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SOUND FIELDS IN URBAN STREETS WITH DIFFUSELY REFLECTING BOUNDARIES

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1. INTRODUCTION

When calculating sound propagation in urban streets it is essential to consider the effect of building surfaces [1-6]. If street boundaries are relatively smooth, the image source method or ray-tracing techniques can be employed. Previous work on this aspect has contributed significantly towards a fundamental understanding of the behaviour of sound in urban streets [1]. If there are irregularities on building or ground surfaces, it is necessary to take diffuse reflection into account [4]. Most existing investigations concerning this aspect, however, have focused upon improving the accuracy of prediction models [5-6]. The analysis of the fundamental characteristics of the sound field resulting from diffusely reflecting boundaries appears to be insufficient.

The objectives of this work are therefore to investigate
(1) The fundamental characteristics of SPL (sound pressure level) distribution and reverberation in urban streets with diffusely reflecting boundaries;
(2) The effectiveness of urban design options, such as street aspect ratio, building height and street layout, for the sound field; and
(3) The usefulness of boundary treatments for noise reduction. This includes comparison between diffusely and geometrically reflecting boundaries, effect of strategic absorber arrangements, and so on.

A radiosity-based computer model has been developed for simulating sound propagation in urban streets with diffusely reflecting boundaries. This paper starts with a brief description of the model; it then presents typical results of a parametric study using the model.

2. MODEL

The radiosity method was originally developed for the study of radiant heat transfer in simple configurations. With rapid development of computing resources, the techniques have been continuously developed and widely used in computer graphics and lighting simulation [7-8]. By considering relatively high frequencies, the method has also been used in room acoustics [9-11], but the application in urban streets for simulating sound propagation has been rather limited.

Basically, the model developed in this paper divides the building façades and the ground of a street into a number of patches (i.e. elements), and then simulates the sound propagation in the street by energy exchange between the patches. The energy exchange between pairs of patches depends on a form factor, which is defined as the fraction of sound energy emitted from one patch which arrives at the other by direct energy transport. The model considers both a single street and a typical urban element consisting of a major street and two side streets. For the sake of convenience, it is assumed that the sound energy reflected from a boundary is dispersed over all directions according to the Lambert cosine law.

The modelling process is divided in the following steps [12]:

(1) Division of each boundary into a number of patches. The simulation is more accurate with finer patch parameterisation, but there is a square-law increase of calculation time in the number of patches. Given the fact that for a constant patch size, form factor calculations become less accurate as the patch moves closer to an edge, in the model the boundaries are so divided that a patch is smaller when it is closer to an edge. For convenience, the patches are all rectangular, and the patch size varies in the manner of a geometric series. An absorption coefficient can be given for each patch. This allows a detailed study of strategic absorber arrangements.

(2) Determination of form factors. The model considers two kinds of relative orientation between pairs of patches, either parallel or orthogonal. For the former, the form factor is calculated by projecting the receiving patch onto the upper half of a cube centred about the radiation patch. For the latter, computing a form factor is equivalent to projecting the receiving patch onto a unit hemisphere centred about the radiation patch, then projecting this projected area orthographically down onto the hemisphere's unit circular base, and finally dividing by the area of the circle. The accuracy in calculating form factors can be checked by the fact that the sum of the form factors from any one patch to all the other patches should be 1. To achieve a required accuracy with a minimum number of patches, there is an initial stage of determining patch division.

(3) Distribution of the energy from a source to the patches. Providing there is a line of sight between the source and a patch, the energy fraction on the patch can be determined by the ratio of the solid angle subtended by the patch at the source to the total solid angle. If the source is directional, the energy fraction in each direction should be adjusted accordingly.

(4) Exchange of energy between patches. With the energy distributed on patches, the energy exchange can be processed using the form factors obtained above. During the exchange process each patch is regarded as an energy source, which is expressed in a form of energy response. Note that the energy exchange depends only on the form factors and the patch energy after the preceding energy exchange. This 'memory-less' feature can significantly reduce the requirement for computer storage. The absorption from air and vegetation can be easily included in the energy exchange process. After each order of energy exchange, the total residual energy on all patches is calculated. The energy exchange process stops when this total energy reduces to a certain amount, typically 10^{-6} of the source energy.

(5) Calculation of acoustic indices at receivers. For each order of energy exchange, while energy is travelling between patches, the contribution of each patch to each receiver is calculated. An energy response can then be obtained for each receiver, from which the steady-state SPL, RT (reverberation time), and EDT (early decay time) can be determined. The energy response is also vital for street auralization.

By modifying the boundary layout above, the model has been shown to correctly calculate the acoustic characteristics of a cube [11]. This can be regarded as a validation of the algorithms.

3. COMPUTATION

By using the above model a parametric study has been carried out and some typical results are presented below. Except where indicated, the configurations used are as follows. The buildings are continuous along a street and of constant height on both sides. Each boundary is divided into 400-600 rectangular patches. For the varied patch sizes, the ratio between two adjacent patches is typically 1.1-1.5. Using these parameters the program calculates the form factors and the source energy distribution on patches accurate to four decimal places. The façades and ground have a uniform absorption coefficient of 0.1, and this coefficient is considered as angle-independent. The absorption from air and vegetation is not included. The source is omni-directional. The source and receiver heights are 1m. The source-receiver distance refers to the distance along the street length. The SPL at receivers is relative to the source power level, which is set as 100dB.

3.1 A Single Street

Firstly, the SPL attenuation in a single street is analysed. The street length, width and height are 200m, 20m and 30m, respectively. A point source is positioned at one end of the street. In Figure 1 the SPL distribution on a horizontal plane of 10m above the ground is shown. It is noteworthy that although the boundaries are diffusely reflective, the SPL varies significantly on the plane. For example, the SPL attenuation is 28dB at source-receiver distances of 1m through to 200m. As expected, the SPL variation becomes less when the horizontal plane is farther from the source. On a plane of 30m above the ground, for example, the SPL attenuation is 21dB.

Further calculations indicate that the sound distribution in a cross-section is rather even unless the cross-section is very close to the source. For the configuration in Figure 1, the SPL variation in a cross-section is generally less than 1-2dB beyond the source-receiver distance of 10-15m. Generally speaking, the SPL attenuation curve along the length is concave. In other words, the attenuation per unit distance becomes less with the increase of source-receiver distance.

In Figure 1 the SPL attenuation with geometrically reflecting boundaries is also shown. The calculation is made using the image source method [12]. It can be seen that by replacing diffuse boundaries with geometrical boundaries in the street, the sound attenuation along the length becomes considerably less, typically by 10dB with a source-receiver distance of 200m. This suggests that, from the viewpoint of urban noise reduction, it is better to design the building façades and the ground of an urban street as diffusely reflective rather than acoustically smooth. Although it might be unrealistic to design all the boundaries as pure diffusely reflective, some diffuse patches on a boundary, or boundaries with a high diffuse coefficient, are helpful in making the sound field fairly close to that resulting from diffuse boundaries, especially when multiple reflections are considered [13]. Similar to diffuse boundaries, street furniture, such as trees, lampposts, fences, barriers, benches, telephone boxes, bus shelters, and so on, can also be effective in reducing noise.

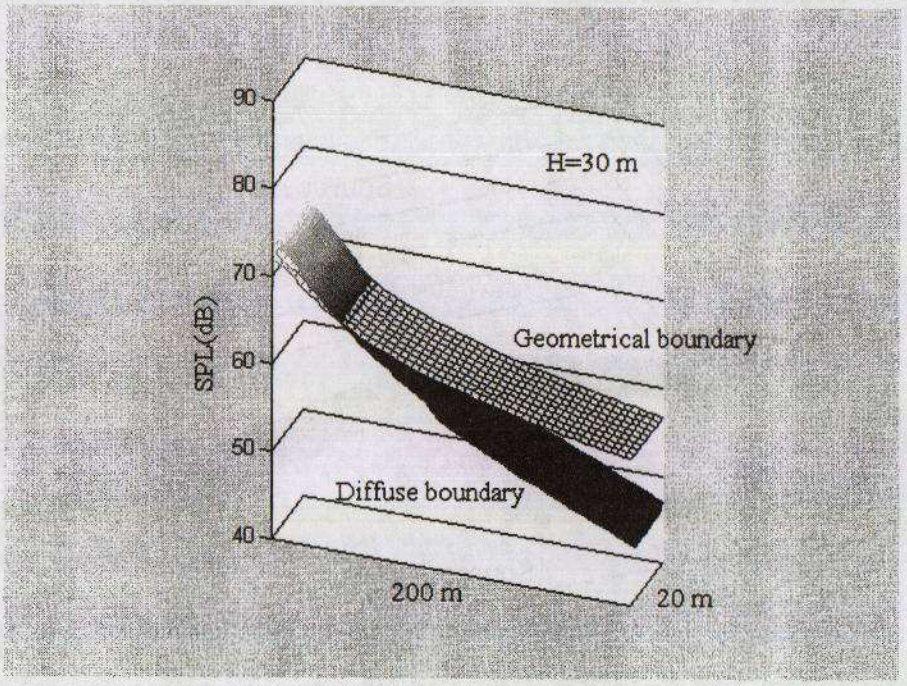

***Figure 1.** SPL distribution on a plane of 10m above the ground, and comparison with the SPL attenuation with geometrically reflecting boundaries.*

3.2 A Major Street with Two Side Streets

For a better understanding of the sound field in a network of interconnecting streets typical of urban areas, it is useful to investigate the behaviour of sound at street junctions and the sound propagation from one street to an intersecting street. Figure 2 shows the SPL distribution with nine evenly distributed point sources from position A to B. The size of the urban element is 120m by 120m, and the street width and height are 20m. In the calculation the diffraction over buildings is ignored because in the configurations considered, the energy transferring through street canyons is dominant. From Figure 2 it can be seen that the average SPL in the major street (i.e. the street with sound sources) is considerably higher than that in the side streets, at 9dB in average. Also, the SPL attenuation along the side streets is significant, at about 15-17dB. These results quantitatively demonstrate that if noise sources are along a major street, it is an effective way to reduce noise by arranging buildings in side streets.

The results in Figure 2 can also be approximately regarded as the Leq (equivalent continuous sound level) when a single source is moving from position A to B. As expected, when the source is closer to the middle of street junction, the average SPL in the streets becomes higher because less energy from the source can be reflected out of the street canyons.

To investigate the effect of side streets on the sound field of the major street, calculation is made with various geometrical and absorption conditions in the side streets. It is interesting to note that despite the significant changes in the side streets, the SPL variation in the major street is only about 1dB. This suggests that the energy reflected from side streets to the major street is negligible.

If noise sources are in one side street, considerable extra SPL attenuation can be obtained in the other side street if the two streets are staggered, because this can diminish the direct sound, lengthen the reflection path, and increase the number of reflections. For the configuration in Figure 2, the extra attenuation is 4-5dB if a side street is staggered by 20m, and this attenuation increases to 10-15dB if the staggered distance becomes 40m.

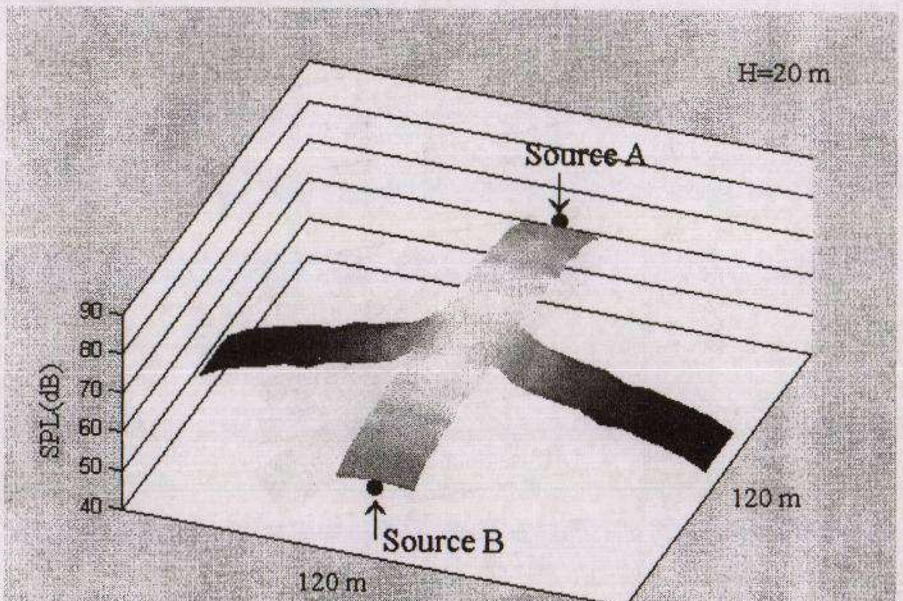

Figure 2. *SPL distribution with nine sources from position A and B, or with a single source moving from A to B.*

3.3 Absorption

Boundary absorption is useful for diminishing reflection energy and consequently, reducing the overall SPL in urban streets. Broadly speaking, absorbers on street boundaries can be absorbent materials, open windows as sound energy sinks, gaps between buildings, and so on. Figure 3 shows the SPL attenuation along the length with six typical absorption conditions. The street length, width and height are 120m, 20m and 18m, respectively. A point source is at (30m, 6m, 1m). The calculation of SPL attenuation along the length is based on the average of four receiver lines, namely (31-90m, 2m, 1m), (31-90m, 2m, 18m), (31-90m, 18m, 1m), and (31-90m, 18m, 18m).

From Figure 3 it can be seen that in comparison with the case where the absorption coefficient of all the boundaries is 0.1, an extra SPL attenuation of 3-5dB can be obtained by increasing the absorption coefficient to 0.5, or taking one side of buildings away, or treating the ground as totally absorbent. In Figure 3 the SPL attenuation in the free field is also shown, which indicates the limit of absorbent treatment. The extra SPL attenuation caused by air absorption with M=0.015Np/m is about 2-6dB. Where M is an intensity-related attenuation constant in air. M=0.015 corresponds approximately to the air absorption at 5kHz at a temperature of 20°C and relative humidity of 40-50%.

For a given amount of absorption, it is useful to investigate the effect of strategic arrangement of the absorbers in cross-section. It has been demonstrated that the sound attenuation along the length is highest if certain absorbers are arranged on one boundary and lowest if they are evenly distributed on all boundaries.

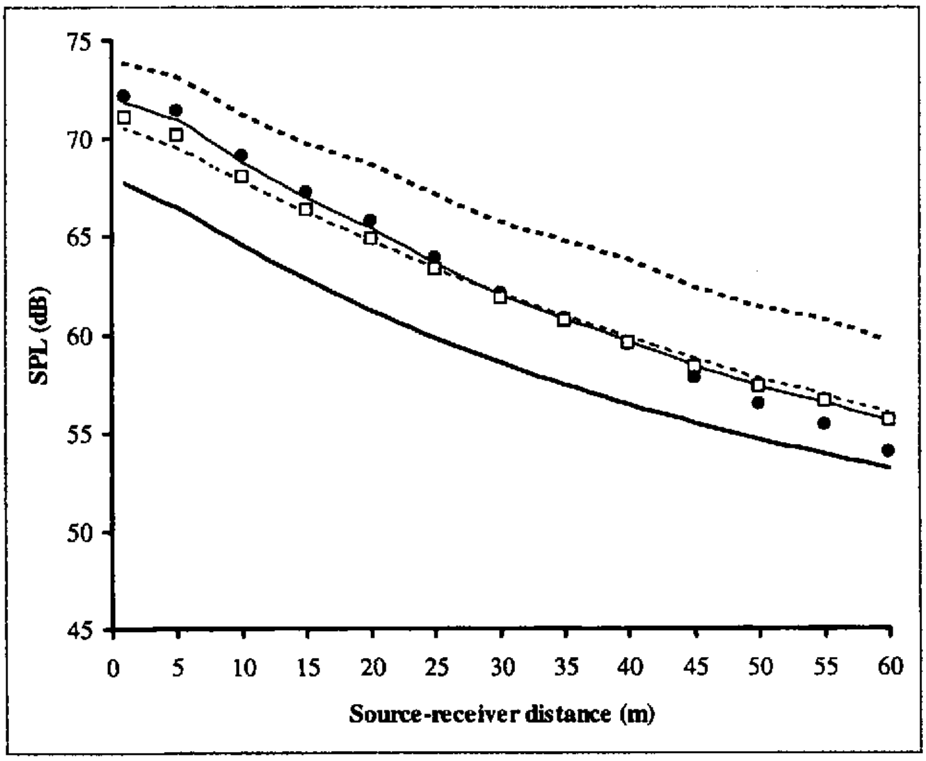

***Figure 3.** SPL attenuation along the length in six typical cases. ▪▪▪ , boundary absorption coeffcient 0.1; □, boundary absorption coeffcient 0.5; —, buildings on one side of the street only; ---, ground totally absorbent; ●, air absorption M=0.015;. ▬, free field.*

3.4 Street Geometry

To investigate the effect of street aspect ratio on the sound field, calculation is carried out with a range of street heights from 6m to 54m, which corresponds to a change in height/width ratio of 0.3 to 2.7. Again, the street length and width are 120m and 20m, and a point source is positioned at (30m, 6m, 1m). Figure 4 shows the sound attenuation along the length with four street heights, where the receivers are 1m above the ground, and the SPL is based on the average of five receivers across the width. As expected, the sound attenuation becomes less with increasing street height. In the near field, say within 10m from the source, the difference between various street heights is relatively less, which indicates the strong influence of the direct sound. With the increase of source-receiver distance, the effect of boundaries becomes more important and thus, the difference between various street heights becomes greater.

It is noteworthy that when the street height is 54m, although the street height/width ratio is rather high and the boundaries are diffusely reflective, the SPL still varies significantly along the length. For example, the sound attenuation is 19dB at source-receiver distances of 5m through to 90m.

The effect of street geometry has also been investigated for the urban element in Figure 2. With street width of 40m the SPL is about 3-8dB lower than that with street width of 10m. Similarly, the SPL is systematically increased by the increased street height. For example, with street height of 60m the SPL is about 3-6dB higher than that with street height of 20m. In the side streets the SPL variation is greater than that in the major street. This is probably because in the major street the direct sound plays an important role, whereas in the side streets the sound field is dominated by reflected energy.

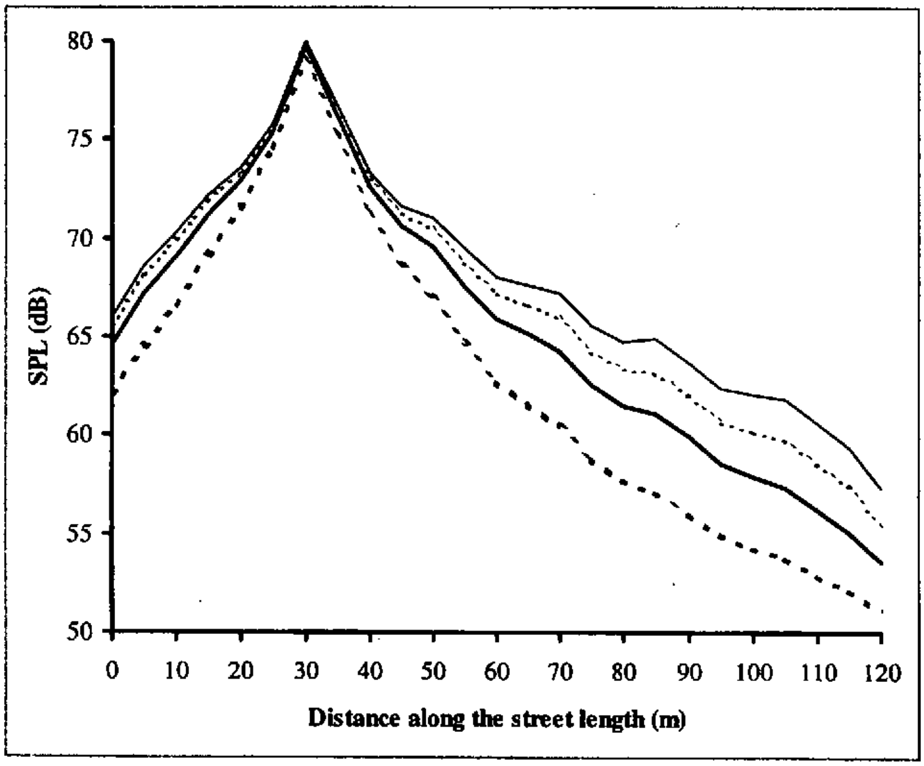

Figure 4. SPL attenuation along the length with increasing street height/width ratio. •••, street height 6m; ▬, 18m; ---, 30m; —, 54m.

3.5 Reverberation

In comparison with the application in lighting simulation and computer graphics, an important feature of using the radiosity method in acoustics is that the time factor, or reverberation, should be considered. This can increase the computation time significantly. Reverberation is an important index for the acoustic environment in urban streets [14]. On the one hand, with a constant SPL, noise annoyance is greater with a longer reverberation [15]. On the other hand, suitable reverberation time, say 1-2s, can make 'street-music' more enjoyable.

Figure 5 shows the effect of source-receiver distance, street height and boundary absorption on decay curves. In the calculation the street length and width are 120m and 20m, and a point source is positioned at (30m, 6m, 1m). By comparing Curves 3-5, where the street height is 18m and the source-receiver distance varies from 5m to 60m, it can be seen that reverberation increases systematically with increasing distance from the source. A similar phenomenon also occurs in long enclosures [11,16]. By comparing Curves 1, 4 and 6, where the source-receiver distance is 20m and the street height varies from 6m to 30m, it can be seen that reverberation increases significantly when the street height becomes higher. The effect of boundary absorption can be seen by comparing Curves 2 and 4, where reverberation is approximately doubled when the absorption coefficient decreases from 0.5 to 0.1. Overall, in the configurations in Figure 5, the RT is about 0.7-2s. This suggests that the reverberation effect is significant in such a street.

Reverberation has also been calculated for the urban element shown in Figure 2. In the side streets the reverberation is systematically longer than that in the major street. This is particularly significant for EDT. The main reason for the long reverberation in the side streets is the lack of direct sound.

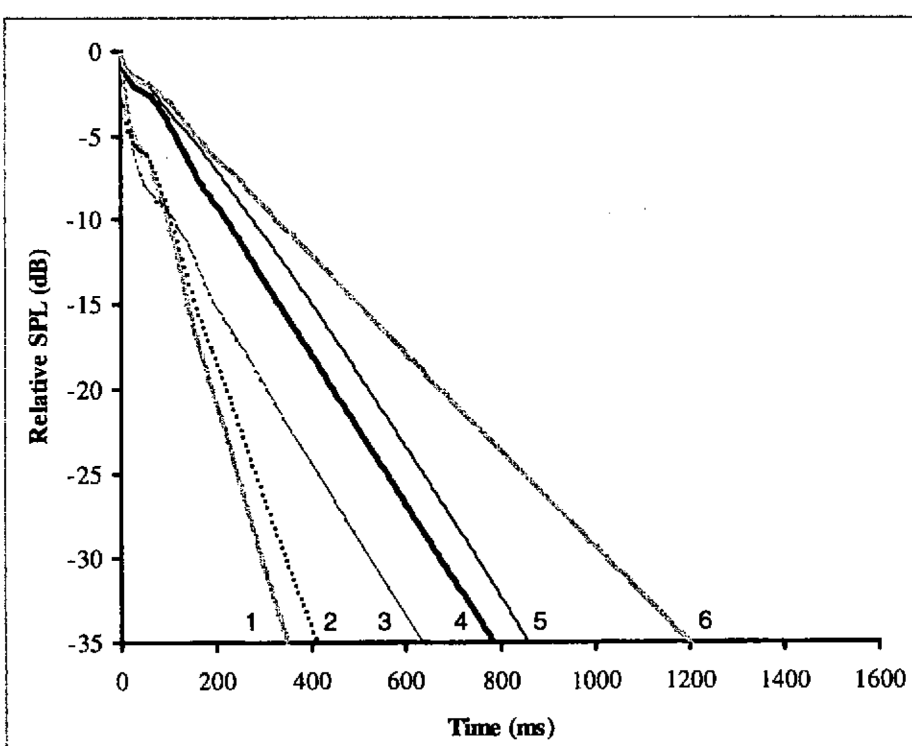

Figure 5. Deacy curves in six typical cases. Curve 1, street height H=6m and source-receiver distance SR=20m; Curve 2, H=18m, SR=20m and the boundary absorption coeffcient 0.5; Curve 3, H=18m and SR=5m; Curve 4, H=18m and SR=20m; Curve 5, H=18m and SR=60m; Curve 6, H=30m and SR=20m.

4. CONCLUSIONS

A radiosity-based theoretical/computer model has been developed for calculating the sound fields in urban streets with diffusely reflecting boundaries. Using the model, a parametric study has been carried out for a single street and for a typical urban element consisting of a major street and two side streets. The main results are:

(1) Even with diffusely reflecting boundaries, the sound attenuation along a street is significant;
(2) The sound distribution in a cross-section is rather even unless the cross-section is very close to the source;
(3) In comparison with geometrical boundaries, with diffuse boundaries the sound attenuation along a street is considerably greater, typically by 10dB with a source-receiver distance of 200m;
(4) With multiple sources or a moving source along a major street, the average SPL in a side street is typically 9dB lower than that in the major street;
(5) By increasing boundary absorption, considerable extra sound attenuation can be obtained, typically 5dB in a single street. Air absorption has a similar effect;
(6) When changing the width/height ratio of a single street, say from 0.3 to 2.7, the variation in average SPL is typically 3-8dB.
(7) With boundary absorption coefficient of 0.1, the reverberation time in a street is typically 0.7-2s. This suggests the importance of considering reverberation in urban streets.

REFERENCES

1. D. J. OLDHAM and M. M. RADWAN 1994 *Building Acoustics* **1**, 65-88. Sound propagation in city streets.
2. D. C. HOTHERSALL, K. V. HOROSHENKOV and S. E. MERCY 1996 *Journal of Sound and Vibration* **198**, 507-515. Numerical modelling of the sound field near a tall building with balconies near a road.
3. H. KUTTRUFF 1975 *Acustica* **32**, 57-69. Zur Berechnung von Pegelmittelwerten und Schwankungsgrößen bei Straßenlärm.
4. R. H. LYON 1974 *Journal of the Acoustical Society of America* **55**, 493-503. Role of multiple reflections and reverberation in urban noise propagation.
5. H. G. DAVIES 1978 *Journal of the Acoustical Society of America* **64**, 517-521. Multiple-reflection diffuse-scattering model for noise propagation in streets.
6. K. HEUTSCHI 1995 *Acustica* **81**, 26-35. Computermodell zur Berechnung von Bebauungszuschlägen bei Straßenverkehrslärm.
7. F. X. SILLION and C. PUECH 1994 *Radiosity and global illumination.* San Francisco: Morgan Kaufmann Publishers, Inc.
8. J. D. FOLEY, A. van DAM, S. K. FEINER and J. F. HUGHES 1990 *Computer graphics: principle and practice.* Reading, Massachusetts: Addison-Wesley Publishing Company, second edition.
9. G. R. MOORE 1984 *Ph.D. dissertation, University of Cambridge.* An approach to the analysis of sound in auditoria.
10. U. M. STEPHENSON 1996 *Acustica / acta acustica* **82**, 517-525. Quantized pyramidal beam tracing – a new algorithm for room acoustics and noise immission prognosis.
11. J. KANG 1998 *Acustica / acta acustica,* submitted for publication. Reverberation in rectangular long enclosures with diffusely reflecting boundaries.
12. J. KANG 2000 *Journal of the Acoustical Society of America,* **107**, in press. Sound propagation in street canyons: Comparison between diffusely and geometrically reflecting boundaries.
13. H. KUTTRUFF 1997 *Acustica / acta acustica* **83**, 622-628. Energetic sound propagation in rooms.
14. P. STEENACKERS, H. MYNCKE and A. COPS 1978 *Acustica* **40**, 115-119. Reverberation in town streets.
15. J. KANG 1988 *Chinese Noise and Vibration Control* **5**, 20-28. Experiments on the subjective assessment of noise reduction by absorption treatments.
16. J. KANG 1996 *Journal of the Acoustical Society of America* **99**, 985-989. Acoustics in long enclosures with multiple sources.