INCORPORATION OF THE QUIET SIDE IN NOISE MAPS

Estévez-Mauriz, Laura; Forssén, Jens; Kropp, Wolfgang; Zachos, Georgios.
Division of Applied Acoustics. Department of Civil and Environmental Engineering.
Chalmers University of Technology
Sven Hultings gata 8A. SE-41296, Gothenburg, Sweden.
Tel. +46 (0)31-772 2200
laura.estevez@chalmers.se; jens.forssen@chalmers.se; wolfgang.kropp@chalmers.se;
georgios.zachos@chalmers.se

ABSTRACT
Nowadays noise maps are focused on the noise level at the most exposed façade, leading to underestimations on the shielded areas. Previous research showed that quiet areas have positive effects for the inhabitants' quality of life.

To solve this problem, an engineering method was developed within the QSIDE project. This method aims to improve noise maps in terms of multiple reflections in an efficient way. Two different terms, attenuation due to the barrier and the canyon will be incorporated. In this paper, the suggested model from QSIDE has been further developed for its inclusion in noise map calculations.

RESUMEN
Hoy en día, los mapas de ruido se centran en el nivel sonoro en la fachada más expuesta, llevando a subestimaciones en las zonas tranquilas. Se ha demostrado que dichas zonas tienen efectos positivos en la calidad de vida de sus habitantes.

Como solución, un método de ingeniería fue desarrollado dentro del proyecto QSIDE, el cual mejorará los mapas de ruido en cuanto a las múltiples reflexiones de una manera eficiente. La atenuación debida a la barrera y al efecto cañón serán incorporados. En este trabajo, el modelo sugerido ha sido desarrollado para su inclusión en los mapas de ruido.

INTRODUCTION

From the 70s, concern for the environment has been increasing. Regarding exposure to noise, since the 90s various regulatory requirements have been developed, which have been incorporated into national legislation until the appearance of the Directive 2002/40/EC [1]. This concern has reached into our days as the idea of the city as a complex system in which environmental qualities are crucial for the sustainability of cities. In this sense, there has been an increasing concern about excessive noise in cities and how it can harm human health and affect people's daily activities [2]. For this reason, noise restoration, understood as the

restorative environment free from disturbing noise, is one of the main fields to look upon. In this context, restoration is understood as the recovery process of the physiological, psychological and social resources that have decreased their efforts to satisfy the demands of everyday life [3]. For this restoration to occur, the environment needs to permit and promote it [3], where higher quality of the outdoors can increase the effect of it [4].

One of the most common restorative places present in our cities is the inner yard. Having access to these places can mitigate the negative effects of traffic noise [5, 6]. But these spaces act also as an interspace between the system and the self-organisation, encouraging relationship among small communities.

In this sense, the *quiet side concept* can be significant when it comes to *moderating the adverse effects of road traffic noise* [7]. The effect of quiet façade on annoyance has been largely neglected, but average annoyance has been shown to reduce when noise levels at the least exposed façade are significantly lower than the ones found at the most exposed façade [4]. According to the directive [1], there is a need to preserve quiet areas in agglomerations and have them at a walking distance. It also defines a quiet façade as a façade with relative low noise exposure, at least 20 dB below the most exposed façade.

Nowadays, noise prediction focuses on the most exposed façade and regularly underestimates noise levels in quiet areas as inner yards [4]. To be able to evaluate noise levels found in different scenarios, an engineering model was developed as part of the *Qside project* [8]. In the present work an implementation thereof (here referred to as *Qside implementation*) has been developed, as a part of noise map calculation.

QSIDE MODEL AND QSIDE IMPLEMENTATION

The *Qside model* [9] has been developed with the intention to get reliable results to estimate the noise levels on the shielded façade. This need arises due to the fact that noise prediction software often underestimates these levels, where the multiple reflections in street canyons and yards are normally overlooked. We have to remark that the intention of the standards used in the noise prediction software, like the Nord2000, was not for that purpose; shielded areas were of lesser interest. However, the situation has changed due to different policies, like the END [1] and several legislations in European countries, where noise levels in shielded areas are used, allowing further construction of buildings, i.e. densification [10]. In this paper, the *Qside model* has been slightly modified in order to enable implementation for inner yard situations of interest.

The *Qside model* has been extended in order to make it closer in agreement to the noise mapping software used. The extension here is made for the standard case of a single building:
- Explicit inclusion of image source and receiver, therefore, inclusion of ground reflection.
- Inclusion of air attenuation, decorrelation and scattering.
- Development of geometrical parameters at complex situations, i.e. a possible difference in height between the canyon street and the courtyard has been incorporated.
- Development of cases where the ratio H_s-H_i or H_r-H_i varies.
- Road traffic source model Nord2000 has been implemented.

 Background noise level

The focus of the model is mainly in the diffraction over the buildings due to reflections in the street canyon and yard. The diffraction part is based on Pierce's theory [11]. The noise level computed from noise prediction software includes the diffraction around the vertical edges, i.e. direct sound reaching an open inner yard. For that reason, the noise levels found here are called as *background noise level* [9].

First, the contribution of the background noise level in a homogeneous atmosphere is stated as $L_{pdb} = L_W - A_{free} - A_{diffr} - A_{inter}$, where:

- L_w = the sound power level per octave band (or third octave bands) of a point source (dB). In our case, we consider third octave bands.
- A_{free} = 3D free field divergence (dB). In the case of a point source $A_{free} = 10\log_{10}(4\pi R^2)$.
- A_{diffr} = the shielding limited by diffraction over the building roof (dB). To understand the contribution to the background noise level, the attenuation due to diffraction (A_{diffr}) is the term that played the main role for this model: $A_{diffr} = -10\log_{10}(10^{-0.1A_{bar}} + 10^{-0.1A_{can}})$. For its understanding, it is divided into:
  1. The attenuation by the building cutting the direct path between source and receiver limited by diffraction over it, including the presence of the ground. Only taken into account the direct diffraction path in the canyon (A_{bar}),
  2. The attenuation following a path between source and receiver including at least one reflection in source and/or receiver canyon (A_{can}).

  When canyons are present, the attenuation due to them dominates over the attenuation due to the building and determines de A_{diffr} term.

  If the yard is completely shielded, the model presented here will dominate the contribution. On the other hand, if the inner yard is not totally shielded, the reflection in the horizontal plane will dominate.
- A_{inter} = the attenuation caused by diffraction over the different intermediate canyons [dB]. According to the data collected in [9], this value is 1 dB every 100 m up to a maximum of 5 dB: $if\ a < 500, then\ A_{inter} = {}^{a}/_{100}$, $if\ a \geq 500, then\ A_{inter} = 5$.

For the contribution by scattering from atmospheric turbulence (*Qside implementation model*): $L_{pb,scatter} = L_w + L_{p,scatter,re,free} - A_{free}$.

Finally, adding the contribution caused by the scattering from atmospheric turbulence, results in the background sound level that will be incorporate as $L_{pb} = 10\log_{10}(10^{0.1L_{pdb}} + 10^{0.1L_{p,scatter}})$.
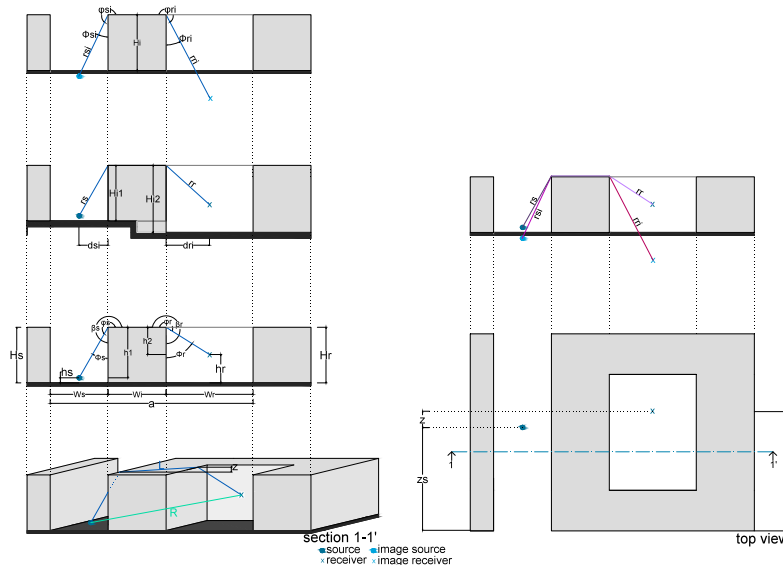
Geometric parameters

Figure 1. Street canyon and inner yard: geometric paraméters.

Geometry plays an important role in the correct implementation of the model, where:

- L is the distance from source to edge to receiver: the shortest non-penetrating path connecting source and receiver: $L = \sqrt{(r_s + r_r + W_i)^2 + (z_s - z_r)^2}$.
- R is the length of the shortest penetrating path, meaning the direct path:
$R = \sqrt{(z_s - z_r)^2 + (r_s + r_r + W_i)^2 + (h_r - h_s)^2}$.

Attenuation by the building: Abar

This term is divided into the attenuation caused by the building with flat roof and the effect of the gable roof (in case is needed). Contributions from image source and image receiver due to ground reflections are added to the model, including four paths passing the edge of the building:

$A_{bar} = -10\log_{10}\left(10^{0.1A_{bar,flat,path0}} + 10^{0.1A_{bar,flat,path1}} + 10^{0.1A_{bar,flat,path2}} + 10^{0.1A_{bar,flat,path3}}\right) \ldots$
$+ A_{bar,roof}$), where:

Path0 (*p0*) = from source - building edge1 - building edge2 - to receiver,
Path1 (*p1*) = from image source - building edge1 - building edge2 - to receiver,
Path2 (*p2*) = from source - building edge1 - building edge2 - to image receiver,
Path3 (*p3*) = from image source - building edge1 - building edge2 - to image receiver.

The resulting equation for the attenuation by the building found in the *Qside model* is:

$A_{bar,flat,i} \approx -10\log_{10}\left[\left(\frac{R}{L_i}\right)^2 \left(\frac{0.37}{X_{1\_i}+0.37}\right)^2 \left(\frac{0.37}{X_{2\_i}+0.37}\right)^2\right]$, where the non-penetrating path (L) need to be adapted for these paths, as well as X_1 and X_2. Further explanation of the variables involved can be found in [8, 9].

Ground effect

To have the interference due to ground reflection, it was here formulated as complex valued pressures for four paths: p_0, p_1, p_2 and p_3, added to the current model as $p = p_{diffr,0} + p_{diffr,1}Q_1 + p_{diffr,2}Q_2 + p_{diffr,3}Q_1Q_2$, where Q_1 is the spherical reflection factor at source side and Q_2 at receiver side, where $p_{diffr,i} \approx -10\log_{10}\left[\left(\frac{R}{L_i}\right)^2 \left(\frac{0.37}{X_{1\_i}+0.37}\right)^2 \left(\frac{0.37}{X_{2\_i}+0.37}\right)^2 \left(\frac{e^{-ikL_i}}{L_i}\right)\right]$.

The interference pattern is altered due to random propagation properties. Here, the so-called mutual coherence function for a Kolmogorov velocity turbulence spectrum has been used, with strength $C_v^2/C_0^2 = 10^{-6}\ m^{-2/3}$ (e.g. [12]). The reduced coherence has been inferred to all combinations of the four rays. In addition, reduced coherence due to the frequency band approximation has been used, as described in [13].

Attenuation by the canyon effect: Acan

This term includes the effect of the building cutting the direct path source-receiver and the presence of a gable roof (if needed) has also been include as $A_{can} = A_{can,flat} + A_{can,roof}$,

where $A_{can,flat} = -F(0)10\log_{10}\left[\begin{array}{c} F(1)\frac{C_{1s}\rho_s^2\ R^2}{(C_{3s}+W_s)^2}\ 10^{0.1L_{hs}} + F(2)\frac{C_{1r}\rho_r^2\ R^2}{(C_{3r}+W_r)^2}\ 10^{0.1L_{hr}} \\ +F(3)\frac{\rho_s^2\ \rho_r^2\ R^2}{\left(\frac{3.31h_1}{\sqrt{\lambda}}+C\right)\left(\frac{3.31h_2}{\sqrt{\lambda}}+C\right)}\ 10^{0.1L_{hs}}10^{0.1L_{hr}} \end{array}\right]$, in which C_{1i}, ρ_i, C_{2i}, C_3

and C are explained in [9]. Further description to the *Qside model* is included in this paper for its better understanding. In this sense, the model includes different situations according to the ratio $(H_s - h_s)/(H_{i1} - h_s)$. It occurs the same for the ratio $(H_r - h_r)/(H_{i2} - h_r)$.

- If $\frac{1}{3} < \frac{H_s-h_s}{H_{i1}-h_s} < 1$, then $L_{hs} = -6.17\left(1 - \frac{H_s-h_s}{H_{i1}-h_s}\right)\left[1 - 1.37\log_{10}\left(\frac{\sqrt{\lambda W_s}}{W_i}\right)\right]$.
- If $\frac{H_s-h_s}{H_{i1}-h_s} > 1$, then $L_{hs} = 0$, i.e. the canyon effect is saturated.
- If $\frac{H_s-h_s}{H_{i1}-h_s} \leq \frac{1}{3}$, then $L_{hs} = -\infty$, i.e. the canyon effect is neglected; there are no image sources because the building is too small.
- For the same reason, if $H_{i1} = h_s$, then $L_{hs} = -\infty$.

In case there is a gable roof and:

- $H_s \neq 0$ and $H_r \neq 0$, which means that both canyon source and receiver are present, then $A_{can,roof} = -5$.
- $H_s \neq 0$ or $H_r \neq 0$, which means that one of the canyons is present (source or receiver), then $A_{can,roof} = -2.5$.

Air attenuation and scattering

The propagation effect of air absorption is based on the ISO 9613-1 [14]. This prediction is based on frequency, air temperature, relative humidity and atmospheric pressure and predicts attenuation in third octave bands. The air attenuation also needed to be included in the model. The election of this method among others was in order to compare it with the noise prediction software based on the Nord2000 model, which use the ISO 9613-1 for the air absorption. Furthermore, sound scattering due to atmospheric turbulence is included, according to [15].

COMPARISON OF RESULTS

Comparison for single building

For the validation of diffraction for a single building including ground effect, the *Qside model* was compared with BEM as well as with analytical diffraction theory [11], with the *Qside implementation* (adding diffraction and decorrelation) and with the chosen noise mapping software SoundPLAN v 7.3, with the Nord2000 model.

As can be seen in Fig. 2, the results from the *Qside model* without explicit ground reflection lack the interference pattern. By including the ground reflection, the results tend more toward analytical and BEM, and the inclusion of decorrelation is a further improvement. In general, the results of the further developed *Qside model* tend to the ones from SP, as intended for this situation; it could however be noted that in the limit of low frequencies, the omission of higher order diffraction contributions leads to a deviation from the SP and BEM results. Even though, the agreement between *Qside implementation* and SoundPLAN is good, further work need to be done in order to find solutions for all cases that can be presented in our cities.
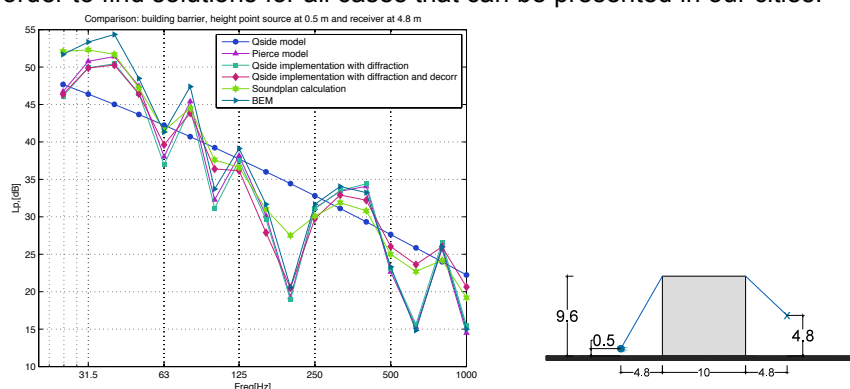

Figure 2. Noise level at the shielded area: building barrier. : Comparison between different models: *Qside model* [9], Diffraction theory [11], *Qside implementation*, SoundPLAN calculation and BEM.

Comparison for urban canyons

As a case study a comparison between the results from the chosen Noise mapping software SP and the *Qside model* implementation was made for an urban canyon situation in three cases:

1. Line source with Lw=100 dB/m in each frequency band.

In Figure 3, the different results from the *Qside implementation* and the SoundPLAN calculations for a receiver placed at the centre of the inner yard are shown. The calculations have been set for hard ground and no façade absorption, since the *Qside model* based its parameters on a hard façade (with an absorption of 3%). As it was expected, the results from the higher order of reflection from the SoundPLAN calculations get closer to the implementation. This considerable increase is due to the fact that the façade surface is considered as hard.
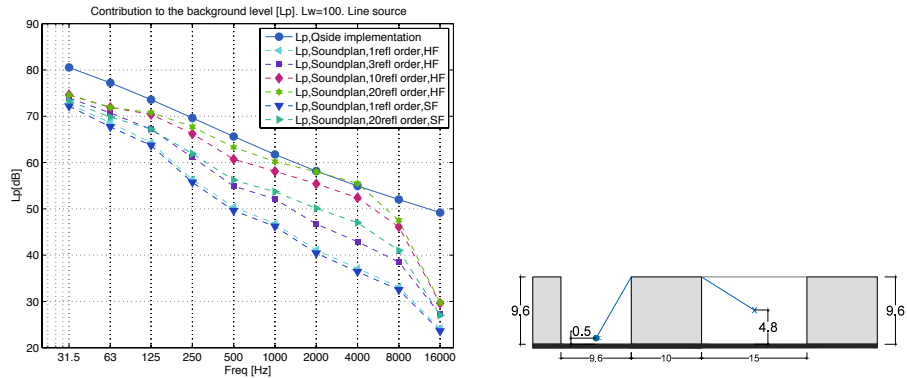
Figure 3. Line source example. Noise level [dB] at the inner yard. Calculations made from the *Qside implementation* and SoundPLAN with hard façade (HF) and soft façade (SF), with 1 dB absorption.

For the SoundPLAN results at mid frequencies and at higher reflection order, the soft façade gives around 7-8 dB lower results than the hard façade. Since the latter coincides with those from the *Qside implementation* at mid to high frequencies, the overestimate from using low absorption values of the façades in the Qside model, compared with more typical values, can be reasoned to be in this order, i.e. around 7-8 dB, at least for similar geometries.

The results for the first reflection order in SoundPLAN deviate from the Qside results by ca 10 dB at low frequencies, increasing at higher frequencies. If we take multiple reflections into account, the agreement is better but still a significant deviation is shown at and below 125 Hz and above 4 kHz; the latter linked to the difference in air attenuation modeling.

An incorporation of the *Qside implementation* into the noise mapping results was made for this case using GIS software (ArcGis) to substitute the noise level values in the inner yard. The façade absorption in SoundPLAN was set to a more realistic value (1 dB as smooth façade). The receivers were placed in a 1-m-grid in the inner yard, at 4.8 m height, as shown in Figure 4.
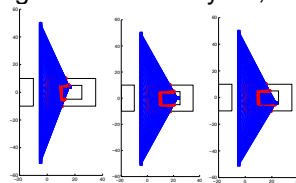

Figure 4. Line source example. Receivers' grid.

The results, shown in Figure 5, show that the equivalent noise levels (L_Eq) increases by 6-9 dB, showing the importance of higher reflection orders, especially at low frequencies.
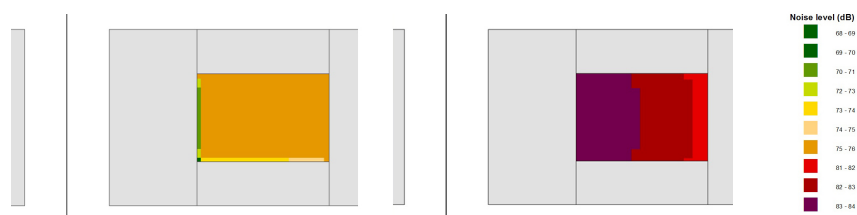

Figure 5. Inner yard grid map. Noise mapping software (1) *Qside implementation* (2).

2. Road with 2 lanes (2.75 m each) implementing the Nord2000 model for road traffic in the model. Traffic flow of 5000/24 h and a speed of 50 km/h.
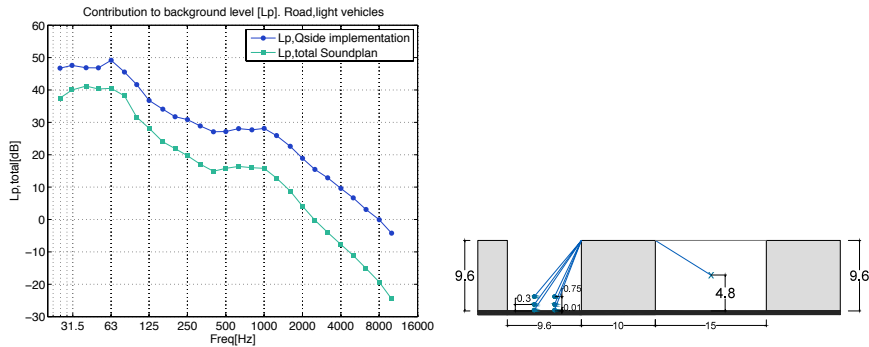

Figure 6. Noise level [dB] at the inner yard. Road (Nord2000).

For the comparison, one reflection order was set. This was chosen due to the reason that most of the large calculations in noise maps set just one reflection order due to computational time. In the Figure 6, the differences are also around 10 dB at lower frequencies, increasing at higher frequencies.

3. Real situation: noise level measurements performed in an inner yard in Göteborg, Sweden [16]. In the comparison, a simplified geometry, similar to Figure 7(b) was used for the *Qside implementation*.
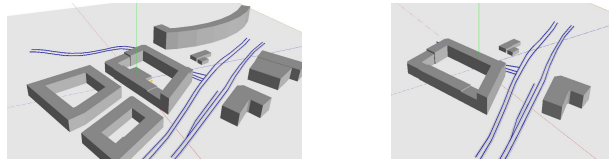

Figure 7. Bomgatan, Göteborg, Sweden. Geometry used for SoundPLAN (a), geometry used for *Qside implementation* and SoundPLAN simplified (b).

Figure 8 shows similar spectra for the *Qside implementation* and the measurements, with a total difference of about 3 dBA. This contrasts to the SoundPLAN results (with 1 reflection order), which show a deviation from the measurements that increases with frequency, giving in total an underestimate of 15 dBA. Differences between the measurements and the *Qside implementation* can be due to geometry simplifications.
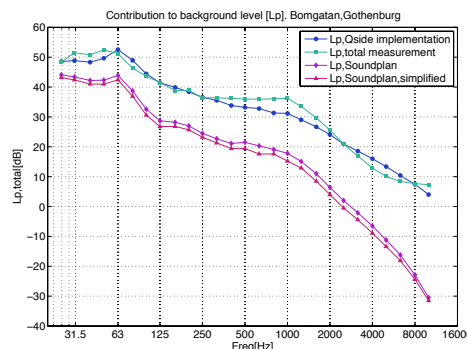

Figure 8. Noise level [dB] at the inner yard, Bomgatan, Göteborg.

CONCLUSIONS

Previous work has proven that having access to quiet areas in cities reduce adverse health effects from road traffic noise, were inner yards can be considered as restorative places. The *Qside model*, a prediction method for the noise level found in the inner yards, considered as an

extension of the current prediction methods, has been further developed in this paper for its compatibility with noise mapping software. In this sense, *Qside model* with the extension of *Qside implementation* can be considered as an improved tool in terms of calculating noise levels at shielded areas. Still, some future work is needed:

- Further adaption/incorporation related with the facade absorption of buildings.
- Further development of the different cases found in the urban environment.
- Study of process automation, such as the incorporation of values from the *Qside implementation* into the noise prediction software.
- Further validation in real but controlled scenarios.

AKNOWLEDGMENTS

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