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A numerical study of sound propagation over urban canyons

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Because quiet areas in dense urban environments are important, there is high interest in propagation to areas shielded from direct road traffic noise. Sound levels in shielded areas are strongly influenced by distant sources, so intermediate propagation factors such as metrology, screening, and intermediate canyons must therefore be addressed in a realistic propagation model.
A numerical investigation of sound propagation across the open tops of intermediate urban canyons has been performed, using the parabolic equation and equivalent sources methods. Results have been collected for various canyon geometries, and the influence of multiple canyons, canyon/rooftop absorption, variable rooftop height, and correlated versus uncorrelated source models has been investigated. By characterizing the "insertion loss" of canyons intermediate to the source and receiver, the influence of these intermediate canyons could be addressed simply, without the overhead of a detailed numerical calculation.

1 Introduction

Environmental noise continues to be one of the most common quality-of-life complaints in many cities. Because of the difficulty of sufficiently reducing noise levels in directly exposed outdoor locations [1], a complementary strategy is to design dwellings with access to a "quiet side"—a sufficiently quiet courtyard or backyard that is shielded from direct noise exposure [2].

Despite being accurate for directly exposed locations, current standardized prediction methods (such as "Harmonoise" or "Nord2000") often fail to accurately predict immission in shielded areas [3]. Recent research has turned instead to using sophisticated numerical methods to evaluate sound propagation. Using the simplified geometry of urban canyons formed by buildings, streets, and yards, these numerical methods can feasibly be used to evaluate propagation within or between canyons, while including important factors such as multiple reflections, diffraction, absorption, scattering, and atmospheric effects. Applying these accurate methods over wide and complex urban areas, however, remains computationally prohibitive.

Intermediate canyons that lie between a source canyon and a receiver canyon represent a significant departure from the flat ground or simple screening assumed in many engineering methods. Knowledge of the influence of these intermediate canyons on long-range sound propagation would be useful to estimate shielded-side noise immission, without the significant computational effort of a detailed numerical calculation. The goal of this paper is therefore to characterize the wide-band "insertion loss" of one or more urban canyons, for the case of grazing sound propagation between a roof-level source and receiver.

2 Tools of analysis

Several numerical methods are suitable for exploring the influence of urban canyons on sound propagation. In the current work, the parabolic equation and equivalent sources methods were used as a basis for analysis and validation of results. The following describes the concepts and assumptions of each method; rigorous treatments of both methods are available in the references [4,5,6].

2.1 Parabolic equation method

In atmospheric acoustics, the Parabolic Equation (PE) method is a versatile numerical method for calculating sound propagation from a monopole point source over a ground surface of arbitrary impedance. In the current work, the Crank-Nicholson PE formulation given by Salomons [4] was used, using the one-way axisymmetric Helmholtz equation. Using r - z coordinates and $\exp(-j\omega t)$ time dependence,

$$\left[\frac{\partial}{\partial r} - jk\sqrt{1+L}\right]q = 0\,; \quad L = \frac{1}{k^2}\left[\frac{\partial^2}{\partial z^2}\right], \qquad (1)$$

where k is the wave number and the complex amplitude $q(r,z)$ is related to the complex sound pressure amplitude $p(r,z)$ by $q = p\sqrt{r}$. A rational-linear approximation of the square-root operator in Eq.(1) is used in Salomons' solution, resulting in an accurate propagation angle limit of approximately ±35° from horizontal.

The resulting parabolic equation is solved by approximating each derivative with a centered second-order finite difference. This leads to a set of linear equations, with one equation for each height point; solving this system numerically leads to an expression for a single PE range step, $q(r) \rightarrow q(r+\Delta r)$. The sound field grid is thereby "marched" from source to receiver as detailed in [4].

This PE method characterizes sound propagation only over flat ground. In the current work, Kirchhoff and complementary Kirchhoff approximations were made at each rooftop edge and canyon wall. At a rooftop edge, the domain is extended downward into the canyon, with grid points along the canyon wall set to zero—the Kirchhoff approximation. For canyon reflections, the complementary approximation is used: the grid values up to the roofline of the canyon wall are reduced by a reflection factor, and the values above the roofline are set to zero. This approach has been validated for screening [7] and multiple reflections [8], though it is less accurate for receivers very near the diffraction point.

2.2 Equivalent sources method

The arrangement of a road between two buildings lends itself to a two-dimensional model, where the road traffic acts as a continuous line source and the buildings form a continuous canyon. The 2-D Equivalent Sources Method (ESM) as applied to the canyon geometry by Ögren and Kropp [5] simplifies this domain by splitting it into two simpler domains with known Green's functions: that of propagation over a flat surface, and that of the sound field inside a closed rectangular cavity (a modal summation). An array of equivalent sources at both sides of the interface is used to marry the two sub-domains, forming a continuous overall sound field as illustrated in Fig.1.

The equivalent source strengths fulfill the Helmholtz equation and continuity of pressure and of normal velocity at the interface. The system can be formed into a set of linear equations by discretizing the equivalent source distribution, allowing solution for the equivalent source strengths.

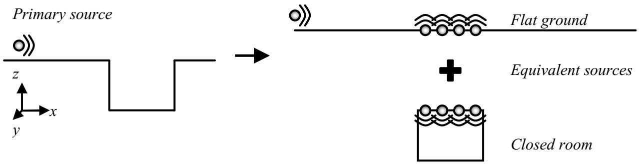

Fig.1 Splitting of the domain in the ESM.

In [6], Hornikx and Forssén extended the 2-D ESM to a "2.5-dimensional" geometry; that is, a geometry that is still invariant in the y-direction, but producing a 3-D point source solution of the Helmholtz equation, which also can be used to obtain an incoherent line source solution.

3 Analysis and results

Here, the L_p excess attenuation of adding a canyon to a rooftop —or the difference in receiver level between the cases with the canyon present and without the canyon present—will be explored for a variety of configurations.

3.1 ESM versus PE

To validate the PE-Kirchhoff method for this problem, a simple case was chosen for analysis in the ESM, which has been previously validated for the canyon geometry [2,5]. The comparison was performed for the geometry shown in Fig.2: source and receiver at roof level, 200 meters apart, with a 20x20 m canyon located in the center of the field. All roof and canyon surfaces are perfectly reflecting.

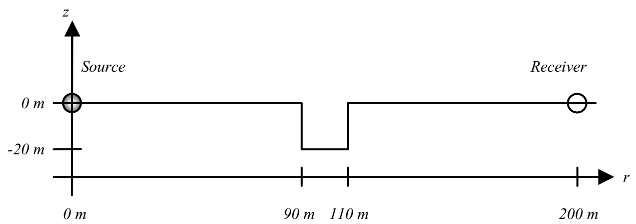

Fig.2 Initial source/receiver/canyon geometry.

The ESM-calculated excess attenuation arising from this arrangement is shown in Fig.3. In the figure, 1/3-octave band values are superimposed over the narrow-band results, which were generated for 20 frequencies within each 1/3-octave band. As shown in the figure, the narrowband excess attenuation oscillates widely due to resonances within the canyon. However, the 1/3-octave band values all lie close to the average value of -1.74 dB (that is, the simple arithmetic average of the 1/3-octave band L_p values).

Next, this arrangement was analyzed using the PE method, first with 30 total reflections within the canyon (in excess of the 25 reflections validated for hard obstacles by Aballéa and Defrance [8]). On a 1/3-octave band basis, this result was nearly identical to the ESM result, with less narrowband oscillation due to the finite reflection order.

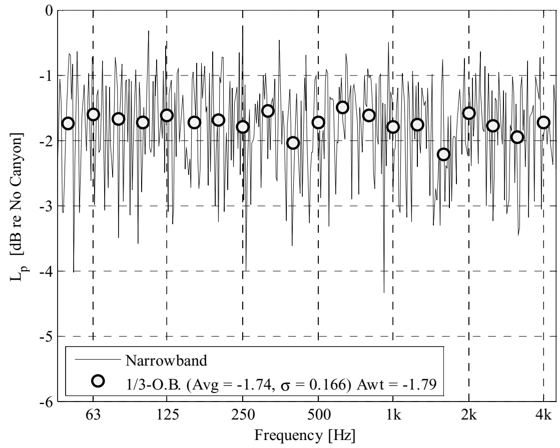

Fig.3 ESM result, geometry as Fig.2.
(Avg = average 1/3-OB L_p value; σ = standard deviation in 1/3-OB L_p values; Awt = A-weighted overall value)

To further examine the influence of reflection order on this agreement, analysis was performed with no reflections, or the case of simple diffraction over both canyon edges. This case also corresponds to that of total sound absorption within the canyon. The result appears in Fig.4; in this figure, the oscillation about the average is eliminated, leaving a nearly constant narrowband spectrum. The 1/3-octave band spectrum is also nearly constant, with an average value of -1.8 dB, the same as was found with 30 reflections and with the ESM.

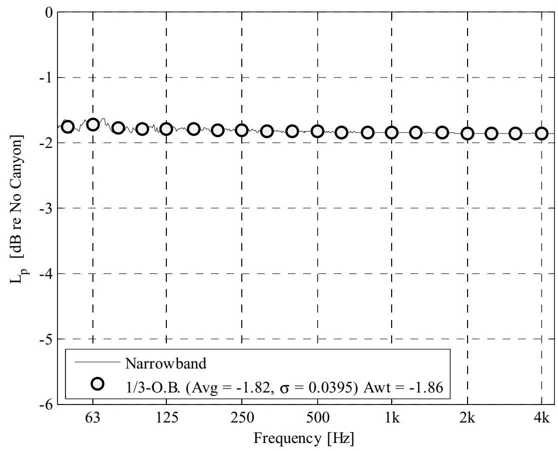

Fig.4 PE result, 0 reflections, geometry as Fig.2.

These results suggest that on a 1/3-octave band basis, the canyon excess attenuation is virtually independent of the number of canyon reflections included in the calculation. Considered another way, it indicates that canyon attenuation is independent of the canyon interior absorption, since absorption is not considered in a 0-reflection analysis. This is in contrast to the analysis of the sound field *within* a source or receiver canyon, where surface properties must be considered for accurate results [2,9,10,11].

3.2 Influence of source model

The PE method describes propagation from a point source in an axisymmetric domain, while the ESM describes a coherent line source in a 2-D domain. However, a finite incoherent line source is a more accurate model for traffic noise emission from a finite roadway; it has been shown that using a coherent or an infinite incoherent source model can be overly optimistic when evaluating noise control measures [12].

A sample calculation was made for a 400m long finite incoherent line source, according to the formulation in [12]; on an average 1/3-octave band basis, the finite incoherent ESM result differed from both the coherent ESM and the zero-reflection PE result from the previous section by only 0.04 dB. In this comparison, the 1/3-octave band excess attenuation of the canyon did not differ significantly among the different source models.

3.3 Canyon depth

Since the efficient 0-reflection PE method was shown above to agree well with the other methods and source models, it was used in nearly all the remaining analyses. The influence of canyon depth was examined first. Using the geometry in Fig.2, the analysis was repeated using canyon depths of 8 m and 40 m. In each case, 1/3-octave band values remained fairly constant about the average (still -1.8 dB in each case), especially for greater canyon depths. Still, it may be the case that for canyons having shallow depth compared to the width, reflections from the canyon bottom may begin to influence the results.

3.4 Canyon width and location

Numerical studies varying the width and location of the canyon between the source and receiver were performed next. In almost every case, the resulting spectrum was nearly constant on a 1/3-octave band basis. In evaluating these results, it was found that the average 1/3-octave band value depends not on the absolute canyon width, but on the width *relative to* the overall source-receiver distance. Calculations with the same ratio of canyon width to field distance yielded nearly the same average 1/3-octave band excess attenuation.

Figure 5 is a scatter plot of nine such PE method results, showing the average excess attenuation versus the normalized canyon width (for a constant normalized canyon center location of 0.5, or exactly midway between source and receiver).

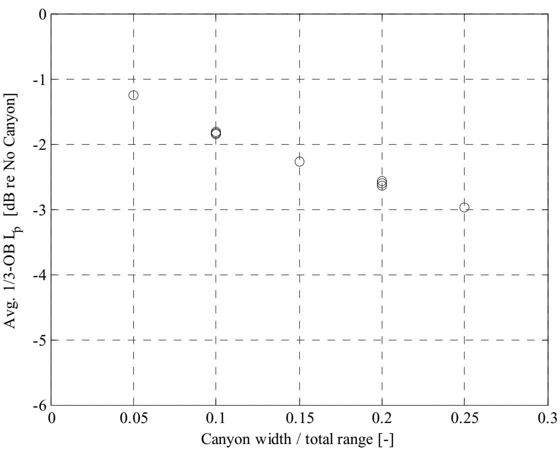

Fig.5 Average 1/3-octave band excess attenuation versus the canyon width, normalized by the total field length. Normalized canyon center location of 0.5 throughout.

As shown in Fig.5, the excess attenuation varied between -1.25 dB and -2.97 dB. The tight group of points at the normalized widths of 0.2 and 0.1 (three points each) illustrates the results of calculations with different absolute widths, but identical normalized widths.

Similarly, the average excess attenuation value depends not on the absolute source-canyon distance, but on the canyon location *relative to* the total source-receiver distance. Calculations with the same ratio of source-canyon distance to overall field distance yielded nearly the same average 1/3-octave band result, as shown in Fig.6 for eleven PE calculations with a normalized canyon width of 0.1.

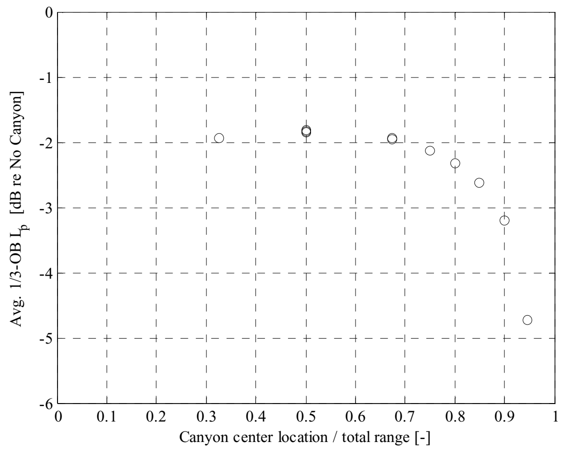

Fig.6 Average 1/3-octave band excess attenuation versus the canyon center location, normalized by the total field length. Normalized canyon width of 0.1 throughout.

In Fig.6, excess attenuation ranged from -1.82 dB to -4.72 dB, and the tight grouping of points (three points at location 0.5 and two points at location 0.675) shows similar results for calculations with the same normalized width. The similarity of the result at location 0.325 to the two results at location 0.675 illustrates the expected reciprocity between source and receiver.

These figures illustrate some general trends in the excess attenuation for an urban canyon. As canyon width grows in comparison to the total source-receiver distance (Fig.5), the effect of the canyon increases in a fairly linear fashion. Likewise, as the canyon grows closer to the source or receiver (Fig.6), its effect increases.

It should be noted that the results in Fig.6 were generated using the PE method, but the Kirchhoff approximation may lead to inaccurate results for receivers very close to the canyon edge. Reproducing the situation of a receiver 1 m from the edge of a 20 m wide canyon in a 200 m field using the ESM, the average 1/3-octave band result of -3.7 dB was significantly different than the PE result of -4.7 dB seen in Fig.6. This confirms that the Kirchhoff approximation used in the PE method is less accurate for receiver locations very close to the diffraction point.

3.5 Multiple canyons

All of the previous results were obtained for a single canyon in a flat rooftop. It is not immediately obvious whether inserting additional canyons in this rooftop will result in an overall effect that is the simple sum of the influences of each individual canyon; nor can it be taken for granted that the "0-reflection" diffraction-only PE calculation scheme remains accurate for multiple canyons.

To investigate this, calculations were made for a single 20x20 m canyon located eccentrically in a 200 m field (with canyon center 65 m from the source), and this result was compared with a calculation including an identical second canyon in the reciprocal location (the same distance from the receiver). For the single canyon, the 1/3-octave band spectrum was again quite constant, with an average value of -1.93 dB. The results from a similar calculation with two canyons (centered at 65 and 135 m) produced similarly consistent values, with an average excess attenuation of -3.78 dB—double the single-canyon value. In this case, then, the wideband influence of multiple canyons can be seen as the simple addition of their individual decibel influences. However, additional trials must be examined to determine if this simple addition is correct in a wider variety of arrangements.

3.6 Source and receiver height

Each of the prior results was calculated for a source and receiver exactly at roof level—the configuration most relevant to propagation over canyon openings. When both are elevated, however, significant frequency dependence is expected due to interference between the direct and reflected waves (the "interference dip"). However, to the extent that the frequency dependence of the canyon result matches the flat-roof frequency dependence, the result "re no canyon" could still be nearly constant, even if the result "re free field" shows significant variation with frequency.

To illustrate this, Fig.7 shows the results for a source and receiver elevation of 4 m, again for the case of a single 20x20 m canyon in the center of a 200 m field. Two separate regions can be identified in the spectrum. In low frequencies, up to about 500 Hz (i.e. below the first interference dip), the canyon influence was nearly constant at about -1.8 dB in each 1/3-octave band—the same result as was obtained for source and receiver at roof level. For higher frequencies, near the region of each interference dip, the result relative to the no-canyon case becomes very high, since the receiver pressure magnitude is finite, while without the canyon it is nearly zero.

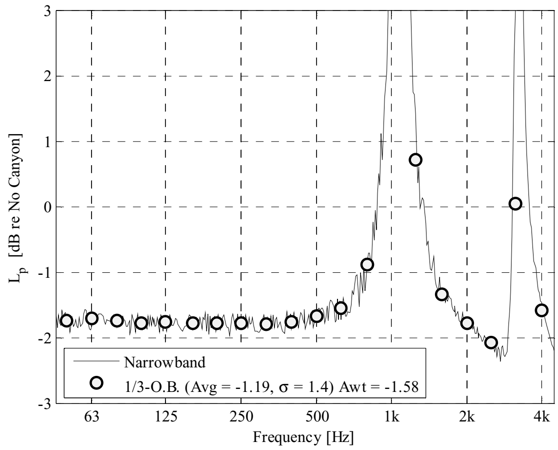

Fig.7 PE result, 0 reflections within canyon. Source and receiver 4 m above roof level, otherwise geometry as Fig.2.

With a lower source and receiver height, the frequency of the first interference dip is higher, and a wider frequency range of near-constant results can be expected. Repeating the above for a source and receiver height of 1 m showed the nearly constant 1/3-octave band result of -1.8 dB re no canyon, the same as with source and receiver at roof level. At this low source and receiver elevation, the frequency of the first interference dip (approximately 17 kHz) is now well above the frequency range of interest.

3.7 Roof height

The presence of a change in roof height was investigated next. In such an arrangement, the different roof levels eliminate the direct line-of-sight path from source to receiver, as shown in Fig.8.

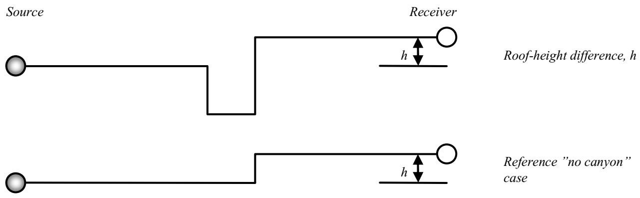

Fig.8 The modeled roof-height difference.

First, a 4 m increase in roof height across the canyon was investigated, with other geometry aspects remaining as in Fig.2. The results relative to the no-canyon case are plotted in Fig.9. In this case, the reference "no canyon" field is that of a flat roof with a 4 m jump in roof height at $r = 110$ m (the location of the far canyon wall), with source and receiver at their respective roof heights, as shown in the lower half of Fig.8. This reference field was computed using the same PE method used for the canyon case.

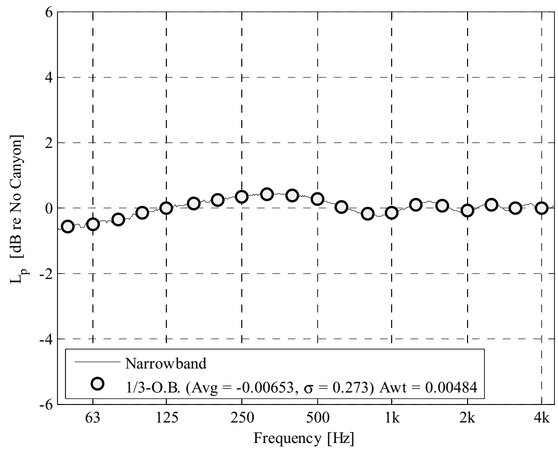

Fig.9 PE result, 0 reflections. Receiver roof level 4 m higher than source roof level; otherwise geometry as Fig.2.

The results in Fig.9 are near zero across all bands, and especially so at higher frequencies. The canyon has little influence on the receiver level, compared to the screening effect of the 4 m jump in roof height. Results calculated for greater roof height differences showed even less influence.

In contrast, the results with a 1 m roof height difference clearly show the influence of the canyon, as shown in Fig.10. In low frequencies, the canyon influence is -1.8 dB, the same as with constant roof height. As the frequency increases, the influence remains close to zero, as was seen with the 4 m roof jump; as the wavelength shortens in comparison to the 1 m height difference, the screening effect begins to dominate.

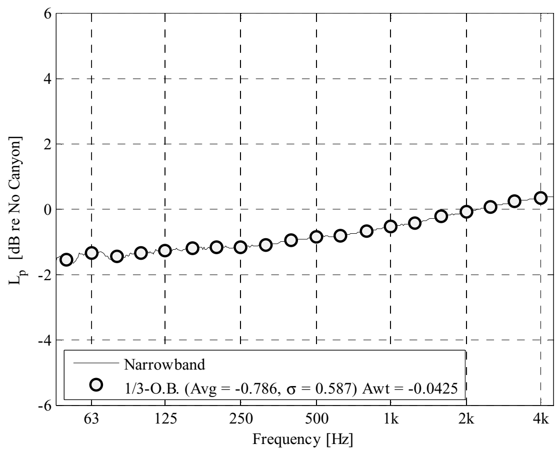

Fig.10 PE result, 0 reflections. Receiver roof level 1 m higher than source roof level; otherwise geometry as Fig.2.

3.8 Roof impedance

All of the prior results assumed hard surfaces, but real roof structures likely provide some finite impedance. Since the acoustic impedance of common roof constructions has not been widely studied, a real normalized impedance (Z_n) of 78 was used as an approximation, corresponding to an absorption coefficient (α) of 0.05. Fig.11 shows the result where the reference calculation comprises an impedance roof with a 20 m hard strip replacing the canyon.

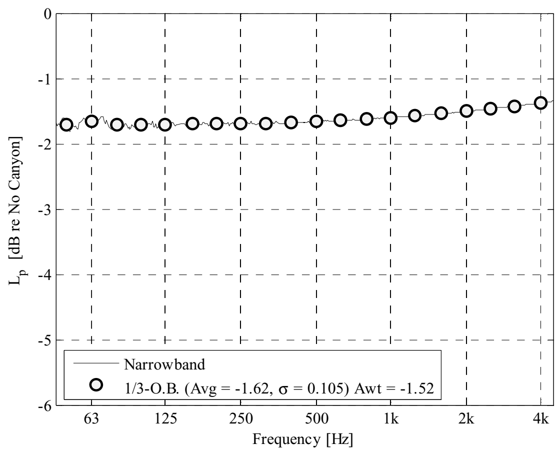

Fig.11 PE result, 0 reflections. Rooftop $Z_n = 78$, otherwise geometry as Fig.2. In reference, hard strip replaces canyon.

The results reach -1.7 dB across the low frequency range, similar to a canyon in a hard roof. Some shifting of high frequency values is apparent, possibly due to diffraction at the boundaries of the hard strip in the reference case.

4 Conclusion

Calculations using the parabolic equation and equivalent sources methods showed that intermediate urban canyons have a consistent, attenuating influence on propagation between roof-level sources and receivers. This influence appears to be independent of the interior properties of the canyon; only parameters such as canyon width and field location proved to be significant. On a wide frequency-band basis, this attenuation can often be predicted using an efficient application of the parabolic equation method, in which interior canyon reflections are neglected in favor of diffraction at the edges of the canyon opening.

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http://publications.lib.chalmers.se/cpl/record/index.xsql?pubid=69676

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