tree belts (Van Renterghem et al., 2012). Where applicable, tree belts seem to make good economic sense and should be tried out (Klæboe et al., 2013). Whereas it is the acoustic benefits of the tree belts that dominate, aesthetic/amenity effects are non-negligible contributing to the relative high cost efficiency of this measure. Green roofs and façades benefiting a sufficient number of residents were also shown to be robustly cost efficient – mainly because they provide substantial visual aesthetic and amenity effects in addition to the smaller acoustic benefits (Veisten et al., 2012). Surface treatments such as inexpensive brick lattices (Bashir et al., 2013) are estimated to be cost efficient. In situations with heavy traffic, these can be used in addition to source measures such as dual layer porous asphalt. Analyses of the rationale of adding sub-surface resonators underneath dual layer porous asphalt suggests this could be a good idea (Maennel et al., 2013), given that the improvements in acoustic durability proves to be correct. Economic analyses are often applied in the last stages of a project to choose between promising alternatives. However, they could also be used earlier in the design process in a more explorative fashion, thereby promoting innovative solutions that provide a better balance between the input factors and effects (Klæboe et al., 2013).

8. Conclusion

This paper describes noise abatement approaches resulting from a recent project. Significant noise reductions, for road and rail traffic, are shown for various tools, including new barrier designs, planting of trees, treatments of ground and road surfaces and greening of building façades and roofs, using natural and recycled materials. The abatements are assessed in terms of numerically predicted sound level reductions, perceptual effects and cost–benefit analysis.

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