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Performance of a Low-Height Acoustic Screen for Urban Roads: Field Measurement and Numerical Study

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Colour Figures: Figures in colour are given in the online version

Summary
Field measurements and numerical modelling were used to study the acoustic performance of a low screen in an urban road setting. The results show the usefulness of low screens as well as suggests improvements in screen design. For the measurements, an acoustic screen built up from concrete modules was temporarily installed beside a small park on the reservation between a two-lane road and a track for walking and cycling. A larger traffic system, of which the two-lane road is a part, determines the daytime equivalent noise level within the urban area. The screen height was about 1.4 m as measured from the level of the road surface and the width of the screen top was 0.3 m. Measurements were carried out both at 20 m distance from the road (within the park) and at 5 m distance from the road (at the cycle track). Insertion loss in maximum level, using controlled light-vehicle pass-by at 50 km/h, was measured to 10 dB at 5 m distance and to 6 dB at 20 m distance, at 1.5 m height. Insertion loss in equivalent level was measured within the park to 4 dB at 1.5 m height. A listening experiment confirmed a perceived improvement from installing the screen. The measured results were also compared with predicted results using a boundary element method (BEM) and a noise mapping software, the latter showing good agreement, overestimating the equivalent level insertion loss by 1 dB in the park. The BEM comparison showed reasonable agreement in maximum level insertion loss considering that facade reflections were excluded, with an overestimation of 5 dB at the cycle track, and good agreement in the park, overestimating by up to 1 dB the equivalent and maximum level insertion losses. BEM predictions were used to also investigate other screen designs, showing a positive effect of an acoustically soft screen top, significant for a screen width of 0.2 m and increasing for wider screens.

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1. Introduction

1.1. Introduction to the project

In cities, high noise levels from road traffic is a significant environmental problem [1]. Acoustic screens are often perceived as aesthetically unwanted and as physical barriers, which hinders their use for traffic noise reduction in urban environments. The main motivation of the work presented here is to demonstrate the efficiency of a low-height acoustic screen in an urban setting. The long-term aim being to contribute to an improved urban quality, free from disturbing road traffic noise in housing environments and recreational areas, the project goal is to develop and disseminate a concept for low-height acoustic screens intended for urban road traffic noise situations, incorporating acoustical, architectural and practical aspects. For this purpose, also an initial step of a prediction scheme is described here.

As for the European market, it is estimated that the construction of noise barriers along major roads costs about 700 million euros per year [2]. Through the comprehensive mapping of noise in the EU, it is estimated that over 30 million people live along major roads with noise levels from traffic above 55 dB (Lden), about which many European countries have their limit values. The number of people exposed to the same level of exposure in the major cities (of more than 250 000 inhabitants) is even greater, over 60 million people [1]. Hence, there is a potential benefit of applying low-height barriers in cities.

During the previous few decades, the interest has increased on the topic of low-height shielding devices for road traffic noise (e.g. [3]–[7]), including optimisation of

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1-m-tall devices with acoustic absorption using 2D boundary element modelling followed up by successful scale model validation [6, 7]. More recent work includes modelling of vegetated screens and gabion barriers (e.g. [8]), full-scale lab measurements for further investigating the potential of using porous stones in gabion barriers [9] and modelling of the effects of low-height barriers in street canyons [10, 11]. Concerning field measurements, the reduction of urban road noise of a low-height vegetated barrier was evaluated including its perceptual performance [12] and a low-height barrier prototype was measured to give 13 dB insertion loss for a tramway [13]. Future implementations of low-height barriers would benefit from further field measurements.

Concerning the prediction scheme, it is of interest to enable noise mapping software to predict the effects of various designs of low-height acoustic screens. A way to do this is to provide input datasets that are precalculated. In the current paper, an initial version of such a dataset is presented, using a 2.5D Boundary Element Method, modelling 3D point sources in a 2D domain, and evaluated in relation with the measured results from using the temporarily installed prototype screen. In the planning of the measurement campaign, a noise mapping software was used, whose results are also evaluated in respect to measured results.

1.2. Introduction to the measurement site

The measurement site, *Holmiaparken*, is a small park in Stockholm, Sweden, bordering to an arterial road, a part of *Drottningholmsvägen* (see Figures 1–2). The road traffic noise within the park is largely determined by the two nearest lanes of the road *Drottningholmsvägen*, with estimated 12000 vehicles per 24h, whereof 7% heavy, driving at 50 km/h. The further two lanes are at a lower height and thereby largely shielded. Within the park, the sound environment is also affected by the surrounding road system, a subway line and a water fountain at the centre of the park. Between the park and the road, there is a pedestrian pavement and a cycle track running in parallel with the road, and between the cycle track and the road there is a ca 1 m wide reservation on which the screen is to be placed (see Figure 2).

2. Method

2.1. Application of noise mapping software for pre-study

A commercial noise mapping software, Soundplan (v7.3), was used to estimate the current traffic noise situation at the site as well as the effects of various low-height noise barrier configurations. Including the nearest surrounding traffic system (search radius 5 km), the 24-hour equivalent noise level (L_{AEq24h}) was calculated on a 5×5 m grid at a receiver height of 1.5 m. In order to study the effects at a higher level of detail, difference noise maps were calculated with a grid spacing of 3 m using no interpolation.

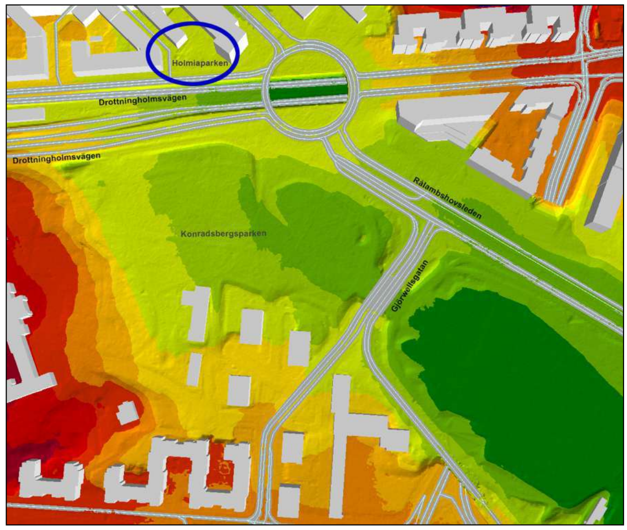

Figure 1. Elevation map of the area with the park that constitutes the measurement site marked.

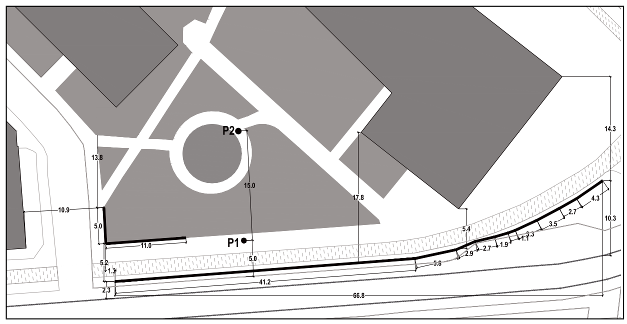

Figure 2. Detailed sketch of the measurement site with screen location and measurement positions P1 and P2 marked. P1 is located on the edge of the cycle track and P2 is inside the park.

The calculations were made using the Nordic environmental noise prediction method, referred as Nord2000 model, with first order reflections (i.e. at maximum one reflection in vertical surfaces, following Swedish guidelines), humidity 70%, temperature 8 °C and moderate downwind condition (roughness length 1 mm and wind speed 1.5 m/s). Also the source strengths used here are according to the Nord2000 model. The assumed pavement, as judged at the measurement site, was dense asphalt concrete with stone size up to 11 mm and a surface age of 2 years. These calculations included grid noise maps, cross section noise maps and difference noise maps representing the screen caused insertion loss.

2.2. Approach of measurement campaign

Two approaches were selected for the measurements: a series of controlled single-vehicle pass-by measurements and a campaign of long-term unattended measurements. The prototype screen was built up by placing L-shaped blocks with a height of 1.2 m onto the reservation, thereby giving a total screen height of about 1.4 m above the road surface. The screen was made of a solid, dense and smooth concrete, and the width of the top of the screen was 0.3 m.

The single pass-by measurements were carried out for the hours just prior to and just after the disassembly of the prototype screen. The sound pressure level was measured at two distances from the road source, at points P1 and P2, ca 5 and 20 m from the centre of the nearest driving lane, respectively (see Figure 2), at two heights above ground at each point: 1.2 and 1.5 m. Two vehicles were available for the pass-by measurements, one with petrol engine and one electric car.

The long-term measurements were initiated one week before the assembly of the prototype screen and ended one week after the disassembly in order to get good statistical ground for comparing the situations with and without screen. (The total duration with screen was ten days.) By this method, a minimum of seasonal and weather-related variation in the results could be achieved. The long-term measurements were made at a location close to point P2, at three different heights above ground: 1.2, 1.5 and 2 m.

Concerning equipment, the acoustic measurements were made using B&K Pulse for the pass-by measurements and a battery operated *Sigicom infra system* for the long-term measurements. Simultaneously with the long-term sound level measurements, the speed and traffic flow of light and heavy vehicles were measured hourly.

2.3. Application of the Boundary Element Method

The Boundary Element Method (BEM) approach is a numerical technique based on the integral description of the acoustic pressure field. In the case here considered, an acoustic screen of boundary S is placed above an infinite flat ground where the acoustic pressure at any point M can be written as

$$P(M) = P_{\text{inc}}(M) + \int_S P(Q)\Big(\rho\omega^2 Y(Q)\, G(M,Q) - \frac{\partial G(M,Q)}{\partial n}\Big)\mathrm{d}S(Q). \qquad (1)$$

Here, $G(M,Q)$ is the Green function representing the pressure field at M due to a unit source placed at Q, in the absence of the screen, but with the ground, $P_{\text{inc}}(M)$ is the actual pressure without the screen; Y is the surface mobility, modelling the acoustic impedance of the material, which may vary with frequency and position along S.

The above equation is here applied for 2D geometries in the x-z plane (see Figure 3), therefore assuming that both the source and the receiver are invariant and of infinite extent along the traffic direction y. The screen is described by a simple contour and the source in 2D is assumed to be a coherent line. From the solution of a set of different 2D problems where the geometry is unchanged but where the spectrum of Y is modified for each 2.5D frequency, it has been shown [14] that one may recover the 2.5D solution where the geometry is still infinite, but where the source is a point source and consequently may consist of several uncorrelated point locations. The MICADO software [15, 16] developed at CSTB exists either in 2D, 2.5D or 3D versions and is used here in its 2.5D version in order to solve the problem corresponding to the geometry shown in Figures 3–4. MICADO uses a variational approach which is known to regularize the numerical problem and to avoid the drawback of irregular frequencies. This program is strongly optimized with respect to computation time [15], which is a necessity when doing a large set of 2.5D calculations.

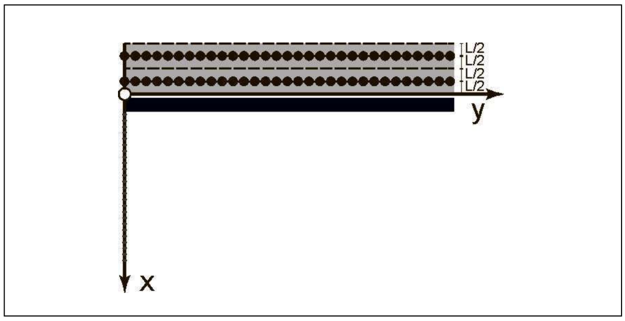

Figure 3. Top view of source positions (black filled circles), area of placement of noise reducing devise (black area) and line of receivers along the x-axis. (The z-axis points upwards.)

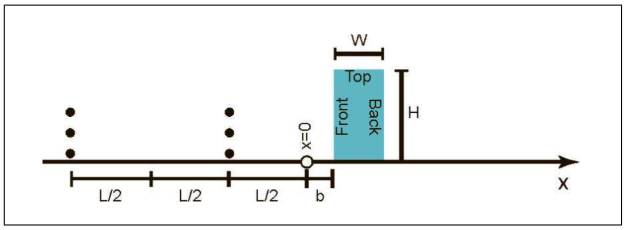

Figure 4. Cross-section view of the calculation cases in the boundary element modelling.

The noise reducing device modelled in BEM is a thick screen with height 1.2 m. The location of front, top and back sides are described in Figure 4, where the width of the top, W, may be varied. The screen height, H, is fixed here. In Figure 4, the filled dots represent possible positions of sources: two columns, each centred in the driving lane, with three sources in each. The three source heights follow the Harmonoise/Imagine model where the lowest, at height 0.01 m, is for rolling noise and the higher ones, at heights 0.3 and 0.75 m, is for propulsion noise of light and heavy vehicles, respectively [17]. The horizontal offset, b, from the lane edge to the foot of the screen is 0.6 m. (In the measurement campaign, this distance was about the same.) The lane width, L, set to 3.4 m makes the horizontal distance to the device from nearest source line equal to 2.3 m ($L/2 + b$).

It should be noted that the measured case had a lane width of about 3.2 m, where the two lanes are running in the same direction. Since this width is unusually small, the more representative width of 3.4 m is chosen for the boundary element calculations, with the aim for the resulting datasets to be more generally applicable. The spacing from the lane edge to the foot of the screen, 0.6 m, is chosen as a minimum distance still allowing for cleaning, snow removal and fulfilling safety demands. The road surface is modelled as acoustically hard whereas the fround on the other side of the screen is modelled either as acoustically hard or as a grass ground representing the park area. For the latter, a slit-pore model with hard backing has been used, modelling an urban grass ground, with effective flow resistivity 59 kPa s/m^2, effective porosity 0.52, and layer thickness 0.05 m (see [18]).

The level relative to free field is calculated at a grid of receivers, for each source position and for each third-octave band 12–5000 Hz. The locations in the horizontal plane of sources and receivers are shown in an x-y coordinate system in Figure 3. The sources are placed along lines (source lines) at centre of driving lanes, parallel with the y-axis; the source positions start at $y = 0$ and end at $y = 100$ m with a resolution of 2.5 m. The source lines are located at $x = -0.5L$ (first lane) and $x = -1.5L$ (second lane). The receivers are located at $y = 0$ and at $x = 1, 2, 3, \ldots, 50$ m, i.e. with a 1-m-resolution along the x-axis up to 50 m range. The receiver height used here is 1.5 m. With such input together with a source model, the noise immission to any point in the receiver area can be calculated for any source position along the source lines. It should be noted that the choice of source and receiver grids can be further optimised with respect to the amount of data needed at a desired interpolation accuracy [19]. The maximum level, e.g. L_{AFmax}, can be estimated from the peak level using source positions at only $y = 0$, whereas the equivalent level can be estimated from energetic averaging over sources along the whole source line; corresponding to incoherent line sources with a length up to 200 m using symmetry around the x axis. It should be noted that the purpose of the BEM modelling used here is to provide a dataset that can be used to estimate the effects of low-height acoustic screens, e.g. within noise mapping software.

2.4. Listening experiment

In parallel with the field measurements, a listening experiment was conducted to investigate whether people could perceive any difference between before and after the prototype screen was installed. The experiment was conducted in a soundproof listening room at the Department of Psychology, Stockholm University. Time restrictions did not allow for a listening test in situ.

In total, 32 students (16 female, 16 male) with normal hearing ability took part. They were aged 19–41 yrs. (M_{age} = 26.6 yrs., $SD_{\mathrm{age}} = 5.7$).

Eight experimental sounds and 12 filler sounds were used. The latter were included to mask the purpose of the experiment. All sounds were excerpts (30 s) from binaural recordings. The eight experimental sounds were recorded on the sidewalk by Drottningholmsvägen (5 m from the roadside, near measurement positions P1 in Figure 2), as well as in Holmiaparken (23 m from the roadside, near P2).

On the sidewalk, the microphones were located approximately 1.5 m above the ground, representing an adult standing up. In the park, the microphones were located approximately 1.2 m above the ground, representing an adult sitting on a park bench by the fountain. The audio recordings were conducted shortly before the City of Stockholm installed the prototype screen, as well as during the period the screen was tested on the site.

The sounds were recorded in the afternoon during weekdays when there was a high level of road traffic flowing out from Stockholm. The 30 s of each experimental sound represented the highest levels of road traffic in each of the eight conditions. The experimental sounds were recorded using a binaural system (Brüel & Kjær Type 4100 head and torso simulator; NEXUS Type 2690 microphone conditioner amplifier; Sound Devices 788T digital recorder; 24-bit resolution, 48 kHz sampling frequency). In the listening experiment the sounds were reproduced at the authentic sound levels by headphones (Sennheiser HD 600), connected to a stereo headphone amplifier (Lake People G109-P), which in turn was connected to a soundcard (RME Fireface 400). The data collection instrument included a set of scales for assessing perceived affective quality: "To what extent do the following 8 adjectives correspond to how you experience the sound environment in this recording?" ("Pleasant," "Chaotic," "Exciting," "Uneventful," "Calm," "Annoying," "Eventful," and "Monotonous," respectively). The endpoints of the 100-mm scales were defined by "Not at all (0%)" and "Perfectly (100%)." Pleasantness scores were calculated by

$$\begin{aligned}\text{Pleasantness} = {} & \text{Pleasant} - \text{Annoying} + \sqrt{1/2}\text{Exciting} \\ & - \sqrt{1/2}\text{Monotonous} + \sqrt{1/2}\text{Calm} \\ & - \sqrt{1/2}\text{Chaotic}\Big/\left(1+\sqrt{2}\right). \end{aligned} \tag{2}$$

3. Results

3.1. Predicted insertion loss using noise mapping software

Our noise mapping result for the current situation was about 66 dB (L_{AEq24h}) within the park area (see Figure 5). By including a long, continuous screen with height 1.4 m, the equivalent noise level was predicted to be reduced by about 5 dB within the park, as seen in Figure 6. At the location of the measurement receiver P2 at height 1.5 m, the predicted insertion loss was 5.1 dB. Since the real-life installation of the screen needed to have an opening to the West of the park, for access into the area, the length of the screen was adjusted and an L-shaped screen element was inserted on the other side of the pedestrian pavement (see Figure 2). (The screen setup including the opening and the L-shaped element was used also in the measurement campaign.)

In addition to the above described screen, the insertion of a 1.2 m tall fence screen between the nearest two lanes and the depressed road system was tested. The predicted effect of the fence screen to further shield the remaining traffic system amounted to less than 1 dB improvement in this case, whereby it was decided to not include a fence screen in the real-life test.

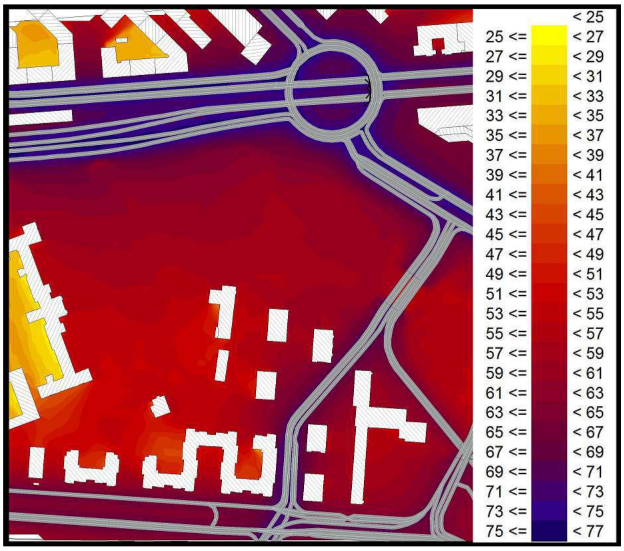

Figure 5. Predicted 24-hour equivalent noise level, L_{AEq24h} (dB), at height 1.2 m.

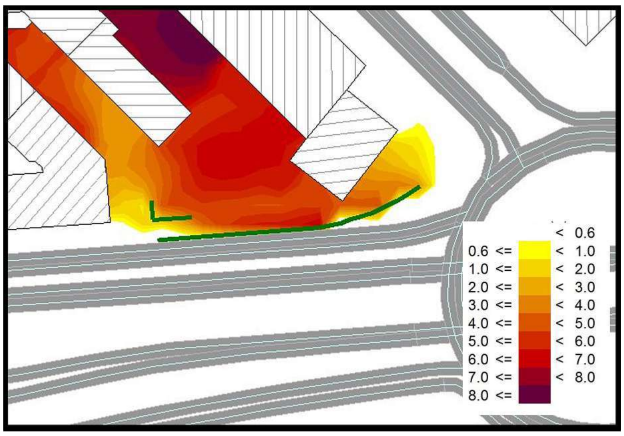

Figure 6. Predicted reduction in L_{AEq24h} (dB) at height 1.2 m in the park area.

3.2. Results from measurement campaign

The long-term measurement (one week without screen and one week with screen) was analysed as 1-hour equivalent levels. The 24-hour equivalent levels at 1.5 m above ground were measured to 63.6 and 67.0 dB, with and without screen, respectively. It can be noted that during nighttime, the lower traffic flow results in lower traffic noise levels, which increases the proportion of other sounds, causing a smaller measured effect of the screen at those hours. Averaged over 24 hours, and compensated for the measured 1-hour variations in total traffic flow, the resulting insertion loss was 4.0 dB. (The Thursday data of the second week contained unreasonably large peaks in sound level that were identified to come from a nearby construction site, whereby Thursday data were omitted from both weeks before averaging.)

The resulting spectra of the single pass-by measurements are shown in Figures 7–8. Due to poorer signal-to-noise ratio of the electric car, only the data from the petrol car could be used. Nearest to the road (point P1),

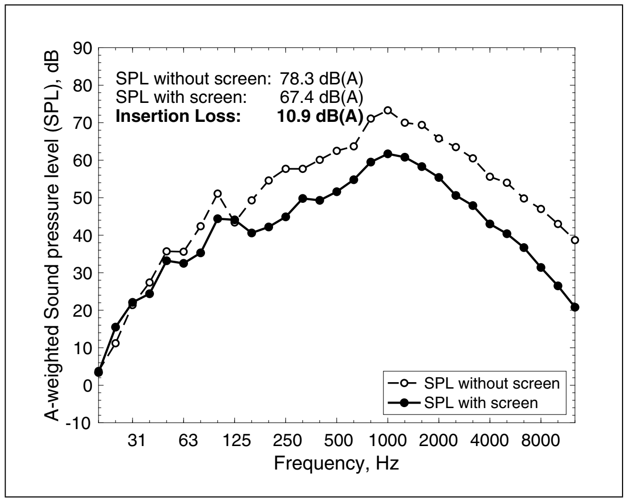

Figure 7. Measured L_{AFmax} spectra with and without screen at point P1, averaged over the two heights 1.2 and 1.5 m. A-weighted total insertion loss is 10.9 dB.

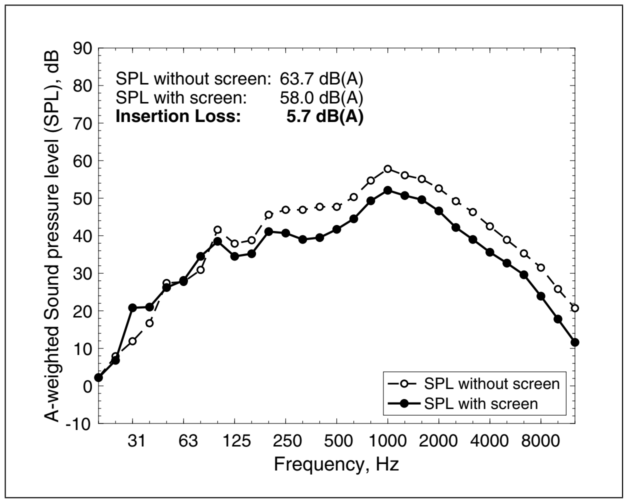

Figure 8. Measured L_{AFmax} spectra with and without screen at point P2, averaged over the two heights 1.2 and 1.5 m. A-weighted total insertion loss is 5.7 dB.

the L_{AFmax} insertion losses at heights 1.2 m and 1.5 m were measured to 12.2 and 9.9 dB, respectively. Within the park (point P2), the L_{AFmax} insertion losses at heights 1.2 m and 1.5 m were measured to 5.4 and 5.9 dB, respectively. It can be noted that the insertion loss starts to be visible at around 50 Hz at point P1 and at around 100 Hz at point P2. The measured values of L_{AFmax} at heights 1.2 m and 1.5 m without screen were both around 78 dB at P1 and 63 and 64 dB at P2. Energy averaging the measured levels over the two heights, the L_{AFmax} insertion loss of the screen amounted to 10.9 dB near to the road (P1) and to 5.7 dB in the park (P2).

3.3. Results from using the BEM output

The resulting relative levels of the point-to-point BEM calculations, as function of frequency, are combined with a source model to predict the absolute levels. (All three source heights were used, as described above.) To set

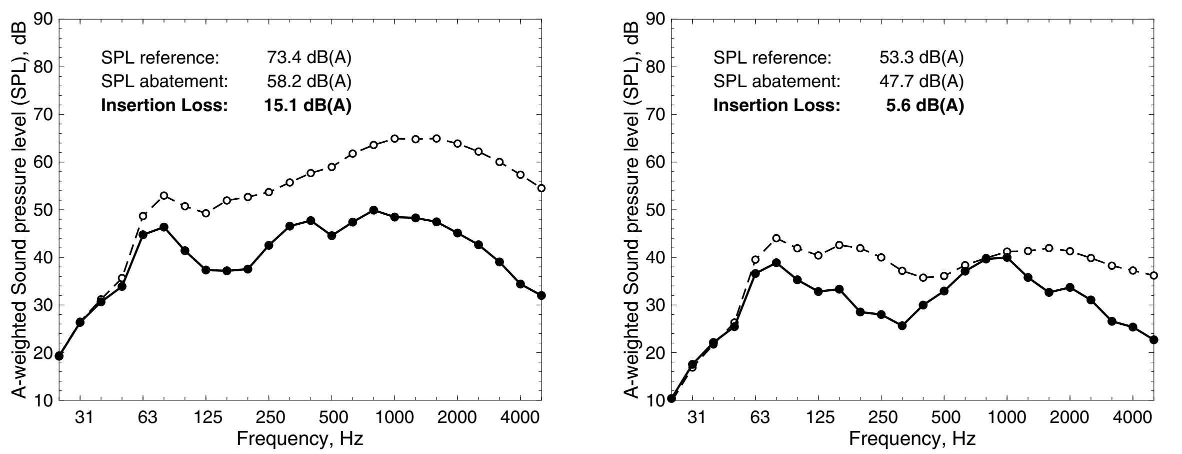

Figure 9. Calculated L_{AFmax} values with screen using calculated insertion loss and measured L_{AFmax} values without screen. Results are for points P1 (left) and P2 (right).

the strengths of the point sources in general, a road traffic source model is needed that considers various vehicle types and different driving speeds. For a general European applicability, rather than a Swedish applicability, the third-octave-band Harmonoise/Imagine source model is used here as a basis to model heavy and light vehicles driving at given speed, using the prescribed source heights. Concerning the strengths of the sources, after the publishing of [17], a revised source model has been introduced in noise mapping software, which has a largely reduced propulsion noise level at lower frequencies. The revised model is officially unavailable, however in concordance with the octave-band source model from the more recent EU noise mapping harmonisation approach, CNOSSOS-EU [20, 21]. The source model used here is a third-octave band interpolation of the CNOSSOS-EU model, where the extension to lower frequencies, below 63 Hz, uses the values at 63 Hz and the extension to higher frequencies, above 8 kHz, is made as a linear extrapolation (in terms of frequency band number and power level). No further correction is made here concerning road slope, acceleration, temperature or road surface.

3.3.1. Comparison with measured data

The measured data are compared with the results calculated for a screen with a height of 1.2 m and a width of 0.4 m, for a receiver position at height 1.5 m and for distances corresponding to measurement points P1 and P2. Point P1 is close to the screen and has propagation over hard ground whereas propagation to point P2 is over a mixed ground with grass in the park area. Both ground situations are modelled in BEM. The insertion loss, measured as difference in L_{AFmax} values with and without screen for a passenger car, is compared with calculated insertion losses using a point on the source line centred at y=0 of the nearest lane. Here, the BEM results are used together with the adapted CNOSSOS-EU source model, as described above, to predict the effect of the screen for a light vehicle driving on the nearest lane at 50 km/h. The results are shown in Figure 9, where the total calculated A-weighted insertion loss is about 15 dB at point P1 (left plot), which is an overestimation compared with the corresponding measured result of about 10 dB. Looking at the spectral behaviour, it can be noted that the effect of the screen is predicted to start at around 63 Hz, i.e. similarly to the corresponding measured data. Around 1 kHz, the calculated insertion loss is about 16 dB whereas the measured one is closer to 11 dB. The lower value of the measured insertion loss might be due to reflections in the facades of the nearby buildings. At point P2 (right plot) the calculated insertion loss is 5.6 dB, showing good agreement with the corresponding measured value (5.9 dB). The near-zero insertion loss at around 800 Hz is concluded to be due to the change in the effect of the ground reflection when the screen is present.

The equivalent level, L_{AEq24h}, is calculated for two-lane road traffic at 50 km/h with 7% heavy vehicles. The result at point P2, including propagation over grass land, plotted in Figure 10, shows a total predicted insertion loss of 4.7 dB, which is close to the measured result (4.0 dB).

3.3.2. Further calculated results including screen variations

By varying the acoustic properties of the screen surface and the screen width in the BEM model, further situations can be investigated. The results shown below are for screen widths of $W = 0.1$, 0.2, 0.4 and 0.8 m. For the surface, either a zero velocity boundary condition (acoustically hard) or a boundary condition modelling a porous substrate has been used. The porous substrate boundary condition models a 0.2 m thick substrate, suitable for vegetation, on hard backing, using data from a previous project [22]. The two-parameter slit-pore model is used with a flow resistivity of 6700 Pa s/m^2 and a porosity of 0.76 [18]. The modelled absorption of the substrate is plotted for normal incidence in Figure 11. The results shown here are for a driving speed of 40 km/h, as an update to a currently more common value for urban areas.

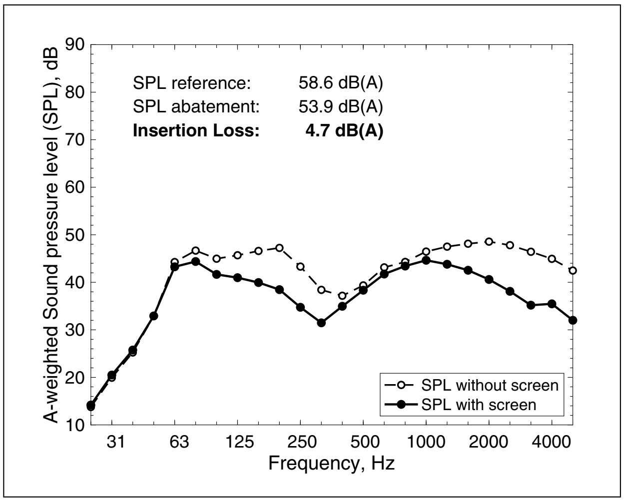

Figure 10. Calculated equivalent level, L_{AEq24h}, at point P2, height 1.5 m, for a driving speed of 50 km/h, for a two-lane road with 7% heavy vehicles.

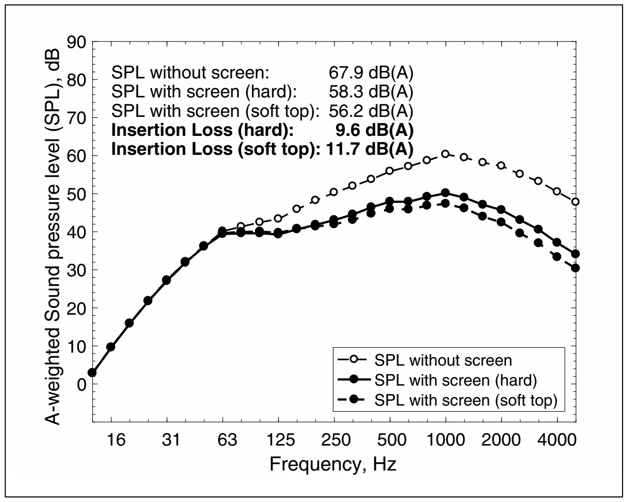

Figure 12. Calculated equivalent level, L_{AEq24h}, at point P1, height 1.5 m, for a screen width of 0.4 m, with and without an acoustically soft top, for a driving speed of 40 km/h, for a two-lane road with 7% heavy vehicles.

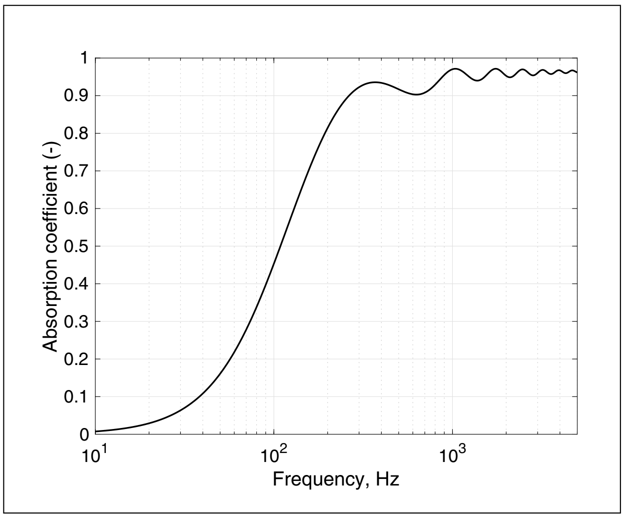

Figure 11. The energy absorption coefficient of the modelled substrate (normal incidence).

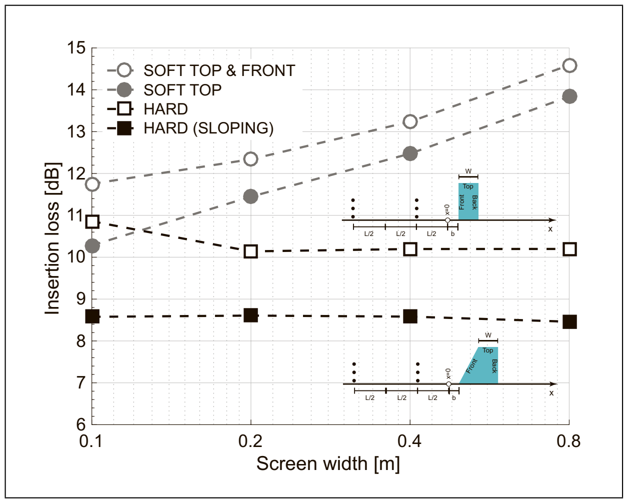

Figure 13. Calculated insertion loss as function of screen width, for different screen types, for a driving speed of 40 km/h, for a two-lane road with 7% heavy vehicles.

In Figure 12, the effect of making the screen top acoustically soft, by here assuming a porous substrate, is exemplified for a screen width of 0.4 m. For that case, the insertion loss of the A-weighted traffic noise level is predicted to increase from 9.6 dB, for the hard screen, to 11.7 dB, for the screen with soft top, i.e. the acoustically soft top is predicted to give an improvement of about 2 dB. It can be noted that this type of modelling is not available in regular noise mapping software.

By plotting the single-number insertion loss as function of screen width, the trend in the effect of introducing an acoustically soft top can be studied. This is shown in Figure 13, including the results for when also the face of the screen toward the source is made acoustically soft, and for a hard screen that has its face toward the source tilted 30°. (The sloping screen is sketched in the insertion in Figure 13; note that the foot of the screen is located at the same position as for the straight screen, at a distance b=0.6 m from the edge of the driving lane.)

As seen in Figure 13, the positive effect of having an acoustically soft top is predicted to increase with screen width, from about 1 dB at a width of 0.2 m to about 3 dB at a width of 0.8 m, whereas the acoustically hard screen shows a near to constant insertion loss as function of screen width. By having the substrate layer also on the screen face toward the road, the insertion loss is predicted to be improved further, by about 1 dB for the 0.2 m wide screen and slightly less for the larger screen widths. Comparing the screen with sloped front with the straight screen, both with hard surfaces, the performance of the sloping screen is predicted to be more than 1 dB worse.

Table I. Arithmetic mean values and standard error of the means (±1 SE) for pleasantness scores.

Location	Screen	M	SE
Sidewalk	Present	−13.80	4.82
	Absent	−45.75	5.06
Park	Present	−7.99	5.18
	Absent	−29.54	5.10

3.4. Results from the listening experiment

This is a summary of the result presented in [23]. Data related to the four conditions of the 2 (Location) × 2 (Screen) factorial design was analysed. An ANOVA for repeated measures (General Linear Model in SPSS 23 for Windows) was conducted with Pleasantness (Equation 2) as dependent variables. Table I presents the arithmetic mean values and the standard errors of the means (±1 SE) for the pleasantness scores.

The ANOVA resulted in statistically significant two-way interaction effects between Location and Screen ($F_{1,31} = 6.95$, $p = 0.01$, $\eta_p^2 = 0.15$). A test of estimated marginal means, with Bonferroni adjustment for multiple comparisons of the probability values and confidence intervals (SPSS 23 for Windows), showed that the cause of the interaction effect between Location and Screen was that the screen had a stronger positive effect on the pleasantness scores on the sidewalk ($MD = 24.73$, $F_{1,31} = 36.23$, $p < 0.001$) than in the park ($MD = 13.80$, $F_{1,31} = 14.06$, $p < 0.01$). Conversely, the distance to the roadside had a larger positive effect on the pleasantness scores when the screen was absent ($MD = 20.90$, $F_{1,31} = 28.50$, $p < 0.0061$) than when it was present ($MD = 9.97$, $F_{1,31} = 7.49$, $p = 0.01$).

Though, the main question remains. Is the effect of the screen statistically significant? To test this, a t-test for reappeared measures (df = 31) was conducted for the mean difference with and without the screen inside the park by measurement position P2. The mean difference was 21.55 and the estimated standard deviation 5.25. This provides a 95% confidence interval for the mean difference of 21.55 ±10.70 = [10.85, 32.25]. Because the zero-term is not included in this interval, it is safe to say that the screen had a statistically significant effect ($p < 0.001$) on the Pleasantness scores in the park.

4. Discussion and conclusion

Concerning the various road traffic source models available, in the pre-study we used the Nordic model (as given when choosing the Nord2000 model in the software Soundplan), since we aimed at predicting the effect of the screen at the actual site. For the further predictions, using the output point-to-point dataset from the boundary element modelling (BEM), we used the source strengths in line with the CNOSSOS-EU model, for a more general applicability.

Averaging the levels over the two heights 1.2 and 1.5 m, the measured L_{AFmax} insertion loss of the screen amounted to about 11 dB near to the road (point P1) and to about 6 dB in the park (point P2). At the height 1.5 m, near to the road (point P1), the measured L_{AFmax} insertion loss was about 10 dB. The corresponding predicted insertion loss using the BEM results was about 15 dB, thus overestimating the screen performance. Considering the idealisations of the BEM model used here, mainly considering the omission of the reflections in the surrounding building facades, the deviation is not seen as unreasonable. Within the park area (point P2), the BEM result compared well with the measured L_{AFmax} insertion loss (within 1 dB).

Concerning the equivalent level, L_{AEq24h}, the noise mapping software predicted an insertion loss of about 5 dB within the park, including all traffic in the area. (Concerning the Lden indicator, insertion loss in L_{AEq24h} value provides a reasonable approximation.) The corresponding measured result, corrected for traffic flow, based on 1-week-data with screen and 1-week-data without, was 4 dB, thus showing a good agreement between noise mapping prediction and measured results. Using the BEM results to predict the equivalent level within the park (point P2 at height 1.5 m), including the grass ground of the park area, gave an insertion loss deviation from the measured value of less than 1 dB.

A reduction in equivalent level of 4–5 dB, at a site where the L_{AEq24h} value is around 66 dB, was predicted to improve the situation, but not to make it good. This conclusion was based on previous studies of how park visitors perceive the acoustic environment in parks in Stockholm, which have shown that the equivalent levels from road traffic must be below 50 dB for at least 80% of the visitors to report that they experienced a good acoustic environment during the visit [24]. At 55 dB, the proportion of satisfied visitors was 50%, and 20% at 60 dB.

In order to analyse the perceived improvement for the case study presented here, a listening experiment was conducted, based on binaural recordings during the measurement campaign with and without the screen. The results show that the situation turned from bad to acceptable when the screen was installed [23].

The numerical design improvement studies shown here indicate that the introduction of an acoustically soft screen top, here in the form of a 0.2 m thick porous substrate on hard backing, can enhance the insertion loss of road traffic noise. The enhancement predicted here was 1 dB for a 0.2 m wide screen and the enhancement increased with increasing screen width, with about 1 dB per doubling of width. The results also indicate that when the face of the screen toward the road is made softer, as well as the top, the insertion loss can be further increased somewhat; here, by 1 dB for a screen width of 0.2 m, slightly decreasing with increased screen width.

The results for a sloping screen front indicate that such designs are not favourable, at least for the relatively open type of terrain studied here. If the screen could be placed closer to the source, the conclusion might be different.

However, it was due to safety reasons considered unrealistic to allow a placement of the sloping screen much closer to the source than for the straight screen.

The results presented here show that installation of low-height acoustic screens can lead to useful amounts of road noise reduction. Furthermore, the comparisons between measured and predicted results indicate the validity of using noise mapping software to predict the insertion loss for a regular low-height barrier. The agreement between the BEM results and the measurements, for insertion losses in both equivalent and maximum level, was shown to range from reasonable to good, indicating a usefulness of the BEM approach. Using BEM to study improvements in screen design can be assumed to have a higher accuracy in terms of the enhancement in insertion loss, whereby it can be considered a versatile and useful tool.

As a concluding remark it should however be noted that, even for light-vehicle dominated traffic noise, the A-weighted noise level in the shadow of a low-height screen can be significantly influenced by the propulsion noise. Therefore, in situations where higher insertion loss is wanted, noise reduction during propagation, as provided by a low-height screen or other device, might be weakly cost effective, in which case the priority could rather be directed toward tackling the propulsion noise at source.

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References

[1] EEA (European Environment Agency): Laying the foundations for greener transport - term 2011: transport indicators tracking progress towards environmental targets in Europe. EEA Report No 7, 2011.

[2] F. de Roo, M. Dittrich, C. Bosschaart, B. Berry: Reduction of vehicle noise emission - Technological potential and impacts. Report TNO - DV 2012 C100, April 2012.

[3] V. K. Horoshenkov, D. C. Hothersall, E. S. Mercy: Scale modelling of sound propagation in a city street canyon. Journal of Sound and Vibration **223** (1999) 795–819.

[4] P. J. Thorsson: Optimisation of low-height noise barriers using the equivalent sources method. Acustica - Acta acustica **86** (2000) 811–820.

[5] S. J. Martin, D. C. Hothersall: Numerical modelling of median road traffic noise barriers. Journal of Sound and Vibration **251** (2002) 671–681.

[6] M. Baulac, J. Defrance, P. Jean: Optimization of low height noise protections in urban areas. Proc. Forum Acousticum, 2005, 1075–1080.

[7] M. Baulac, J. Defrance, P. Jean, M. Florence: Efficiency of noise protections in urban areas: Predictions and scale model measurements. Acta Acustica united with Acustica **92** (2006) 530–539.

[8] T. Van Renterghem, J. Forssén, K. Attenborough, P. Jean, J. Defrance, M. Hornikx, J. Kang: Using natural means to reduce surface transport noise during propagation outdoors. Applied Acoustics **92** (2015) 86–101.

[9] T. Van Renterghem, I. Van Ginderachter, P. Thomas: Porous stones increase the noise shielding of a gabion. Appl Acoust. **145** (2019) 82–88.

[10] T. Van Renterghem, D. Botteldooren, M. Hornikx, P. Jean, J. Defrance, Y. Smyrnova, J. Kang: Road traffic noise reduction by vegetated low noise barriers in urban streets. Proceedings - European Conference on Noise Control, 2012, 944–948.

[11] G. Echevarria-Sanchez, T. Van Renterghem, P. Thomas, D. Botteldooren: The effect of street canyon design on traffic noise exposure along roads. Build Env **97** (2016) 96–110.

[12] M. Rådsten-Ekman, B. Vincent, C. Anselme, A. Mandon, R. D. Rohr, J. Defrance, D. V. Maercke, D. Botteldooren, M. E. Nilsson: Case-study evaluation of a low and vegetated noise barrier in an urban public space. Proc. Inter-Noise, Osaka, Japan, September 4-7, 2011.

[13] A. Jolibois, J. Defrance, H. Koreneff, P. Jean, D. Duhamel, V. Sparrow: In situ measurement of the acoustic performance of a full scale tramway low height noise barrier prototype. Appl Acoust **94** (2015) 57–68.

[14] D. Duhamel: Efficient calculation of the three-dimensional sound pressure field around a noise barrier. Journal of sound and vibration **197** (1996) 547–571.

[15] P. Jean: A variational approach for the study of outdoor sound propagation and application to railway noise. Journal of sound and vibration **212** (1998) 275–294.

[16] P. Jean, J. Defrance, Y. Gabillet: The importance of source type on the assessment of noise barriers. Journal of Sound and Vibration **226** (1999) 201–216.

[17] R. Nota, R. Barelds, D. van Maercke: Engineering method for road traffic and railway noise after validation and finetuning. Technical Report HAR32TR-040922-DGMR20, Harmonoise WP 3, 2005.

[18] K. Attenborough, I. Bashir, S. Taherzadeh: Outdoor ground impedance models. Journal of the Acoustical Society of America **129** (2011) 2806–2819.

[19] M. Kamrath, P. Jean, J. Maillard, J. Picaut, C. Langrenne: Extending standard urban outdoor noise propagation models to complex geometries. J Acoust Soc Am. **143** (2018) 2066–2075.

[20] S. Kephalopoulos, M. Paviotti, F. Anfosso-Lédée: JRC reference report on common noise assessment methods in eu (CNOSSOS-EU). Publications Office of the European Union, Luxembourg, 2012.

[21] S. Kephalopoulos, M. Paviotti, F. Anfosso-Ledee, D. Van Maercke, S. Shilton, N. Jones: Advances in the development of common noise assessment methods in Europe: The CNOSSOS-EU framework for strategic environmental noise mapping. The Science of the total environment, 482-483:400-10, 2014.

[22] J. Defrance, P. Jean, F. Koussa, K. Horoshenkov, A. Khan, H. Benkreira, T. Van Renterghem, J. Kang, Y. Smyrnova, J. Forssén: Intermediate report of task 2.3. FP7 HOSANNA Deliverable 2.3, Collaborative project under the Seventh Framework Programme, Theme 7, Sustainable Surface Transport, 2013.

[23] Ö. Axelsson: Effects of a low-height sound absorbent street furniture and a fountain on the soundscape in a Stockholm pocket park. Proc. Inter-Noise, Hamburg, August 21-24, 2016.

[24] M. E. Nilsson: Soundscape quality in urban open spaces. Proc. Inter-Noise, Istanbul, August 28-31, 2007.