

NOISE PROPAGATION IN URBAN AND INDUSTRIAL AREAS

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SUMMARY

Simple acoustical ideas can be used to describe the direct and multiply reflected paths involved in the propagation of noise in regions with complicated shapes such as those found in urban and industrial areas. Several studies of propagation in streets, and the discrepancies between theoretical analyses and field measurements are discussed. Also a cell-model is used to estimate the general background level of noise due to vehicular sources distributed over the urban area.

INTRODUCTION

This paper describes some aspects of the propagation of sound in urban areas and in open industrial plants. Of the many factors that are important in determining noise levels due to various sources in such areas only the geometric or topographic effects will be discussed here. Sound propagation in urban areas involves multipath propagation, and reflection, absorption and scattering must all be taken into account. The geometries discussed are of interest for sources such as automobiles, construction sites, machinery in open industrial sites, and, in some cases for low-flying aircraft.

Factors such as wind and temperature gradients are not included. These are not thought to be of great importance over short distances. Atmospheric absorption is included only in the estimates of general background noise levels.

Much of the author's work that is described here was done at MIT as part of a program on Transportation Noise. The program was directed by R. H. Lyon. Much of the work of the group has been reviewed by Lyon (ref. 1); the present paper extends and complements Lyon's review. The author is grateful for the help and encouragement offered by Professor Lyon.

Each section of the paper deals with a particular approach to the problem of noise propagation. The topics include simple source models and eigenfunction models for estimating noise levels due to identifiable sources, and a cell-like model for estimating general background noise levels. Acoustic scale model experiments are discussed briefly.

Barriers such as earth berms are used quite extensively now for noise control along highways. Diffraction over barriers is a topic in itself and

is not discussed here.

SIMPLE SOURCE MODELS

Incoherent Point Sources

The most obvious and important geometric factor in sound propagation from a single point source is the 6dB/dd (dB per doubling of distance) due to geometric spreading. Salmon (ref. 2) has characterised the propagation from various shapes and arrays of incoherent point sources.

Manning and others (ref. 3) have shown how the very simple technique of adding the energies from incoherent point sources can be used very effectively in determining noise levels adjacent to certain types of open industrial plants. The technique has been used to help design new plant layouts to reduce noise levels in nearby communities.

Application to Propagation in City Streets

Noise propagation in city streets involves multiple reflections in the building facades bordering the streets. Typical field data taken by Delaney and others (ref. 4) is shown in figure 1. The L_{50} level is shown (the level exceeded 50% of the time). The source of sound is freely flowing traffic in the main artery. The variation of noise level with distance from the source is quite complicated.

Lyon's group at MIT has done considerable theoretical and experimental work on the propagation of sound in city streets, so called channel propagation (see, for example, refs.1, and 5 to 10). The results to date are encouraging yet no firm conclusions can be made about the important role that scattering seems to play in the propagation, and no theory can predict accurately all the features of experimental results such as those shown in figure 1. Several aspects of the problems involved are discussed below.

Wiener and others (ref.11), Schlatter (ref.5), and Lee and Davies (ref.6) have described the multiple reflections in channel propagation in terms of image sources along the line perpendicular to the street through the source position. None of them consider surface scattering. The noise level is estimated by adding the mean square sound pressure levels due to each source in a simple extension of Salmon's work. Sufficiently far down the street the decay must be at 6dB/dd except when the absorption coefficient α of the building walls equals one, in which case the decay (from an infinitely long line source) is only at 3dB/dd. Schlatter showed that both incoherent and pure-tone sources lead to essentially similar results provided an average of the sound level is taken for various receiver positions across the width of the street.

Lee and Davies (ref.6) summed the source and image fields numerically,

and included also the effects of propagation across intersections and around corners. All the data were reduced to a single nomogram for estimating noise levels.

Typical values obtained from the nomogram are shown in figure 1. A single source at the centre of the artery and side street intersection was used. The sound power output was chosen arbitrarily to be 105 dB. Two estimates using different values of the absorption coefficient are shown.

There are marked discrepancies between measured and estimated values particularly at large distances from the source. The houses along the street are typical British suburban two-storey semi-detached with gaps between the buildings. $\alpha = 0.2$ seems a reasonable number for the average value of the absorption coefficient of the building walls. Several factors should be included to improve the theoretical estimates. Donovan (ref.7) has suggested that the effect of scattering can be approximated by using an artificially high value for the effective absorption coefficient. But in this case the comparison between observed and estimated data for $\alpha = 0.5$ is hardly improved. The precise role that scattering plays is by no means clear. Certainly a considerable amount of scattering must be involved in Delaney's field situation.

Donovan's suggestion was made on the basis of scale model studies with artificially roughened building facades. Delaney and others (ref.12) comment that scale model experiments can only be made to reproduce full scale field data if the model building surfaces are made irregular. The role of scattering is an important one that needs further investigation.

An equally important effect not accounted for in the estimates shown in figure 1 involves the differences in spatial extents of the sources. Those sources with no line of sight along the side street are not included in the estimates. Such sources would increase markedly the sound field close to the artery but would have a negligible effect on noise levels further up the side street. Quantitative work on this aspect remains to be completed. However, preliminary estimates suggest that including no-line-of-sight sources does not explain the discrepancies completely.

In this context it is interesting to note that the nomogram of Lee and Davies predicts a drop of between 10 and 20 dB as the receiver "turns" a corner away from a source. This is consistent with measured values. However, the amount of the drop depends very much on the absorption coefficient; high absorption coefficients give large drops. This may well have a bearing on Donovan's scale model studies.

It is reasonable to ask if simple studies such as those above with stationary sources can estimate the noise levels due to flowing traffic. Kurze (ref.13) has estimated the mean and standard deviations of noise from freely flowing traffic when the receiver can see either a very long straight road or is shielded from part of the road by barriers. He showed that the value of the mean noise level can be estimated from stationary sources spaced

$1/\lambda$ apart where λ is the average number of vehicles per unit length of roadway. For long stretches of roadway the standard deviation is $1.8(\lambda d)^{-1/2}$ where d is the perpendicular distance from the observer to the road. The mean level is equivalent essentially to the L_{50} level. Higher levels such as the L_{10} level are important in determining noise intrusion. Kurze finds, as might be expected, that levels such as L_{10} and L_1 are far more sensitive than L_{50} to non-uniform traffic flows. Kurze's work did not include channel propagation, but it seems reasonable that here again mean levels at least can be estimated from stationary source distributions.

The geometry of Delaney's experiment (ref.4) is very similar to the geometry involved when a helicopter or V/STOL aircraft flies low over a city street. A receiver at street level is shielded from the noise until the aircraft is almost overhead. Pande (ref.8) and Pierce and others (ref.9) have shown that the sound level when the aircraft is overhead may be increased typically by 5 dB over the direct or open terrain level because of the multiple reflections.

OTHER MODELS FOR NOISE PROPAGATION IN STREETS

Sound propagation in corridors with absorbing walls has been discussed by Davies (ref.14). The results are applicable mainly to interior noise propagation. The sound field is described in terms of the eigenfunctions for a hard-walled corridor and each eigenfunction is expressed as a set of four plane waves. Each wave loses energy when it is reflected in absorbing material. This approximate ray tracing technique appears to work quite well close to the source. It works well also when only two opposite walls of the corridor absorb energy, and predicts correctly in this case a 3 dB/dd rate of decay at large distances from the source. However, when several walls are absorbing such as in a street (where the "top" of the corridor is open) the theory underestimates the attenuation quite considerably. Many of the results presented in reference 14 are for the most part neither adequate nor very appropriate to propagation in streets.

A different eigenfunction approach has been taken recently by Bullen and Fricke (ref.15). They attempt to account for some aspects of scattering at the building walls along the street. In particular, protrusions on buildings are regarded as constituting a change in the width of the street. An example of the geometry discussed is shown in figure 2. The walls are hard. Eigenfunction or modal expansions are written for each region with continuity of pressure and velocity used to match the expansions at the boundaries between regions. The assumption is made that coupling occurs only between a mode in region 1 and the mode in region 2 that has the closest wave number. The agreement obtained between their theory and scale model experiments is excellent for the range that was measured, namely up to eight street widths from the source. But the types of protrusions used still lead over most of the measured range to attenuation rates of less than 6 dB/dd. It remains to be seen whether the theory can be extended to include absorbing walls and a

stronger amount of scattering.

An interesting limiting case can be evaluated if the scattering is sufficiently strong that the sound field may be assumed diffuse at all points, that is, there is equal energy propagating in all directions down the street. In figure 3 only a fraction of the energy propagating in a given direction is reflected at the wall within the distance dx . From the results of reference 14 for equal energy in all directions the total power incident on the element dx is

$$P^+ \left(1 - \frac{2}{\pi} \tan^{-1} \frac{2L}{dx} \right) \approx P^+ \frac{dx}{\pi L}$$

where P^+ represents the total input acoustic power at station x . It is assumed that a fraction α of this incident power is absorbed, and the remainder of the incident power is scattered equally in all directions so as to maintain the diffuseness of the sound field. An energy balance then gives

$$P^+ \Big|_{x+dx} = P^+ \Big|_x \left(1 - \frac{dx}{\pi L} \right) + \frac{1}{2}(1-\alpha)P^+ \Big|_x \frac{dx}{\pi L} + \frac{1}{2}(1-\alpha)P^- \Big|_{x+dx} \frac{dx}{\pi L}$$

where P^- represents power propagating in the negative x direction. A similar equation exists for P^- .

The solution of the resulting pair of differential equations for P^+ and P^- gives

$$P^+ = P_{IN} \exp\left(-\alpha \frac{1}{2} \frac{x}{\pi L}\right)$$

where P_{IN} is the known power input at $x = 0$. The noise level decays linearly with distance. Attenuation such as this has been measured in coal mine tunnels by Leehey and Davies.

CELL MODEL FOR ESTIMATING BACKGROUND NOISE LEVELS

The studies above have all been concerned with estimating noise levels due to identifiable sources, even though the source may be out of sight around a corner. The residual background level that exists in any environment is that heard when no single source can be identified and when the noise seems to come from all around. Noise intrusion above this level due to isolated and specific events can cause annoyance. This residual background level corresponds approximately to the L_{90} level. A reasonable level is acceptable, and in fact

serves to mask sounds that would otherwise be intrusive.

Several field studies have been made of the background noise level. A particularly complete study is the Community Noise Survey of Medford, Massachusetts (ref.16). Theoretical estimates have been made by Shaw and Olson (ref.17) and Davies and Lyon (ref.18).

In the Shaw and Olson model the urban area is treated as a uniform, circular, spatially incoherent source of radius a that radiates power $NW/\pi a^2$ per unit area. N is the total number of sources each of power output W . Extensions to the results can be made easily to include source-free regions representing parks, for example, within an urban area. Since now contributing sources may be large distances from the receiver atmospheric absorption must be included in the model. The Shaw and Olson model leads to estimated values about 10 to 15 dB higher than the values they measured in Ottawa. The difference is attributed to a shielding factor due to buildings.

The Davies and Lyon cell model includes barriers and may be used to estimate this shielding factor. The urban area is modelled as a circular source region broken up into an array of square cells of dimension L . The cells each contain n sources of power output W . The cell walls are semi-permeable and reflect, absorb, and transmit sound. Figure 4 shows the cell-like structure in an urban area. The absorption is that due to the walls of the buildings; the average absorption coefficient of the walls of the cell is denoted by α . The transmission coefficient τ of the walls is given approximately by the ratio of street width to distance between streets. More accurate estimates would include diffraction. The reflection coefficient of the cell walls is $(1-\alpha-\tau)$.

The effective absorption coefficient $\bar{\alpha}$ for the cell accounts for both absorbed and transmitted power:

$$\bar{\alpha}A = L^2 + 4Lh(\alpha+\tau)$$

$$\text{where } A = 2L^2 + 4Lh$$

is the total surface area of a cell, and the room constant for a cell is $R = (1-\alpha)/(\bar{\alpha}A)$.

The noise level in each cell has both direct and reverberant components. The direct field can be calculated from Shaw and Olson's results. The intensity associated with the reverberant field in a cell is $p_m^2/4\rho c$ where p_m^2 is the mean square reverberant sound pressure in the m^{th} cell, ρ is density, and c is the speed of sound.

A power balance equation can be written as follows. The power removed from the reverberant field is $p_m^2 \bar{\alpha}A/4\rho c$. The power input is the contribution

$nW(1-\bar{\alpha})$ from the contained sources after the sound has undergone one reflection, plus the contributions $4nWLh\tau/A$ from the direct fields, and four contributions of the form $p_{m+1}^2 Lh\tau/4\rho c$ from the reverberant fields of the four adjoining cells.

If the number of cells in the source region is large the resulting power balance equation can be treated as a differential equation for the reverberant mean square sound pressure p^2 in the cells distant η cells from the centre of the source:

$$\frac{1}{\eta} \frac{d}{d\eta} \left(\eta \frac{d}{d\eta} p^2 \right) - \beta^2 p^2 = -nW \frac{4\rho c}{Lh\tau} \left(1 - \frac{L^2 + 4Lh\alpha}{A} \right)$$

where $\beta^2 = (L^2 + 4Lh\alpha)/Lh\tau$.

Well within the source region the approximate solution is $p^2 = 4\rho c nW/R = 4\rho c nW/MR$ where M is the total number of cells. MR represents the room constant for the whole urban area. When the direct field as calculated from Shaw and Olson is included the total mean square pressure is

$$p^2(\text{barrier}) = \rho c \left(\frac{NW}{\pi a} \right)^2 \left(1 + \frac{1}{2} \ln N + \frac{4L^2}{R} - \frac{1}{2} \ln M \right).$$

The corresponding estimate from Shaw and Olson's work is

$$p^2(\text{no barrier}) = \rho c \left(\frac{NW}{\pi a} \right)^2 \left(1 + \frac{1}{2} \ln N \right).$$

The numerical difference in these estimates typically is not large, suggesting as might be expected that most of the noise is generated by nearby sources.

The situation when the receiver is outside the source region, for example in a park in an urban area is quite different. Davies and Lyon find

$$p^2(\text{barrier}) = \rho c nW \left(\frac{L}{\pi R} \right)^2 \frac{e^{-\mu r}}{r^2},$$

where r is the distance from the source centre and μ represents the atmospheric absorption constant. Comparison with Shaw and Olson's work gives

$$\frac{p^2(\text{barriers})}{p^2(\text{no barriers})} = \frac{\bar{\alpha} A}{2 \tau L^2 (1-\bar{\alpha})}.$$

Numerical estimates of this ratio for typical values of α and τ give a barrier attenuation of 7 to 15 dB which is consistent with the values measured by Shaw and Olson.

The noise field in a traffic-free cell can be estimated, modelling, for example, the noise at an intersection when the traffic at the intersection is halted temporarily. The Davies and Lyon model gives the estimate

$$p^2 \text{ (barriers)} = \frac{16 \rho c n W L h \tau}{R(L^2 + 4Lh\alpha)} .$$

Comparison with the corresponding Shaw and Olson result again suggests a building shielding factor on the order of 10 to 15 dB.

Finally it is of interest to estimate the noise field directly. For a source density $N = 50$ vehicles per square kilometer and a power level output from each source of 105 dB re 10^{-12} Watts, the Davies and Lyon model gives estimates of 67 dB and 51 dB when sources are and are not, respectively, present in the receiver cell. These levels are considered fairly representative of measured levels.

CONCLUSIONS

Little has been added to our knowledge of urban sound propagation since Lyon reviewed work in this area three years ago. Agreement between theoretical estimates and field data in general is quite poor. The discrepancies serve to emphasize quite strongly Lyon's conclusion that scattering plays a very important role in noise propagation. Work on this aspect of the problem is beginning. Work is needed also on the statistical aspects of traffic noise in urban areas.

Several groups are finding scale model studies of use (see for example DeJong and others, ref. 10). However in view of the comments of Delaney and others (ref.12) great care must be taken to ensure that scale model results compare accurately with field data.

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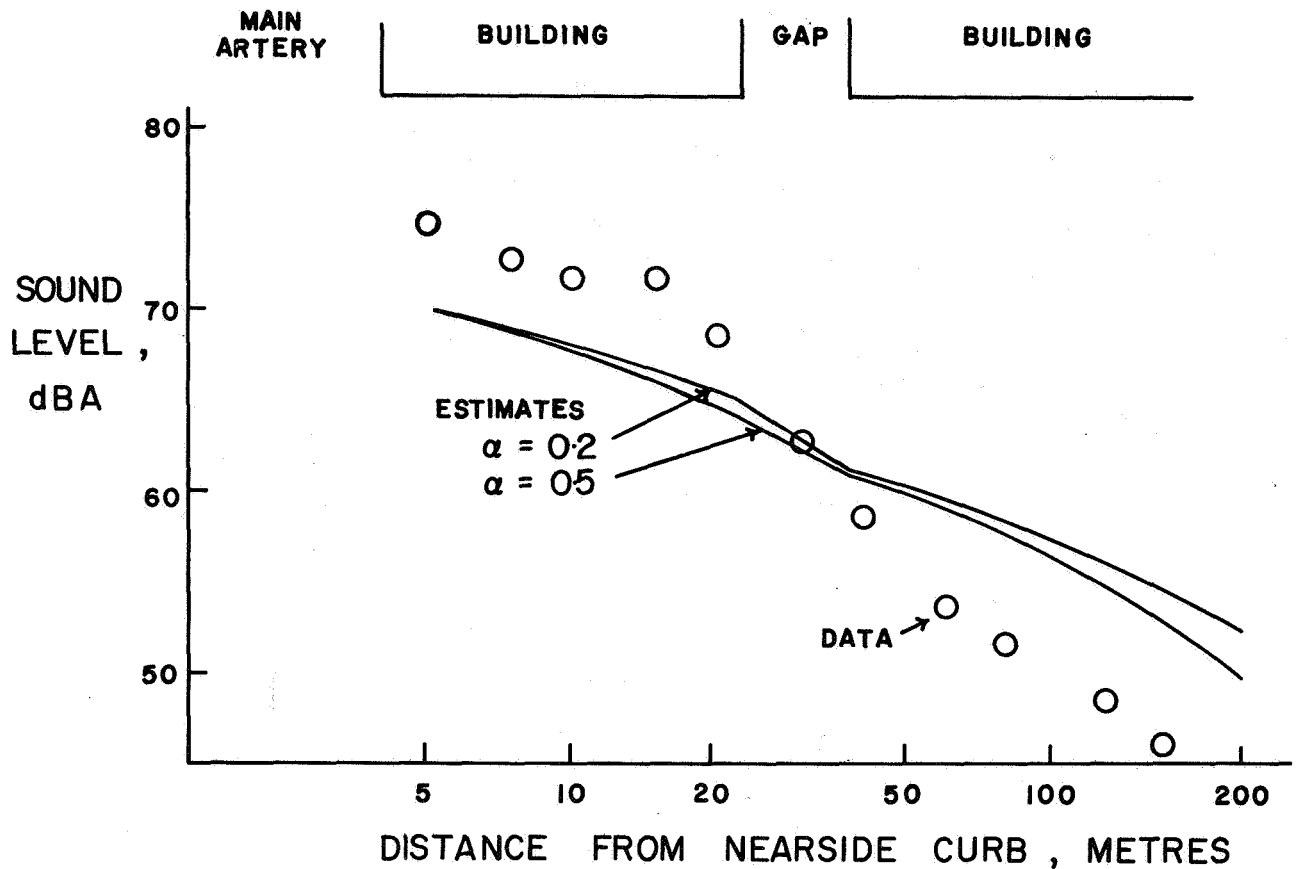


Figure 1.- Variation of noise level with distance along side street due to noise sources in main artery. Field data from reference 4; theoretical estimates from reference 6.

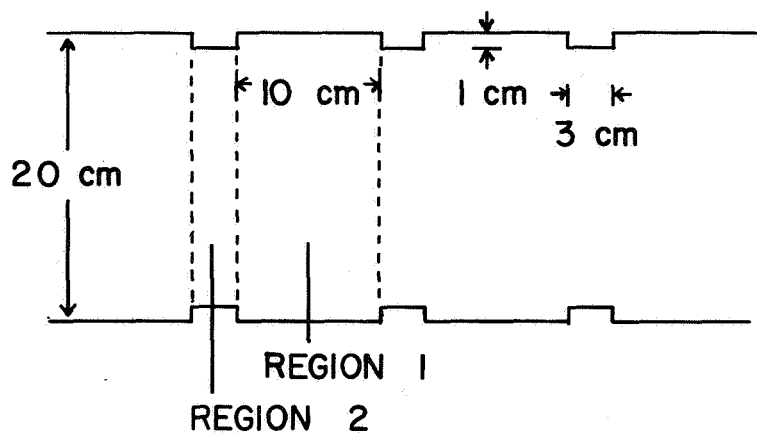


Figure 2.- Typical geometry of scale model street discussed in reference 15.

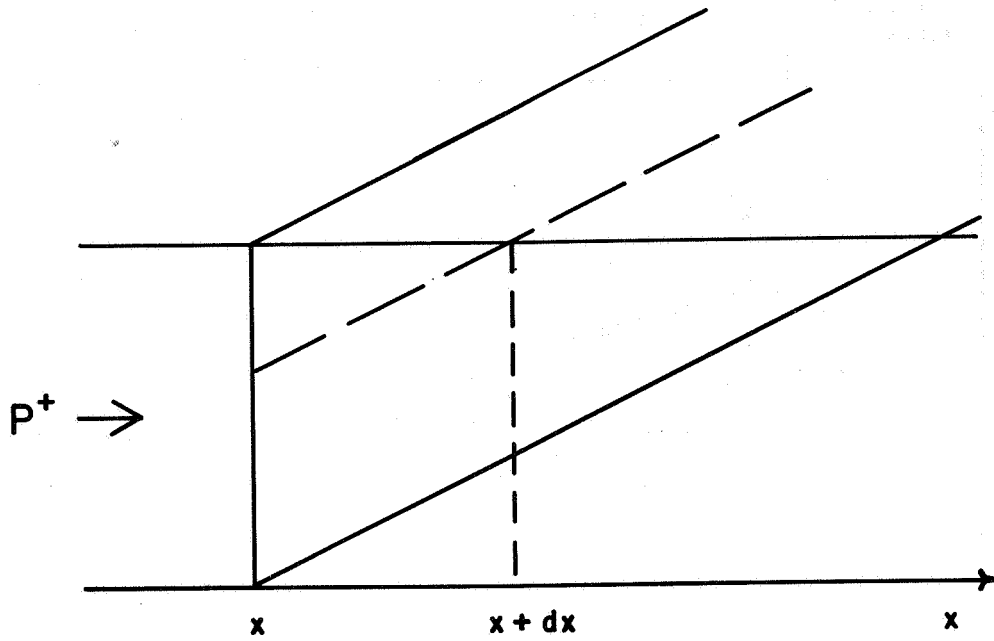


Figure 3.- Geometry to estimate power incident on wall element dx from given direction.

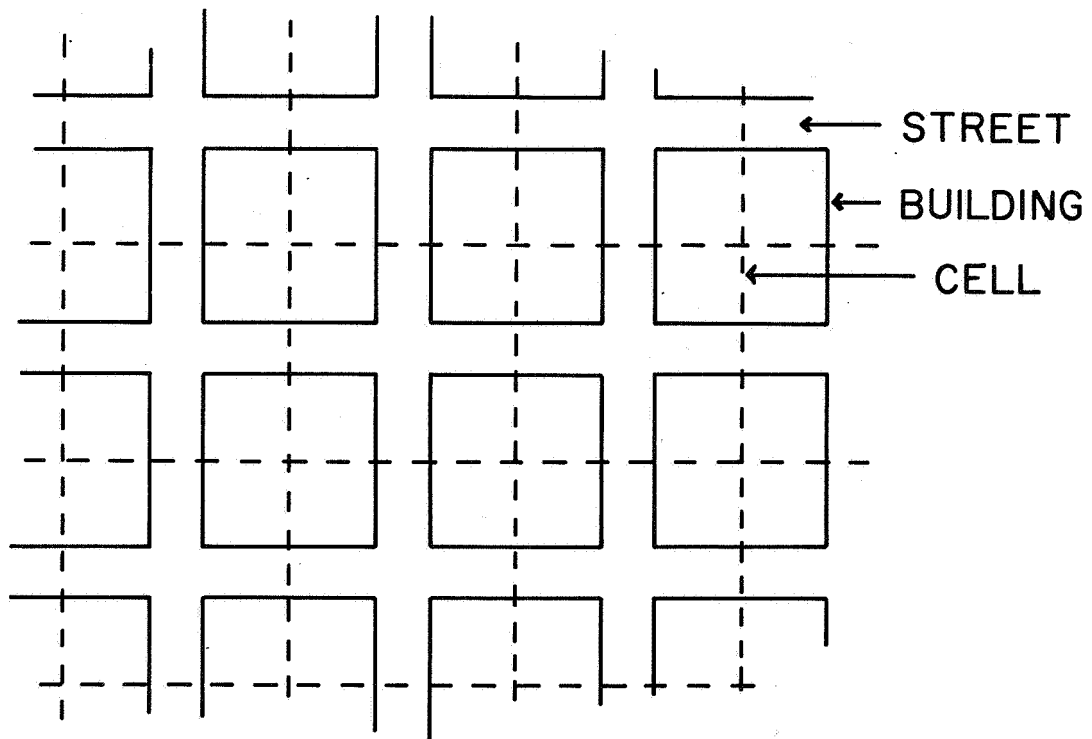


Figure 4.- Geometry of cell-like structure in urban area (ref. 18).