Building and Environment 44 (2009) 1081–1087

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Reducing the acoustical façade load from road traffic with green roofs

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ARTICLE INFO

Article history:
Received 17 June 2008
Received in revised form 19 July 2008
Accepted 21 July 2008

Keywords:
Green roofs
Sound propagation
Road traffic noise
Building geometry

ABSTRACT

Noise annoyance by road traffic is a major issue in urbanized regions. In this study, the influence of a green roof on the façade noise load was investigated numerically for road traffic at close distance. Consistent positive effects of the presence of a green roof are observed at non-directly exposed (parts of) façades. A sufficient green roof area is needed to obtain significant reductions in total A-weighted road traffic noise level. With increasing traffic speed, the green roof effect increases for light vehicles. In case of heavy vehicles, this dependence is less strong. In a street canyon situation, the façade load in the non-exposed canyon is largely influenced by both the roof slope and the presence of a green roof. A flat roof generally results in the best average shielding. A green roof is especially interesting in case of a saddle-backed roof. With a good choice of green roof parameters, the shielding of a flat green roof can be approached.

1. Introduction

Noise annoyance by road traffic in urbanized regions is a major issue. It is estimated that about 44% of the population of the European Union (in the year 2000) was exposed to road traffic noise levels (near their houses) above the World Health Organization's threshold for onset of negative health effects [1]. Although important improvements have been made during the last decades by continued tire engineering, by producing more silent engines and by the development of new types of road surface top layers, the sound pressure levels are most often still too high for dwellings at limited distance from roads.

The propagation path between the source location and receivers can be exploited to further reduce noise levels. A noise barrier for example is an important and adequate measure to reduce sound pressure levels near highways, but its applicability in city centers and even in suburban areas is limited.

The acoustical façade load, i.e. the sound pressure level at the outside of the building, and the façade insulation are key to estimate indoor sound pressure levels. Although façade insulation can be a very successful measure for solving particular sleep disturbance and noise annoyance problems, it has been shown that in general noise annoyance is not reduced by insulation as much as could be expected on the basis of levels [2]. The simple explanation for this is that people open windows and spend time outside their dwelling. Thus, measures for reducing façade load such as the roof coverage (with focus on greening) and roof type studied in this paper remain very attractive complements.

Green roofs (or vegetated roof tops) have important noise reducing properties, besides a large number of economic and ecological advantages (e.g. Refs. [3–7]). A straightforward acoustical application of green roofs is the increased sound insulation of the roof system. This could lead, depending on the geometry of the building, to large reductions of indoor noise levels for example during a plane fly-over. In this study, it will be shown that there are also interesting applications for reducing exposure to road traffic noise and noise from other sources situated at low altitude. Indeed, since the exterior of a non-vegetated roof is most often a rigid material (acoustically reflecting to a large extent), there is potential in reducing acoustic waves diffracting over buildings or parts of buildings. The typical substrates used in both extensive and intensive green roofs are porous and thus allow sound to enter the growing mediums. Because of the large number of interactions between sound and substrate particles, attenuation occurs. Moreover, the modified sound waves can destructively interfere at locations where quietness is desired.

Extensive green roofs only need a thin layer of soil substitute i.e. a granular substrate. They support low-growing plants like Sedum species and grasses. Intensive green roofs, on the other hand, require larger soil depths and may allow growing shrubs or even trees. They typically contain uncompacted (loose) earth. Both types of substrates can be categorized as acoustically soft mediums.

In a previous study [8], different aspects of numerical modelling of diffracting sound waves over green roofs were considered. The influence of substrate depth of extensive and intensive green roofs was studied in detail.

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doi:10.1016/j.buildenv.2008.07.013

In this work, an assessment is made of the noise reducing capabilities of green roofs for overall A-weighted traffic noise at building façades. In particular, road traffic at short distance from the building façade is considered. Numerical calculations will be performed for two geometries, more precisely a terrace covered with green and a green roof in a street canyon configuration. In both cases, the sound pressure level at the façades in the presence of green roofs is compared to exactly the same geometry, but with the green roof replaced by a fully rigid roof.

This paper is organized as follows. Section 2 briefly describes the numerical sound propagation model. In Section 3, the road traffic source model that will be used for the numerical calculations is discussed. The geometry of the two types of building configurations considered in this study is described in Section 4. In Section 5, the numerical results are shown and discussed. In Section 6, conclusions are drawn.

2. Sound propagation model

The following equations describe sound propagation in air:

$$\nabla \cdot p + \rho_0 \frac{\partial \mathbf{v}}{\partial t} = 0, \tag{1}$$

$$\frac{\partial p}{\partial t} + \rho_0 c_0^2 \nabla \cdot \mathbf{v} = 0. \tag{2}$$

In the linear Eqs. (1) and (2), p is the acoustic pressure, $\boldsymbol{v}$ is the particle velocity, ρ_0 is the mass density of air, c_0 is the adiabatic sound speed, and t denotes time. A homogeneous and still propagation medium is assumed. Viscosity, thermal conductivity, molecular relaxation, and gravity are neglected.

Sound propagation in a porous (rigid-frame) medium can be described by the Zwikker and Kosten phenomenological model [9]:

$$\nabla \cdot p + \frac{\rho_0 k_s}{\varphi} \frac{\partial \mathbf{v}}{\partial t} + R\boldsymbol{v} = 0, \tag{3}$$

$$\frac{\partial p}{\partial t} + \frac{\rho_0}{\varphi} \frac{c_0^2}{k_s} \nabla \cdot \mathbf{v} = 0. \tag{4}$$

In Eqs. (3) and (4), R is the flow resistivity of the porous medium, φ its porosity and k_s the structure factor. Appropriate substrate parameters for both intensive and extensive green roofs were found by means of a literature study [8].

The finite-difference time-domain (FDTD) method is used to solve Eqs. (1)–(4). All important wave aspects like multiple reflections, multiple diffractions, and the interaction between sound and the green roof substrate are accurately modeled. The staggered-in-time and staggered-in-space discretisation approach is chosen [10]. The advantages of this numerical scheme were described elsewhere [11]. The FDTD method has become a reference solution in non-trivial applications [12]. This numerical method has been validated thoroughly by comparison with measurements, analytical solutions and other numerical methods, over a wide range of acoustical applications [13–16].

The FDTD method is a volume-discretisation technique and is therefore computationally costly. Simulations are limited to 2D, implying an infinitely long (coherent) line source and buildings having a constant cross-section. Although road traffic is more accurately modeled as an incoherent line source (i.e. the phase difference between the different point sources forming the line source is random), it was shown that source type is not important when comparing the effect of roof coverage [8].

On the other hand, the use of a time-domain model is advantageous. With a single simulation, the response over a wide range of frequencies can be calculated when working with a pulse-like source and when applying a Fourier transform afterwards. Most road traffic source power models are available in 1/3 octave bands. To obtain accurate propagation data, at least 10 frequencies per 1/3 octave band need to be obtained. A frequency-domain technique requires a new calculation for each of these frequencies while the time-domain approach produces the required spectrum at once.

3. Road traffic source spectrum

The Harmonoise/Imagine road traffic source model is used. This is a state-of-the-art model, based on numerous measurements and outcomes of national and international research projects. A summary of this calculation method can be found in Ref. [17]. According to this model, each vehicle can be represented by two (incoherent) omni-directional point sources. The first source is placed at a height of 0.01 m above the road surface, and the second one at a height of 0.30 m or 0.75 m, respectively, for light vehicles (e.g. person's cars) and heavy traffic. The first source point is associated with rolling noise and the second one with engine noise. 80% of the rolling noise source power model given by the Harmonoise model should be attributed to the lowest point source and 20% to the highest source point. The engine source power, on the other hand, is assigned for 80% to the source at 0.30 m (or 0.75 m), and for 20% to the source at 0.01 m. The source powers depend on the sound frequency, traffic speed and vehicle type.

Default values of the basic model are assumed for the calculations in this study. This implies that the vehicles are driving at constant speed on a dense asphalt concrete road top layer, and the air temperature is 20 °C.

4. Building configurations studied

The acoustical effect of the presence of a green roof was studied in two situations. In the first configuration, the façade under study is partly in the acoustic shadow zone, while in the second configuration, the (full) façade is only indirectly exposed.

The first configuration is shown in Fig. 1. A green roof is present on a terrace, which is an extension of the main building. Façades A and B constitute of a brick-wall and each have a window of 2 m high, starting from the floor levels. Façade A has a height of 3 m, while the maximum building height equals 7.5 m. Terraces with lengths of $D_2 = 5$ m and $D_2 = 10$ m are considered. The road is located at, respectively, $D_1 = 10$ m and $D_1 = 5$ m from façade A. These configurations will be indicated as the 5-m and 10-m building extensions, respectively. The sound pressure levels are evaluated very close to façade B (at 0.5 cm).

The second configuration, depicted in Fig. 2, is an idealized street canyon, which is common in a dense, urban setting as can be found in many (old) European cities. The street canyons have a width of 10 m and a width-height ratio of 1 in case of a flat roof. The road traffic source is located in the street on the left side of the middle building and the influence of the green roof on the acoustical load at façade C (at 0.5 cm) is considered. The source is located at 4 m from façade A. Given the large number of reflections in the street canyons, the exact location of a source near ground level was shown to be of minor importance [18]. The roof slopes α considered were 0° (flat roof), 15°, 30°, and 45°. To allow for a fair comparison, the volume of the buildings is kept the same when varying roof slope. This leads to façade heights H of 10 m, 9.33 m, 8.56 m, and 7.5 m, respectively. All building façades consist of bricks and are fully specularly reflecting.

In both configurations, all horizontal surfaces and roofs are rigid, except at the locations where a green roof is present. Both extensive and intensive green roofs are considered. Sound propagation in the substrate layer itself is explicitly modeled. Based on previous optimizations of substrate depths [8], and taking into account

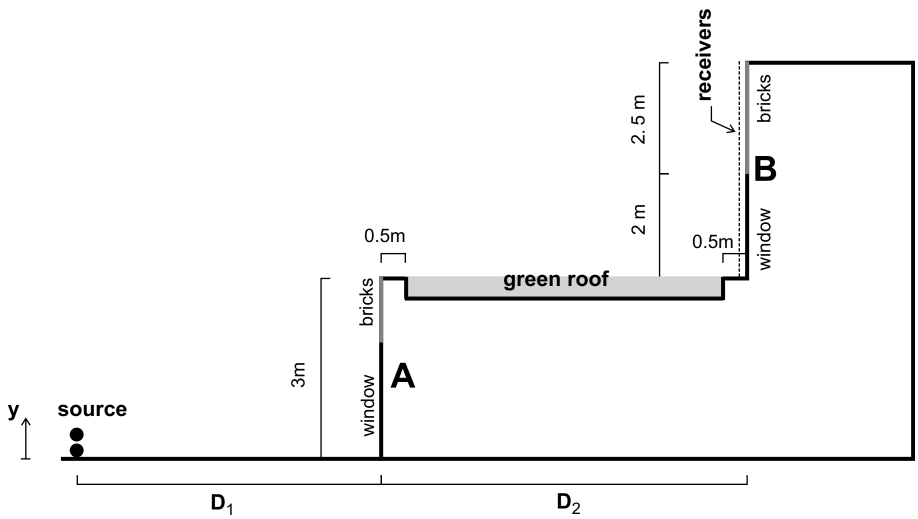

Fig. 1. Representation of a green roof on a building extension (configuration 1). The couple (D_1,D_2) takes the following values in the numerical simulations: (5,10) and (10,5). Receivers are located along façade B. The window under study is located between $y = 3$ m and $y = 5$ m.

practical limits, extensive green roofs with a depth of 5 cm, 10 cm and 20 cm are modeled, and intensive green roofs of 10 cm and 20 cm. In configuration 1, the green roof starts at 0.5 m from façade A and ends at 0.5 m from façade B. In street canyon configuration 2, the green roof starts at 0.5 m from the roof-gutters, measured along the roof slope.

Windows are modeled as rigid planes and the bricks were assigned a reflection coefficient of 80% [19]. The latter is modeled in FDTD using the approach described in Ref. [10]. At the left, right and upper side of the simulation region, perfectly absorbing boundaries (perfectly matched layers [20]) are applied to simulate an unbounded atmosphere.

5. Numerical results

All of the results shown in this section are expressed in terms of total A-weighted sound pressure levels resulting from road traffic noise. The Harmonoise/Imagine road traffic noise spectra are used for light vehicles (type 1) and heavy vehicles (type 3), at driving speeds ranging from 30 km/h to 130 km/h (in steps of 10 km/h). Although not all vehicle speeds are possible or appropriate in the geometries considered, such a broad range is however useful to assess the effects that can be expected.

5.1. Configuration 1

In Figs. 3 and 4, the total A-weighted traffic sound pressure levels over the full height of façade B are shown, for a light vehicle traveling at 70 km/h. In Fig. 3 the extension of 5 m is considered, and in Fig. 4 the extension of 10 m. The corresponding differences in predicted sound level between the rigid roof and the green roof configurations are shown in Figs. 5 and 6, respectively, over the height of the window in façade B. Negative values indicate that the green roof reduces the sound exposure at the façade.

The effect of the presence of a green roof, relative to a rigid roof, is small in the case of an extension of 5 m. An increase in shielding is only observed when there is no direct view between the source and receivers at the façade. Once outside this diffraction zone caused by the extension, direct sound is dominant and the effect of the green roof becomes negligible. The diffraction zone along façade B ranges from $y = 3$ m (roof level) to $y = 4.2$ m for engine noise of heavy traffic, and to $y = 4.5$ m for rolling noise. The impedance change between the (rigid) window and the (partly) reflecting bricks near 5 m leads to the small discontinuity when plotting total traffic noise along façade B.

For the extension of 10 m, positive effects are observed over the full façade height of the building. Since the source position relative to façade B was not changed, the full façade has no direct view towards the source, even when considering the heavy traffic engine noise source height at $y = 0.75$ m. The total A-weighted sound pressure levels caused by the traffic are therefore consequently smaller. This difference between the 5-m and 10-m extension, for a fully rigid roof, is about 5 dBA just above the terrace level. The green roof effect, which is normalized for this difference, is larger for the 10-m extension than for the 5-m extension. This clearly shows that the green roof surface area is an important parameter:

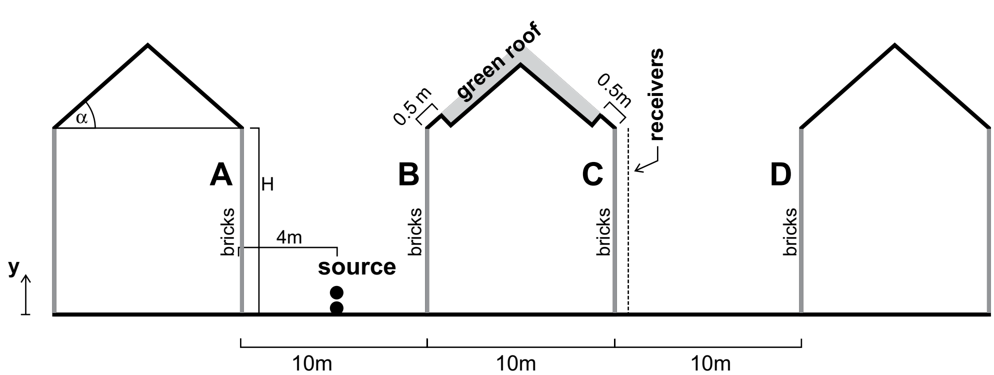

Fig. 2. The idealized street canyon configuration 2. The façade height H depends on the slope angle of the roof α (values of α equal to 0°, 15°, 30°, and 45° correspond to values of H equal to 10 m, 9.33 m, 8.56 m, and 7.5 m). Receivers are located along façade C.

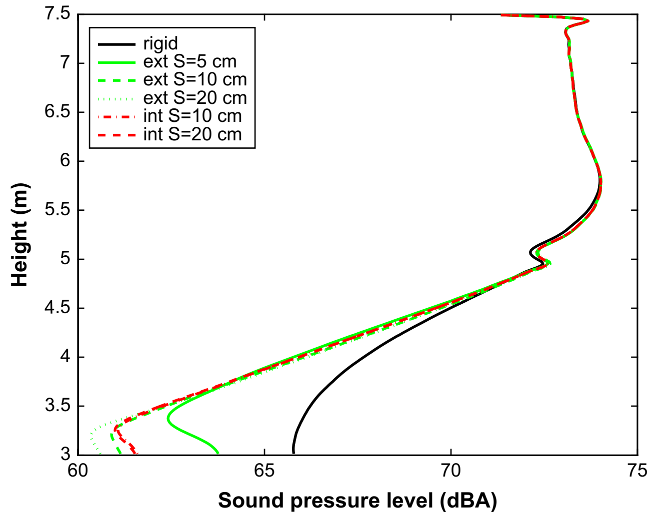

Fig. 3. Sound pressure level over the full height of façade B in configuration 1, for a light vehicle at 70 km/h, in case of the 5-m building extension $(D_1,D_2) = (10,5)$. A rigid roof, extensive green roofs ("ext") with substrate thicknesses S equal to 5 cm, 10 cm and 20 cm, and intensive ("int") green roofs with thicknesses of 10 cm and 20 cm are shown.

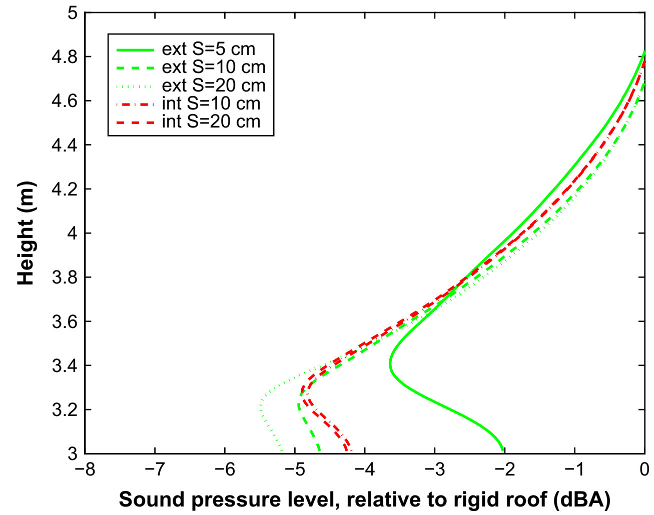

Fig. 5. Sound pressure level, relative to a rigid roof, over the full height of the window at façade B ($y = 3$ m to $y = 5$ m). A light vehicle is considered at 70 km/h, in case of the 5-m building extension. Extensive green roofs with substrate thicknesses S of 5 cm, 10 cm and 20 cm, and intensive green roofs of 10 cm and 20 cm are shown.

diffracting sound waves interact longer with the green roof before reaching the façade.

In Figs. 7 and 8, the averaged attenuation by the green roofs over the full height of the window ($y = 3$ m to $y = 5$ m) is shown in function of vehicle speed. Both the extension of 5 m (dashed lines) and 10 m (full lines), and both light (Fig. 7) and heavy (Fig. 8) vehicles are considered. For light vehicles, the green roof effect is strongly dependent on vehicle speed. With increasing traffic speed, the effect increases. Starting from about 100 km/h, the green roof attenuation saturates. This dependence can be explained by looking at the traffic noise spectrum. At low speeds, engine noise is dominant, which is characterized by low frequencies. At higher speeds, the high-frequency rolling noise becomes more important. This means that for high vehicles speeds, the high frequency part of the spectrum gives the largest contribution to total A-weighted traffic noise levels. The impedance of the green roof substrate decreases with frequency and consequently the amount of absorption increases with frequency. Therefore, the green roof effect at higher vehicle speeds will be larger.

The dependence of the green roof effect on vehicle speed is less strong for heavy vehicles. At all speeds, the (low-frequency dominated) engine noise has an important contribution to the overall level caused by heavy vehicles. Furthermore, the engine is located at a higher position, resulting in a smaller acoustical shadow zone along the façade. The difference in green roof effect between the lowest (30 km/h) and highest vehicle speed (130 km/h) that was modeled is only between 1 and 2 dBA. For light vehicles, this difference amounts up to 4 dBA. For a heavy vehicle at 30 km/h, the green roof may already give a significant reduction in façade noise load (up to 4 dBA).

The influence of green roof type (intensive or extensive) and substrate depth was shown to be rather unimportant for the small building extension. The difference between maximum and minimum effect, when varying substrates, is only 0.5 dBA for light vehicles and 1 dBA for heavy vehicles. For the 10-m building extension, a good choice of green roof characteristics becomes more important, in particular near heavy-traffic dominated roads. For light vehicles, only the extensive green roof of 5 cm gives significantly lower positive effects. The difference between

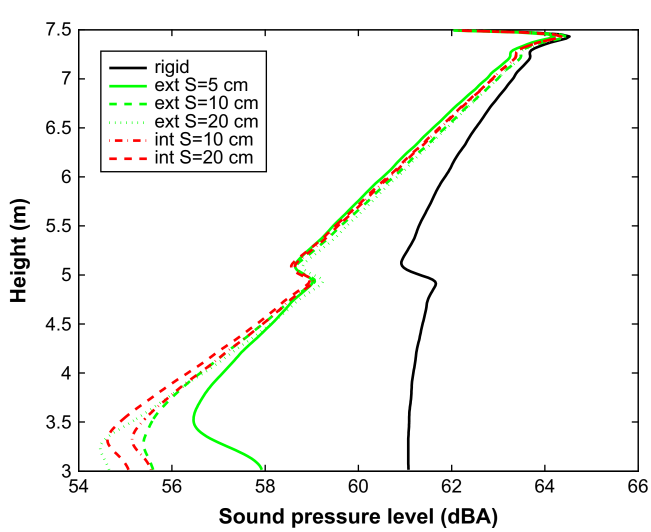

Fig. 4. See caption of Fig. 3, but now for the 10-m building extension $(D_1,D_2) = (5,10)$.

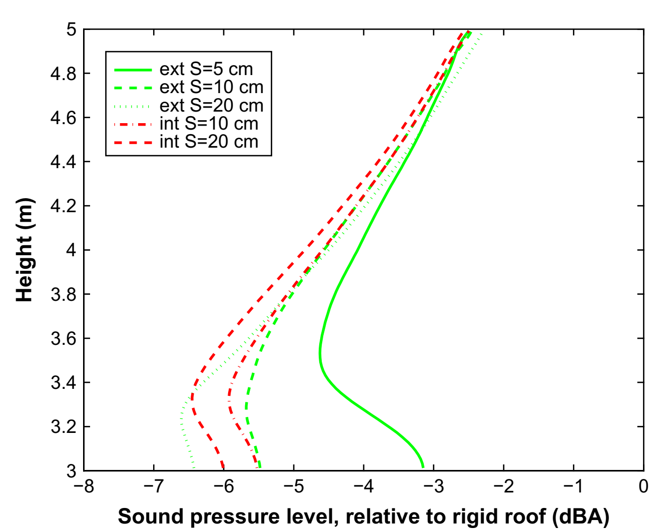

Fig. 6. See caption of Fig. 5, but now for the 10-m building extension.

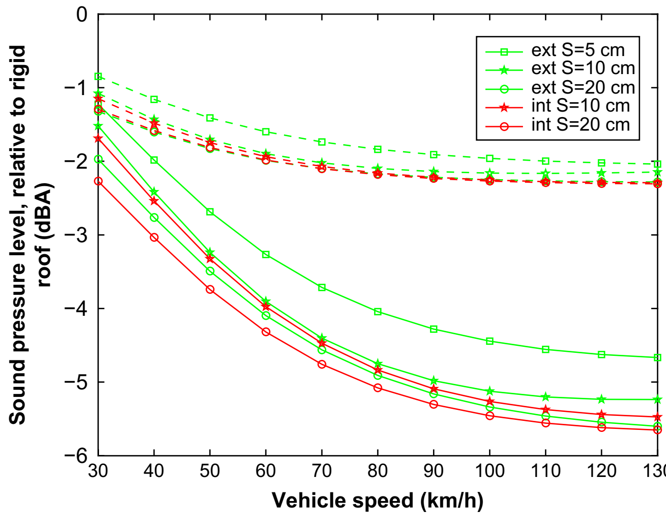

Fig. 7. Average sound pressure level, relative to a rigid roof, over the full height of the window ($y = 3$ m to $y = 5$ m) at façade B, for a light vehicle in function of vehicle speed (configuration 1). Both the 5-m building extension ((D_1,D_2) = (10,5), dashed lines) and 10-m building extension ((D_1,D_2) = (5,10), full lines) are shown. Extensive green roofs ("ext") with a thickness S of 5 cm, 10 cm and 20 cm, and intensive ("int") green roofs with a thickness S of 10 cm and 20 cm are shown.

extensive green roofs of 10 cm and 20 cm, and intensive green roofs of 10 cm and 20 cm, is rather small. For heavy traffic, the influence of substrate depth is large in the case of the extensive green roof. An extensive green roof of 20 cm, which is close to the maximum depth found in practice, results in an important improvement upon a layer of 10 cm. The influence of substrate thickness in case of intensive green roofs is very small for heavy traffic. Calculations in Ref. [8] show that an anti-node is needed near the green roof top to achieve important reductions in the sound pressure level. At each vehicle speed, the low-frequency component of heavy traffic noise is important, and a thick but highly permeable substrate like the one found in extensive green roofs is beneficial.

5.2. Configuration 2

In configuration 2, façade C is situated in the acoustic shadow zone over its full height. Although the middle building is an efficient noise barrier, sound pressure levels at façade C are still large, as depicted in Fig. 9. This is caused by the fact that the sound waves undergo a large number of reflections in both canyons, and multiple sound rays reach the diffraction points at the edges of the middle building. Given the low-frequency dominated spectrum of heavy traffic, shielding by diffraction will be much more limited than in the case of light vehicles.

To limit the number of calculations, extensive green roofs with layer thicknesses of 10 cm and 20 cm were considered, and intensive green roofs of 20 cm. Roof effects will be averaged over heights ranging from street level ($y = 0$ m) up to $y = 7.5$ m, which is the maximum height of the façade for the 45° roof (see Section 4).

The comparison of rigid roofs with different slopes in Fig. 10 reveals that saddle-backed roofs lead in general to higher sound pressure levels at the non-exposed façade than flat roofs. The sound propagation problem is very complex, including multiple reflections, multiple diffractions, and interactions between both. Qualitative explanation is therefore difficult and beyond the scope of this paper. In case of a flat roof, there are always two diffraction points needed to reach façade C. These diffraction points are located at the building edges. After each diffraction, sound energy is spread over a range of angles and less energy reaches the receivers. For the tilted roof top, sound rays may undergo diffraction near a single point (located at the maximum roof height), near two points, or near three points along the roof to reach façade C. In case of a single point or two-point diffraction, reflections at façade A and/or D are needed. Given the approach of equal volume of the houses when changing roof slope angle, the height of the vertical part of the façades differs and determines the number of reflections in the street canyons. Sound energy may come as well from the interaction of sound waves with the roofs of the left and the right buildings. Nevertheless, such calculations can be accurately performed by using the (full-wave) FDTD method.

When comparing the non-zero roof slopes, a characteristic behavior is found in function of height, slightly influenced by the traffic spectrum. This is depicted in Fig. 9. At low heights, the 15° and 45° roofs behave more or less similarly, while the 30° roof results in less shielding. At larger heights, the 45° roof leads to the smallest sound pressure levels and the 30° roof starts to give more shielding than the 15° roof. Close to its gutter height, the 30° saddle-backed roof is optimal and approaches the behavior of the flat roof. Averaged over the full façade (from $y = 0$ m to $y = 7.5$ m),

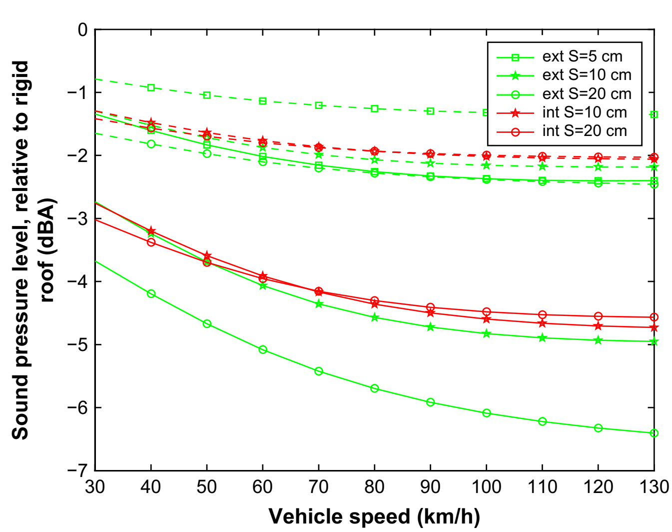

Fig. 8. See caption of Fig. 7, but now for heavy vehicle spectra.

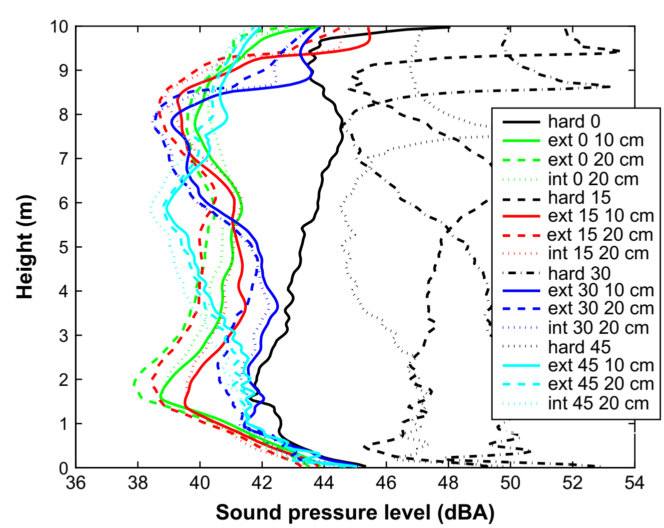

Fig. 9. Sound pressure level over the full height of façade C, for a light vehicle at 70 km/h, in configuration 2. Roofs with slopes α of 0° (flat), 15°, 30° and 45° are shown, made of rigid materials or with a green roof cover. Extensive green roofs ("ext") with a substrate thickness S of 10 cm and 20 cm are shown, and intensive ("int") green roofs with a substrate thickness S of 20 cm.

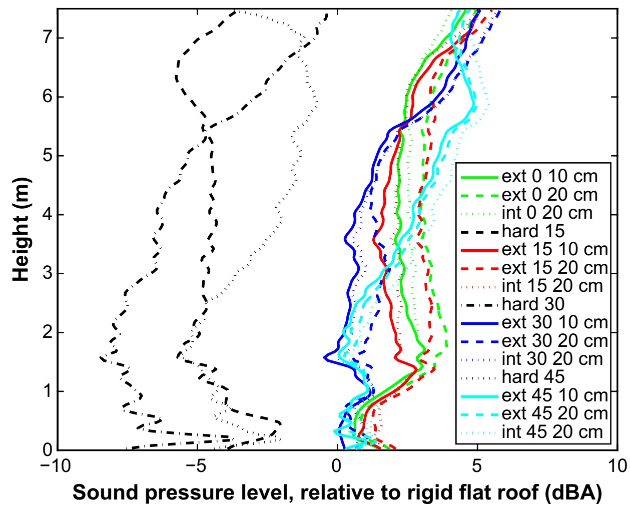

Fig. 10. Sound pressure level, relative to a rigid flat roof, over the full height of façade C, for a light vehicle at 70 km/h, in configuration 2. Roofs with slopes α of 0° (flat), 15°, 30° and 45° are shown, made of rigid materials or with a green roof cover. Extensive green roofs ("ext") with a thickness of 10 cm and 20 cm are shown, and intensive ("int") green roofs with a thickness of 20 cm.

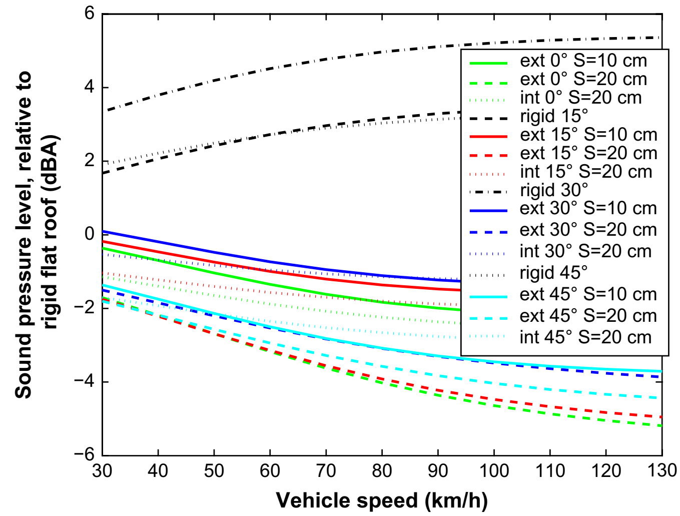

Fig. 12. See caption of Fig. 11, but now for heavy vehicle spectra.

a flat roof is optimal, followed by a 45° slope, and then a 15° slope. This is shown in Figs. 11 and 12. The least interesting saddle-backed roof in the numerical simulations performed has a 30° slope. For heavy traffic, a slope of 15° and 45° has a similar average shielding.

Figs. 11 and 12 further show that with increasing vehicle speed, the effect of roof slope becomes more prominent. At low speeds, the contribution of low frequencies to total traffic noise is large. These frequencies are diffracted over the building to a large extent and the actual shape of the roof is less important. At higher vehicle speed, high frequencies are more important, and the exact roof configuration then plays an important role.

The presence of a vegetated roof top largely decreases the sound pressure levels at façade C. For flat roofs, the presence of a green roof results in a shift towards lower sound pressure levels, while the form of the profile is only slightly changed (see Fig. 9). With

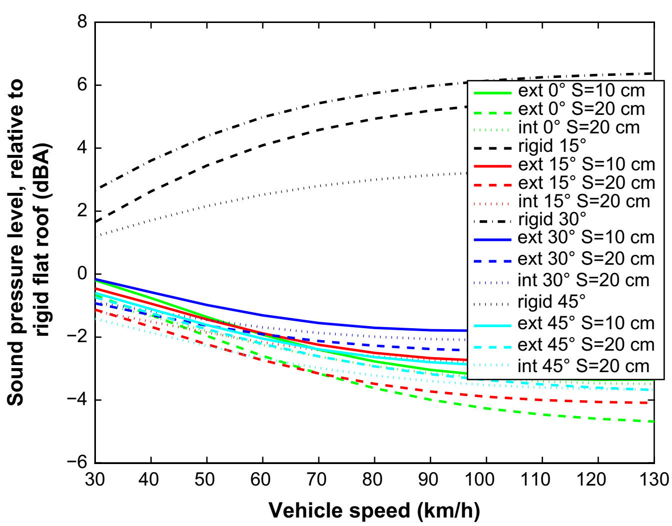

Fig. 11. Average sound pressure level, relative to a rigid flat roof, over façade C (from $y = 0$ m to $y = 7.5$ m), for a light vehicle in function of vehicle speed (configuration 2). Roofs with slopes α of 0° (flat), 15°, 30° and 45° are shown, made of rigid materials or with a green roof cover. Extensive green roofs ("ext") with a substrate thickness S of 10 cm and 20 cm are shown, and intensive ("int") green roofs with a substrate thickness S of 20 cm.

increasing height along the façade, there is a general trend towards more shielding by the green roof (see Fig. 10).

For the saddle-backed roofs, the improvement by a green roof relative to a rigid roof is even larger. Note that sound pressure levels are compared to a fully rigid flat roof. The average difference between a 30° rigid roof and a 30° extensive green roof with a substrate thickness of 20 cm is near 8 dBA (see Fig. 12), for heavy traffic at 70 km/h, while the maximum difference along the façade amounts up to 14 dBA (not shown). In case of a non-zero slope, the area over which sound waves interact with the green roof during diffraction is larger. This leads to a saddle-backed green roof shielding which approaches the one of a flat green roof. Note that the green roof characteristics are now much more important to reach optimal shielding than roof angle.

The dependence of the green roof effect on vehicle speed is less pronounced in the street canyon configuration than in configuration 1. Sound waves can only reach the receiving canyon by multiple diffractions or by a single diffraction in combination with façade reflections. The increase of the high-frequency component in the receiver canyon when increasing vehicle speed will therefore be more limited. For this same reason, the magnitude of the green roof effect is smaller in the street canyon configuration. This becomes clear when comparing the 10-m extension and the (flat roof) street canyon configuration. Such a comparison is possible since both geometries have an equal green roof area.

6. Conclusions

The finite-difference time-domain method was used to numerically evaluate road traffic noise reduction at building façades by the presence of green roofs. The Harmonoise/Imagine road traffic source model was used. Two building configurations were chosen. In a terrace-like configuration, the façade of the upper floor was partly in the acoustic shadow zone. In a street canyon configuration, the façade was situated in a nearby, non-exposed canyon.

Positive effects by the presence of a green roof are only observed at non-directly exposed parts of façades. A sufficient green roof surface area is needed to obtain significant effects. With increasing traffic speed of light vehicles, the green roof effect increases. In case of heavy vehicles, this dependence is less strong. In the street canyon configuration, a lower influence of vehicle speed on green roof effect is found when compared to the terrace configuration.

In a street canyon configuration, the acoustical façade load in the non-exposed canyon is largely influenced by both the roof slope and the presence of a green roof. A flat roof generally results in the best shielding. A green roof is especially important in case of a saddle-backed roof. The negative effect of the saddle back form is completely compensated and the shielding approaches that of a flat green roof, since the area over which sound waves interact with the green roof substrate during diffraction is larger.

Numerical simulations in idealized situations are very interesting to reveal qualitative trends. However, the application of the results presented to specific situations needs caution, since quantitative predictions strongly depend on geometrical details of buildings, the building setting, and local road traffic characteristics.

It has to be noted as well that the results presented in this paper only apply for noise produced by a single traffic lane with either light or heavy vehicles, at a constant vehicle speed. In practice, multilane roads are present, characterized by a typical traffic composition and speed distribution. By appropriate weighting of the results presented in this paper, an estimation of the green roof attenuation in the presence of realistic roads can be made. Including the multilane aspect when evaluating noise reducing measures for road traffic was shown to be important [21].

Nevertheless, it is clear that roof type and roof coverage are important parameters for the acoustical quality of housings. These aspects should be considered during building design and city planning, especially when road traffic is situated close to the building façades.

References

[1] den Boer L, Schroten A. Traffic noise reduction in Europe. Report of CE Delft, Commissioned by the European Federation for Transport and Environment (T&E), Brussels; 2007.
[2] Miedema H, Borst H. Rating environmental noise on the basis of noise maps within the framework of the EU Environmental Noise Directive. Proceedings of 36th International Congress and Exposition on Noise Control Engineering (INTERNOISE), Istanbul, Turkey; 2007.
[3] Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A, Mihalakakou G. Analysis of the green roof thermal properties and investigation of its energy performance. Energy and Buildings 2001;33:719–29.
[4] Wong N, Tay S, Wong R, Ong C, Sia A. Life cycle cost analysis of rooftop gardens in Singapore. Building and Environment 2003;38:499–509.
[5] Mentens J, Raes D, Hermy M. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landscape and Urban Planning 2006;77:217–26.
[6] Schrader S, Boening M. Soil formation on green roofs and its contribution to urban biodiversity with emphasis on Collembolans. Pedobiologia 2006;50:347–56.
[7] Alexandri E, Jones P. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Building and Environment 2008;43:480–93.
[8] Van Renterghem T, Botteldooren D. Numerical evaluation of sound propagating over green roofs. Journal of Sound and Vibration 2008;317:781–99.
[9] Zwikker C, Kosten C. Sound absorbing materials. New York: Elsevier; 1949.
[10] Botteldooren D. Finite-difference time-domain simulation of low-frequency room acoustic problems. Journal of the Acoustical Society of America 1995;98:3302–8.
[11] Van Renterghem T, Botteldooren D. Prediction-step staggered-in-time FDTD: an efficient numerical scheme to solve the linearised equations of fluid dynamics in outdoor sound propagation. Applied Acoustics 2007;68:201–16.
[12] Van Renterghem T. Time-domain modelling in outdoor sound propagation. Applied Acoustics 2007;68:157.
[13] Xiao T, Liu Q. Finite difference computation of head-related transfer functions for human hearing. Journal of the Acoustical Society of America 2003;113:2434–41.
[14] Blumrich R, Heimann D. A linearized Eulerian sound propagation model for studies of complex meteorological effects. Journal of the Acoustical Society of America 2002;112:446–55.
[15] Van Renterghem T, Botteldooren D. Numerical simulation of the effect of trees on downwind noise barrier performance. Acta Acustica united with Acustica 2003;89:764–78.
[16] Liu L, Albert D. Acoustic pulse propagation near a right-angle wall. Journal of the Acoustical Society of America 2006;119:2073–83.
[17] Jonasson H. Acoustical source modelling of road vehicles. Acta Acustica united with Acustica 2007;93:173–84.
[18] Van Renterghem T, Salomons E, Botteldooren D. Parameter study of sound propagation between city canyons with coupled FDTD-PE model. Applied Acoustics 2006;67:487–510.
[19] ISO 9613-2. Acoustics – attenuation of sound during propagation outdoors. Part 2: general method of calculation. Geneva, Switzerland: International Organization of Standardization; 1996.
[20] Berenger J. A Perfectly matched layer for the absorption of electromagnetic waves. Journal of Computational Physics 1994;114:185–200.
[21] Walerian E, Janczur R, Meissner M, Czechowicz M. Influence of vehicle noise emission directivity on sound level distribution in a canyon street. Part II: experimental verification. Applied Acoustics 2006;67:659–79.