Title

Reducing surface transport noise during propagation outdoors using natural means

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ABSTRACT

This paper reviews ways of reducing surface transport noise by natural means. The noise abatement solutions of interest can be easily (visually) incorporated in the landscape or help with greening the (sub)urban environment. They include vegetated surfaces (applied to faces or tops of noise walls and on buildings' façades and roofs), caged piles of stones (gabions), vegetation belts (tree belts, shrub zones and hedges), earth berms and various ways of exploiting ground-surface-related effects. The ideas presented in this overview have been tested in the laboratory and/or numerically evaluated in order to assess or enhance the noise abatement they could provide. Some in-situ experiments are discussed as well. When well designed, such natural devices have the potential to abate surface transport noise, possibly by complementing and sometimes improving common (non-natural) noise reducing devices or measures. Their applicability strongly depends on the available space reserved for the noise abatement and the receiver position.

1.Introduction

Traffic noise significantly impacts our health and wellbeing [1]. The dominating sources are from surface transport, where road traffic noise is more important than noise from rail traffic. Indoors as long as the façade insulation is of adequate quality, the traffic noise can be sufficiently reduced to achieve a good sound environment by closing windows. With open windows or in the vicinity of dwellings, however, a decent sound environment is more difficult to guarantee, and there is a greater stress and health risk. For a sufficient improvement all tools at hand must be employed, so tackling both the source emissions as well as achieving reduction during propagation. Both traditional and novel noise control engineering approaches should therefore be mixed.

This paper focuses on natural devices reducing noise during propagation in the outdoor environment. More specifically, green noise solutions are defined as devices or measures that can be rather easily (visually) incorporated in the landscape, or that can help greening the (sub)urban environment. The following topics have been considered: stand-alone vegetation, planted surfaces (applied to faces or tops of noise walls, building façades and roofs), caged piles of stones (so-called gabions), earth berms (mounds) and exploiting ground-related effects (replacing acoustically hard ground by acoustically soft (porous) grounds and roughening of ground).

Meteorological effects strongly affect sound propagation outdoors [2][3]. Where relevant, calculations have been performed to analyse noise reduction under realistic outdoor conditions including atmospheric refraction of sound, i.e. curving of sound paths due to temperature profiles and wind.

Moreover, some green measures are specifically studied as a means to tackle negative meteorologically-induced effects.

The current paper reviews findings with relation to the aforementioned noise reducing devices, amongst which achievements made by the recently finished FP7 EU-funded research project HOSANNA ("Holistic and sustainable abatement of noise by natural and artificial means"). The bulk of this work is based on numerical predictions utilizing various numerical approaches, trying to optimize such devices. Although not detailed explicitly everywhere in this paper, cross-validations between various numerical techniques have been performed to gain confidence in purely numerical results, and predictions have been validated by field studies and scale-models measurements.

This paper presents ideas for several noise reducing devices rather than identifying the most suitable green noise abating solution for a given situation. The calculation results are presented relative to a well-defined reference situation that might change depending on the context. It is possible that some of the proposed designs might pose constructional problems. However, the practical restrictions related to aspects of construction are not reviewed since they are considered to be beyond the scope of this research, which aims to bring together new ideas and concepts for acoustical treatments.

Despite the growing evidence that vegetation by itself affects noise perception positively [4][5][6][7][8], this aspect is not treated in this paper which is concerned, primarily, with systems for physical noise reduction.

This review paper mainly focuses on road traffic noise abatement. Some calculations have been performed for realistic road traffic configurations, including multiple lanes. Other noise reducing devices and experiments have focused on the insertion loss obtained with a single point source, to which a traffic noise spectrum has been added to estimate the response to total traffic noise. A few green propagation measures for rail traffic were studied as well: low noise barriers near tramways, the effect of grass-covered ground beside a tramway track, and small berms along train tracks. This paper aims at describing the physical propagation-related principles involved and providing a general idea about the noise reductions that can be achieved with a specific measure (by citing experiments and calculation results). However, as such values often strongly depend on specific source and receiver distances, the reader is encouraged to consult the references that have been given for more detailed information.

2.Noise barriers

Noise barriers prevent direct line-of-sight propagation between noise sources and receivers. Diffraction of sound over their horizontal edges is typically the dominant contribution to the sound field behind the barrier. Consequently, good designs of the top could improve their efficiency without increasing the total barrier height (see Section 2.1.2). Transmission through the barrier can be kept sufficiently low e.g. by providing an adequate surface density (see e.g. Ref. [9]).

A noise barrier is especially efficient at close distances, where a deep acoustic shadow zone is formed. With increasing receiver or source distance from the barrier, its shielding decreases as the difference between the length of the path sound has to travel from source to receiver over the barrier and the

length of the (virtual) direct sound path between source and receiver decreases [9]. Under downwind conditions, open-field refraction or screen-induced refraction further limits their efficiency (see Section 2.1.3). A noise barrier is also strongly influenced by the ground type [10][11][12]. Typically, a barrier has a higher insertion loss when placed on a rigid surface relative to a porous ground.

2.1. Highway noise barriers

2.1.1. Vegetated traditional noise walls

If rigid noise walls are placed parallel to each other on either side of a road, there can be multiple reflections between them, significantly lowering the performance relative to a single noise wall on one side of the road [13]. Good practice demands that in case of parallel noise walls, their surfaces should be sufficiently absorbing. Even in case of a single noise wall, absorption at its faces has been shown to be beneficial for its shielding [12][14].

One way to introduce absorption at the faces of a noise wall is to use a green-wall system. The increase in noise shielding by covering 4-m high rigid noise walls (on either side of a road) by a layer of green-wall vegetation substrate (see Ref. [15] for the material characterization; see Fig. 1) has been studied using the Boundary Element Method (BEM) in 2D [16][17]. A 4-lane motorway with 85 % light vehicles driving at 120 km/h, and 15 % heavy vehicles at 90 km/h, was located on a flat terrain, or depressed (3 m below the surrounding flat terrain, with a grass-covered slope), or on a grass-covered embankment (3 m above the surrounding flat terrain). In addition, a 6-m depressed road was considered (in a trench, with rigid vertical edges); vegetation was then added to the vertical walls bordering the motorway. The Harmonoise/Imagine road-traffic source-power spectra appropriate to the assumed traffic composition and speed have been utilized [18].

In the case of a flat terrain, the noise reduction due to two fully covered barriers (compared with the same situation with perfectly reflecting barriers) is predicted between 5 and 6 dBA for a low receiver zone (receiver heights from 1 m to 2 m, up to 50 m from the road edge) and between 7 and 8 dBA for the upper receiver zone (extending from 3.5 to 4.5 m height and up to 50 m from the road edge) [17]. For a "pedestrian" receiver (or bicyclist), thought to be at 1 m from the noise wall (at a height of 1.5 m), the noise reduction is about 4 dBA [17]. In the case of a road on an embankment and fully covering the barrier with substrate, the noise reducing effects of the green-wall substrate are generally on the order of 2 dB lower than those relative to flat terrain [17]. On the contrary, in the case of a depressed road infrastructure, the effects of green-wall abatements are generally about 2 dBA higher than those relative to flat terrain [17].

Using 0.5-m high strips of green-wall material followed by rigid strips of equal height [17] leads to the best performance when aiming at halving the amount of greenery, with only an average decrease in noise reduction of between 1 and 3 dBA, compared to the fully covered wall. Least efficient are the middle-half and upper-half arrangements [17].

In case of the modelled trenches in Ref. [17], the narrower the trench, the higher the acoustic gain by applying vegetation. Fully covering the two walls (compared with the same situation with fully rigid walls) gives a noise reduction of between 10 and 12 dBA for the lower receiver zones and between 7

and 12 dBA for the upper ones. When direct line-of-sight propagation is possible (e.g. for a pedestrian receiver), only a moderate gain is predicted (between 2 and 3 dBA). When only half of the wall surface is made absorbing, the decrease in reduction is between 3 and 4 dBA at all receiving zones. Although the specific arrangement of green-wall material is not of major importance, the lower-half arrangement shows again a somewhat better performance.
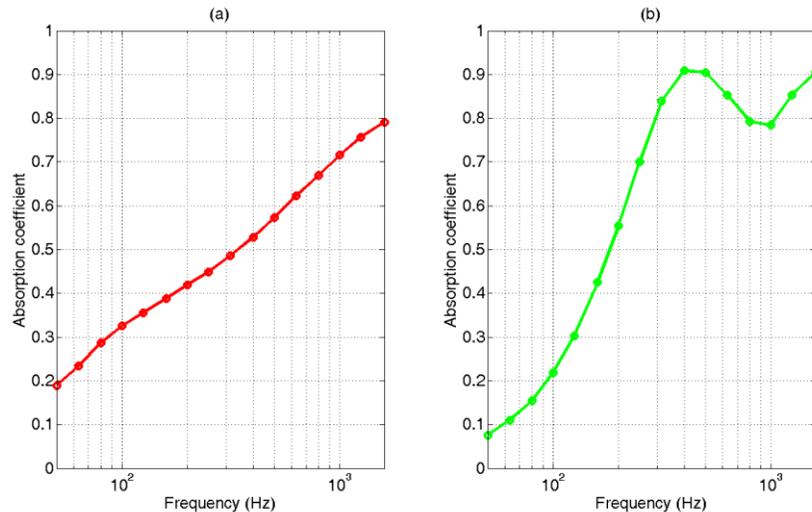

Figure 1. Green-roof substrate (a) and green-wall (b) substrate absorption coefficient upon normal incident sound used in the calculations in Refs. [17], [47] and [159].

2.1.2. Noise walls with vegetated caps

Caps could increase the barrier efficiency without increasing its height, when the following conditions are fulfilled [18][20][21][22]: the size of the cap should not be too small, the cap should be absorbing and the receiver is located in the barrier's shadow zone. Barrier caps, in theory, allow improving barriers already put in place (retrofitting). Complex shapes have been studied and optimized before [21][22][22] [24][25]. To study the improvement in performance by adding absorbing caps, three basic shapes were numerically evaluated with a 2D-BEM technique in Ref. [17]: cylinders, T-shaped caps and vertical straight baffles. A green-wall substrate [15] has been applied to the caps, added to a 4-m high rigid barrier (barrier thickness of 10 cm) beside a 4-lane motorway (single noise wall); the overall height of the noise wall, including the cap, is kept constant at 4 m.

Cap designs needed to achieve a preset barrier insertion loss improvement of 5 dBA (at a receiver height of 1.5 m, up to 20 m from the barrier) were studied in Ref. [17]. Following designs were found to be appropriate: a cylinder with minimum diameter of 100 cm, a T-shaped cap (all faces of the cap being absorbent) with a minimum width of 90 cm, a T-shaped cap (substrate placed in a container with a rigid bottom) with a minimum width of 130 cm, or a vertical baffled cap (parallel to the noise wall, at both the source and receiver height) with a minimum height of 50 cm. When this baffle height is reduced to 20 cm, only 3 dBA additional road traffic noise reduction is achieved.

Very close behind the barrier (at 1 m), a half-cylinder cap (on the receiver's side) with a diameter of 40 cm gives 5 dBA additional noise reduction relative to a straight rigid noise wall [17]. In case of a full cylinder covered with green-wall substrate, a somewhat smaller diameter of 30 cm is needed to reach this goal [17]. A T-shaped cap, with all faces being absorbent, needs a minimum width of 50 cm to gain 5 dBA at a pedestrian receiver; a vertical baffle should be at least 20 cm in height.

2.1.3.Rows of trees behind noise walls

Downwind sound propagation over a noise wall leads to a drastic decrease in its performance relative to a windless atmosphere [26][27][28][29][30][31][32]. Evaluating noise-wall efficiency without considering wind effects therefore often leads to too optimistic assessments. At long distances, refraction as observed above unscreened ground is expected. At short distance, however, wind effects are of more concern as these can be quite detrimental due to the so-called RESWING (refraction of sound by wind-induced gradients)[28] effect. This is caused by the presence of strong gradients in the horizontal component of the wind speed in the zone above the barrier top. This results in strong downward refraction of sound into the acoustic shadow zone. Unfortunately, this occurs in the zone where we would expect the strongest shielding in absence of wind. This effect has been analysed in detail before by various researchers by means of wind tunnel experiments, in-situ measurements and numerical simulations [26][27][28][29][30][31][32]. Depending on local wind statistics and barrier orientation, the limited performance in downwind episodes could become dominant for long-term equivalent sound pressure levels.

A possible green solution to limit such negative wind effects is deliberately positioning a row of trees behind the noise wall acting as a wind break [30][31][32]. Canopies of trees can be quite effective in reducing wind speed.

As a proof of concept, the use of synthetic windscreens to improve wind fields near noise walls has been analysed in a wind tunnel experiment at scale for various configurations of single noise walls and noise walls at either side of a line source [30]. A real-life field experiment along a motorway [31] showed that with increasing (down)wind speed, the positive effect of the presence of trees increased linearly. At a wind speed of 12 m/s at a height of 10 m, 3.5 to 4 dBA of the noise shielding that was lost by the action of the wind was recovered by the trees (see Fig. 2). Furthermore, this effect was shown not to be restricted to the exact downwind direction [31].
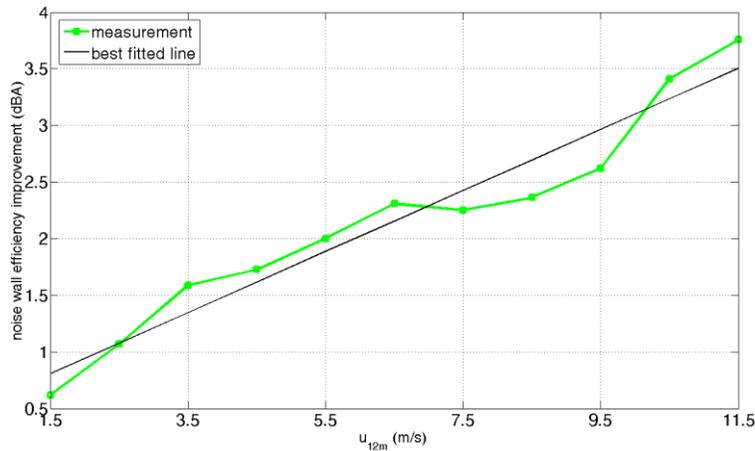
Figure 2. Measured noise wall efficiency improvement resulting from the presence of a tall row of trees at close distance behind a 4-m high motorway noise barrier as a function of downwind wind speed measured at a height of 12 m (u_{12m}) (from Ref. [31]).

The positive action by a row of trees is caused by the removal of momentum from the wind flow. To some extent, downward refracting gradients are shifted towards the top of the canopy. Consequently, dense and tall canopies are preferred [33]. Furthermore, the specific distribution of biomass with height in the canopy is important [33]; most efficient seems a triangular shape, where most biomass is located near the bottom of the canopy, resulting in a smooth transition near its top to limit the occurence of wind speed gradients there. This means that conifers are most suited, not only because of their typical canopy shape, but also for their larger needle-area densities, larger drag coefficients and since they do not drop leaves during winter.

The use of a row of trees in preventing negative wind effects seems especially interesting in case of a single noise wall [34]. The distinction has to be made whether the canopy starts below or at the top of the noise screen, or whether a gap in between the bottom of the canopy and the top of the screen is present. This choice strongly affects the downwind wind field, and determines at what receiver ranges the largest wall efficiency improvement takes place [34].

The absence of gaps mainly improves shielding close behind the barrier in wind. With increasing downwind distance, the positive action of the wind-breaking trees become smaller and the canopies might even give rise to a (slightly) negative effect [34].

When a gap is present, the wind effect is not recovered at close distance [34]. However, the positive action of the trees remains up to a larger distance downwind relative to the absence of a gap in the canopy. An overall stronger improvement is therefore predicted [34].

If there are fully reflecting noise screens on either side of the road, the presence of trees is expected to give strong improvements at short downwind distances only. Care is needed since pronounced negative effects are predicted at larger downwind distances [34]. Predictions further indicate that gaps between the bottom of the canopy and top of the barrier should be avoided if there are reflecting screens on both sides of a road. The choice whether to plant trees or not in such a case will depend on the distance

to receivers and local wind characteristics. Note that if the screens are (partly) absorbing, which should be common-practice nowadays, the tree effect will be closer to what is observed near single noise walls.

2.1.4. Earth berms

An earth berm (bund, earth mound) is a popular alternative for a noise wall on condition that sufficient space is available beside the road. Typical advice from earlier work [35] is to make an earth berm slightly higher than a straight noise wall to achieve comparable noise reduction (to compensate for the fact that the greatest height of a berm is reached somewhat further away from the road). Hutchins et al. [36] proposed, as an alternative, to place a small screen on top of the berm, or to construct a flat-topped berm. Busch et al [37] stressed the importance of the acoustical properties of the material constituting the berm. An acoustically soft berm, and especially when slope angles are limited, was found to outperform a noise wall with similar top height in their scale modelling of a typical motorway setup.

2.1.4.1. Berm shape

Traditionally, berms have rather simple triangular or trapezoidal cross sections. It has been studied in Ref. [17] if alternative shapes influence the shielding berms provide. Numerical simulations with the BEM in case of 4-m high berms beside 4-lane mixed traffic (85 % light vehicles at 120 km/h, and 15 % heavy vehicles at 90 km/h) showed that care is needed when changing the cross-section of earth berms (with a flow resitivity of 400 kPas/m^2). Some shapes clearly outperform others. Compared to a rigid straight noise wall (4 m high), positioned at the same location as the foot of the berms, positive and negative effects were obtained for the various predefined berm shapes when averaged over a receiver zone up to 40 m from the border of the road; the effects ranged from -4 dBA to +6 dBA. Especially interesting were asymmetric berms with a vertical part facing the road edge. This shifts the main diffraction edge closest to the traffic lanes <u>resulting in a greater noise screening effect.</u>

A genetic algorithm was used to further optimize earth-berm shape in Ref. [17], starting from a vertical rigid sustaining wall of minimum 2 m high facing the road and by employing 6 vertices to prevent non-realizable forms. About 9 dBA could be improved by such automatic optimization relative to non-optimized forms (flow resitivity of the berm was equal to 300 kPas/m^2).

2.1.4.2. Berm roughening

One possibility to further increase berm shielding, in addition to (macro-)shape optimisation, is making the surface(s) of the berm rough. The latter corresponds to effectively making a surface acoustically softer [38][39][40] (See also Section 4.3). Starting from a symmetric trapezoidal berm (15 m wide, 4 m high, with a 3-m wide top), consisting of compacted earth (represented by a flow resistivity of 300 kPas/m^2), positioned near a 4-lane road with mixed traffic, various roughening approaches were numerically studied in Ref. [17] by means of the 2D-BEM method. Complex roughness patterns (either V-shaped or rectangular), at different indentation levels (orders), both regular or random in nature, were numerically evaluated.

As an example, irregular rectangular roughness at 3 orders is shown in Fig. 3 (from Ref. [17]). Table 1 summarizes the extra insertion loss provided by the roughening, relative to the same berm with fully flat faces.
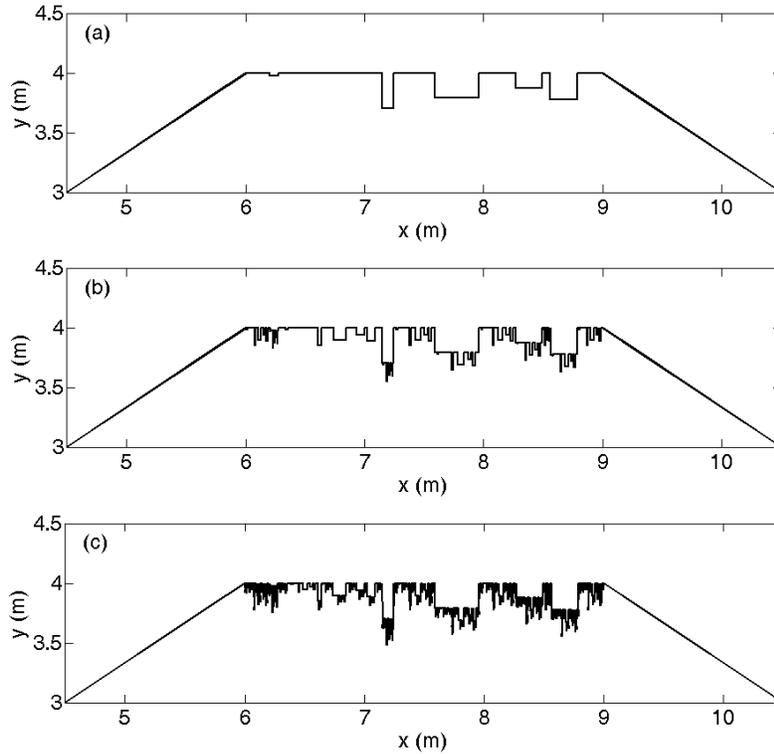

Figure 3. Realisations of roughening the top surface of a trapezoidal berm using rectangular and irregular indentations at orders 1 (a), 2 (b) and 3 (c) (from Ref. [17]).

Table 1. Predicted extra noise reduction due to various roughening scenarios, relative to fully flat berm surfaces, in a 4-lane mixed road traffic situation. The first 3 lines correspond to the 3 shapes depicted in Fig. 3 (from Ref. [17]).

Roughness approach	IL Random (dBA)	IL regular (dBA)
Only top roughened at order 1	2.9	2.2
Only top roughened at order 2	4.7	4.2
Only top roughened at order 3	6.2	6.7
3 sides roughened at order 1	4.4	4.2
3 sides roughened at order 2	7.4	7.2
Source and receiver side roughened at order 2, top side at order 3	8.4	8.0

Improved shielding is obtained when increasing the order of roughening. More detailed analysis in Ref. [17] showed that the treatment of the source side was more efficient than top roughening. Adding V-shaped indentations showed a lower efficiency than rectangular ones. Treating the receiver side of the

berm, in contrast, only has a limited effect. Regular and random patterns gave rather similar insertion losses for broadband traffic noise.

Surface roughening is especially useful when the berm surfaces would otherwise be acoustically rigid. When berms are grass-covered or when the constituting material is more porous (e.g. non-compacted earth), roughening effects will become less pronounced. Note that calculations in Ref. [17] suggest that the optimal roughness approach will also depend on the overall shape of the berm.

2.1.4.3.Wind effects near berms

Typical earth berms are aerodynamically much smoother than a straight, vertical-sided noise wall. Consequently, they limit the aforementioned strong vertical gradients in the horizontal component of the wind field [41] observed near conventional noise walls. Earth berms, and especially those with a low slope angle, were predicted to be sufficiently unaffected by negative downwind effects [41]. In case of triangular-shaped berms with a slope of 1:3, or berms with steeper slopes but with a flat top (trapezium-shaped), the averaged wind effect (loss in shielding relative to a windless situation) can be smaller than 1 dBA in road traffic noise setups, even in an extended zone up to 250 m from the road [41].

In order to benefit from this additional positive effect of an earth berm, internal slope angles should be limited; berms with a slope of 1:1 (so with an internal angle of 45 degrees) are predicted to still suffer largely from shielding loss when wind is blowing from the road to receivers. Additional calculations further showed that the use of rows of trees near steep berms does not improve downwind shielding [34].

2.2. Urban road traffic noise barriers

In a dense urban setting, many of the traditional noise reducing devices cannot be applied due to safety or visual constraints, or because they are simply not efficient. One possibility to still use barriers is making them sufficiently low. A number of studies have been carried out investigating the use of low-height noise barriers by means of scale modelling and by numerical approaches [42][43][44][45][46]. Such devices can be effective to abate road traffic noise since the typical source generation positions are located rather close to the street surface. An important prerequisite to limit diffraction with low barriers is that they are placed close to the traffic lanes. Similarly, also receivers (e.g. persons on the walkways) should be close to the barrier.

2.2.1.Vegetated low-height noise barriers in urban streets

Different numerical techniques were employed to study the placement of various inter-lane low-barrier configurations in a 19.2-m wide urban street canyon [47]. Although sources and receivers are located in the same reverberant space, noise reduction is nevertheless possible. The use of vegetated [15] thick (0.64 m) and low (0.96 m) barriers has been shown to be effective for reducing sound pressure levels along walkways. In the optimal case, consisting of 3 inter-lane barriers, about 5 dBA noise reduction is predicted on average along the walkways (relative to the absence of such small barriers). In these predictions, traffic was assumed to be equally distributed over 4 lanes, for vehicle speeds ranging

between 30 and 70 km/h, including 5 % heavy vehicles. Along the building façades bordering the street canyon, noise abatement is more limited. The presence of absorption, here by modelling a green-wall substrate [15] covering all faces of the barriers, is an important prerequisite to obtain relevant road traffic noise abatement. Predictions with 3 rigid inter-lane barriers only gave a 1-dBA reduction for persons on the walkways.

2.2.2. Gabions

Gabions [35] consist of series of cages, made of twisted or welded steel wire, filled with stones, which are used in civil engineering and road building applications. They are originally dedicated to the achievement of retaining structures or hydraulic protections. At low frequencies, gabions can be considered to be acoustically transparent. Nevertheless, the single number ratings of transmission and reflection (for road traffic noise, following CEN/TS 1793-5:2003) were measured to be 20 dB and 5 dB, respectively [48], for a 1.1-m thick barrier.

Numerical predictions and measurements have shown that gabion structures can be used as noise barriers in urban areas [48]. The acoustical performance of various 1-m high gabions made of small stones, bigger stones, and with a variation in stone size have been numerically studied. Such low-height gabion barriers could provide up to 8 dBA road traffic noise insertion loss for persons on the walkway directly behind the barrier (no facade reflections included here in contrast to Section 2.2.1; see Ref. [48] for more details on the positioning of sources and receivers). When compared to a fully rigid barrier of the same size, while a somewhat smaller insertion loss is obtained at receivers below the barrier due to transmission of road traffic noise, for receivers above the barrier, the insertion loss is very similar. Calculations in Ref. [49] showed that the acoustic performance could be enhanced by employing porous instead of rigid stones. The calculation results for porous stones were confirmed by means of finite-difference time-domain calculations [49]. The predicted distribution of the pressure field, near and inside such a low-height gabion barrier, is shown in Fig. 4.
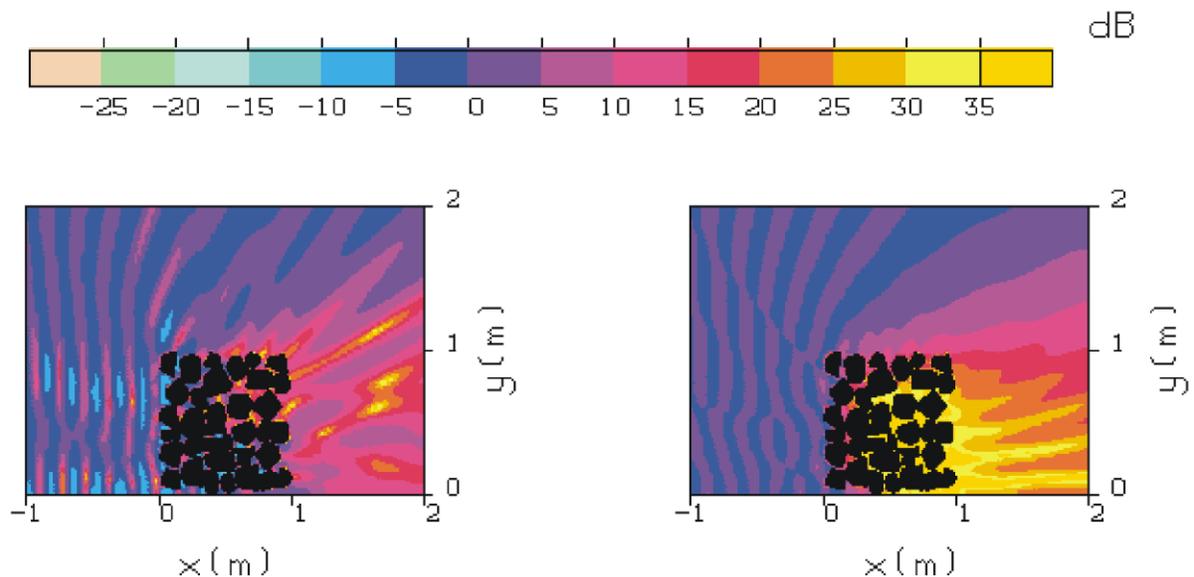
Figure 4. Insertion loss at 1000 Hz near a 1-m high and 1-m wide gabion barrier placed on rigid ground. On the left, rigid stones have been considered, on the right the equivalent case with expanded clay stones (flow resistivity of 82 kPas/m^2) is depicted (From Ref. [49]).

2.3.Rail traffic noise abatement

Low noise barriers along the tracks [50][51][52] are a common way of reducing rolling noise by rail traffic during propagation. The height of such barriers can be kept low since they can be located near to the source. As long as the rail-wheel interaction is the dominant noise generation mechanism, such a measure can be quite efficient.

2.3.1.Low-height noise barriers near trams

The efficiency of 0.4-m wide and 1-m high, vegetated noise barriers [15], placed near a 2-track tramway (trams driving at 30 km/h) is numerically studied with 2D BEM in Ref. [17]. Both cases with and without buildings at either side of the tramways were analysed. The barriers contain a rigid core to prevent transmission. Various combinations of such small barriers, placed at the receiver side of each lane, were evaluated. Both trams driving at the near or far track, relative to the receivers, were separately analysed. The body of the tram is explicitly included in the simulation domain given its importance in estimating barrier performance due to the many reflections between the barrier and tram.

The insertion losses provided by low barriers near tramways strongly depend on the receiver location. Averaged over receivers up to 40 m from the closest track, at 1.5 m high, insertion-loss values easily exceed 10 to 15 dBA and such barriers could therefore be considered as highly efficient. The extra noise attenuation due to the addition of a central inter-track barrier is between 6 and 8 dBA for all receiver zones considered. These results remain of the same order in built-up areas. Note that these simulations assume that the low barriers could be placed very close to the source (only rolling noise considered), the barriers are strongly absorbing and of infinite length, and transmission through the barrier is neglected.

2.3.2.Low-height berms near trains

The efficiency of vegetated low-height berms to abate rolling noise from high-speed trains and from freight trains running on a 3-m high embankment has been assessed in Ref. [17]. The small berms are located on the track base, extending 1 m above the track plane. The various shapes studied yield insertion losses in the range from 3 to 8 dBA when applying a freight train noise spectrum, depending on the receiver location and berm shape. The variation due to berm shape is below 2 dBA at all receiver locations considered. In case of high-speed trains, the rolling noise insertion losses range from 4 to 9 dBA. Note, however, that aerodynamic noise sources near e.g. the pantograph may significantly contribute to the sound radiating from high-speed trains, not abated by such low-height barriers.

3.Vegetation belts

The interactions between sound waves and vegetation belts can be divided into a number of direct and indirect effects. Direct effects are linked to two main processes namely redistribution and redirection of

sound energy on the one hand, and absorption on the other hand. Redistribution and redirection of sound energy occurs mainly due to scattering by above-ground vegetation elements. Only absorption – either by visco-thermal surface effects or by damped vibrations [51][54][55] – leads to effective transfer of acoustical energy into heat. Redirection of sound energy can be effective in achieving noise reduction at a single receiver since some sound is scattered away from the line-of-sight between source and receiver. Reflections at the edge of a vegetation belt [56] and sound diffracting over it are generally considered to be of minor importance in road traffic noise applications.

Indirect effects are caused by a secondary action due to the presence of vegetation. The development of an acoustically soft (porous) soil underneath vegetation [57][58][59][60], called a "forest floor", is the result of plant rooting and the formation of a humus layer consisting of plant litter. Also the change in micro-climatology due to the canopies, in turn influencing the properties of the sound propagation medium, can be an important indirect effect (see Section 2.1.3).

Conclusions in scientific reports regarding the effectiveness of vegetation belts [61][62][63][64][65] are quite divergent. In response, using vegetation belts to tackle road traffic noise has not been promoted in most noise control books (e.g. [66] and [67]). However, several researchers have indicated that much more could be achieved by planting vegetation belts (e.g. [67] and [3]). The large variety one can obtain when measuring the noise reduction near tree belts is nicely illustrated by the experiments conducted by Fang and Ling [63]: Three excess-attenuation groups have been defined (< 3 dBA, 3-6 dBA and 6-9 dBA, for belt depths of 20 m) among the 35 tree belts considered in their field study.

More recently, numerical work has shed new light on noise reduction by vegetation belts [68][69]. The various effects can be more easily separated out in contrast to in-situ measurements constituting the bulk of older research on this topic. Detailed numerical full-wave techniques like e.g. the finite-difference time-domain technique have become mature and the access to computational power strongly increased during the last decade.

3.1.Tree belts

The trunks and the forest floor have been identified as the major road-traffic noise reducing actors in a tree belt [69]. Numerical research indicates that even narrow tree belts can be reasonably effective in reducing road traffic noise on condition that the tree belt is well designed [69]. A 15-m deep optimized tree belt is predicted to be able to compete with a 1-m or even 2-m high single thin concrete noise wall positioned at the source side of the belt [70]. A 30-m deep belt could be close to the shielding obtained by a 3-m or even 4-m high noise wall, depending on the type of soil in between source and receiver [70]. Such comparisons were made for a receiver at close distance from the noise wall or tree belt in a non-refractive atmosphere. It is expected that for receivers further away from the road such a comparison further becomes more advantageous for a tree belt.

As a general rule, high-biomass density should be strived for in a tree belt, close to the biological limits, to obtain significant road traffic noise reduction [69]. A large trunk basal area (i.e. the fraction of the ground area taken by the tree trunk cross-sections in plan view) can be achieved by limiting tree spacing and increasing trunk diameter. Numerical calculations in realistic road-traffic noise settings further show

that there is a linear trend between road traffic noise shielding (in dBA) and tree belt depth (orthogonal to the road) [71]. The necessary length of the tree belt, along the road length axis, should be chosen similar to guidelines for estimating noise-wall length (see Refs. [35] and [71]). Longer tree belts might be needed for receivers further away from the road [71]. Trunk height (starting from roughly 2 m) was shown to be relatively unimportant on condition that the tree belt is located close to the road [69]. Interestingly, the tree belt shielding is hardly influenced by receiver distance relative to the road because tree belts reduce sound during propagation through the belt [71]. In contrast, noise wall shielding is governed by diffraction : receivers at longer distance therefore experience a smaller insertion loss. The presence of some randomness in trunk location and trunk diameter can enhance road traffic noise shielding [69]. Most likely, such variation will be present anyhow.

Numerical calculations convincingly showed that planting schemes, or the specific combination of tree ordering, tree spacing and trunk diameter, strongly effects the noise reduction that can be obtained [71]. It was shown that at a basal area of 1 %, the variation in predicted effect ranges from 2.7 dBA to 5 dBA (for a 15-m deep tree belt near a 4-lane road, with a uniform distribution of light vehicles over all lanes at a fixed vehicle speed of 70 km/h). Near a basal area of 2 %, this variation ranges from 3.6 to 8.3 dBA.

Some interesting approaches relaxing the need for high biomass density, without affecting noise shielding to an important extent, are rectangular planting schemes (with a close spacing along the road, while the spacing orthogonal to the road can be relaxed), omitting full rows parallel to the road, and randomly omitting trees (thinning) inside the belt [71] (see Fig. 5). Densely positioned paired rows parallel to the road length axis, followed by open spaces, could be a practical but efficient solution.
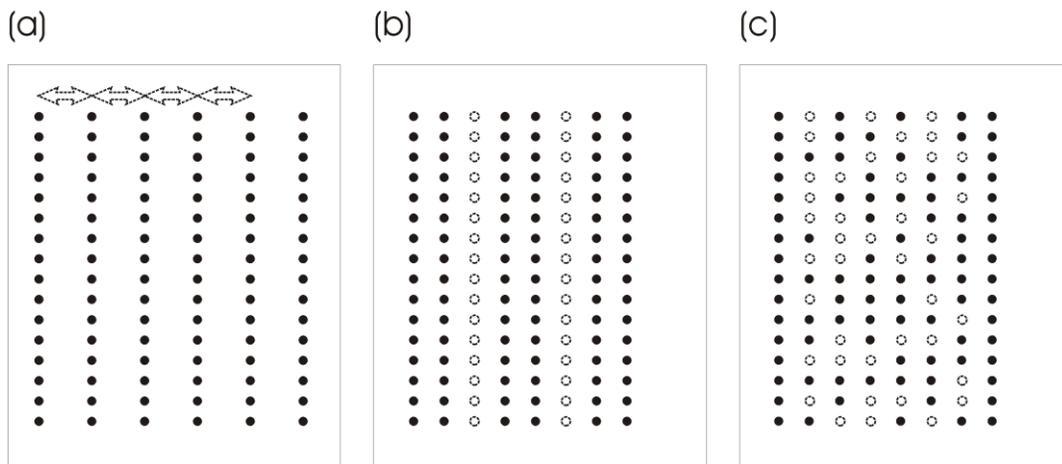

Figure 5. Strategies to decrease tree trunk biomass density without significantly affecting road traffic noise shielding : (a) increasing spacing orthogonal to the road, (b) leaving out full rows of trees, (c) thinning of the tree belt. The filled circles indicate trunk cross-sections, the open circles gaps (from Ref. [71]).

Scattering by canopies [72][73] could be either slightly negative or positive. Downward scattering of high-frequency sound will be observed when source and receiver are located below the bottom of the canopy. In contrast, when a straight line connecting source and receiver crosses the canopy, this scattering process is expected to be positive.

3.2.Meteorological effects near strips of forests

After sunset, the soil typically cools down much faster than the layers of air in the atmospheric boundary layer. This nightly ground-based temperature inversion results in downward refraction of sound and thus larger sound pressure levels compared to sound propagation in a homogenous atmosphere (meaning a constant air temperature with height in its lowest part). The presence of vegetation prevents the soil from freely radiating to the sky, and part of the heat is trapped in the zone below the canopy [74], affecting sound propagation [75][76].

Numerical predictions show that a 50-m deep forest strip may strongly decrease night noise levels in situations with a nocturnal inversion layer. At a receiver height of 2 m, and at a distance of 200 m from the road edge, this benefit could easily exceed 10 dBA compared to sound propagation over grass-covered soil [77]. The state of the atmosphere, which is changed in a positive way from the viewpoint of noise abatement, adds to the noise shielding provided by the combination of the soft forest floor and the presence of trunks. With increasing receiver height, the influence of refraction on the sound pressure levels is in general smaller, but the benefit of e.g. the forest floor reduces as well [77].

During daytime, on the other hand, the presence of a tree belt results in a slightly worse atmospheric condition [77]. Due to the shading provided by the canopies, the zone close to the soil heats up much slower than the layers of air above the canopy. In this way, a temperature inversion condition is created. On the other hand, in an open non-vegetated environment, an upwardly refracting atmosphere is built up as bare soil typically heats up much faster than the air. This means that the positive action of the upward refraction of sound is (partly) counteracted by the presence of vegetation.

Note, however, that in case of a strong temperature decrease with height, a shadow zone will be formed at some distance from the source. As a result, sound pressure levels will be very limited in this zone. This means that in practice, the increase in sound pressure levels due to the presence of the vegetation may be of limited importance. Moreover, the presence of the shielding by the forest floor and above-ground biomass will partly counteract this negative refraction effect.

3.3.Hedges and shrubs

The physical noise reduction provided by hedges along roads has been scrutinized in Van Renterghem et al. [78]. This study summarized various types of in-situ measurements near hedges: a statistical pass-by experiment measuring the real insertion loss, three controlled pass-by experiments using a reference microphone at close distance, and transmission-loss measurements using a point source. Even thick (depths ranging from 1.3 m to 2.5 m) and dense hedges were found to provide only small light-vehicle noise reduction at low speeds. The measured insertion losses ranged from 1.1 dBA to 3.6 dBA. The higher noise reductions in this range were associated with an increased ground effect e.g. by the presence of a few meters of grassland in front or behind the hedge.

As hedges are mainly comprised of leaves and other small vegetation elements like twigs and branches, road traffic noise reduction is –not unexpectedly– poor. At high sound frequencies, typically above 4 kHz, hedges might provide relevant noise reduction (exceeding 5 dB [78]). The strong impact of leaves

on high sound frequencies is commonly observed by many researchers [54][55][61], but not effective in tackling road traffic noise [79].

Even in case of deeper shrub layers or bushes, larger road traffic noise reduction is not expected. The longer interaction path-lengths that can be achieved with a shrub zone, relative to a hedge, come at the cost of a much smaller biomass density per unit surface. Numerical simulations employing small and slightly absorbing scattering elements as a means to mimic the multiple-scattering process by above-ground vegetation elements, predict limited road traffic noise reduction [68]. This holds even when the volume occupied by the above-ground biomass is taken close to the maximum values found for specific types of shrubs. The soft ground effect due to decaying leaf litter, when sufficiently developed, is expected to be the major effect in dense shrub belts. This contrasts to a tree belt where both trunks and the forest floor contribute to road traffic noise reduction.

4.Ground

Ground effects are the result of interaction between direct sound travelling from source to receiver and sound from source to receiver that is reflected at the ground. They include both destructive interference or cancellation and constructive interference or reinforcement. Over smooth acoustically-hard ground, the frequencies at which cancellations and reinforcements occur depend only on the difference between the lengths of the ground-reflected and direct path. The size of this difference depends only on source and receiver heights and the distance separating source and receiver positions. For road/tyre noise sources and a 1.5-m high receiver over hard ground, the destructive interferences are at too high frequency for there to be much influence on the spectrum so the presence of hard ground leads more or less to doubling of sound pressure compared with no ground. In practice, complicating factors such as multiple sources including engine and exhaust, atmospheric turbulence and naturally uneven and non-uniform ground mean that the increases in level due to hard ground corresponds more nearly to energy doubling [9]. If the ground is porous then not only is the magnitude of sound reduced on reflection but the phase change due to the finite (complex-valued) ground impedance combines with the phase change due to path length difference with the consequence that, for a given source-receiver geometry, the first destructive interference occurs at a lower frequency than over hard ground. This leads to the so-called ground dip or ground attenuation, the well-known reduction in outdoor noise levels that features in many prediction schemes and has been studied extensively [3]. This represents attenuation in excess of that which would be predicted from wave-front spreading and air absorption and is known as excess attenuation (EA), sometimes expressed as the sound level relative to free field. Even if the ground is flat, alongside typical surface transport corridors the ground impedance varies with range. The influence of impedance discontinuities has also been studied and is incorporated to an extent in prediction schemes. Also, particularly if the ground is otherwise acoustically-hard, ground roughness, even at scales smaller than the shortest wavelength of interest, affects sound propagation. This aspect has been studied less extensively and while allowance for the influence of ground roughness on coherence between direct and ground-reflected components is included, the influence on the effective ground impedance and the associated potential for noise reduction does not feature so far in prediction schemes.

So, although prediction schemes allow for ground effect, none of them suggest ways of exploiting ground effects for noise control. Such ways include replacing acoustically-hard ground by soft ground such as grassland in a single strip or in multiple strips or patches, choosing the soft surface that achieves greatest attenuation, and deliberate roughening of hard ground.

4.1. Porous soils

Most naturally-occurring outdoor surfaces are porous. As a result of being able to penetrate the porous surface, ground-reflected sound is subject to a change in phase (time-delay) as well as having some of its energy converted into heat. In earlier outdoor noise prediction schemes, ground surfaces were considered as either "acoustically-hard", which means that they are perfectly reflecting, or "acoustically-soft", which implies that they are perfectly absorbing. According to ISO 9613-2 [9], any ground surface of low porosity is "acoustically-hard" and any grass-, tree-, or potentially vegetation-covered ground is "acoustically-soft". Although this might be an adequate representation in some circumstances, it oversimplifies the considerable range of properties and resulting effects. Even the category of ground known as "grassland" involves a wide range of ground effects, as further discussed below. Porosity is not the only factor that influences the acoustical properties of porous ground. They are affected most by the ease with which air can move in and out of the ground surface. This is indicated by the *flow resistivity* which represents the ratio of the applied pressure gradient to the induced steady volume flow rate of air through the surface of the ground. The porosity of naturally-occurring ground surfaces does not vary as much as their flow resistivity. If the ground surface has a high flow resistivity, it means that it is difficult for air to flow through the surface. This can result from very low surface porosity. Hot-rolled asphalt and non-porous concrete have a very high flow resistivity whereas many forest floors and freshly-fallen snow have very much lower flow resistivity.

The HARMONOISE and NORD2000 prediction schemes [80][81] identify eight categories of ground for the purposes of predicting the extra sound attenuation associated with porous ground effect. The categories are used in these prediction schemes to specify an effective flow resistivity that, in turn, can be used to predict the corresponding ground effect using an impedance model. More accurate allowance could be made for a particular soft ground if its surface impedance is known. It is common to deduce parameter values for impedance models by fitting short-range level-difference spectra using "template" methods [82][83]. Subsequently these models and parameter values can be employed in prediction schemes. Although a one-parameter semi-empirical model [84] has been used widely for outdoor sound prediction, there are many other impedance models for the acoustical properties of rigid-porous materials. A recent comparison of the applicability of many of these models [85], based on fitting the difference in spectra measured by vertically-separated microphones at a fixed distance from a point source in connection with the NORDTEST [82] and ANSI [83] standards, has shown that, for many grasslands, two-parameter models lead to better agreement with measured data than the semi-empirical one-parameter model.

Not surprisingly, the most common ground type for which ground effect data are available is "grassland". It should be noted that in Refs. [80] and [81] "turf/grass", "pasture/field" and "compacted lawn" appear in different ground effect categories; yet all can be considered to be "grassland". Table 2

lists relevant best fit effective flow resistivities and porosities for several types of grassland [85]. They were obtained by fitting short-range sound propagation data after assuming various models for the acoustical surface impedance. The fitted flow resistivity values vary by a factor of twenty. On the other hand, with the exception of the sports field, the fitted porosity values are similar. Such large differences in the effective flow resistivity values can lead to substantial differences in the corresponding predictions of ground effect at 1.5-m high receivers 50 m from a motorway (see Section 4.4). To make such predictions it is necessary to allow for the discontinuity in impedance between the acoustically-hard road surface and the receiver over acoustically-soft ground.

Table 2. Parameters giving best fits to level-difference data obtained over several types of grassland using a two-parameter slit-pore model [85].

Surface description	Porosity	Flow resistivity kPa s m^{-2}
Arable	0.50	2251.0
Pasture	0.5	1344.0
Sports field	0.22	664.0
Lawn	0.5	176.0
Long grass	0.36	104.0

4.2.Impedance discontinuities

When sound propagates over a mixed-impedance ground surface, it diffracts at each impedance discontinuity. The models developed to predict such sound propagation fall into two major categories: numerical and semi-analytical. A numerical method based on a boundary-integral equation formulation [86] for calculating the sound propagation over single or multiple impedance discontinuities has been found to give very good agreement with data also. Semi-empirical methods need less computational resources. De Jong *et al.* [87] have presented a widely used semi-empirical model for sound propagation over a single hard-to-soft impedance discontinuity with the discontinuity perpendicular to the direction from the source to receiver axis. The De Jong model uses semi-empirical modifications of analytical expressions for diffraction by a rigid half-plane. Boulanger et al. [88] have shown that De Jong's model gives good agreement with laboratory data for propagation over a single impedance discontinuity; however it fails if there are multiple impedance discontinuities. Lam and Monazzam [89] observed that the De Jong semi-empirical model, derived initially for a hard-to-soft discontinuity (during propagation away from the source) fails to satisfy reciprocity and modified it accordingly. They found that their modification improves the agreement between data and De Jong type predictions for propagation from soft to hard ground.

Much previous work has focussed on a single impedance discontinuity and less attention has been given to multiple impedance discontinuities. The simplest semi-analytical approach for predicting sound propagation over generally mixed impedance ground is the Fresnel-zone method proposed by Hothersall and Harriott [90]. It assumes that the reflecting area in a discontinuous plane is related simply

to the region around the specular reflection point defined by a Fresnel-zone condition. A Fresnel-zone method is used to account for discontinuous terrain in the HARMONOISE prediction scheme [80]. As has been noted elsewhere [3][88][91], a Fresnel-zone approximation, while potentially satisfactory for predicting overall broadband levels, is not useful for detailed predictions over multiple discontinuities.

Laboratory experiments measuring excess attenuation (EA) spectra over various mixed impedance surfaces were reported in Ref. [91]. In comparison to those for the smooth hard surface, the maximum values of EA are at lower frequencies for both mixed impedance and rough hard surfaces. In comparison, hard rough surfaces produce multiple distinct and sharp EA maxima. While these are present to some extent in the EA spectra obtained over mixed impedance surfaces, for the latter they are broader and their magnitudes are less [91]. The strength of EA maxima depends on the impedance contrast. The EA spectra obtained with the source-receiver axis normal to the mixed impedance area, i.e. normal to the strips, are more or less similar which suggest that there is little advantage for overall attenuation in using a 3D "chequerboard" arrangement of patches rather than 2D strips for the measured configuration [91]. However, the attenuation due to 2D strips depends on the angle to the strips made by the source-receiver axis whereas that due to 3D "chequerboard" arrangements have less dependence on the direction of the source-receiver axis [91].

4.3.Ground roughening

If a surface is artificially or naturally rough, incident sound is not reflected perfectly but is scattered by the roughness. The distribution of the scattered sound depends on the roughness topology, the ratio of the roughness dimensions to the incident wavelength and the relative locations of source and receiver [3]. As long as a sufficient fraction of the reflected sound retains a phase relationship with the incident sound (i.e. there is significant *coherent scattering and reflection*) there can be a significant change in ground effect. Many laboratory experiments have shown that the influence of small scale roughness on propagation over hard and soft surfaces can be considered in terms of effective surface impedance [38][39][40][91][92]. Particularly if the surface is acoustically-hard, roughness induces a surface wave. Tolstoy [93][94] predicted "boundary waves" due to energy trapped between the roughness elements and formulated boss models that can allow for different roughness-element shapes. However these do not include incoherent scatter and predict that the effective impedance of a rough hard surface is purely imaginary. A boss model due to Lucas and Twersky [95] includes incoherent scatter and results in a non-zero real part of the effective surface impedance.

One method of deliberately introducing roughness outdoors is to construct an array of low parallel walls. The potential usefulness of regularly-spaced low parallel walls for road-traffic noise reduction was suggested and demonstrated by outdoor experiments in 1982 [96]. An array of sixteen 0.21-m high parallel brick walls with edge-to-edge spacings of about 20 cm, placed on compacted grassland, was found to give a broadband (between 100 and 12 500 Hz) insertion loss (IL) of slightly more than 4 dBA, including insertion losses of up to 20 dBA in the 1/3-octave bands between 400 and 1000 Hz. The creation and subsequent attenuation of surface waves was considered as the main mechanism for noise reduction. Although surface-wave creation is one of the acoustical effects of a low parallel-wall array

placed on an acoustically-hard ground, the array has a significant influence on ground effect over a wider range of frequencies than those affected directly by the surface-wave generation (see Fig. 6).
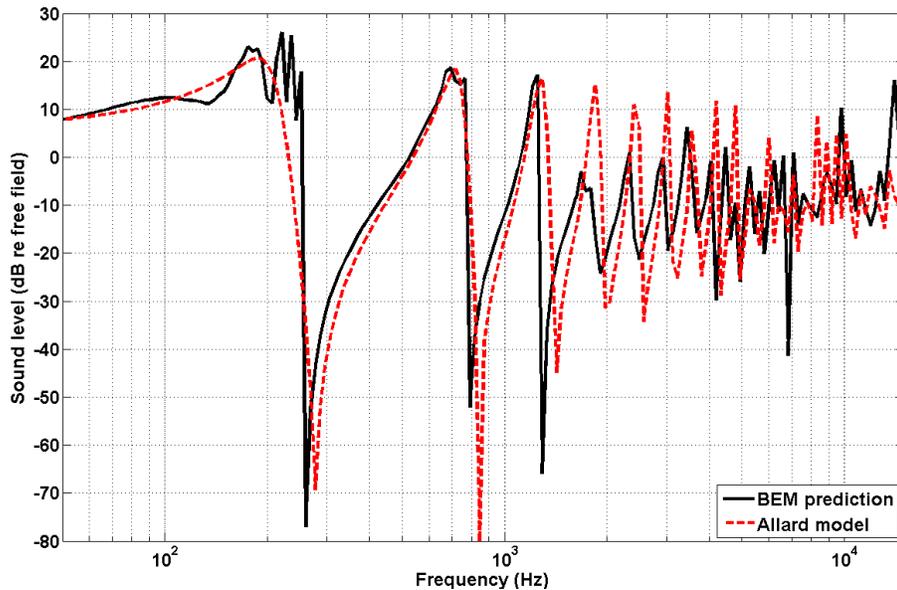

Fig. 6. Example calculation showing the spectrum of sound pressure level, relative to free field, due to a 0.3-m high parallel-wall array in which each wall is 0.05 m thick, predicted using BEM and a semi-analytical model (Allard model) for a point source over a slit-pore layer impedance. The source and receiver are assumed to be at a height of 0.05 m above the top of the wall array and separated by 4.0 m. The edge-to-edge spacings assumed is 0.05 m corresponding to flow resistivity 0.174 Pas m^{-2} and porosity 0.5 (from Ref. [99]).

Bougdah *et al.* [97] reported laboratory measurements over arrays of up to 17 thin walls with (equal) heights and spacing between 8 and 25 cm. They measured a maximum overall insertion loss of 10.3 dB for a 3.25-m wide 14-wall array with height and spacing of 0.25 m with the wall nearest the source located at the specular reflection point halfway between source and receiver which were at 0.4 m height and separated by 10 m. They discussed three physical effects other than surface-wave creation and the effective ground impedance that may be involved. One of these is quarter-wave resonance. In an array of identical 0.3 m high walls, this resonance would occur below 300 Hz. Predictions and data discussed later show that this mechanism is not important. They refer also to diffraction-grating effects. Essentially these are related to the diffraction-assisted ground effect, which has been explored subsequently in more detail [98]. The third additional mechanism they suggest is that of interference between direct and multiply-reflected paths between adjacent walls. But this mechanism could be regarded as part of diffraction-assisted ground effect rather than as a separate phenomenon. More extensive laboratory measurements have shown that excess-attenuation spectra are influenced by the number and spacing of roughness elements and by their profile or shape [98]. These factors are not investigated in Bougdah et al. [97] since only identical rectangular, thin acoustically-hard rib-like elements (vertical strips) were considered.

Comparisons of averaged excess-attenuation spectra measured over various shapes of roughness elements in the laboratory [91][98] show that random spacing of roughness elements leads to a broad

and relatively shallow ground-effect dip whereas up to three distinct narrow attenuation maxima are observed if the identical roughness elements are distributed periodically. A heuristic effective impedance model for a periodically-rough surface has been obtained by adding a modified Tolstoy imaginary roughness-induced impedance component to the impedance of a lossy hard-backed layer [98].

Several papers have reported laboratory data showing that the effect of adding small scale roughness to a surface, whatever its original impedance, is to modify its impedance [3][85][91][92][98]. If the original smooth surface is acoustically-hard then the effective impedance of the roughened surface is finite. If a surface is acoustically soft then the influence of roughening is to make the effective surface impedance less than the original surface impedance mainly through a reduction in its real part.

4.4.Applying ground treatments to road traffic noise abatement

Table 3 shows example predictions of the insertion loss of various ground treatments at a 1.5-m high receiver, 50 m from the nearest edge of a two-lane urban road. A 2D-BEM method has been used to predict the insertion loss caused by ground treatments parallel to the road. The insertion loss is calculated with respect to a smooth acoustically-hard surface. The treatments have been assumed to start 2.5 m from the nearest lane of vehicles.

Table 3. Insertion losses compared with smooth hard ground predicted for various ground treatments including low parallel wall and lattice configurations for a receiver at a distance of 50 m and at height of 1.5 m; walls are assumed to start 2.5 m from the edge of a two-lane urban road (95% cars, 5% heavy vehicles travelling at 50 km/h) [91][100].

Ground treatment	Predicted road traffic noise insertion loss (dBA)
Replacing a 50-m strip of hard ground by high flow resistivity grassland	5.3
Replacing 25 m of hard ground nearest the road by alternating 1-m wide strips of hard ground and gravel (flow resistivity 10 kPa s m^{-2} at least 0.1 m deep)	7.5
1.65-m wide array of 9 parallel walls 0.3-m high, 0.05-m thick, 0.2 m centre-to-centre spacing	5.8
12.05 m wide array of 61 parallel walls 0.3-m high, 0.05-m thick, 0.2 m centre-to-centre spacing	8.6
Replacing a 50-m strip of hard ground by low flow resistivity grassland	10.5
Replacing 25 m of hard ground nearest the road by gravel (flow resistivity 10 kPa s m^{-2} at least 0.1 m deep)	9.1
1.65-m wide 0.3-m high 0.2 m square cell lattice	6.2
12.05-m wide 0.3-m high 0.2 m square cell lattice	10.5

Lattice configurations are predicted to give higher insertion loss than parallel wall arrays of the same width and height. The predicted noise reduction due to the proposed deliberate introduction of roughness elements is lower if the proportion of heavy vehicles is greater and if there are traffic lanes further from the treatment.

Although there is some effect due to the cross-sectional shape of the roughness elements, the predicted increase in noise reduction that would result from using equilateral triangular wedges rather than 0.3-m high rectangular wall cross sections (with the same cross-sectional area) for this motorway case is less than 1 dBA. Calculations show that an increase of between 1 and 2 dBA in the insertion loss would follow from deploying a 2-m wide low parallel-wall or lattice configuration in the central reservation as well as along the side of the road [100]. As far as the overall reduction of traffic noise is concerned, there is no clear advantage in the use of periodic rather than random spacing of identical low walls. But periodic arrangements may be preferred for aesthetic or practical reasons.

Numerical comparisons between the acoustical performances of raised lattices and those of equivalent recessed systems, having identical "roughness" dimensions, show that typically a raised-configuration insertion loss is predicted to be between 3 and 4 dBA higher than that for the equivalent recessed one [100]. While recessed systems are predicted to be acoustically less effective and, potentially, they are more expensive to construct, they might be preferred where there are restrictions on above ground constructions close to roads or where they might be combined usefully with drainage arrangements. It is possible to recover some of the reduced insertion loss by starting them closer to the noise source or by making the recessed configurations deeper than 0.3 m. Placing a roughness-based noise reduction nearer to the source will make it less susceptible to meteorological effects.

Bashir et al. [100] have conducted car pass-by measurements over low parallel brick walls and brick lattices (height 0.2 m) deployed on the asphalt surfaces of car parks. Insertion losses in between 2.4 to 4.6 dBA were measured for 2.5-m wide brick setups. The rectangular lattice was found to offer a similar insertion loss to regularly spaced parallel wall arrays with twice the total width. Part of the insertion loss due to the roughness configurations was the result of transfer of incident sound energy to surface waves which can be reduced by introducing wall absorption or material absorption in the form, for example, of a shallow gravel layer. Predicted finite-length effects were explored in Ref. [100] using a Pseudo-Spectral time-domain method, which models the complete 3D roughness profile. As for the impedance changes described above, the lattice design (3D) shows less dependence on source-receiver angle than parallel wall configurations.

Measurements at close distance from a tramway track, before and after changing the asphalt by strips of grass in between the tracks, were described in Ref. [101]. The recording height was 1.5 m, at either 4 or 7 m from the track. The equivalent levels in a 4-s time-window, centred around various tram passages, showed hardly any effect at the microphone position at 4 m (median of the insertion loss very close to 0 dBA), while at 7 m an insertion loss of 3 dBA was measured. The main noise reduction in the latter was observed for sound frequencies larger than 300 Hz.

5.Building envelope greening

In densely built-up areas, the presence of mainly acoustically rigid materials leads to a significant amplification of the sound emitted by road traffic. This amplification effect is most pronounced in case of small street widths [102][103]. Due to the multiple interactions of sound waves with façades, their properties were shown to be important in city streets [104][105][106][107] and on squares [108]. In

particular, the degree of absorption and diffusivity may have an important effect. In a numerical study simulating sound propagation along a narrow street, Kang [109] showed that the extra attenuation provided by placing absorbers on façades increases with greater source-receiver distance along the street.

Besides attempting to reduce noise levels in streets and squares (so at the most-exposed façade), the positive influence of quiet urban areas and quiet building façades has been convincingly shown [110][111][112][113]. Consequently, this concept has become part of the noise policy in a number of European cities [114]. Therefore, potentially quiet areas, like urban courtyards, have been studied in detail [115][116][117][118][119][120][121][122]. Although courtyards are often strongly shielded from direct exposure to road traffic noise, many of such places were found to exhibit noise levels that are too high to function as quiet areas [123]. The amplification effect due to multiple interactions with the façades is there in general much greater than for a receiver within the street canyon Therefore, mitigation measures to reduce noise levels in urban courtyards are required to fully benefit from access to quietness. The potential of various measures has already been explored [115][119][124][125]. It was found that both façade and roof treatments can contribute significantly to the mitigation of noise from road traffic outside the courtyard. Regarding façade treatments, both the effect of increasing absorption and diffusivity of façades was shown to reduce noise levels in the courtyard [115][119][125]. However, road traffic noise could not only reach the courtyard by propagation over roofs, but also through openings in the building blocks forming the courtyard. These openings could either face a busy road or a calm side or back street. Few studies have investigated the negative impact of such openings. De Ruiter [126] claims that even small openings in façades (5–10 m^2) could lead to an increase of more than 3 dBA in the case of buildings higher than 20 m. In a study by Hornikx and Forssén [125], a 3D numerical study of sound propagation to an urban courtyard revealed that a 9-m^2 opening to an untrafficked cross street could lead to a 10-dBA increase of the noise level in the courtyard.

Vegetation and its soil substrate offers a way of increasing absorption and/or diffusivity in an urban setting. Note that building-envelope greening is often the only possibility to apply vegetation in densely built-up cities due to lack of space. In addition, there are many advantages for the environment, ranging from increasing the thermal insulation of the building envelope and reduction of urban heat island effects [127][128][129][130][131][132][133][134][135], acting as a buffer for storm water [135][136][137][138][139][140], improving air quality and increased carbon-dioxide uptake [141][142][143], increasing urban biodiversity [144][145][146][147], providing a visually pleasant environment [148], to even crop harvesting. Also from an economical point of view, building greening seems interesting [149][150][151][152].

The potential of green roofs in decreasing the intensity of diffracting waves over buildings has been originally identified by numerical work presented in Refs. [153] and [154], and subsequently by in-situ [155] and laboratory measurements [156]. The porous substrate of a green roof is expected to exert the main effect. Green-wall systems, usually consisting of highly porous and low-weight materials placed in a confinement system, make useful sound absorbers [15][157]. In contrast, common building skins are rigid or close to being rigid.

The experimentally characterized acoustic properties of two examples of such greening materials (see Fig. 1), more specifically a 20-cm thick green-façade substrate [15] and a 10-cm thick semi-extensive lime-stone based green-roof substrate [158], were used to numerically evaluate their potential in various inner-city road traffic noise applications [159]. More specifically, their application to urban courtyards (including courtyard openings) and urban squares has been investigated. In addition, low-height noise barriers, covered with a green-façade substrate (see also Section 2.2.1), positioned near roof edges, were considered. Calculations were averaged over vehicle speeds ranging from 30 km/h to 70 km/h, for 4-lane traffic, with 95% light vehicles and 5 % heavy vehicles [159].

5.1. Fully enclosed courtyards

The full-wave calculations presented in Ref. [159], in both 2D and 3D, showed that green roofs have the highest potential to reduce noise levels at non-directly exposed façades. The road traffic noise reduction provided by a green roof strongly depends on roof shape [154][159]. In case of a ridge roof, the largest insertion losses were found (relative to the same roof shape but rigid), amounting up to 7.5 dBA as an average all over the courtyard (both along the courtyard floor and constituting façades; the courtyard height and width were both 19.2 m) (see Fig. 7). Note, however, that in a street-canyon configuration, a rigid ridge roof shields road traffic noise to a lesser extent than a rigid flat roof (when assuming the same internal building volume) [124]. Improvements obtained by green roofs placed on flat roofs are more modest and near 3 dBA (relative to a rigid flat roof). As a conclusion, a non-optimal roof shape, from the viewpoint of noise reduction, can be counteracted when there is a large interaction zone with a green roof.
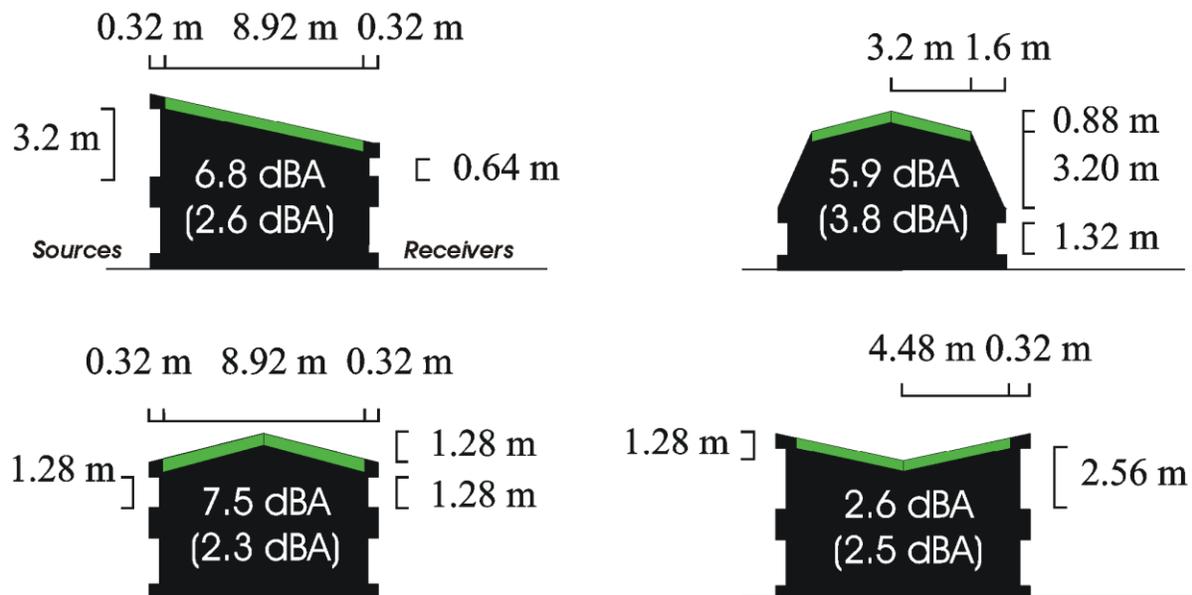
Figure 7. Green-roof road traffic noise insertion losses for different building shapes in a street-canyon setup, referenced to identical building shapes but with perfectly reflecting roofs. The values in between brackets are referenced to a rigid flat roof

having the same total building volume (from Ref. [159]). Note that only the top is shown of the six-storey, 19.2-m high buildings that were considered in the simulations.

Low screens on roofs were shown to be useful, but only when they are absorbing and when placed close the roof's edges. When using the same low-height absorbing screens as considered in Section 2.2.1 (there at street level), up to 3 dBA noise reduction could be achieved when applying screens near all building edges of both the source and receiver canyon.

Calculations in Refs. [115][119] showed that applying façade absorption in the source canyon is especially interesting to achieve noise abatement in an adjacent canyon. In Ref. [159], green façades covering the lower half, the upper half or the full source or receiver canyons' façades have been investigated. The computed insertion losses depend on the assumed reflection coefficient of the reference case, e.g. brickwork. If an absorption coefficient for normal sound incidence of 0.33 is assumed for bricks [9], the effectiveness of green façades becomes rather modest: the maximum reduction is below 2 dBA. Calculations assuming acoustically harder brickwork (absorption coefficient of 0.10 [160]), on the other hand, result in an insertion loss of 4.4 dBA in the case of a fully vegetated source canyon façade. The main zone of influence regarding vegetated façades at the street side seems the upper half. Fully vegetating the source canyon does not give additional benefits compared to only treating the upper half in case of softer bricks, while additionally 1 dBA can be gained in case of more rigid bricks. The presence of façade vegetation only in the lower part results in a rather limited insertion loss. Fully greening the courtyard façades is beneficial compared to only putting a green façade in the upper half, showing the importance of reverberation in the receiving canyon.

The combination of different greening measures results in a lower combined effect than when the separate effects would have been linearly added [160]. The combination of green roofs or façade vegetation with roof screens seems most interesting, since different physical noise reducing processes are involved. The combination of green façades and green roofs is less effective [160].

5.2.Courtyards with façade openings

The effects of greening façade openings to a courtyard have been studied in a full 3D model in Refs. [159] and [161]. Openings toward a trafficked main street and an untrafficked cross street were considered. Opening widths of 3 m were assumed, and the height of the opening was assumed to be either 3 m or of equal height to the building. An insertion loss of 4 dBA was obtained, averaged over all façades forming the courtyard. An absorption coefficient for normal sound incidence of 0.33 [9] of the baseline façade material of the openings was used. Similar to the discussion in Section 5.1, a lower absorption coefficient would lead to a larger insertion loss. The effect of vegetated façades was shown to be highly dependent on the location of the receiver in the courtyard, with the highest reductions at positions close to the opening. This building-envelope greening mitigation method is rather efficient, as a limited surface area of green façade is needed to significantly reduce the noise in the courtyard.

5.3.Streets and squares

To abate noise in streets and squares, that is, when no geometrical shielding is present between (some of) the noise source(s) and the receiver positions, green-façade systems are the only building envelope greening measure that could be relevant. Upon each interaction with the green façade, part of the acoustical energy is absorbed and street amplification is reduced. The potential for reducing noise in streets and squares by increasing absorption was investigated before without aiming at a specific material [104][108]. In Ref. [162], the impact of green façades on the noise levels in streets and squares, averaged over receiver positions at both the façades and along the walkways, was studied with a 3D full-wave technique (PSTD) [163] and a ray-based approach combined with a radiosity model (CRR) [164].

When all the façade's brickwork parts bordering a 19.2-m wide street were covered with a green façade material, the averaged reduction of noise was only 1 dBA. When an absorption coefficient in the reference case (for normal incidence) of 0.10 [160] was assumed, the effect of the green façades is about 2 dBA larger. Their effect is largest for receivers at higher storeys.

The effect of applying green façades has also been quantified for a roadside square [162], sized 38.4 m x 57.6 m, with the latter dimension in the direction of the traffic lanes. Green façades replaced all brickwork parts of the street and square façades. The computed noise reduction was only 1 dBA, averaged over many receiver positions on the square. If acoustically harder bricks were assumed in the reference case [160], the effect of the green façades was predicted to be 2.5 dBA larger. The largest effect is obtained for receivers farthest away from the traffic lanes (and thus closest to the façades).

6. Conclusions

This paper shows that there are many ways of reducing surface transport noise by natural means between the road/track and receivers. The choice of a specific measure strongly depends on the setting (urban, suburban, rural), the available space for the noise abatement solution, and the receiver position (distance relative to the road/track and receiver height).

Increasing absorption at the surfaces of noise walls by means of planted substrates is a useful technique where there are parallel road traffic noise walls. A row of trees behind a noise wall was shown to improve the noise wall efficiency under downwind conditions and further reduces the visual impact of motorway noise walls in an open landscape. Canopy design was shown to be important for the latter. Vegetated barrier caps could increase noise wall efficiency, but only at short distance behind the wall.

On condition that sufficient space is available, earth berms (mounds) should be considered as an environmentally friendly noise abatement solution. Although with a traditional (triangular) berm the diffracting edge is located somewhat further from the source compared to a noise wall positioned at the source-side foot of the berm, thus lowering efficiency when keeping top height fixed, optimization of the macro and micro shape was predicted to be able to strongly enhance the noise shielding. In particular source-side surface roughening of highly-compacted berms is worth mentioning. In addition, their more aerodynamical shape, compared with a vertical noise wall, means that downwind shielding loss can be avoided to an important extent.

Low-height absorbing barriers were shown to have many applications, and have been evaluated in a street canyon setup, on building roofs and along rail and tram tracks. For both single and multiple lanes/tracks, a good performance was predicted, with a further improvement using additional barriers between the lanes/tracks. Absorption at the surfaces, here by means of green-wall substrates, was

shown to be essential. Also a sufficiently low transmission through the barrier must be ensured. Low gabion barriers, although transparent to low frequencies, could be effective as a noise barrier for broadband sources as well, with an enhancement when using porous stones. Such low barriers strongly reduce the visual impact, increasing their applicability.

The road traffic noise reduction from tree belts can be mainly attributed to the forest floor effect and scattering, shielding and absorption by trunks. Even narrow tree belts (15 m wide) were shown to provide relevant road traffic noise reduction based on numerical analysis, on condition that specific design rules are followed. High-biomass density of the trunks should be strived for, while planting schemes were shown to be of high importance. The physical noise reduction provided by hedges and shrubs was concluded to be small, although positive psycho-acoustical effects are expected. Larger strips of trees along roads were shown to mitigate nocturnal temperature inversion episodes, otherwise significantly increasing noise levels during the noise sensitive period at night. During daytime, a negative atmospheric effect is expected.

As long as sufficient space alongside a surface transport source is available, ground treatments offer substantial noise abatement, while fully preserving the openness of the landscape. One way is to replace acoustically-hard ground by porous soil (e.g. a low-flow resistivity grassland) beside a road. A succession of strips of soft and rigid soil, although less efficient than making all available soil soft, benefits from the presence of impedance discontinuities which can be used as walkways and for access. Low parallel walls were shown to abate road traffic noise efficiently and optimized configurations for multi-lane roads have been found through numerical simulations. In a lattice configuration, the efficiency of such walls is further enhanced since the dependency of the insertion loss on the angle of incidence is lowered.

Building greening is often the only way to increase the amount of vegetation in densely built-up city centres. Green roofs are particularly helpful to achieve a quiet side, compared to traditional rigid roofs. In addition to noise reduction, many environmental and economic benefits are to be expected. The largest green-roof insertion losses are obtained in case of ridge roofs. Vegetated façades were predicted to be especially interesting for façade openings towards courtyards. In situations without façade openings, vegetation-treated façades may give significant improvement in the courtyard compared with acoustically hard façades. When source and receiver are in the same reverberant space, like a trafficked street canyon or square, green façades are much less efficient.

In order to increase the knowledge of when and how the various measures presented in this review come in best use, they should be implemented in noise action plans. To match this progress, also noise mapping software needs further development since currently they are unable to model many of the here described measures for surface transport noise abatement.

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Table captions

Table 1. Predicted extra noise reduction due to various roughening scenarios, relative to fully flat berm surfaces, in a 4-lane mixed road traffic situation. The first 3 lines correspond to the 3 shapes depicted in Fig. 3 (from Ref. [17]).

Table 2. Parameters giving best fits to level-difference data obtained over several types of grassland using a two-parameter slit-pore model [85].

Table 3. Insertion losses compared with smooth hard ground predicted for various ground treatments including low parallel wall and lattice configurations for a receiver at a distance of 50 m and at height of 1.5 m; walls are assumed to start 2.5 m from the edge of a two-lane urban road (95% cars, 5% heavy vehicles travelling at 50 km/h) [91][100].

Figure captions

Figure 1. Green roof substrate (a) and green wall (b) substrate absorption coefficient upon normal incident sound used in the calculations in Refs. [17], [47] and [159].

Figure 2. Measured noise wall efficiency improvement resulting from the presence of a tall row of trees at close distance behind a 4-m high motorway noise barrier as a function of downwind wind speed measured at a height of 12 m (u_{12m}) (from Ref. [31]).

Figure 3. Realisations of roughening the top surface of a trapezoidal berm using rectangular and irregular indentations at orders 1 (a), 2 (b) and 3 (c) (from Ref. [17]).

Figure 4. Insertion loss at 1000 Hz near a 1-m high and 1-m wide gabion barrier placed on rigid ground. On the left, rigid stones have been considered, on the right the equivalent case with expanded clay stones (flow resistivity of 82 kPas/m^2) is depicted (From Ref. [49]).

Figure 5. Strategies to decrease tree trunk biomass density without significantly affecting road traffic noise shielding : (a) increasing spacing orthogonal to the road, (b) leaving out full rows of trees, (c) thinning of the tree belt. The filled circles indicate trunk cross-sections, the open circles gaps (from Ref. [71]).

Fig. 6. Example calculation showing the spectrum of sound pressure level, relative to free field, due to a 0.3 m high parallel wall array in which each wall is 0.05 m thick, predicted using BEM and a semi-analytical model (Allard model) for a point source over a slit-pore layer impedance. The source and receiver are assumed to be at a height of 0.05 m above the top of the wall array and separated by 4.0 m. The edge-to-edge spacings assumed is 0.05 m corresponding to flow resistivity 0.174 Pas m^{-2} and porosity 0.5.

Figure 7. Green roof road traffic noise insertion losses for different building shapes in a street-canyon setup, referenced to identical building shapes but with perfectly reflecting roofs. The values in between brackets are referenced to a rigid flat roof having the same total building volume (from Ref. [159]). Note that only the top is shown of the six-storey, 19.2-m high buildings that were considered in the simulations.