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Acoustic screening effect on building façades due to parking lines in urban environments. Effects in noise mapping

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ABSTRACT

European Directive 2002/49/EC indicates that strategic noise maps are the main tool for assessing the exposure of the population to environmental noise. When these are made through computational methods, the presence of lines of parked vehicles on the sides of urban streets is not usually considered, but recent studies suggest the possibility that its effect on real exposure to noise on buildings façades is not negligible. In this study, the effect of parking lines in urban street design on sound level distribution is numerically studied with the Boundary Element Method (BEM). A screening effect associated with the presence of parking lines is observed. This effect varies depending on the height for measurement and the distances between the sound source, the parked vehicles and the facade of buildings. The results show that the effect can be significant in many urban street configurations in order to determine the exposure to traffic noise of dwellings. As a consequence, by not considering it in noise mapping, the accuracy of the outcomes of noise maps conducted according to European Directive can be influenced.

1. Introduction

Noise pollution is considered today as one of the main environmental problems in cities, cited by the World Health Organization [1] as the second among a series of environmental stressors for their public health impact in a selection of European Countries. In this regard, as outlined in the European Directive 2002/49/EC [2], strategic noise maps are the main tool for assessing the exposure of the population to environmental noise.

Different strategies can be considered for noise mapping. One is the elaboration of noise maps through computerized methods, usually performed by different commercial software, whereas a second option is "in situ" measurements [3–6].

One of the references for the evaluation of noise pollution outdoors are the international standards ISO 1996-1: 2003 and ISO 1996-2: 2007 [7,8], which have helped as a basis for the development of both national and international legislation, because, among other things, they describe aspects of the calculation and measurement procedure of sound pressure level outdoors. Other references in this regard are the standards ANSI S12.9-1, ANSI S12.9-2, ANSI S12.9-3 and ANSI 12.18 [9–12], which describe the procedures for the description and measurement of environmental sound and, in the latter case, for the outdoor measurement of sound pressure level.

If it is intended to determine the noise level incident on the façades of buildings in a particular urban environment, it is known that this parameter depends on multiple factors, both temporal [13–18] and spatial [19–23]. Thus, for an adequate evaluation, it will be necessary to consider not only the characteristics of the source, but also the situation of the measuring point relative to the source and the specific urban environment of each street or façade assessed; and therefore, the effect on the measurement result that the different elements or configurations of urban environment will have [24].

In connection with this topic, many workers consider the urban design of streets as an important factor to reduce the exposure of the population to traffic noise. Echevarria et al. [25] study the impact of building shape and street geometry on people's noise exposure. Variations of up to 7.0 dB(A) occur for pedestrians depending on the building shape; substantial reductions of noise exposure at windows are obtained related to building-façade design. Jang et al. [26] use a scale-model method for measuring noise reduction in residential buildings due to vegetation in façades. The results show that the noise reduction due to the vegetated façades was less than 2 dB at pedestrian level in a two-lane street canyon. Sakamoto et al. [27] perform a numerical and experimental study on the noise shielding effect of eaves/louvers attached on building façades, concluding that the inclined type

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eaves are effective as a noise reduction measure. Castiñeira-Ibañez et al. [28] conduct a study about how building façades can be protected from transport noise using acoustic barriers based on arrays of isolated scatterers.

In this regard, some researchers consider that the results of noise mapping are very important in the design of buildings in urban streets. On the one hand, Kurra et al. [29] describe a model to determine the required insulation performances for buildings' external elements using strategic noise maps. An insulation map is proposed as a visual tool that could facilitate building noise control and could be utilized in preparation for building specifications before the construction phase and in developing the insulation codes by local administrations. On the other hand, Barclay et al. [30] present a method to quantify the interaction of building noise exposure with natural ventilation potential. Their results show that the introduction of noise reduction equal to 10 dBA resulted in reductions in cooling energy consumption that varied from 28 to 45% of the original cooling energy consumption.

In the same manner, others works study the influence of common elements in sound field propagation in urban environments. Van Renterghem [31] tries to evaluate the screening effect produced by the presence of hedges in urban streets of different cities in Europe. As a sound source, both light vehicle traffic and white noise emitted by an omnidirectional speaker were used. Hedges of different dimensions are analysed by the "in situ" and computerized methods. The conclusions obtained indicate that the analysed hedges provide a small reduction in the noise level for light vehicles at low speeds. The medians of experimental values obtained for the noise reduction in each case range between 1.1 and 2.8 dBA, depending on the characteristics of the hedge and other parameters such as vehicle speed and the height of the microphone.

Montes González et al. [20] study the effect of the variation of microphone position in height and distance to the building façade. To do this, simultaneous measurements are made using two sound level meters at several points in the city with different urban geometries. Based on the analysis of the differences of the sound level in octave bands, the results show the existence of a possible shielding phenomenon associated with the presence of lines of parked vehicles on the sides of urban streets, whose effects are important above 250 Hz, so that sound level meters placed higher record greater values of sound level. This fact is observed even for the comparison between the measurement positions at 4.0 and 6.0 m height.

Another issues of considerable relevance in noise mapping, to evaluate the results obtained by both simulations and "in situ" measurements, are the sound source characteristics. In this way, the ISO 1996-2 standard establishes some generalities to be considered for all types of sound sources, adding some considerations for certain particular types of sources, such as road, rail and air traffic, etc. However, they are related to the representativeness of the measurement with respect to the average conditions of the source in the environment under evaluation, so this standard does not assess the effect that each of the source parameters may have on the results of the measurements.

Since in this case road traffic is considered as the sound source, a parameter such as the height associated with the sound source could be of interest. In this sense, Jonasson's study [32] of the propagation model Nord 2000 for road traffic proposes that each vehicle be represented by six point sources; three situated at heights of 0.01, 0.15 and 0.30 m for modelling the rolling, engine, exhaust and aerodynamic noise. For the remaining three sources, varying heights are proposed depending on the type of vehicle. Later, a new report was published for modelling sound sources [33], related to the Harmonoise method [34]. [33] proposes that each vehicle be represented by two point sources, one simulating the contribution of road noise (0.01 m), and the other the propulsion noise (0.30 m for light vehicles and 0.75 m for heavy vehicles). The French standard NF S 31-133 [35], recommended by the European Commission for traffic noise in Directive 2002/49/EC [2], suggests that elementary point sources with a height of 0.5 m should be used for road traffic. Subsequently, Directive 2015/996 [36] proposes common methods for noise assessment that replace those indicated in Directive 2002/49/EC, where the use of an equivalent point source at a height of 0.05 m above the ground is indicated for light, heavy and two-wheel vehicles.

Another aspect of interest concerning the sound source in computational methods for the case of road traffic is the location of the equivalent source with respect to the longitudinal axis of vehicles, when they circulate in a lane. In this sense, [33] concerned acoustic modelling of sources for road traffic, using the longitudinal axis of the vehicle located in the nearest wheel as a reference point for modelling. On the other hand, Directive 2015/996 [36] indicates that the ideal case is to represent each lane with a line of sources located in the centre of each lane, which therefore correspond to the centre of the vehicle in the longitudinal direction.

Research on sound field propagation, mainly related to aspects like traffic noise and the urban environment, is extensive [25,37]. A wide variety of methods has been used to study the sound field behaviour in different types of environments: the boundary element method (BEM) [38–41], the finite element method (FEM) [42–44], the method of finite difference time domain (FDTD) [45–47], and the method of fundamental solutions (MFS) [48,49] are examples of the most common numerical methods used in this area of research.

Here, we present a study of the shielding phenomenon associated with the presence of lines of parked vehicles on the sides of urban streets [20] and its possible influence on the accuracy of the results obtained for the incident sound level on the façades of buildings when strategic noise maps are made through computational methods. Section 2 describes the numerical model used to this end by the boundary element method (BEM) in two dimensions. In Section 3, some parameters mainly related to the geometry of the street have been modified to analyse whether they are relevant in the propagation of sound outdoors.

2. Methods

Following the description of the problem and of the state-of-the-art in the introduction, let us now define the methods and parameters used for the analysis. The numerical method (BEM) will be briefly described, and an overview of the analysis performed is given.

2.1. Formulation of the BEM

As noted above, we study the phenomenon of shielding associated with the presence of lines of parked vehicles on the sides of urban roads. For this purpose, a numerical model using the boundary element method (BEM) in two dimensions has been elaborated as a first approach to the problem.

The BEM model used here is formulated in the frequency domain, solving the conventional Helmholtz equation normally used in acoustic analysis, of the form

$$\nabla^2 p(\mathrm{x},\omega) + \left(\frac{\omega}{c}\right)^2 p(\mathrm{x},\omega) = 0 \tag{1}$$

where $p(\mathrm{x},\omega)$ is the acoustic pressure at point x for an excitation frequency ω, and $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$ for 3D problems, and $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ for 2D problems. When 2D problems are considered, the effect of a harmonic source located at position x_s can be written as

$$G(x,x_s,\omega) = \frac{-i}{4} H_0^{(2)}(k_\alpha r) \quad (2)$$

where $r\|x - x_s\|$ and $k_\alpha = \frac{\omega}{c}$.

The problem to be solved in this paper concerns a spatially uniform acoustic medium bounded by one horizontal flat surface, simulating a rigid ground, and by a vertical surface, simulating the façade of a building. Obstacles to the propagation of sound are placed inside the acoustic medium. The pressure field defined by Eq. (2) needs to be reformulated to satisfy the boundary conditions: null normal velocities at the horizontal flat surface of the ground and at the rigid vertical façade. Under these conditions, the Green's function can be written using the image source method as

$$G_4(x,x_0,\omega) = \sum_{j=1}^{NS} \frac{-i}{4} [H_0(k_\alpha r_j)] \quad (3)$$

in which $NS = 4$,

$$r_1 = \sqrt{(x - x_0)^2 + (y - y_0)^2}$$

$$r_2 = \sqrt{(x - x_0)^2 + (y + y_0)^2}$$

$$r_3 = \sqrt{(x + x_0)^2 + (y - y_0)^2}$$

$$r_4 = \sqrt{(x + x_0)^2 + (y + y_0)^2}$$

The classical boundary integral equation can be derived from the Helmholtz equation in the frequency domain by applying the reciprocity theorem, leading to:

$$C\,p(x_0,\omega) = \int_\Gamma q(x,\omega,\mathbf{n})\,G_4(x,x_0,\omega)\,d\Gamma - \int_\Gamma H_4(x,x_0,\omega,\mathbf{n})\,p(x,\omega,k_z)\,d\Gamma + p_{inc}(x_0,x_s,\omega) \quad (4)$$

where G represents the Green's function for the pressure defined before, and H is its first derivative with respect to the normal direction to the boundary Γ; similarly, p and q are respectively the pressure and its first derivative in the normal direction to the boundary ($\mathbf{n}$), at point x. The factor C equals 1/2 if $x \in \Gamma$, and 1 for points not in the boundary but within the domain ($x \in \Omega$). $p_{inc}(x_0, x_s, \omega)$ represents the effect of an emitting source within the propagation medium, and is also given by Eq. (3).

For a generic problem, in which the boundary is discretized into N straight boundary segments (elements), each of the previous equations can be defined at each nodal point i, and the relevant integrals can be transformed into discrete summations as

$$C\,p(x_i,\omega) = \left[\sum_{m=1}^{N} q(x_m,\omega,\mathbf{n}) \int_{\Gamma_m} G(x,x_i,\omega)\,d\Gamma_m\right] - \sum_{m=1}^{N}\left[p(x_m,\omega)\int_{\Gamma_m} H(x,x_i,\omega,\mathbf{n})\,d\Gamma_m\right] + p_{inc}(x_i,x_s,\omega) \quad (5)$$

where $\mathbf{n}_k$ represents the outwards-pointing normal to the element k. If, as here, only rigid objects are discretized using the BEM, Eq. (5) can be simplified, and written as

$$\sum_{m=1}^{N}\left[p(x_m,\omega)\int_{\Gamma_m} H(x,x_i,\omega,\mathbf{n})\,d\Gamma_m\right] + C\,p(x_i,\omega) = p_{inc}(x_i,x_s,\omega) \quad (6)$$

Applying Eq. (6) at each nodal point, a system of N equations on N unknowns can be assembled; its solution leads to the nodal acoustic pressures at each node of the BEM model. Later, these nodal pressures allow the calculation of the acoustic pressure at any point within the acoustic domain as

$$p(x_i,\omega) = -\sum_{m=1}^{N}\left[p(x_m,\omega)\int_{\Gamma_m} H(x,x_i,\omega,\mathbf{n})\,d\Gamma_m\right] + p_{inc}(x_i,x_s,\omega) \quad (7)$$

2.2. Definition of the analysis setup

In order to validate the developed BEM model in aspects related to the propagation of the sound wave, an urban environment has been selected to be modelled. A series of "in situ" measurements were carried out under different configurations, following the guidelines of ISO 1996-2, both normative and those indicated in Annex B (informative). From the results of the measurements and simulations, differences of sound levels, global and in octave bands, have been calculated between the positions on the façade, free field and 0.5 m from the façade.

Subsequently, the BEM model was applied to a situation in which, for a given geometrical configuration of a street used as the reference, different hypotheses have been considered for the distance between the sound source, the façade of the building and the position of the shielding associated with the presence of a parking line.

In relation to the sound source, road traffic has been considered. Since this is a two-dimensional simulation, a point source has been used. To obtain the values of global sound levels for traffic noise spectrum, a correction to pink noise was considered adding up the value of traffic noise spectrum in each octave band, obtained as an averaging energy of the corresponding third octave bands of the traffic noise spectrum proposed in EN 1793-3 [50].

Another aspect related to the sound source is the height of the point source. In this study, a height of 0.30 m [32–34] is used. In the simulations, a vehicle has been placed as though it were parked in a linear configuration. A vehicle with front dimensions of 1.5 × 1.5 m was used. Bearing in mind that this is a simulation in two dimensions, it was decided not to include the vehicle's wheels, so that they do not block the propagation of sound waves through the space between the bottom of the vehiclés body and the ground.

The simulations were conducted in two blocks considering some important aspects for urban street design and noise mapping that could influence the sound level distribution on the building façades. In block I, the effect of varying the distance between the parked vehicle and the sound source is studied. In this case, for a fixed position of the parked vehicle with respect to the façade under evaluation (4 m), the relative position of the sound source to the vehicle (at 0.5, 1, 1.5, 2, 4, 8, 16 and 24 m) is changed. In block II, for a fixed position of the sound source, the effect of varying the distance between the reflective façade and the parked vehicle (1, 2, 4, 8, 16 and 24 m) is analysed. In this case, two source positions with respect to the façade (16 and 29.7 m) are considered. In both blocks, the point source is placed at a height of 0.3 m.

In the two blocks indicated, the results were evaluated placing a vertical line of microphones located on the reflective surface that simulates the façade of a building. These receivers were located between 1.5 and 8 m above the ground (Fig. 1).

3. Results and discussion

3.1. Verification of BEM model

Initially, a process of verification of the BEM model was made, for which a comparison of results obtained by "in situ" measurements in an urban environment to those obtained by simulation

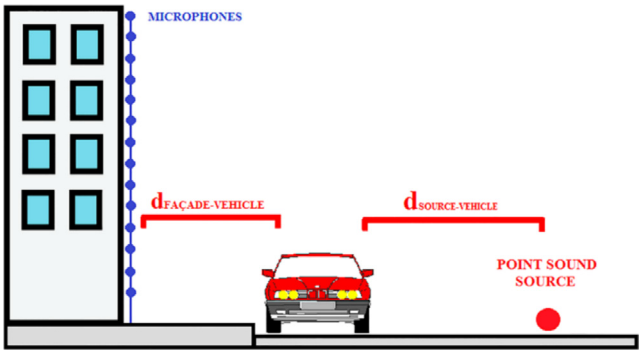

Fig. 1. General configuration for simulations.

was performed. Fig. 2 shows a graphical scheme of the measurement environment. The measurements were performed simultaneously with three sound level meters. Two were located in positions close to the façade (Fig. 2a); the first microphone was flush mounted on the facade and the second was 0.5 m away. The third microphone was placed in free field conditions (Fig. 2b), at the same distance from the source that the microphone located on the façade. In the simulations, a point source located in the centre of all the lanes was used.

The values obtained by measurements and simulation for the difference in equivalent sound level, for various configurations of sound level meters, are shown in Tables 1–3. In the case of "in situ" measurements, the difference in sound levels refers to the average equivalent level of five measures of 5 min each.

As can be seen, the results for global values with the BEM model are quite close to those obtained through the "in situ" measurements. In the analysis in octave bands, good agreement between the values obtained by measurements and simulation is also appreciated. However, in the bands of 125 and 250 Hz, some significant differences are detected for the two cases in which one of the microphones is located 0.5 m from the façade. In any case, the degree of agreement between the measured values and the results obtained by simulation can be considered as acceptable, since it is a two-dimensional BEM model.

3.2. Variation of source-vehicle distance

In this section, the effect of varying the distance between the parked vehicle and the sound source is studied ($d_{SOURCE-VEHICLE}$). For this, given a fixed position of the parked vehicle with respect to the façade under evaluation (4 m), the position of the sound source is varied, considering distances to the parked vehicle of 0.5, 1, 1.5, 2, 4, 8, 16 and 24 m.

The results obtained in the vertical array of microphones located on building façade for the difference in overall sound levels between configurations without and with vehicle, and for different distances between the sound source and the vehicle, are represented in Fig. 3 for some different microphone heights.

Several conclusions can be drawn from the results shown in Fig. 3:

(a) For distances between the source and the parking line not exceeding 4 m, and for many heights, there are important differences between the situations with and without a parked vehicle. For example, more than 3 dB for 2 m height. In the case of low source-vehicle distances, these important differences occur even at the maximum height of 8vm.
(b) In the cases of receivers located at heights of 1.5 and 2 m, curves for the differences of sound levels have values, for all distances, of between 3 and 6 dB. At these heights, a large screen effect is detected by all the source-vehicle distances studied.
(c) For the remainder of the heights, a decrease of the screening effect can be observed as the distance between the source and parked vehicles increases. As expected for a barrier, the reduction of this effect occurs at lower heights when the distance is increased.
(d) Differences in the behaviour of the barrier effect between the heights of 1.5 m and 4 or more meters is of great importance in the case of assessing the impact of noise on the population through measures in an urban environment. Note that for any distance greater than 4 m, differences between the results of the screen effect for 1.5 and 4 m are very important. We should consider that these configurations correspond to many secondary avenues of cities all over the world.
(e) On the other hand, we note the significant difference observed between the predicted values 4 and 8 m in height in the range of distances between the source and the parked vehicle for 1.5–2 m. We should consider that these configurations correspond to many streets of European cities with three-storey buildings. In this regard, it is important to indicate that 4 m is the reference height for the calculations for

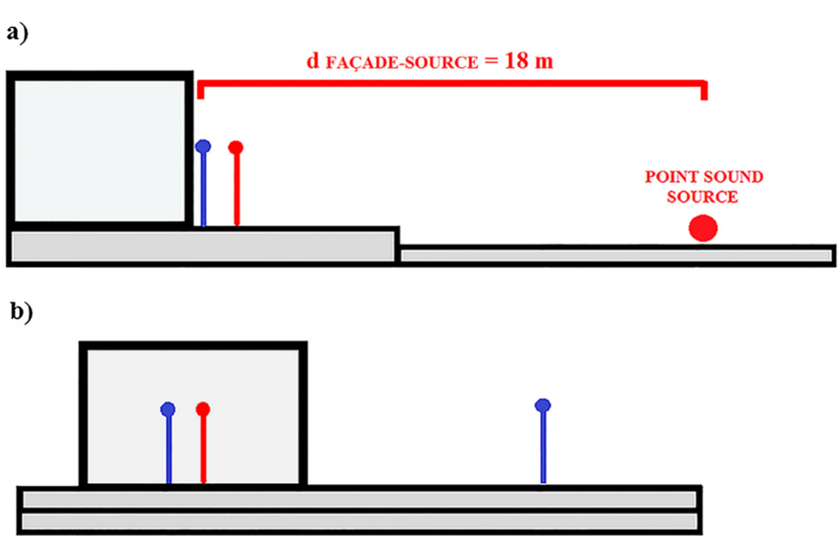

Fig. 2. Lateral view (a) and front view (b) of the environment where verification measures of the BEM model were carried out and the three microphone positions.

Table 1
Difference in sound levels between the microphones located on the façade and in free field.

	$\Delta L_{P\ FAÇADE\text{-}FREE\ FIELD}$ (dBA)						$\Delta L_{P\ OVERALL}$ (dBA)
f (Hz)	125	250	500	1000	2000	4000	
"In situ" measurements	6.8	5.6	5.8	6.2	6.1	5.0	6.3
Simulation (traffic noise)	7.3	6.0	6.5	6.3	6.3	6.0	6.4

Table 2
Difference in sound levels between the microphones located 0.5 m from the façade and in free field.

	$\Delta L_{P\ 0.5\text{-}FREE\ FIELD}$ (dBA)						$\Delta L_{P\ OVERALL}$ (dBA)
f (Hz)	125	250	500	1000	2000	4000	
"In situ" measurements	4.1	0.4	2.4	2.9	3.2	2.9	2.9
Simulation (traffic noise)	1.6	3.1	3.1	2.9	2.7	3.0	2.9

Table 3
Difference in sound levels between the microphones located on the façade and 0.5 m from it.

	$\Delta L_{P\ FAÇADE\text{-}\ 0.5}$ (dBA)						$\Delta L_{P\ OVERALL}$ (dBA)
f (Hz)	125	250	500	1000	2000	4000	
"In situ" measurements	2.7	5.3	3.4	3.3	3.0	2.1	3.3
Simulation (traffic noise)	5.7	2.9	3.4	3.5	3.6	3.0	3.5

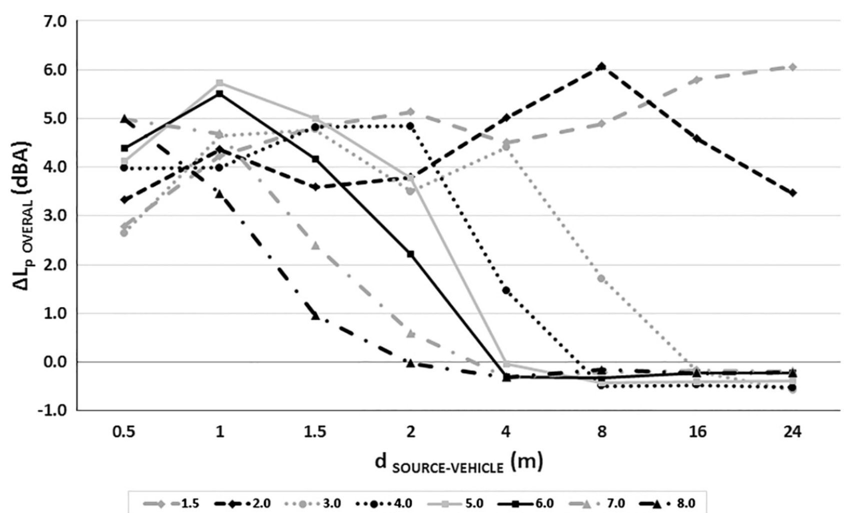

Fig. 3. Difference in overall sound levels between configurations with and without a vehicle for different microphone heights.

noise mapping using models, to compare calculations and measurements and, consequently, to validate the calculation models.

(f) Another interesting result can be observed in Fig. 3. Two combined effects with an opposing trend take place: the screening effects indicated previously and a transmission through the gap located between the ground and the vehicle. These opposing effects cause a maximum of the screen effect for a given height that does not match with the shortest source-vehicle distance. The source-vehicle distance at which this maximum is observed decreases as the height of receiver on the façade increases. Note that at 8 m height, an appreciable effect does not exist of sound energy transmission through the gap and the curve for the screening effect related to the source-vehicle distance that is expected for a barrier.

Then, the behaviour in octave frequency bands for some selected heights (i.e. 1.5, 4 and 8 m) is analysed. The results obtained for the difference in sound levels in a receiver located on the façade at a height of 1.5 m are shown in Fig. 4.

From the results shown in Fig. 4, some conclusions can be drawn. Globally, important screening effects can be observed for all the octave bands at all the considered source-vehicle distances. In the octave bands of 125, 250 and 500 Hz, a similar trend can be seen. However, the values of the difference in sound levels at 250 and 500 Hz are around 3 or 4 dBA above those recorded at 125 Hz for most of the source-vehicle distances analysed. In the octave band of 1 kHz, an increase in the difference in sound levels is observed as the distance between the sound source and the vehicle increases. The value of −3.3 dB at 0.5 m from the source may be due to the geometric configuration of the emitting vehicle, the parked vehicle and the gap between the ground and the parked vehicle. This result is particularly interesting and is not detected at any other frequency, so we believe it should be analysed in more detail in following studies. Finally, in the bands of 2 and 4 kHz, a similar pattern to the octave bands of 250 and 500 Hz is observed, although some interference phenomena appear.

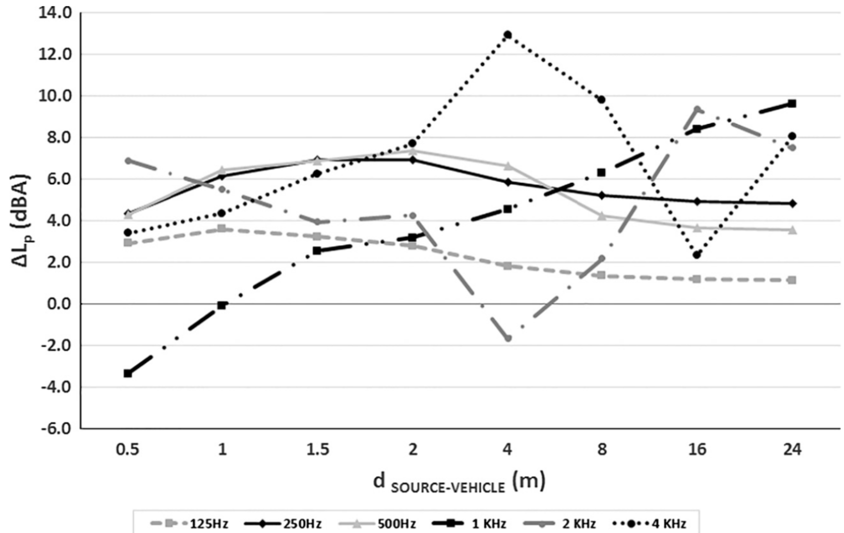

Fig. 4. Difference in octave band sound levels between configurations with and without a vehicle at 1.5 m.

The results obtained for the difference in octave band sound levels in a receiver located on the façade at a height of 4 m are shown in Fig. 5. The screening effect that occurs when the distance between the source and the parking line is between 0.5 and 2 m for the octave bands of 1, 2 and 4 kHz is remarkable. In addition, we note the important difference between the behaviour at this height in the octave band of 1 kHz with respect to 1.5 m (Fig. 4). Furthermore, the results obtained in the bands of 250 and 500 Hz may indicate the existence of interference effects between direct and reflected waves.

At 8 m height (Fig. 6), it can be seen that, from a distance of 2 m, the effect of parked vehicles becomes negligible in most octave bands. On the other hand, in the case of small distances between the source and the parking line, this effect is important across nearly all bands.

As an example, the results of the simulations performed with and without a car in the octave band of 1 kHz are shown in Fig. 7 for distances of 0.5, 2 and 16 m between the source and the parked vehicle. Only the area of interest is shown, between 0 and 6 m from the façade.

The first thing to note from Fig. 7, which has not been seen clearly enough in the figures hitherto shown, is the important influence of the parked vehicle on the existing sound field in the area between the façade and the parking line. This effect, as we know, is not considered at present in strategic noise maps made under the European Directive. Another interesting aspect that can be seen in Fig. 7 is the effect of sound transmission through the gap located between the ground and the bottom of the vehicle. In this regard, a decrease of this effect as the distance between the sound source and the parked vehicle increases is seen. Furthermore, it is noted that the screening effect becomes particularly noticeable at all heights when the source is close to the parked vehicle (Fig. 7a), it remains significant between 1.5 and 6 m height at a distance of 2 m (Fig. 7b), and at 16 m (Fig. 7c), it is only important for heights below 2 m.

To sum up, the shielding effects on building façades associated with the presence of parked vehicles, under the conditions discussed in this section, may be of importance even at heights of 8 m, mainly on narrow streets. As is known, this urban configuration is common in many European cities, especially in the streets of residential areas or neighbourhoods of central areas.

3.3. Variation of the façade-vehicle distance

In this new section, for a fixed position of the sound source, the effect of varying the distance between the façade of dwellings and

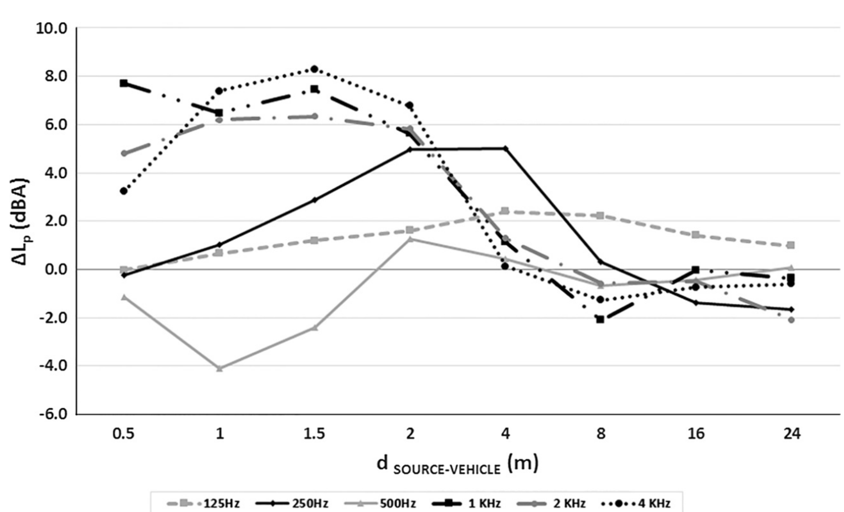

Fig. 5. Difference in octave band sound levels between configurations with and without a vehicle at 4 m.

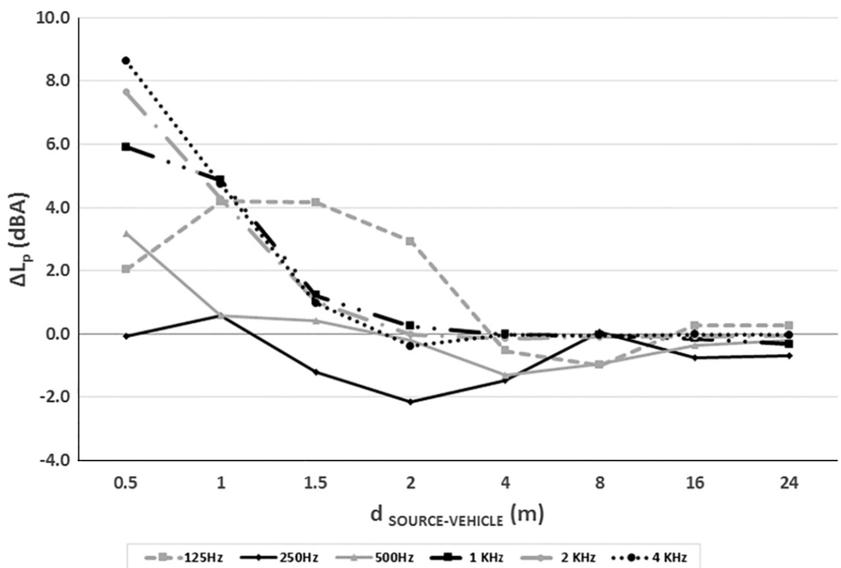

Fig. 6. Difference in octave band sound levels between configurations with and without a vehicle at 8 m.

the parked vehicle (for values of d $_{\text{FAÇADE-VEHICLE}}$ of 1, 2, 4, 8, 16 and 24 m) is now studied. Two source positions with respect to the façade (16 and 29.7 m) were used. In the first case, 8 m is the maximum distance studied between the façade and the parked vehicle.

3.3.1. Sound source located 16 m from the façade

The results obtained on the building façade for the difference in overall sound levels between configurations with and without a vehicle, for a fixed position of the sound source at 16 m from the surface, are shown in Fig. 8 for different microphone heights.

From the results shown in Fig. 8, it can be concluded that:

(a) In general terms, a trend of the difference in sound levels to increase with the distance between the façade and vehicle is noted. Of course, increasing this distance means a greater proximity of the vehicle to the sound source.
(b) In spite of this general trend, the shape of the curve varies depending on the height of the receiver.
(c) In the case of the receiver located at 1.5 m, the difference in sound levels is fairly constant, regardless of the distance between the façade and the vehicle, taking values ranging between 4.8 and 6.4 dBA. For the same reasons indicated in Section 3.2, the large difference (over 5 dB) that exists between the results found at 1.5 m and 4 m height up to a façade-vehicle distance of 4 m is of great interest.
(d) In receivers located at heights between 2 and 3 m, a progressive increase of the screening effect with distance between the façade and the vehicle is observed.
(e) For other receivers placed at heights between 4 and 8 m, the difference in noise levels is negligible until a distance of 4 m between the façade and the vehicle, increasing from this point onward. This increase is higher for those receptors located in lower positions.
(f) It is interesting to highlight the difference of 3 dB obtained for a height of 4 m on the façade and a distance of 8 m between the façade and the vehicle. For the distance between the source and the façade under consideration (16 m), this configuration can be considered as normal in avenues with relatively wide sidewalks. The relevance of these results must be taken into account considering that 4 m is the reference height in noise mapping using calculation models.

Then, the behaviour in octave frequency bands for some selected heights (1.5, 4 and 8 m) is analysed. In this case, due to the lack of relevance (see Fig. 8), the results obtained at 8 m are not shown. The results obtained for the difference in sound levels in a receiver located on the façade at a height of 1.5 m are shown in Fig. 9.

From the results shown in Fig. 9, for a receiver located on the façade at a height of 1.5 m, it can be concluded that, in the octave band of 125 Hz, the screening effect is relatively low, reaching a maximum value near 2 dBA at the façade-vehicle distance of 2 m. In the remaining octave bands, with a variable behaviour in relation to the façade-vehicle distance, the screening effect is relevant. In general, the values range between 4 and 8 dBA. Additionally, some interference effects can be seen for different octave bands.

For the height of 4 m (Fig. 10), in general, for the studied configurations where the distance between the source and the parking line is less than 8 m, the screening effect can be considered negligible in an analysis of the octave bands. However, in the case of a distance between the source and vehicles of 8 m, it is significant in most octave bands.

As an example, the results of the simulations performed with and without a vehicle in the octave band of 1 kHz are shown in Fig. 11 for distances of 1, 2 and 8 m between the façade and the parked vehicle. Only the area of interest is shown, between 0 and 10 m from the façade.

Again, the modification of the sound field that involves the presence of a parking line can be seen clearly in Fig. 11. Because of the distance between the source and façade, it can be verified that the incident sound wave may be considered planar. In the images of Fig. 11 for the octave band of 1 kHz, it can be seen that as the distance between the façade and the parked vehicle increases, for the same source position, the screening effect becomes greater in the zone next to the façade. In the case of the distance between vehicle and façade of 1 m (Fig.11a), the screening effect is localized just behind the vehicle and the remainder of the sound field practically remains invariant. In the case of 2 m (Fig.11b), a modification of the shape of the sound field behind the vehicle is observed, which is affected up to a height of 4 m. In the case of 8 m (Fig. 11c), the modification of the sound field is very important in the whole area behind the vehicle, which clearly affects the façade up to a height of about 4 m.

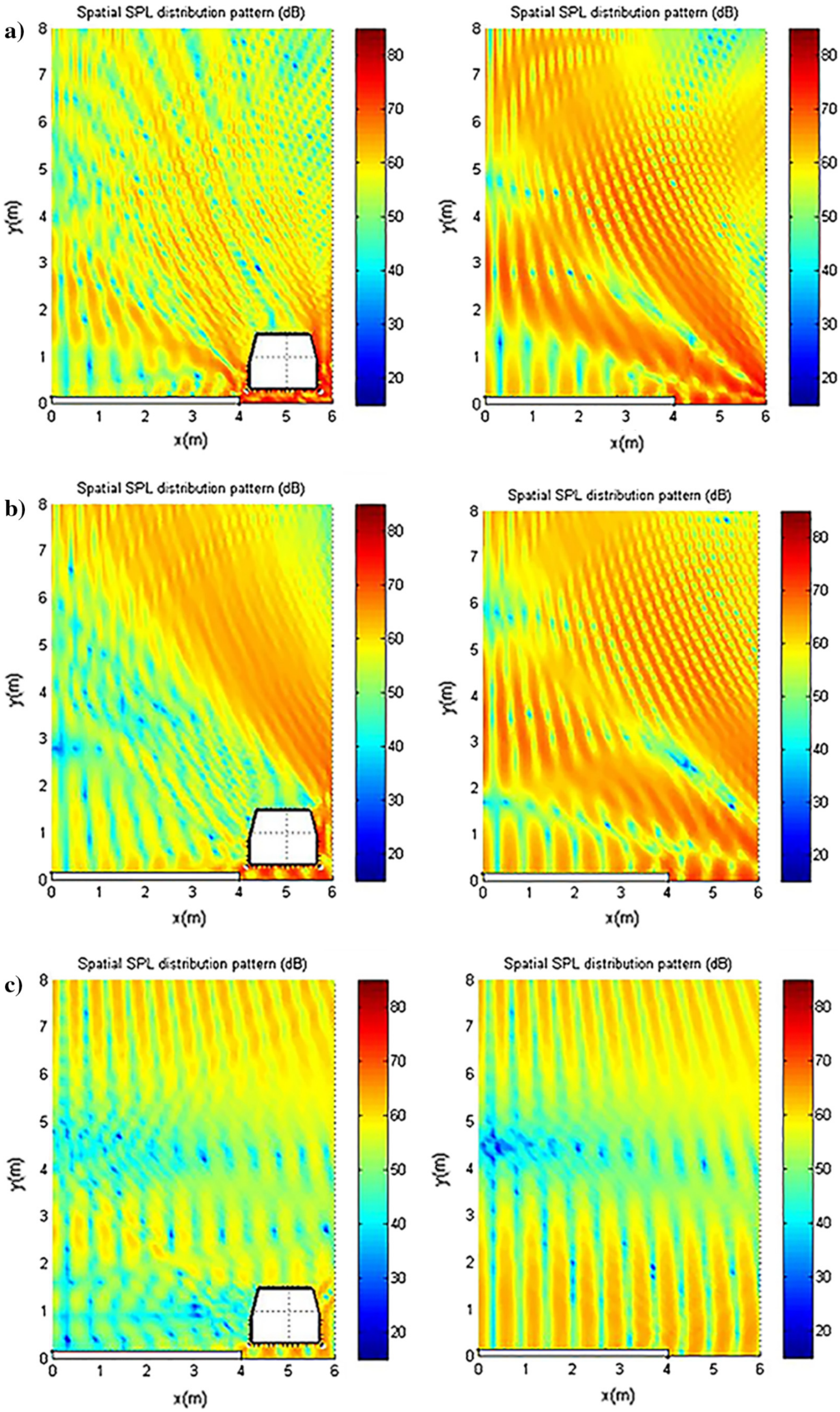

Fig. 7. Simulation with and without car in the octave band of 1 kHz with source at 0.3 m height and at distances of (a) 0.5 m, (b) 2 m and (c) 16 m from the vehicle.

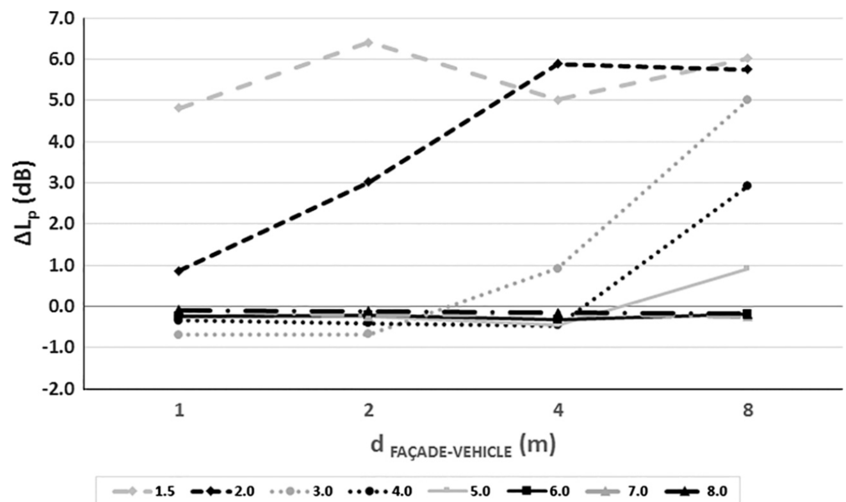

Fig. 8. Difference in overall sound levels between configurations with and without a vehicle for different microphone heights.

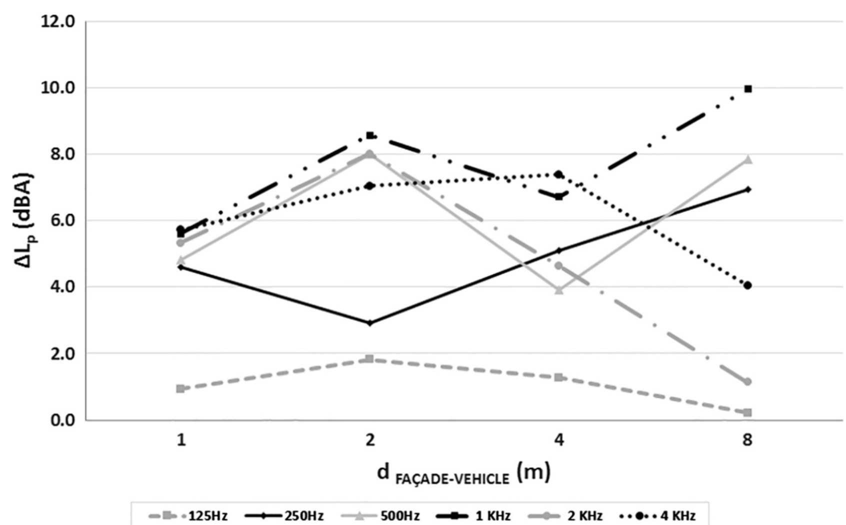

Fig. 9. Difference in octave band sound levels between configurations with and without a vehicle at 1.5 m.

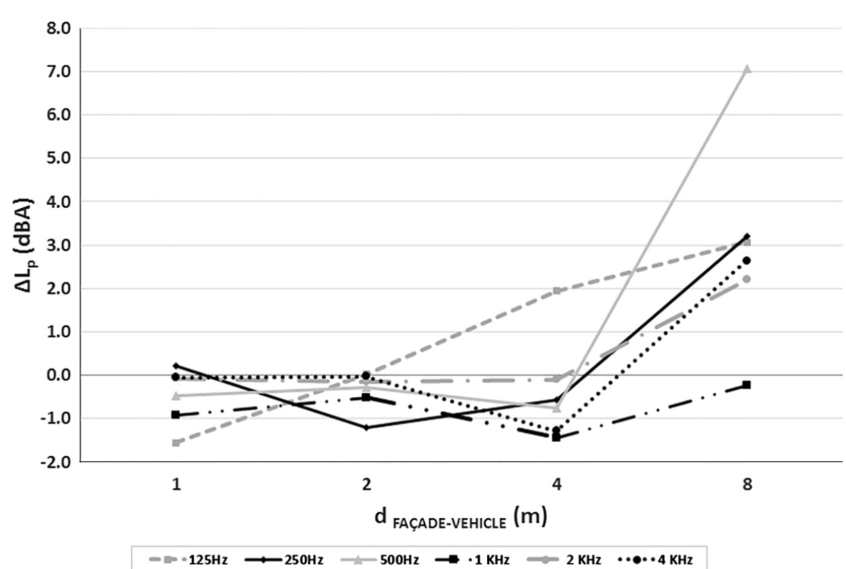

Fig. 10. Difference in octave band sound levels between configurations with and without a vehicle at 4 m.

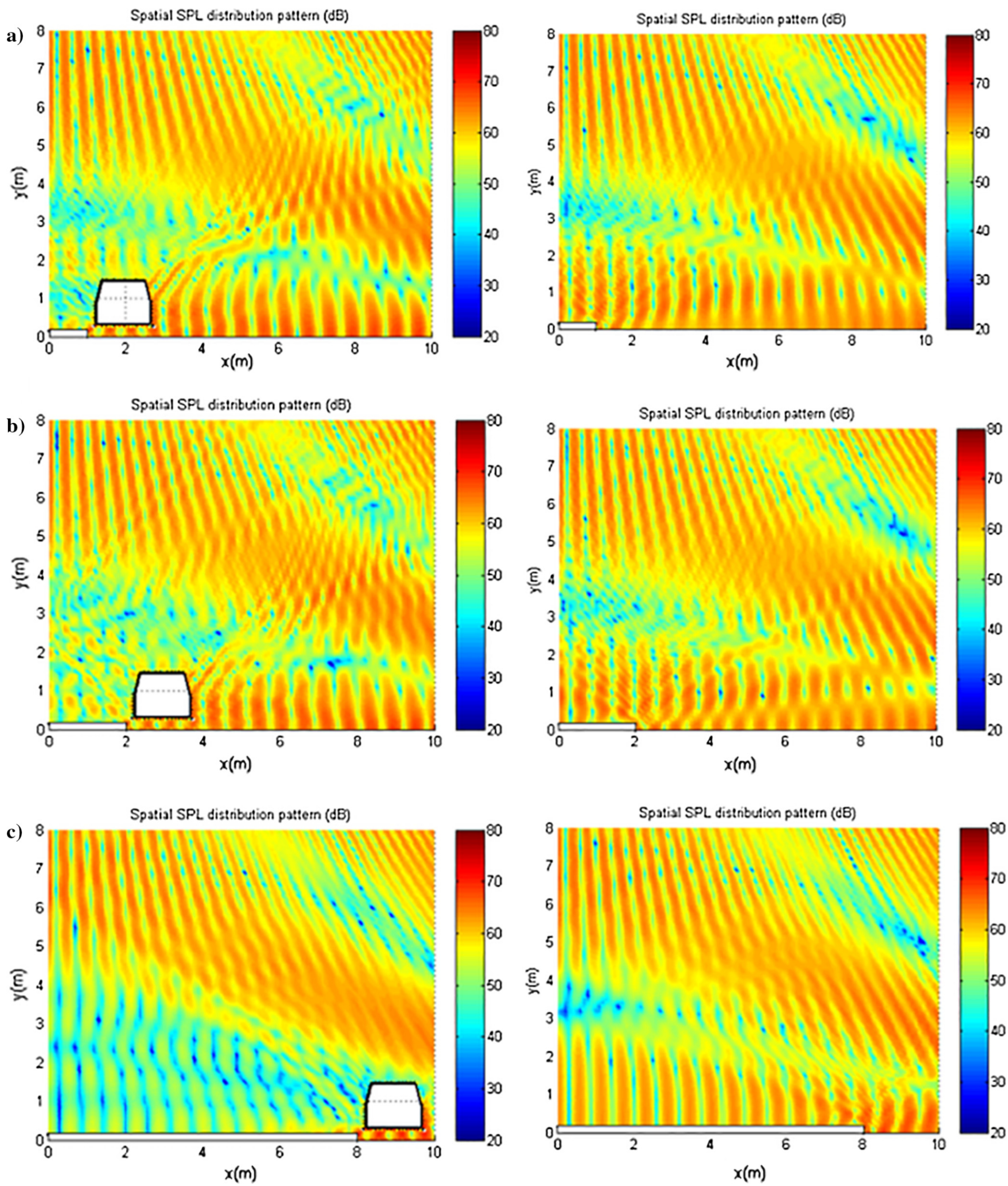

Fig. 11. Simulation with and without a car in the octave band of 1 kHz with source at 0.3 m height and at distances of (a) 1 m, (b) 2 m and (c) 8 m between the façade and the parking line.

To summarize, the shielding effects on building façades associated with the presence of parked vehicles, under the conditions discussed in this section, may be of importance even at heights of 4 m, mainly on wide streets. This urban configuration is common in avenues in many cities in Europe.

3.3.2. Sound source located 29.7 m from the façade

The results obtained on façades for the difference in overall sound levels between configurations with and without a vehicle, for a fixed position of the sound source at 29.7 m from the surface, are shown in Fig. 12 for some different microphone heights.

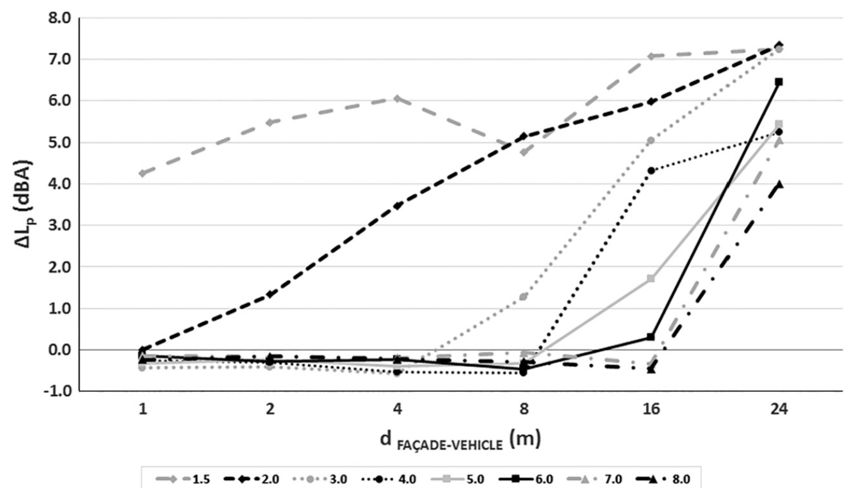

Fig. 12. Difference in overall sound levels between configurations with and without a vehicle for different microphone heights.

From the results shown in Fig. 12, some conclusions can be drawn:

(a) A trend quite similar to that obtained in Section 3.3.1 is seen. That is, an increase in the screening effect as the distance between the façade and the vehicle increases. Also, the shape of the curve varies depending on the height of the receiver, with a very similar pattern to that in Section 3.3.1.
(b) For the receiver located at 1.5 m, the difference in sound levels is relatively constant regardless of the distance between the façade and the vehicle, between 4 and 7 dBA. Similar to the results of Section 3.3.1, the large difference that exists between the results for 1.5 m and 4 m is of great interest, but in this case in all range of distances façade-vehicle. This difference takes high values up to 8 m.
(c) In receivers located at heights between 2 and 3 m, a progressive increase of the screening effect with the distance between the façade and the vehicle is observed.
(d) For other receivers placed at heights between 4 and 8 m, the difference in noise levels is negligible until a distance of 8 m between the façade and the vehicle, increasing from this point onward. This increase is higher for those receptors located at lower positions. In this respect, it is important to note the major difference obtained between the receivers placed at heights of 4 and 8 m for a façade-vehicle distance of 16 m.
(e) It is interesting to highlight the difference obtained, greater than 4 dB, for a height of 4 m on the façade and a façade-vehicle distance between 16 and 24 m. A difference higher than 4 dBA is also remarkable at the distance of 24 m for all studied heights, even at 8 m. For the distance between the source and the façade under consideration (29.7 m), this configuration can be associated with wide avenues in cities.

Then, the behaviour in octave frequency bands for some selected heights (1.5, 4 and 8 m) is analysed. The results obtained for the difference in sound levels in a receiver located on the façade at a height of 1.5 m are shown in Fig. 13. It can be concluded that, in the set of analysed bands, a similar trend to that obtained in Section 3.3.1 is observed. The values are very similar until the distance between the façade and the parking line of 8 m analysed in that section. Only in the band of 1 kHz is a small difference observed, because of the fact of placing the sound source at 29.7 m instead of 16 m. The consistency in the results obtained in both sections

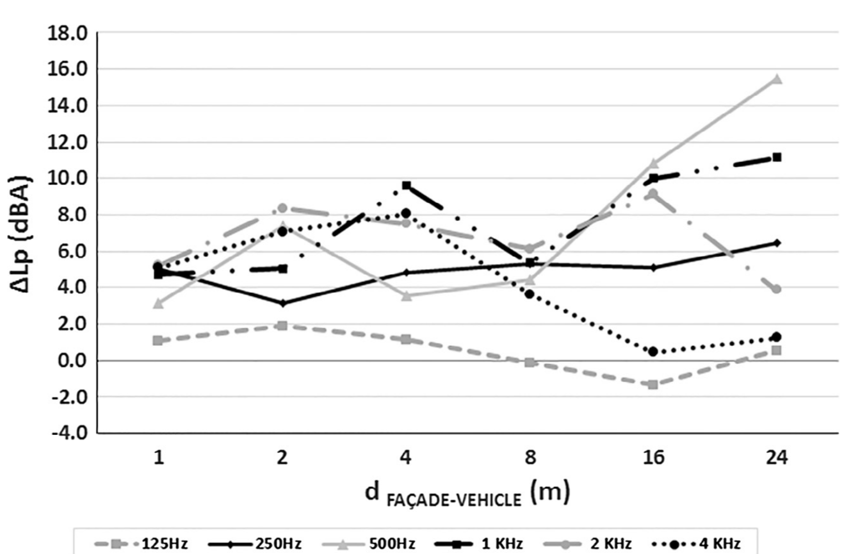

Fig. 13. Difference in octave band sound levels between configurations with and without a vehicle at 1.5 m.

is therefore remarkable. On the other hand, when the distance between the façade and vehicle increases, significant shielding effects are obtained in almost all octave bands. Interference phenomena can be also observed in some frequency bands.

Again in Fig. 14, for a receiver placed at a height of 4 m, the results show a similar behaviour to the previous section, although the values of the shielding at 8 m are lower in this case. Quite high shielding values are observed in almost every octave band at distances of 16 and 24 m, ranging from ~2 to 8 dBA. Moreover, interference effects can be noted in some frequency bands.

The results of the simulations performed with and without a vehicle in the octave band of 1 kHz are shown in Fig. 15 for distances of 1, 8 and 24 m between the façade and the parked vehicle.

The modification of the sound field that involves the presence of a parking line can be seen clearly in Fig. 15. Because of the distance between the source and the façade, it can be verified that the incident sound wave may be considered as planar. It can be seen that, as the distance between the façade and the parked vehicle increases, for the same source position, the screening effect

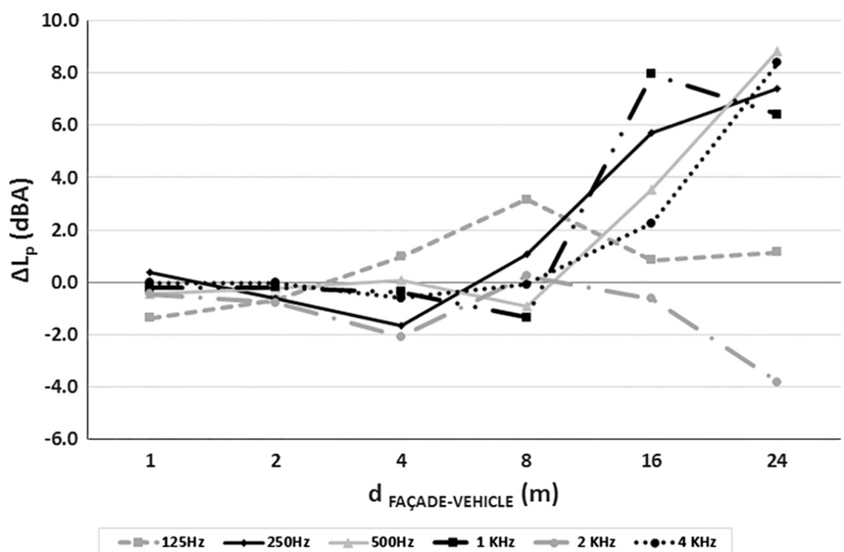

Fig. 14. Difference in octave band sound levels between configurations with and without a vehicle at 4 m.

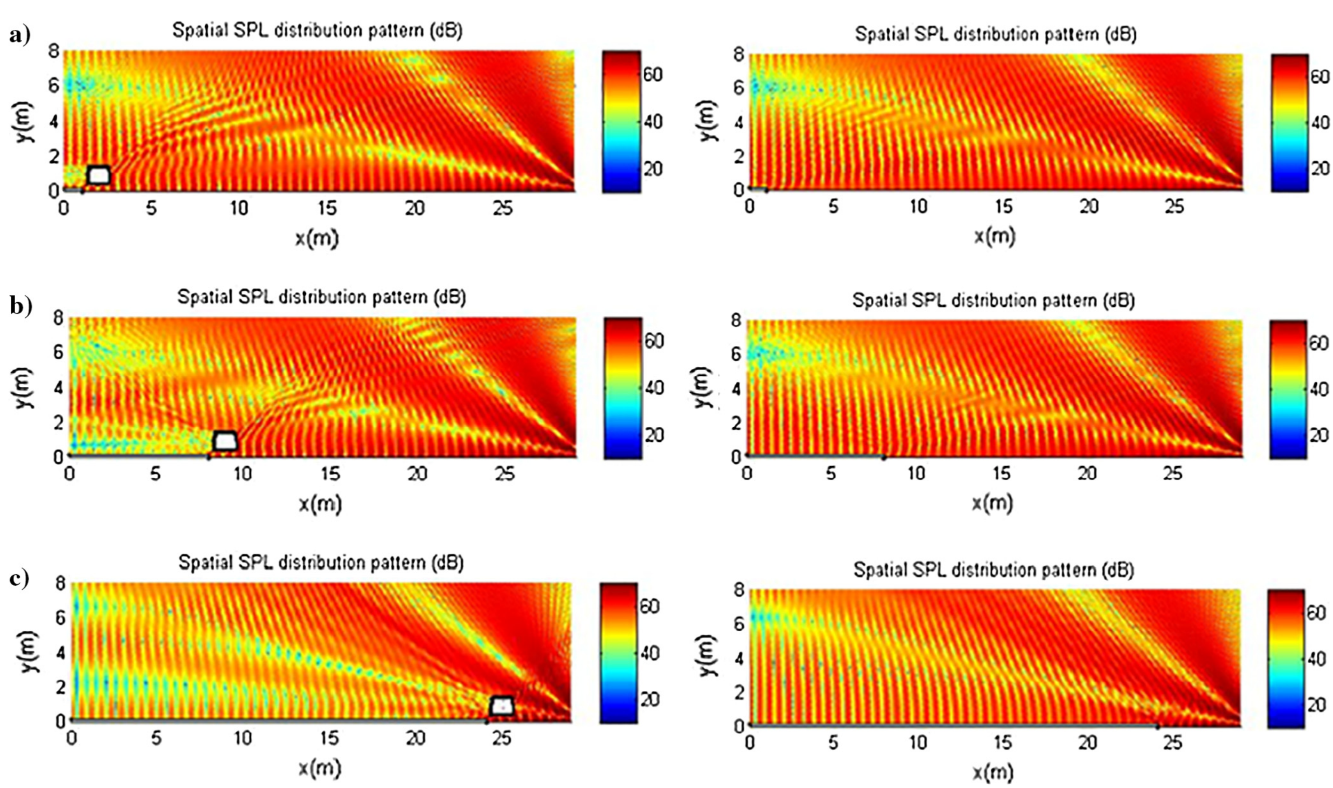

Fig. 15. Simulation with and without a car in the octave band of 1 kHz with source at 0.3 m height and at distances of (a) 1 m, (b) 8 m and (c) 24 m between the façade and the parking line.

becomes greater in the zone next to the façade. In the case of a distance between vehicle and façade of 1 m (Fig. 15a), the screening effect is localized just behind the vehicle and the remainder of the sound field practically remains invariant (interference between the direct and reflected waves in the vehicle can be observed). In the case of 8 m (Fig. 15b), a modification of the shape of the sound field behind the vehicle is observed, which affects the façade up to a height of 2–3 m. Moreover, in the case of 24 m (Fig. 15c), the modification of the sound field is very important in the whole area behind the vehicle; it clearly affects the façade up to a height of about 3–4 m. However, the intensity of the sound field appears to decrease along the façade. The phenomenon of sound transmission through the gap located between the ground and the bottom of the vehicle for a distance of 24 m is interesting.

To sum up, the screening effects on building façade associated with the presence of parked vehicles, under the conditions discussed in this section, may be of importance even at heights of 8 m, mainly on wide streets with parking lines quite far from any dwellings.

4. Conclusions

1. The results obtained for the verification of BEM model proposed show good agreement with the measured values. In this regard, it should be noted that this is a two-dimensional simulation, so the problem is studied in a single vertical plane.
2. The presence of parked vehicles on the sides of urban streets represents a significant modification of the existing sound field in the area between the building façade and parking line.
3. Given a fixed position of the parked vehicle with respect to the building façade under evaluation, if the distance between the parked vehicle and the sound source is varied, the most relevant results are:
   a. For distances between the source and the parking line not exceeding 4 m, over many heights, there are important differences between the situations with and without a parked vehicle. It must be considered that the most common configuration in urban design is that where the traffic lanes are close to the parking lines.
   b. Important differences in the behaviour of the barrier effect between the heights of 1.5 m and 4 or more meters take place from a source-vehicle distance greater than 4 m. Note that these configurations correspond to many secondary avenues of cities all over the world, and it is of great importance to assess the impact of noise on the population through measures in the urban environment.
   c. A significant difference is observed between the predicted values on building façades at heights of 4 and 8 m in the range of distances between the source and the parked vehicle of 1.5–2 m. We consider that these configurations correspond to many European city streets with three-storey buildings. These differences between the results at both heights would lead us to consider that using 4 m as a reference height for the validation of calculated noise maps may not be appropriate. If it is used, the impact of traffic noise on the population in higher levels of the building could be distorted.
4. Given a fixed distance from the sound source to the façade, if the effects of varying the distance between the façade and the parking line are analysed, the most relevant results are:
   a. For a distance between the source and the façade under consideration of 16 m and a distance of 8 m between the façade and the vehicle, it is interesting to highlight the difference of 3 dB obtained for a height of 4 m between the configurations with a without a parking line. It must be noted that 4 m is a reference height in noise mapping and the indicated configurations can be considered normal in city avenues with relatively wide sidewalks.
   b. For a distance between the source and the façade under consideration of 29.7 m, corresponding to wide avenues, it is important to note:
      - The major difference obtained between the receivers placed at heights of 4 and 8 m for a façade-vehicle distance of 16 m.
      - The difference obtained, greater than 4 dB, for a height of 4 m on the façade and at façade-vehicle distance between 16 and 24 m. For this latter distance, the difference is higher than 4 dBA even at 8 m height.
5. Another interesting aspect that can be seen in simulations is the effect of sound transmission through the gap located between the floor and the bottom of the vehicle. This effect varies, depending on the location of the sound source in relation to the vehicle.

Finally, considering all the aspects indicated in the preceding paragraphs, as a general conclusion, a screening effect associated with the presence of parking lines for vehicles on the sides of urban streets is observed. This effect is not considered at present in strategic noise maps conducted under the European Directive for assessing the exposure of buildings to traffic noise in urban environments. Differences in the overall levels of up to 8 dB were obtained in some analysed configurations, which correspond to actual urban environments in many cases. Additionally, the results demonstrate the importance of this effect in the selection of the height for measurements and in the validation of calculated noise maps and, therefore, in assessing the impact of traffic noise on the population.

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