3D numerical assessment of road traffic noise reduction by ordered planting schemes

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Summary

In this study, a 3D Finite-Difference Time-Domain (FDTD) numerical model is used to study the effect of tree planting schemes in vegetation belts with limited depth for road traffic noise reduction. An absorbing soil as typically found under vegetation is fully included in the numerical model. To relax the computational cost of such calculations, only a representative strip of the vegetation setup was considered. In a series of preliminary 2D calculations, it was shown that this approach does not induce errors for symmetric planting schemes. The effect of tree trunk planting scheme, stem diameter and tree spacing was studied. Since scattering from smaller tree elements like leafs and twigs cannot be explicitly modeled without dramatically increasing the computational cost of the FDTD model, an approach was tested to account for this effect.

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1. Introduction

Measuring the acoustical effect of a belt of trees/vegetation is a popular research topic and spans over 40 years, e.g. from Refs. [1] to [2]. The findings from such experiments are often quite different, and general conclusions on the ability of using vegetation belts for road traffic noise reduction are therefore lacking.

Often, the situation to which is referred in these measurements when assessing the effect of the vegetation belts is rather unclear. Furthermore, many effects related to the interaction between sound and vegetation were observed simultaneously. This makes it difficult to derive design rules for vegetation belts. In this study, numerical calculations are used to assess the effect of infinitely long vegetation belts of limited depth along roads. In contrast to in-situ measurements, reference situations are well defined and the various effects operating can be easily singled out.

The interaction between acoustic waves and vegetation leads to reflection, scattering and diffraction at vegetation elements like trunks, branches, twigs and leaves. This could lead to increased downward scattering for low source and receiver heights, close to trees [3]. Alternatively, sound energy can leave the line-of-sight between source and receiver due to multiple scattering, resulting in decreased sound pressure levels. A second mechanism is absorption caused by vegetation, either by mechanical vibrations of plant elements [4][5], or processes near the thermo-viscous boundary layer. As a third mechanism, one might also mention that sound levels can be reduced by destructive interference of sound waves, mainly by the presence of the soil. This results in a more pronounced ground effect in case of typical soils found under vegetation, compared to e.g. sound propagation over grassland [6]. Besides these direct acoustical effects, some indirect effects can be mentioned like changing the local micro-meteorology which can be applied in a positive way near noise barriers [7] or positive psycho-acoustical effects.

Furthermore, research with relation to "sonic crystals" indicated that bandgaps might be present with ordered vegetation rows as well [8], and not only with closely packed artificial cylinders. Such

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effects are worth investigating for the purpose of road traffic noise shielding.

The few numerical assessments of vegetation belts that can be found in literature all start from a random ordering of plant material (see e.g. Refs. [9] and [10]).

2. 3D finite-difference time-domain method

The sound propagation equations in a homogeneous and still medium are numerically integrated by means of the finite-difference time-domain method. An efficient lowest-order staggered-in-time and staggered-in-space discretisation is chosen as described in detail in Ref. [11].

To model reflection from the typical soft soils as found under vegetation, the Zwikker and Kosten phenomenological model is used. A flow resistivity of 6.9 kPas/m^2, a porosity of 0.56 and a structure constant of 1.26 are applied. These parameters give a perfect match (in the frequency range considered in our simulations) with a slit-pore model parameter set consisting of a flow resistivity of 10 kPas/m^2, a porosity of 0.6, and a turtuosity of 1.29 [12]. These values are typical for vegetation covered soil. The slit-pore model was shown to be well-suited to fit parameters to measurements of various types of soils, including soil under vegetation [12].

The spatial discretisation of the FDTD grid is chosen to be 0.02 m, leading to accurate calculations up to 1.7 kHz (assuming a sound speed of 340 m/s). The temporal discretisation step is taken so that the Courant number equals 1.

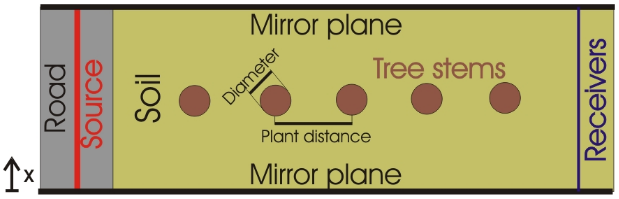

Figure 1. Top view of 3D grid setup

The distance between the (coherent) line source (at a height of 0.3 m) and the receiver plane equals 19 m. In between, a 15-m wide zone is used to study different planting schemes. Since 3D numerical simulations typically need a very large amount of computational resources, symmetry planes are placed, normal to the road axis (see Fig. 1). In this way, only a representative part of the vegetation scheme is explicitly modelled. Such a simulation is representative for an infinitely long symmetric repetition of this strip along the road axis. This approach is common in acoustic simulations.

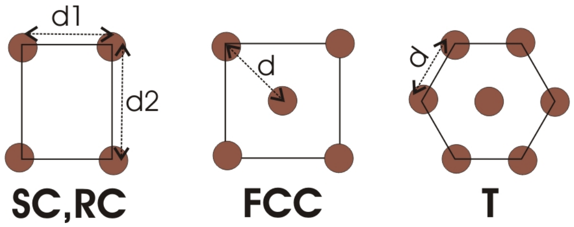

Figure 2. Planting schemes considered

3. Testing symmetrical approach in 2D

The validity of the symmetric approach using mirror planes is firstly checked by two dimensional simulations. Insertion loss values for 1/3 octave bands using a representative strip only (of 1 m wide) is compared to explicitly modeling a wide strip (of 20 m), using the same scheme. Note that the wide strip is also bordered by reflecting planes at the simulation boundaries normal to the road axis. In such 2D calculations, coherent plane waves are modeled, parallel to the infinitely long cylinders, in absence of a reflecting ground plane. A rectangular spacing RC is used for identical cylinders with a diameter of 0.44 m. The spacing parallel and normal to the road axis are 1m and 2m, respectively. Figs. 2 and 3 show very similar results over the full frequency range considered, showing the validity of only modeling a representative strip.

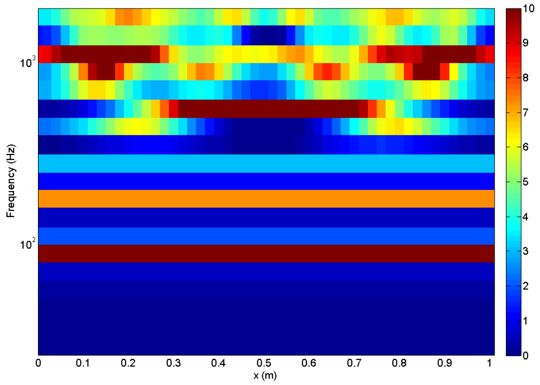

Figure 2. Insertion loss spectra (2D) in dB over a selection of an explicitely modelled wide strip of a rectangular grid setup. For comparison to Fig. 3.

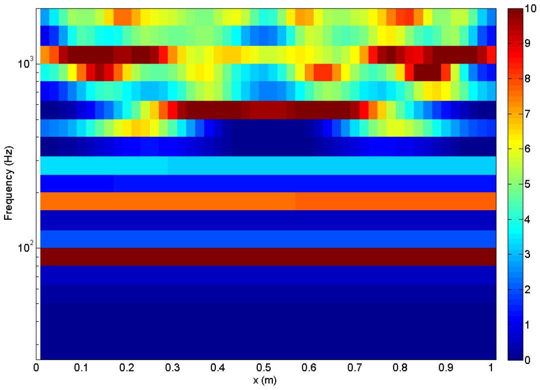

Figure 3. Insertion loss spectra (2D) in dB over a representative strip of a rectangular grid setup. A spacing of 1m on 2m is used, for diameters of 0.44 m.

4. 3D numerical results

4.1. Influence of stem diameter, spacing and planting scheme

In Fig. 4, the total traffic noise insertion loss is calculated for a triangular (T), face-centered cubic (FCC), simple cubic (SC) and rectangular grid (RC), for tree stem diameters of 0.11, 0.22 and 0.44m. Results are averaged over receiver heights between 1m and 2m (typical ear height) in the receiver plane at 19m from the source. The Harmonoise/Imagine road traffic source model is applied, for a light vehicle driving at 70 km/h. The reference situation is sound propagation over grass-covered ground. Such a comparison represents a practical case, namely assigning a piece of grassland for vegetation. Inter-tree distances range from 3 m to 1 m. Note that the positive effect of a different soil is included in the results. The soil under vegetation already gives a reduction in total traffic noise level of 3 dBA at the chosen vehicle speed.

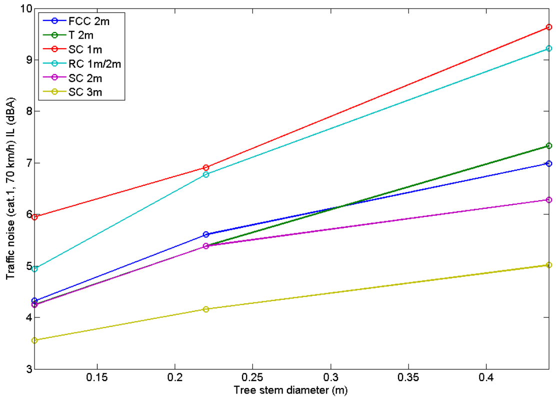

Figure 4. Averaged total traffic noise insertion loss for various schemes and planting distances, in function of tree stem diameter. Receiver heights between 1m and 2m are considered. The reference situation is sound propagation over grassland. “T 2m” indicates a triangular planting scheme, with a minimum distance between tree stems of 2m.

With increasing tree stem diameter, traffic noise insertion loss is more pronounced for each planting scheme considered. Furthermore, with increasing distance between the stems, shielding becomes smaller and the importance of the stem diameter decreases, as illustrated in Fig. 4.

The FCC 2m, T 2m and SC 2m have the same minimum inter-plant distance and the importance of a specific lattice can therefore be compared. For the 0.11 m and 0.22 m diameter, the effect of the scheme considered is rather unimportant. For the 0.44 m diameter, T is preferred upon FCC and SC. The use of a T scheme could lead to an improvement of 1 dBA compared to the SC scheme for total traffic noise of a person’s car at 70 km/h.

The effect of vehicle speed is shown in Fig. 5. A receiver line at a height of y=2 m is considered, and the total traffic noise insertion loss over the modeled strip is shown with increasing vehicle speed. For the higher vehicle speeds, the effect of the planting scheme is clearly more pronounced.

Above 100 km/h, the effect of vehicle speed becomes very small. While for the lower vehicle speeds a more uniform insertion loss is observed over the receiver line, for higher speeds there is more variation. At low frequencies, periodicity is more important leading to some distinct bands where a high attenuation is obtained. At higher frequencies direct shielding is more important, and the location along the receiver line, relative to the position of the trees becomes more important.

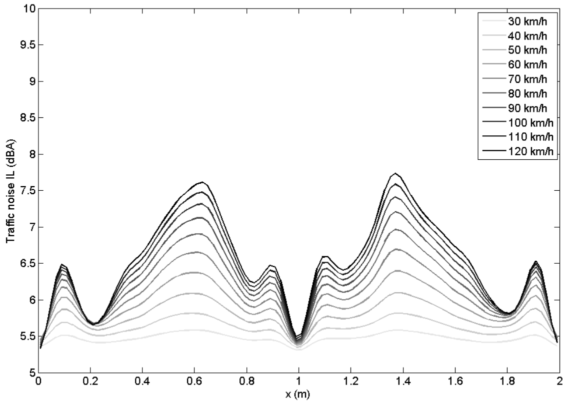

Figure 5. Traffic noise insertion loss over representative strip of a SC 2m scheme (diameters of 0.22 m), for different vehicle speeds. Receiver heights between 1m and 2m are considered. The reference situation is sound propagation over grassland.

4.2. Including scattering from tree crowns

Including tree crowns is mainly intended to estimate the negative effect of downward scattering. The tree crowns are approached as a sphere. The upper half of this sphere is neglected to limit the computational cost. The use of small, scattering elements (i.e. basic grid cell of 0.02 x 0.02 x 0.02 m^3) is applied here. It is assumed that near the centre of the crown, most woody plant material is present, leading to a higher chance of filling a particular grid cell. This also accounts for the prolongation of the tree stem inside the crown, and local clustering of filled cells could be representative for larger structures in the canopy. At the surface of the sphere representing the tree crown, a very small chance of filling cells is applied. Various approaches were tested, like a 3rd order power law to go from a chance of filling a particular cell of 0.01 (at the crown edge) to 0.5 (in the crown centre). In another approach, values ranging from 0.01 to 0.3, and from 0.01 to 0.2 are applied. The hypothetical case of the presence of crowns only, above vegetation ground, leads to a negative effect from -0.6 dBA to -0.9 dBA for light vehicle traffic noise at 70 km/h.

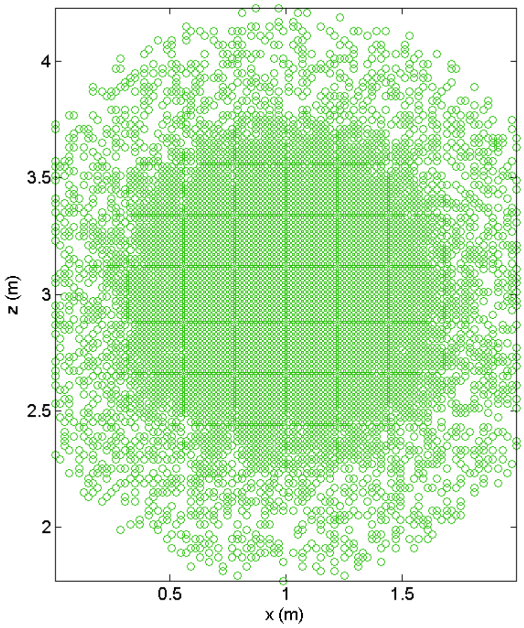

Figure 6. Top view of scattering elements, representing the lower half of a spherical tree crown.

5. Practical realization of dense planting of trees

Well-established empirical relationships exist between the number of trees per unit area and their stem diameter [13]. Based on such relationships the suggested tree density-tree diameter combinations considered in this work are not all realistic in ordinary tree plantings, especially for the stems with a diameter of 0.44 m. Such results should therefore be considered as an absolute maximum effect, but are nevertheless useful to see trends as discussed in Sect. 4.1

Increased traffic noise shielding could be practically obtained taking into account the following two measures.

Firstly, numerical simulations (not shown) indicated that omitting some rows of trees does not affect the traffic noise insertion loss of the tree stand. Trees planted in densely clustered zones followed by open spaces could therefore be practically achievable, as this ensures that sufficient resources (light, water and nutrients) are available for tree growth.

Secondly, pollarded trees of genera such as *Salix* or *Populus* are of special interest as they can attain large stem diameters at high densities and as they have a limited height due to the cyclic removal of the foliage.

6. Conclusions

The numerical simulations performed in this study shows that modeling a representative strip of a planting scheme is accurate and largely reduces the computational cost. The presence of ordered rows of trees (in a 15-m deep belt) increase traffic noise shielding, exceeding 5 dBA for inter-stem distances of 2 m and tree diameters of 0.22 m, compared to sound propagation over grassland. An important part of this positive effect is caused by the typical soft soil appearing under vegetation. Downward scattering by crowns is estimated by a statistical description of scattering elements, leading to a decrease in performance ranging from 0.6 to 0.9 dBA, depending on the parameters applied. Many of the proposed planting schemes can be achieved in practice, e.g. by omitting some rows of trees to allow sufficient growth place for trees, and by selecting specific genera.

Acknowledgement

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