A cellular automaton for urban traffic noise

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Propagation of traffic noise in a city is a complex phenomenon, due to multiple reflection, diffraction, and scattering at irregular facades of buildings. These effects may be calculated with computer models based on numerical integration of the basic acoustic equations, but in practice these models can be applied only to small urban regions due to limited computer power. Here we propose a new approach for simulating urban traffic noise: a cellular automaton (CA) based on simple update rules for the configuration of cars in a city, and simple rules for propagation of sound to receivers. An example is presented for a square model city of 25 km^2, consisting of 10^6 square cells. The CA employs a time integration step of 0.3 s, and includes noise contributions from all cars in the city. The fluctuating sound level is computed for a period of 24 h, both for a receiver along a street and for a receiver that is screened by buildings. While the sound level at the first receiver shows sharp peaks corresponding to passages of cars, the sound level fluctuations at the screened receiver are much smaller as most of the sound energy comes from distant cars in this case.

1 Introduction

In spite of recent developments in computer modeling of environmental noise, reliable simulation of urban traffic noise is still a challenge [1-15]. The basic element of a simulation model is a point-to-point calculation of sound propagation (see Fig. 1). If the source and the receiver are in two different 'street canyons' (*i.e.* areas surrounded by buildings), then we have the case of 'canyon-to-canyon' propagation. Numerical studies [1] indicate that canyon-to-canyon propagation depends sensitively on many parameters, including parameters that characterize the structure of the facades of buildings. This originates from the fact that various effects play a role in urban traffic noise: multiple reflection, diffraction, and scattering at irregular building façades. It is not likely that these complex (3D) effects will be incorporated in an analytical calculation scheme in the near future. And even if such a scheme would be developed, the inevitable uncertainty of the relevant parameters would prohibit accurate deterministic model calculations for practical situations. Consequently, results of current engineering models for noise propagation should be treated with suspicion in the case of urban traffic noise.

In this article we present a new simulation model for urban traffic noise. Keeping in mind the uncertainty and complexity described above, we have devised a simple point-to-point calculation scheme as a basis for the model. The calculation scheme is more or less based on results of numerical studies [1]. The model introduces the new concept of *noise cell*.

Due to the simplicity of the model, computing times are small. Consequently, we can apply the model easily to a large city, and study noise fluctuations due to time-dependent traffic flow in the city. To simulate the traffic flow we use a cellular automaton with simple update rules for movement of cars.

The model makes it possible to find global solutions for urban traffic noise, such as a redistribution of traffic flow.

2 Description of the model

A city is represented in the model by a grid of square cells (see Fig. 2). There are two types of cells: 'building cells' and 'ground cells'. Buildings and houses are composed of building cells, and the remaining city area consists of ground cells. Cars move along lines of ground cells called streets. Receivers are also located on ground cells.

The spatial variation of the sound field *within* a ground cell is neglected. A receiver is placed at the center of a cell, but represents in fact the entire cell. Thus, the sound field is calculated on a grid of discrete *noise cells*, rather than on a continuum. The basic idea is that advanced numerical models [1] and experimental data are used to determine the sound field *within* a noise cell, and that the spatial average of this field is used to derive a simple point-to-point scheme for noise propagation. The point-to-point scheme employed in this study is described at the end of this section.

We use a cellular automaton to model the movement of cars along a street (see Fig. 3) [16]. In this study, each car has the same fixed speed of 50 km/h. We use square cells of 5 m by 5 m, and a time step of 10^{-4} h = 0.36 s, so each car moves one cell in a time step. A minimum distance of two cells between cars is assumed (at least one empty cell between cars).

We simulate a square city of 25 km^2, with 1000 x 1000 = 10^6 square cells (see Fig. 4). There are 49 north-south streets and 49 east-west streets. Each street consists of two lanes with cars moving in opposite directions. Buildings are located along all streets, so the buildings enclose square regions that are shielded from direct traffic noise.

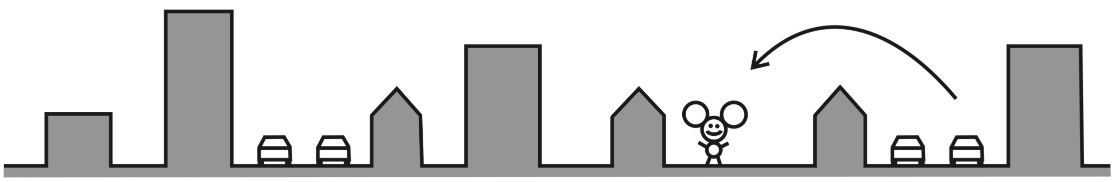

Fig.1 Illustration of a situation with urban traffic noise.
The arrow indicates canyon-to-canyon propagation of noise from a car.

If a car leaves the city at a boundary, a new car is reinserted at the opposite boundary on a road that is randomly selected from the 49 streets. For simplicity, we assume independent traffic flows on north-south streets and east-west streets: no turning of cars at crossings. At a cell at a crossing there could be two cars at the same time, moving in different directions. Of course, more advanced cellular automata may be used to simulate for example the effect of a traffic jam on noise in the city.

Initially the cars are distributed randomly over the streets, taking into account the minimum distance of two cells between cars. The total number of cars depends on the time of the day, and corresponds to the cell occupancy *P*, *i.e.* the statistical probability that a cell is occupied by a car. We assumed the following values for *P* (in %) at the hours 0, 1, …, 23 h (see Fig. 5):

P (in %) = 0.20 0.15 0.11 0.09 0.11 0.15 0.30 0.90 1.00 0.90 0.70 0.60 0.55 0.52 0.55 0.60 0.90 1.00 0.90 0.70 0.50 0.40 0.30 0.25.

This corresponds to a number of $\sum_{j=0}^{23} P_j / dt$ =1238 cars per 24 h and per lane ($dt = 10^{-4}$ h).

During a simulation the total number of cars is controlled according to the function $P(t)$, by creation of new cars at random positions on streets or annihilation of cars.

We use a simple scheme for point-to-point propagation of noise from a car to a receiver. The sound level at the receiver is given by

$$L = L_W - 10\lg 4\pi r^2 - A_{screen}\,. \qquad (1)$$

The first term on the right is the sound power level of the source, for which we use a value of 100 dB. The second term represents geometrical attenuation of sound waves, where r is the distance between the source and the receiver. The third term represents screening of sound waves by buildings between the source and the receiver. The screening term is zero if there is no building between the source and the receiver (that is, if the receiver is in the same street as the car, or if the receiver 'sees' a car passing by at a crossing). We use a fixed screening attenuation of 10 dB for all cases in which there is a building between the source and the receiver. This approach is more or less similar to the model presented in Refs. [8, 9]. Of course, more refined calculation schemes may be used, based on a spectral decomposition or a screening term that depends on the heights of the buildings and the receiver. In the present study, however, we wanted to keep the scheme as simple as possible, as the objective was primarily to demonstrate the power of the new approach. The value of 10 dB may be considered as a representative value for situations with buildings with a height of the order of 10 m, houses for example.

An important advantage of the cell model of a city is that point-to-point calculations have to be performed only once. Before the actual simulation starts we calculate a fixed matrix of point-to-point propagation for all source-receiver combinations. During the simulation the actual sound level at a receiver results from a multiplication of the point-to-point matrix by a matrix that represents the actual configuration of cars on the grid. This considerably improves the computational speed of the model.

To support the approximation of a fixed screening attenuation of 10 dB, Fig. 6 shows results of a numerical calculation with a 2D Boundary Element Method for the model city, using square buildings of 10 m x 10 m and a real normalized impedance of 40 (corresponding to an absorption coefficient of 0.1). The sound level in the receiver canyons is about 10 dB lower than the level in the source canyon. Also included are results of a simple ray model [5], with up to 60 façade reflections (30 in the source canyon and 30 in the receiver canyon), employing Fresnel weighting for finite reflecting obstacles. The ray model results are considerably lower than the BEM results.

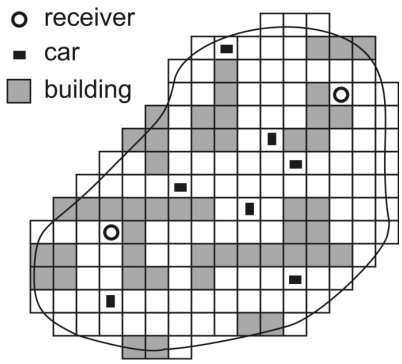

Fig. 2. Representation of a city by a grid of square cells.

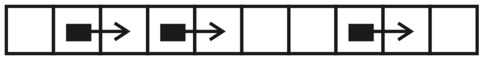

Fig. 3. Illustration of cellular automaton for cars moving along a street.

3 Results of simulations

Figure 7 shows a snapshot of a model simulation at time 8:01:12. Figure 8 shows an enlarged view of a small region of this snapshot, so that cars, streets, and buildings can be distinguished. Figure 9 shows a corresponding snapshot of the sound field in a subregion of the region in Fig. 8. The regions in Figs. 8 and 9 are located near the center of the city. Figure 9 shows that the sound level at the front of the buildings (*i.e.* on the pavement between the buildings and the streets) is higher than the sound level at the back of the buildings.

Figure 10 shows the variation of the sound level in the period from 8:00 to 8:02, for two receivers: a receiver at the front of the buildings and a receiver at the back of the buildings. The sound level at the front is higher than the sound level at the back, and also the fluctuations are larger. Figure 10 also shows that the sound at the front of the buildings is dominated by cars that are closer to the receiver than 200 m: the average level increases by only 0.4 dB if more distant cars are included. At the back of the buildings, however, distant cars have a much larger contribution: here the average level increases by 3.1 dB if distant cars are included. This means that the sound at the back of the buildings consists for more than 50% of sound from distant cars.

The highest levels in Fig. 10 are 75 dB, corresponding to a car at the cell next to the receiver (distance 5 m). Cars on the opposite lane have a minimum distance of 10 m, corresponding to a maximum sound level of 69 dB. For example, the peak of 69 dB near time 8:01:10 is caused by the car near the receiver shown in the snapshot in Fig. 10.

Figure 11 shows the variation of the sound level for a complete period of 24 h, for the receiver at the back of the buildings (indicated by the blue dot in Fig. 10). The graph also shows a running average over intervals of 6 minutes, and the analytical solution for the average sound level as a function of time:

$$L = 10\lg \sum P 10^{L_1/10} \tag{2}$$

where the sum is over all street cells, L_1 is the sound levels contribution from a car at a cell, and P is the probability (in %) that a cell is occupied by a car. The numerical average follows the analytical average closely in Fig. 11.

Figure 12 is as Fig. 11, for the receiver at the front of the buildings (indicated by the red dot in Fig. 10). The levels and the level fluctuations are higher than at the back of the buildings.

4 Further developments

The point-to-point calculation scheme employed in the present study was kept as simple as possible, since a complex scheme would not be justified with respect to the uncertainty and complexity of sound propagation in a city. Nevertheless, a slightly more complex scheme would still be justified. For example, one may use a spectral calculation rather than a broadband calculation. Further, the screening attenuation may be refined, by allowing the screening attenuation to depend on the heights of the buildings and the receiver.

The cellular automaton for traffic flow was also kept simple in this study. A more advanced cellular automaton may be used, allowing for example for speed variations of cars, or cars turning at crossings [17]. Further, a more complex cell model may be used to represent cities more realistically.

The results presented in this paper indicate that sound levels in shielded city areas are determined to a considerable extent by distant cars, so *local* noise reducing strategies may be of limited value for these areas. Global strategies such as variation of traffic flow in the city may be more effective for such areas.

This observation illustrates that the model presented in this paper may be used to develop global strategies for reducing urban traffic noise

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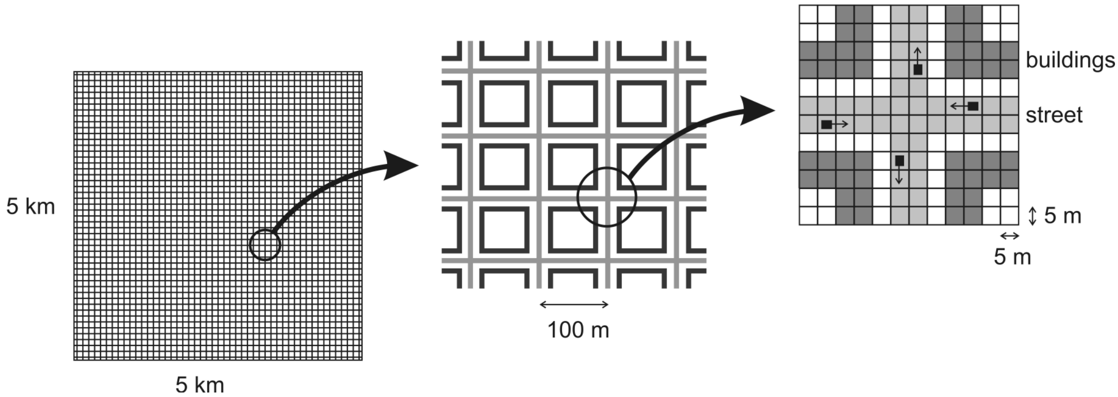

Fig. 4. Left: square model city of 25 km^2. Middle: region with streets (gray lines) and buildings (black lines). Right: region near crossing of two streets, showing the cells and cars moving along the streets.

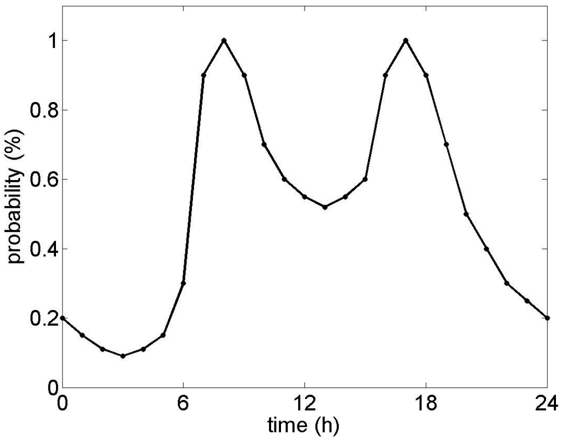

Fig. 5. Cell occupancy as a function of time of the day.

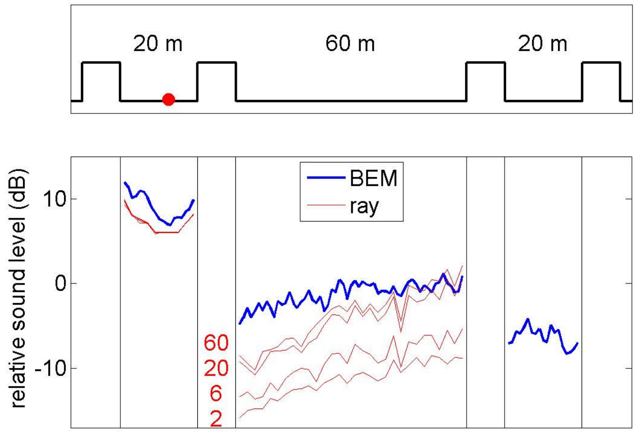

Fig. 6. Relative sound level as a function of position along a cross section of the model city shown in Fig. 4, calculated with a BEM model and a ray model with 2, 6, 20, and 60 canyon reflections. Heights of source (red dot) and receiver are 0.5 m and 0 m, respectively. The sound level is averaged over frequency range 80-730 Hz, using relative traffic noise emission levels of -8.4, -5.4, and -2.4 dB for octave bands 125, 250, and 500 Hz, respectively.

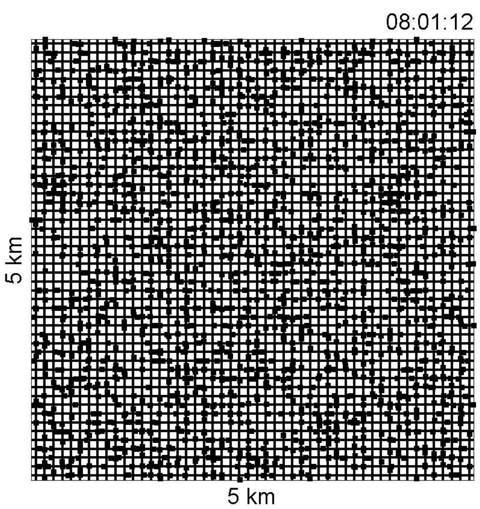

Fig. 7. Snapshot of model simulation at time 8:01:12. The lines represent streets and the dots represent cars.

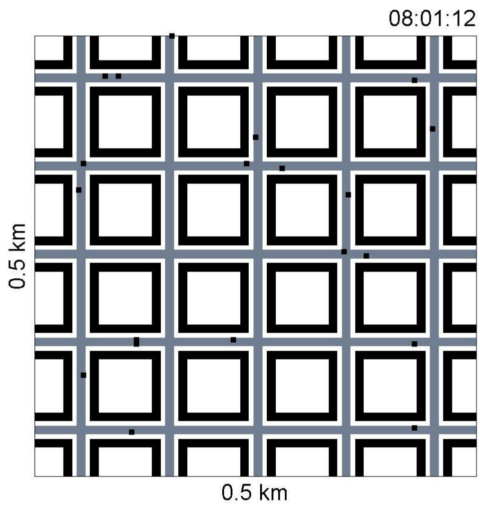

Fig. 8. Enlarged view of a small region of the snapshot in Fig. 7. Gray lines represent streets, black lines represent buildings, and dots represent cars.

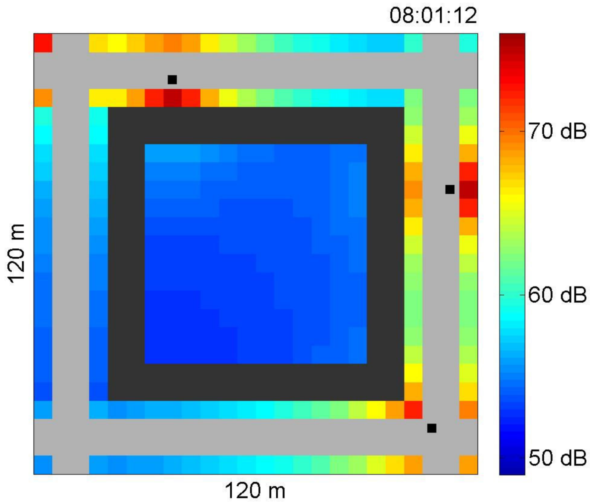

Fig. 9. Snapshot of the sound field at time 8:01:12. The region is located at the center of the city.

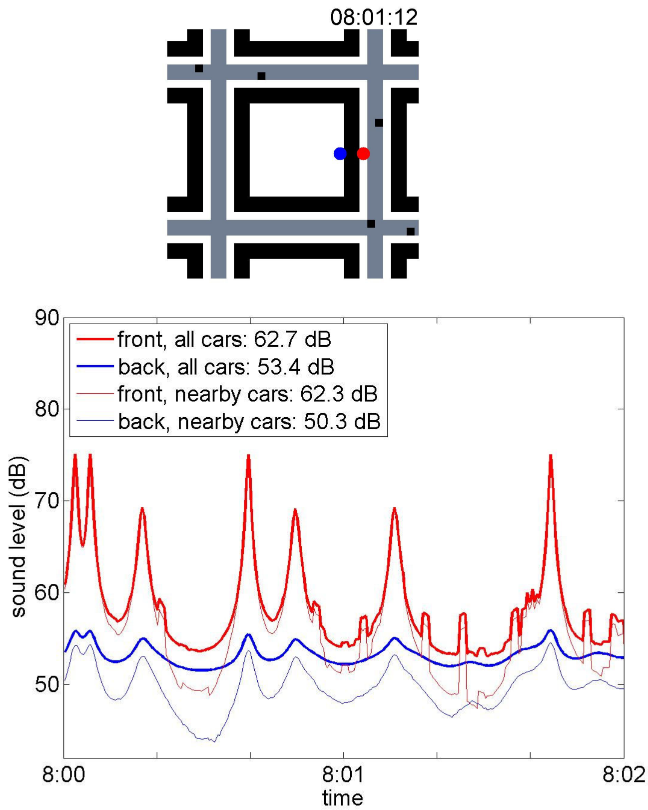

Fig. 10. Sound level as a function of time from 8:00 to 8:02, for two receivers: a receiver at the front of the buildings along a street (red dot in the snapshot above the graph) and a receiver at the back (blue dot in the snapshot). Also included is the contribution from cars within 200 m distance from the receiver. Average levels over the period of two minutes are indicated in the legend.

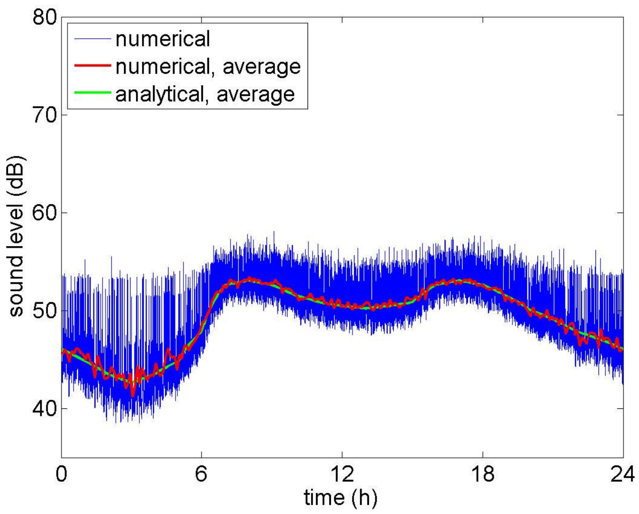

Fig. 11. Sound level as a function of time for a complete period of 24 h, for the receiver at the back of the buildings (see Fig. 10). The blue line represents the direct result of the numerical simulation. The red line represents a running average over intervals of 6 minutes. The green line represents the analytical solution for the average sound level as a function of time.

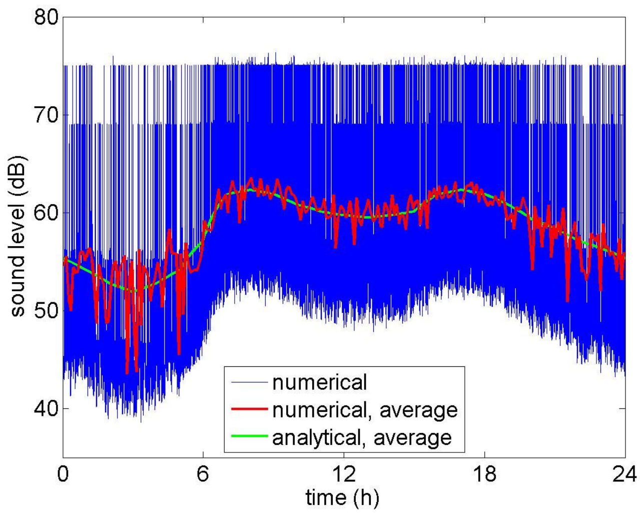

Fig. 12. As Fig. 11, for the receiver at the front of the buildings (see Fig. 10).