TITLE

The effect of street canyon design on traffic noise exposure along roads.

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ABSTRACT

Abating road traffic noise pollution is one of the main urban environmental challenges nowadays. However, architects and urbanists take decisions on urban regulations that define the shape of streets and buildings without taking this aspect into account. Furthermore, there is little information about the influence of urban geometry on traffic noise exposure in streets. In this study, the effect of street canyon design on sound pressure level distribution is numerically studied in high detail with the full-wave finite-difference time-domain method (FDTD). The CNOSSOS equivalent source power spectra were used to approach road traffic noise sources along two traffic lanes. Receivers both along the façades and the sidewalks have been considered in 42 cases. Numerical results demonstrate that building shape, street geometry and the presence of street furniture can have a strong impact on people's noise exposure. Building shape can be responsible for variations of up to 7.0dB(A) at pedestrians. Building-façade design can reduce the average exposure at windows with 12.9dB(A). It was further predicted that street geometry can enhance the positive effect of low barriers to 11.3dB(A) along sidewalks. It was therefore concluded that carefully designing building façades and street geometry could improve the sound climate for people living and walking along busy urban streets and should be considered in future urban street design.

KEYWORDS

Road traffic noise; street design; building envelope design; urban geometry; urban sound propagation; Noise reduction.

1. INTRODUCTION

Road traffic noise problems are typically approached with corrective methods a posteriori. Besides traffic management (e.g. changing vehicle speed, traffic intensity or traffic composition), the application of perishable absorbing pavements and the insertion of unsightly noise barriers, generating visual disconnection in space, are common but unattractive solutions in the urban environment. On the other hand, increasing façade and window sound insulation is only part of the solution as dwellers open windows, while pedestrians in noisy streets will not benefit from this measure.

Nowadays, architects and city planners take decisions on the urban configuration without taking street acoustics into account. Furthermore, there is little knowledge on the architectonic approaches and façade alterations that could reduce noise levels along streets. In this work, it is studied how street design affects directly exposed persons like pedestrians and incident sound on windows facing the street.

In an urban street canyon, there are two mechanisms that can be exploited to reduce the overall sound pressure level: promoting diffusion in order to scatter sound towards the sky and thus leaving the street canyon, and increasing absorption leading to effective loss in acoustic energy. At specific locations sound can in addition be shielded provided that no reflecting or scattering elements provide secondary paths into the shadow zone.

The effect of the multiple reflections and the importance of scattering in the urban environment was first assessed by Lyon [1]. Many studies approach the effect of façade irregularities and thus analyse sound diffusion in streets [2] [3] [4] [5]. Heutschi [6] compiled look-up tables to evaluate the increase of road traffic noise level due to buildings for a long straight street including gaps, taking into account the height of façades, the width of the gorge, the absorption coefficient of façades and the degree of diffusion.

Absorption is an effective means to reduce overall noise levels in a reverberant space like a street. Different studies looked at absorbing (and diffusely reflecting) materials to reduce the overall level along streets [7] [8]. Hothersall studied in detail the sound field near balconies along tall buildings for different absorption scenarios [9].

Also vegetation could be used, as it provides both effective absorption and scattering of sound, and in addition, a pleasant urban space. Low-height noise barriers located close to the source could also be used to reduce traffic noise in urban streets to shield pedestrians or façades [8] [10]. The introduction of low height noise barriers covered by vegetated wall substrate placed close to the source or receiver is discussed in Ref. [11]. Absorption on such low height noise barriers was found to be essential to have positive effects for pedestrians. Vertical greenery systems at building walls are acoustically analysed in [12] showing high absorption, compared with other building materials. A combination of different green elements is explored in [13] where wall vegetation systems, green roofs and vegetated low screens at roof edges were studied while combining different full-wave numerical methods. The influence of building and roof design on non-directly exposed façades has been studied in detail in [14] [15] [16] [17] [13], given the importance of quiet façades in the urban environment [18] [19] [20]. The study of different roof shapes on sound propagation [17] brings interesting conclusions to achieve quiet façades through architectural design. A green roof was shown to strongly decrease the shielded façade noise load caused by nearby road traffic [21].

Balconies are strongly diffusing elements in a street, and their presence and shape have been studied before. El Diem predicted the sound field along high-rise building façades as influenced by the parapet form and balcony depth, giving interesting conclusions that could be taken into account by architects [22] [23]. Naish assessed nine balcony types to provide guidance on optimised acoustic treatment [24]. Janczur assessed the recess of façades and building position to reduce noise levels [25].

The main objective of this research is to provide a systematic overview of a number of architectonic solutions and the detection of influential design elements in a typical urban canyon. The reduction in noise exposure for people living and walking next to roads is of primary concern in this work. In total, 23 different cases of façade geometries are numerically studied and 19 cases of street geometry. Both sound pressure level reductions at pedestrians and along windows facing the street are compared.

2. METHODS AND CALCULATION

2.1 Sound propagation model

The influence of urban canyon design is assessed through the pressure-velocity finite-difference time-domain (FDTD) method [26]. This numerical technique solves the sound propagation equations directly in the time-domain. The efficient staggered-in-space, staggered-in-time numerical discretisation scheme [26] is used.

Rigid surfaces like the street are modelled by setting the normal component of the particle velocity to zero. For the façades, a frequency-independent real-valued surface impedance is employed as proposed in Ref. [27]. The interaction between sound waves and vegetation substrate is modelled by a rigid-porous frame model [28]. Parameter fitting on substrate measurements in an impedance tube has been discussed earlier in Ref. [13] and the same parameters were used in this study. Perfectly matched layers are used as perfectly absorbing boundaries to truncate the infinite propagation domain (i.e. the sky) to a finite simulation domain. The calculations are limited to two dimensions to prevent excessive computational cost. A point source in such a simulation environment represents a coherent line source assuming a constant street canyon cross-section in the third dimension. Experimental validation of the sound propagation model in urban streets in provided in Section 2.6.

2.2 Street geometry

The cases calculated present different detailed geometries derived from a basic canyon section with a 20-m street width and a 25.6-m building height (8 floors) as shown in Figure 1. The configurations are symmetrical relative to the centre of the street.

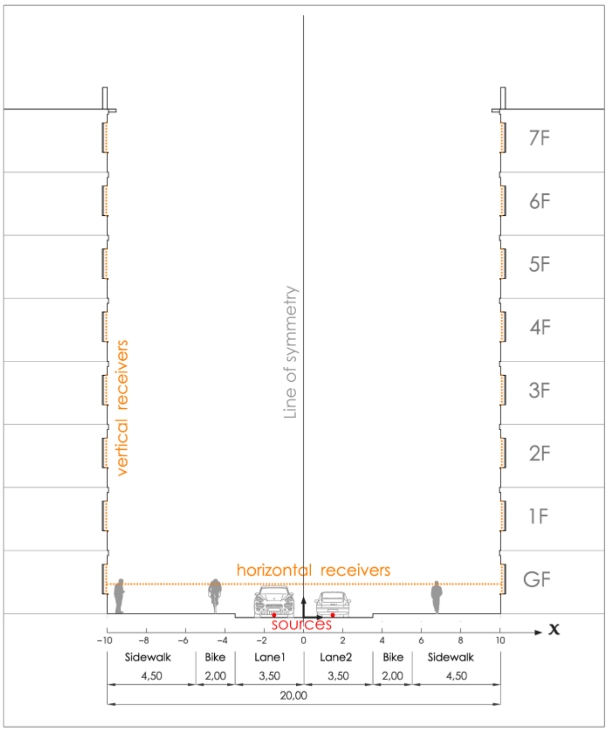

Figure 1: Cross-section of the basic canyon. The street use distribution is marked with architectural dimensions and the position of receiver lines are indicated.

Two road traffic lanes are modelled forming a 7-m wide road 0.2m below the sidewalks. Sources are positioned at 1.5m distance from the centre and 0.05m above street level. The street use is also symmetric in the following order (from the centre): 3.5m for each lane, 2m bike lane and 4.5m pedestrian sidewalk. The body of the car is not modelled.

A horizontal line of receivers, separated each 0.06m, is positioned along the street width at pedestrian ear height (1.5m). Vertical lines of receivers are distributed along the façade at 0.01m distance (pressure values are calculated in the centres of the cells).

42 different cases have been studied and are arranged in sequence groups and classified in façade cases (F) or in the street cases (S). The cases analysed are summarized in Figure 2.

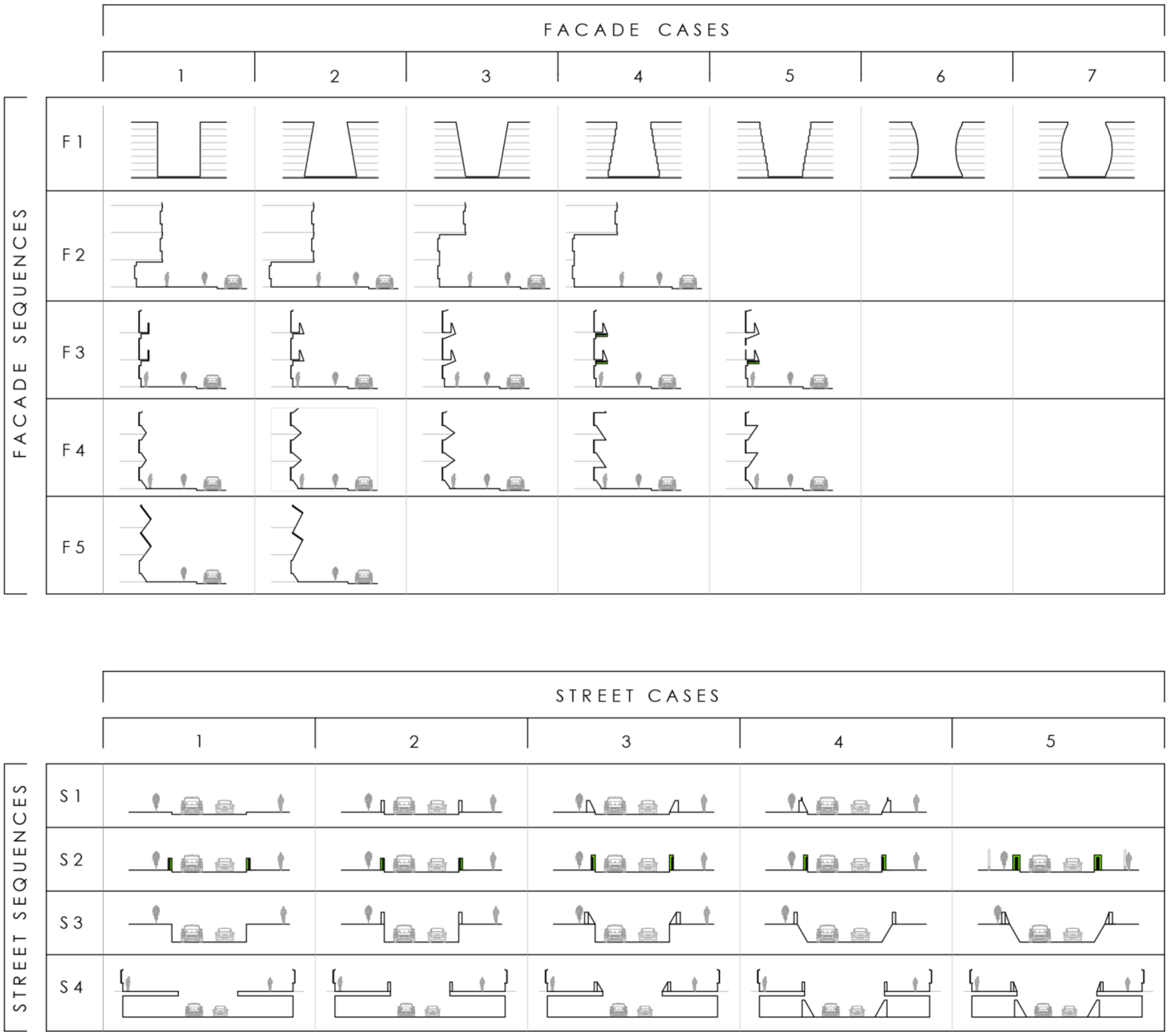

Figure 2: Elements analysed in sequences and cases considered in this study. a) Façade sequences: F1-General building shape. F2-Setback of the lower storeys. F3-Balcony geometry. F4-Triangular prominences on façade. F5-Shielded inclined windows. (b) Street sequences: S1-Low barrier shape. S2-Green absorption on a vertical low barrier. S3-Depressed road. S4-Two level street.

The window heights are 1.5m and are recessed by 0.2m relative to the face of the façade. The windows in balcony cases (F3) are 2.5m high corresponding to a glazing giving access to a balcony. The position of low barriers on the sidewalks edge is at 3.5m from the centre of the canyon except in depressed roads with inclined walls cases (S5.4 and S5.5) where barriers are placed at 4.5m from the centre and in the two level street with inclined walls cases (S6.4 and

S6.5) placed at 4.7m from the centre. Geometries of additional elements are defined for each sequence in the next Table 1.

Table 1. Dimensional details of elements analysed.

FAÇADE SEQUENCES				
Element	**Cases**	**dim x (m)**	**dim y (m)**	**Other parameters**
Vertical building	**F1.1**	13.3	25.6	_
Inclined building	**F1.2-F1.3**	_	_	inclination: 10
Stepped building	**F1.4-F1.5**	_	_	step dim: 0.56
Curved building	**F1.6-F1.7**	_	_	radius of curv.: 24.64
		height (floors)	**depth (m)**	
Setback	**F2.1**	GF	3	_
Setback	**F2.2**	GF	5	_
Setback	**F2.3**	GF+1stFloor	3	_
Setback	**F2.4**	GF+1stFloor	5	_
		dim x (m)	**dim y (m)**	**inclination**
balcony	**F3.1**	0.92	1.26	_
ledge	**F3.2-F3.3-F3.4-F3.5**	_	_	19
ceiling	**F3.3-F3.5**	_	_	19
ceiling absorption	**F3.4-F3.5**	1.32	0.32	_
		dim x (m)	**dim y (m)**	**vertex position**
triangular prominence	**F4.1**	1.67	0.6	middle
triangular prominence	**F4.2**	1.67	0.9	middle
triangular prominence	**F4.3**	1.67	1.2	middle
triangular prominence	**F4.4**	1.67	1.2	down
triangular prominence	**F4.5**	1.67	1.2	up
		dim x (m)	**dim y (m)**	**window dimension**
shielded inclined window	**F5.1**	1.6	1.4	2
shielded inclined window	**F5.2**	0.74	1.2	1.47

STREET SEQUENCES				
Element	**Cases**	**dim x (m)**	**dim y (m)**	**inclination**
Vertical low barrier	**S1.2-S2-S3.2-S4.2-S4.4**	0.3	1.1	0
Inclined low barrier 1	**S1.3-S3.3-S3.5**	0.3-0.8	1.1	30
Inclined low barrier 2	**S4.3-S4.5**	0.3-0.72	1.1	20
Inclined retaining wall	**S4.4-S4.5**	0.3-1.44	2	30

2.3 Simulation parameters

A spatial discretisation step of 0.02m is employed (square cells), allowing to perform accurate calculations up to a sound frequency of 1700Hz assuming that 10 computational cells per wavelength are sufficient for accuracy reasons (with a speed of sound of 340m/s). The temporal discretisation is 20µs leading to a Courant number of 1 in the current simulation setup; this choice minimizes phase errors, guarantees numerical stability and minimum computing time [26]. A Gaussian pulse is emitted with a centre frequency of 850Hz and a time delay of 0.004s. Each simulation took 30 000 time steps, meaning 0.6s real propagation time in the street canyon. This corresponds to 20 reflections at façades. Ground and roads are assigned a perfectly reflective material. Bricks along façades and additional elements are modelled by a frequency-independent impedance of 4080kg.s.m^{-2} following ISO 9613-2 [27] and glazings with 31416kg.s.m^{-2} [29]. A detailed description of the green-wall substrate properties can be found in Ref. [13].

2.4 Road traffic source model

Immission levels are calculated using the CNOSSOS Equivalent source model [30]. Equivalent power spectra at 0.05m height were used to approach road traffic noise sources along the traffic lanes. Category 1 (Light motor vehicles) at a speed of 50km/h was considered. Traffic intensity is of no interest in the current study as absolute levels are of no concern. Sound frequencies higher than 1.7 kHz have been neglected given the interest in low-speed road traffic in urban street canyons. Their contribution to total A-weighted levels are limited.

2.5 Sound pressure level calculation and spatial averaging at receivers

The FDTD method provides the time history of the acoustic pressure following a sound pulse propagation excited at the source position. In a next step, the acoustical energy is grouped in octave bands and expressed relative to free field, sound propagation (relSPL) to work independent of the synthetic source used in the numerical technique.

The immission levels (Lp) are calculated per octave band (up to the one with central frequency 1 kHz) using the CNOSSOS Equivalent source model (Lw) as indicated in (1), where Aff is the attenuation that would be observed in free field:

$$Lp = Lw + relSPL - Aff \quad (1)$$

Atmospheric absorption has not been considered given the dominance of low sound frequencies in urban low-speed road traffic sound. Total sound pressure levels are A-weighted to account for the frequency-dependent sensitivity of the human ear. An average value is specified at each window whereas the median value within 4.5m next to both façades is calculated to assess the impact on pedestrians.

2.6 Experimental validation

Although the FDTD method has been validated with measurements in a wide range of applications, including outdoor sound propagation [31] [32] [33], this section presents an explicit validation for its suitability in urban street canyons, including the choice of model detail and building material characteristics. Street reverberation measurements, conducted in 99 streets [34] in the city of Ghent, Belgium, were used for the validation. The measurement setup was mounted on the roof of a car and consisted in an omnidirectional dodecahedron loudspeaker and two free field microphones placed at 2.48m distance from the source at either side (Figure 3).

To focus the analysis on the effect of the street canyon and its geometry, the reflection ratio (RR) is used. RR is defined as the ratio (in dB) of the energy contained in the reverberation part of the sound field relative to the direct field [34]. To estimate the lower detection limit of RR values with the experimental setup, measurements were done in an open field without reflecting surfaces except for the soil and the body of the car [34].

Following the analysis by Thomas et al. [34], it was shown that the width of the street is the major geometrical factor affecting RR.

The sound field in 13 streets were modelled with FDTD with different widths using the same façade profile as elsewhere in this paper. The building height was chosen to be at the maximum value as observed in the measurement database (16.3m); the building height was shown to have a minor influence only [34]. To calculate RR, the energy of the reverberant field is obtained by subtracting the direct sound and the first reflection on the ground from the modelled time signal.

In this paper, FDTD calculations were performed in 2D cross sections of the streets. Hence, source and receiver need to be located in the same cross section (Figure 3). The choice of the receiver location in this validation exercise is a compromise between avoiding being too close to the source and avoiding being too close to the façade. The latter is particularly important because standing waves close to the façade may cause strong interferences. A distance relative to the source of 2m was deemed to be suited in this respect. As this distance differs from the 2.48m between source and microphone in the experiment, the decrease of the direct sound field with distance was calibrated out. This small difference in location is not expected to significantly affect the reverberant sound field. Note that the results discussed in the later Sections will always consider averages over broader frequency ranges and over many receivers thus avoiding the presence of strong interferences at particular locations as discussed above.

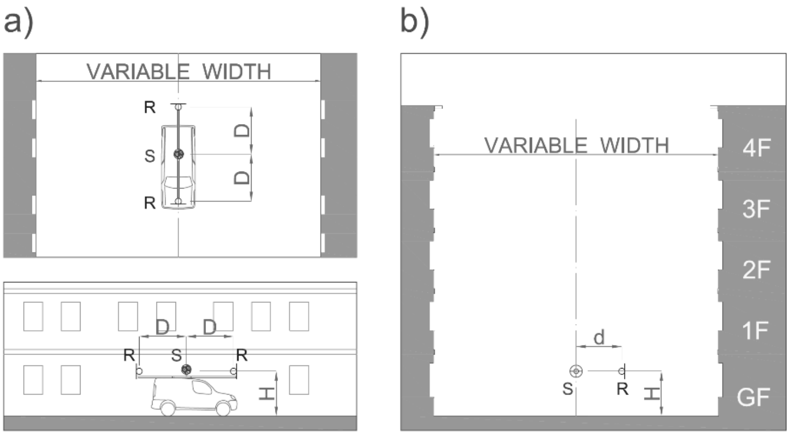

Figure 3: Source (S) and receiver (R) position in a) measurement setup [34] (plan view and side view), b) 2D-FDTD simulation (cross section).

Another important consequence of using 2D FDTD in street cross sections is that the sound source modelled is a line source. In the validation experiment, however, the loudspeaker is not moving during the measurement and approximates a point source. The difference between the propagation from a line source in 2D and a point source in 3D, is that the energy decays with distance as 1/d and 1/d^2 respectively. A transformation from 2D to 3D should therefore be applied. As it is difficult to estimate the distance travelled by every wave reaching the receiver after multiple reflections in the canyon, Heutschi [35] suggested a transformation consisting of multiplying the time signal with $1/\sqrt{(c * t)}$ where c is the sound speed and t the time. In this approach the time travelled by the wave is assumed proportional to the distance travelled.

Figure 4 shows that the measured RR can be well predicted with the 2D-FDTD method over the full range of measured street widths. For the 125Hz and 250Hz octave band the simulated values drop below the measured ones for the wider canyons. This is solely due to the measurement setup that cannot measure RR below the horizontal curve shown in Figure 4 (see [34] for more details).

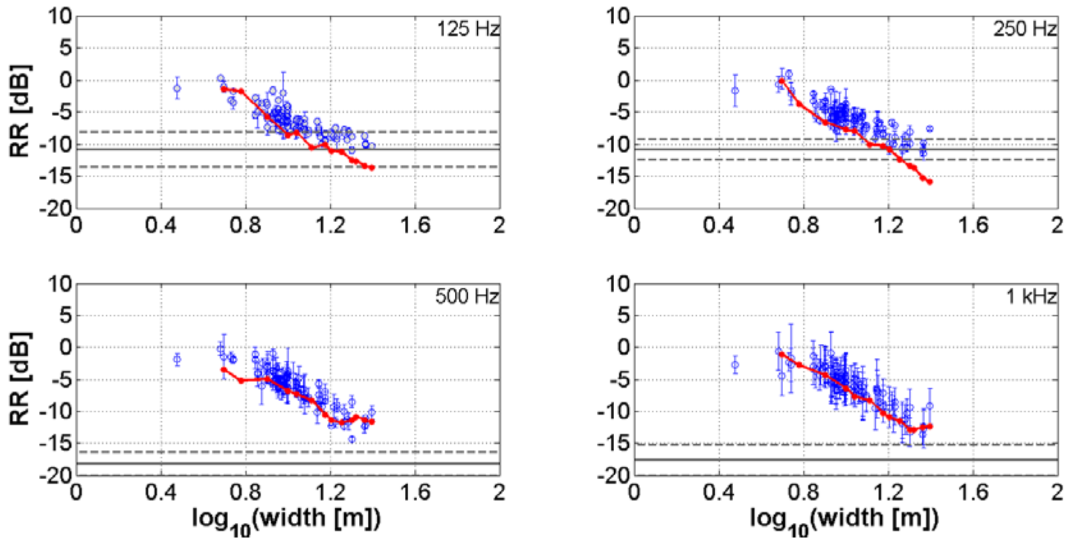

Figure 4: Predicted (red line) versus measured (blue circles (O) with error bars, where the total length equals two times the standard deviation from the mean value at each location) RR plotted in function of street width (logarithmical scale). The lower limit of the measurement setup (RR of the open field) is indicated with the grey horizontal lines (mean value: continuous line, mean value ±standard deviation: dashed line).

Note that the (real-life) measurements include different façade roughnesses, façade materials or the presence of cars along the streets as additional scattering elements, all influencing the Reflection Ratio. The numerical RR matches the lower range of measured data which can be explained by a rather high absorption value assumed for bricks (however, corresponding to ISO 9613-2 [27]). Selecting material characteristics and facade profiling corresponding to this lower range prevents exaggerating the effect of the mitigation measures presented in this work as illustrated e.g. by [13]. In streets with stronger reverberation, the measures proposed in this paper are expected to give a more pronounced effect.

3. RESULTS AND DISCUSSION

Results are presented in a number of sequences, where changes are made relative to a basic reference geometry (indicated as Reference). Sound pressure levels are detailed along a single height throughout the street canyons or along the façade. In addition, the distributions along sidewalks are shown as boxplots and averaged results are presented over windows, where the zero corresponds to the median pedestrian exposure in the reference case. Five sequences assess the effect of façade shape (F) and four sequences evaluate the influence of street configuration (S). The results are summarised in the Appendices.

Sequence F1: GENERAL BUILDING SHAPE

Different general building shapes are analysed in this sequence (Figure 5a). Buildings are geometrically simplified and entirely assigned one material, either glass or bricks. The air volume of the street canyon is kept constant and the extent of the pedestrian zone therefore varies. Only the noise exposure at pedestrians is considered here in seven cases:

- F1.1_Flat vertical.
- F1.2_Flat downwardly inclined.
- F1.3_Flat upwardly inclined.
- F1.4_Downwardly stepped.
- F1.5_Upwardly stepped.
- F1.6_Convex.
- F1.7_Concave.

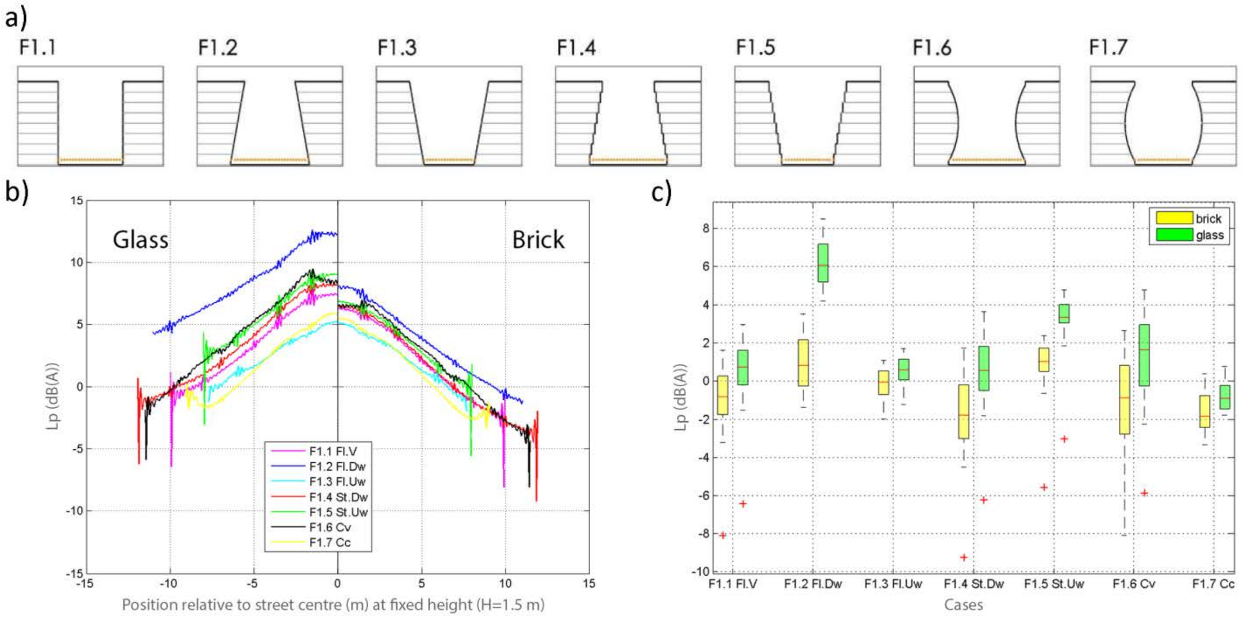

Figure 5: Sequence F1_General building shape. (a) Building geometries considered in the sequence. (b) Comparison of noise exposure along the street width between glass buildings (left) and brick buildings (right). (c) Noise exposure for pedestrians and comparison between glass and brick buildings. The Sidewalk width is variable in this sequence from the fixed position of ±5.5m to the building façade.

Results demonstrate how overall façade shape can have a significant influence on noise levels for pedestrians. This effect is less pronounced when increasing absorption of the building materials: the maximum difference on pedestrian exposure is 7.0dB(A) for glass façades, whereas for brick material the façade shape effect varies within 3dB(A) (Figure 5b). The strong fluctuations close to the facades are caused by interferences between incident and reflected sound.

Flat façade cases (F1.1-F1.3) show very different values as the different inclination of the façade changes the direction of the early reflections. The flat vertical façade case (F1.1), being the most common canyon shape, is taken as the reference.

Flat downwardly inclined façades (F1.2) increase the median value with 6.1dB(A) for glass material (Figure 5c) as the inclination causes a larger amount of sound energy being reflected towards the pedestrians. Furthermore, the effect of the façade material is pronounced.

Upwardly Flat inclined façades (F1.3) behave similarly with different absorptive materials, as upward inclination reflects sound directly towards the canyon opening, reducing the sensitivity to the building material. Noise escapes rapidly from the canyon, avoiding long reverberation.

Stepped façade cases (F1.4-F1.5) show similar values at the same position on the street (Figure 5b). The downwardly stepped case (F1.4) decreases the median value with 1.8dB(A) when modelling brick material relative to the reference case (F1.1) (Figure 5c). In the former, there is a larger pedestrian area further from the road, while the upwardly stepped case (F1.5) increases the exposure 1.0dB(A) compared to the reference case due to the proximity of the road, and increases more than 3dB(A) when modelling glass material.

The convex façade (F1.6) shows similar median value as the reference case (F1.1), however, the sound pressure level increases with roughly 4dB(A) at the same position on the street when assuming glass material (Figure 5b). Concave façades (F1.7) show to be most beneficial for pedestrians (Figure 5c) as they reduce the median value in both materials with about 1.5dB(A) compared to reference case (F1.1).

Sequence F2: SETBACK OF THE LOWER STOREYS

Different realisations of a setback from the façade plane are analysed in this sequence (Figure 6a). The 4.5-m pedestrian area is extended with a setback depth of 3 or 5 meters. Four cases are considered here and compared to the reference case S1.1:

- F2.1_setback of the Ground Floor. 3m depth.
- F2.2_setback of the Ground Floor. 5m depth.
- F2.3_setback of the Ground Floor and 1st floor. 3m depth.
- F2.4_setback of the Ground Floor and 1st floor. 5m depth.

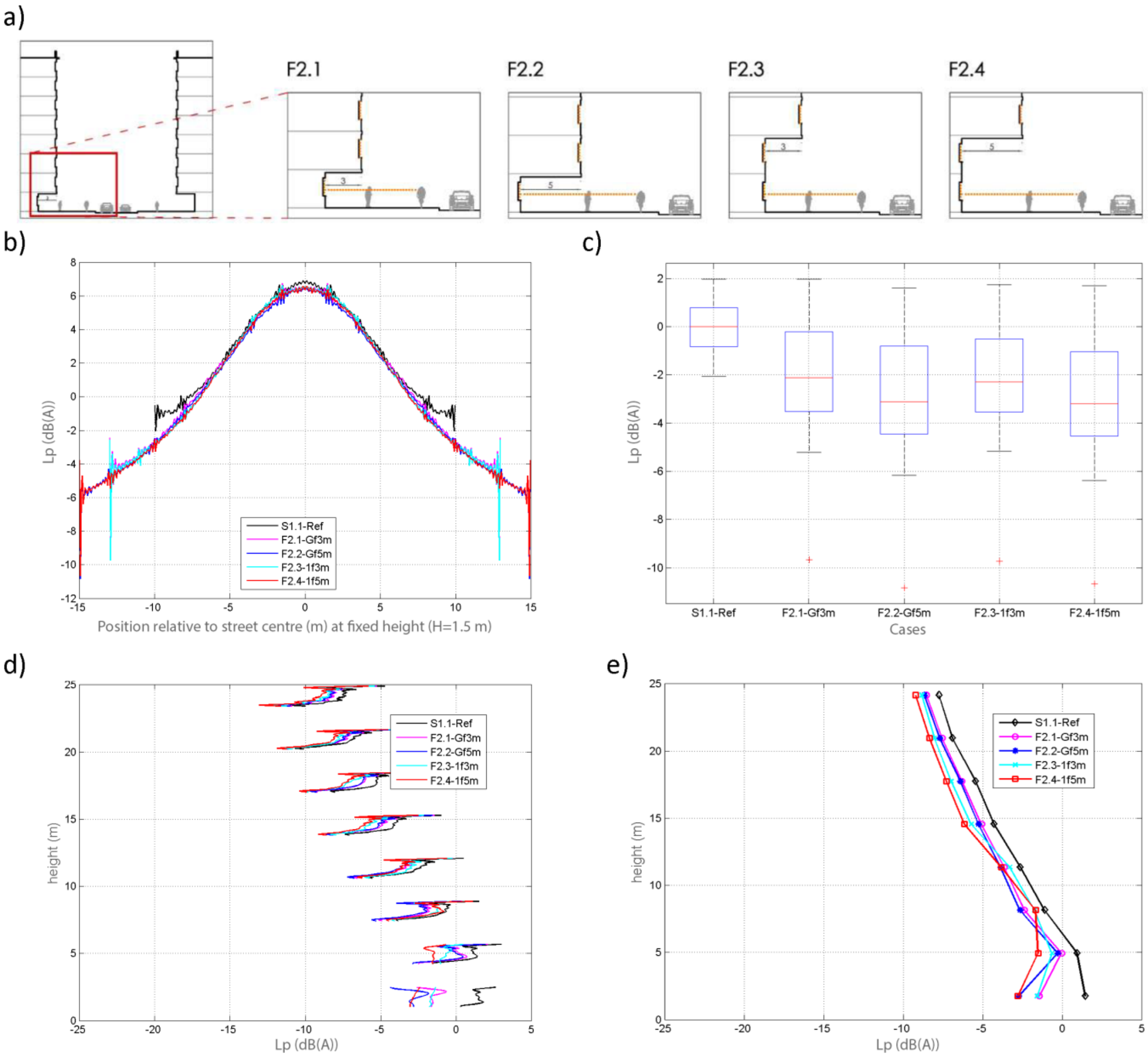

Figure 6: Sequence F2_Setback of the lower storeys.(a) Cross section and geometries considered in the sequence. (b) Noise exposure along the street width. (c) Noise exposure for pedestrians. The Sidewalk dimension is variable in this sequence (4.5m +setback depth). (d) Noise exposure along windows. (e) Average exposure at windows. Reference case S1.1 is included.

Results demonstrate that a setback of the lower floors can significantly reduce noise levels along the façade and for pedestrians. However the effect on the sidewalk and the lower storeys is mainly caused by the increased distance to the source. Furthermore, a setback allows the addition of absorption on the ceiling to increase this advantage.

A maximum reduction of 3.2dB(A) in median exposure is predicted for pedestrians compared to the reference case (S1.1) (Figure 6c). Higher effects are found along the whole façade (Figure 6e). A maximum reduction of 4.2dB(A) as average value is obtained in the ground-floor window, 2.4dB(A) in the first floor, and around 1.5dB(A) at the other floor's windows.

Increasing the setback depth with 2m reduces the pedestrian exposure with 1dB(A). However, it hardly affects the façade exposure, except for the ground floor window. The setback height has a higher influence on the façade than on pedestrians. When this height is increased with one floor, around 1dB(A) additional reduction is found in the average value on every window except in the 1st floor where an increment of noise is predicted.

Sequence F3: BALCONY GEOMETRY

Different balcony geometries are analysed in this sequence (Figure 7a). A glass door of 2.5m high giving access to the balcony is modelled. Five cases are shown and compared to the reference case S1.1:

- F3.1_Vertical ledge.
- F3.2_Inclined ledge.
- F3.3_Inclined ledge and inclined ceiling.
- F3.4_Inclined ledge and absorptive ceiling.

- F3.5_Absorptive ceiling on the first floors, and inclined ledge + inclined ceiling from 3rd to 7th floor.

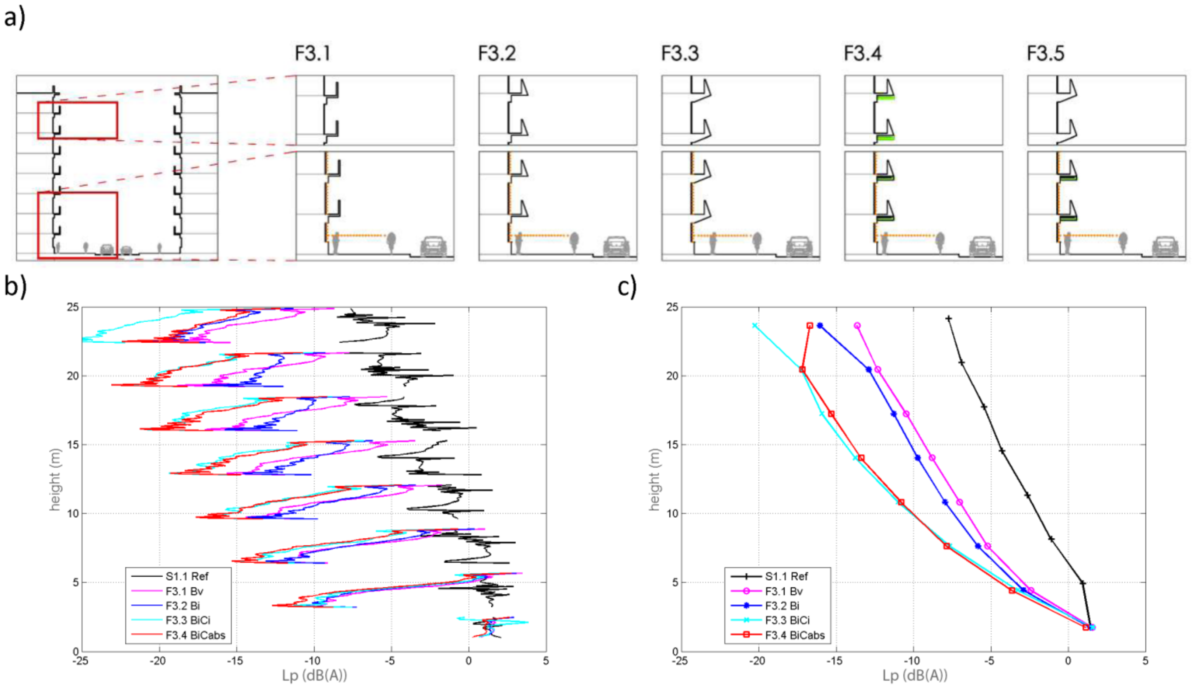

Figure 7: Sequence F3_ Balcony geometry. (a) Cross section and geometries considered in the sequence. (b) Noise exposure along windows. The sidewalk area examined is 4.5m next to façade. (c) Average exposure at windows. Reference case S1.1 is included.

A slight reduction relative to the reference case (S1.1) is observed in the median pedestrian exposure. However, the main positive effects are predicted along the façade as shown in Figure 7c, mainly because of the shielding provided by the balcony on the windows. The average value in the seventh-floor window is reduced with 12.7dB(A). Additionally, 6dB(A) reduction can be achieved by optimizing balcony shape. The inclination of the ledge (F3.2) slightly reduces the average exposure at windows.

The inclination of the balcony ceilings (F3.3) has a great influence on the façade exposure, reducing average noise levels along windows with more than 12dB(A), especially in upper floors. F3.3 is the most advantageous case within the sequence. The addition of absorption on the ceiling of each balcony (F3.4) also results in an important reduction of façade noise level.

Sequence F4: TRIANGULAR PROMINENCES ON FAÇADE

Different triangular prominences added to the façade are analysed in this sequence (Figure 8a). The position of the triangle vertex is changed horizontally (distance from façade alignment) and vertically (middle, up or down). Five cases are studied and compared to the reference case (S1.1).

- F4.1_Middle-vertex 0,6m
- F4.2_Middle-vertex 0,9m
- F4.3_Middle-vertex 1,2m
- F4.4_Down-vertex 1,2m
- F4.5_Up-vertex 1,2m

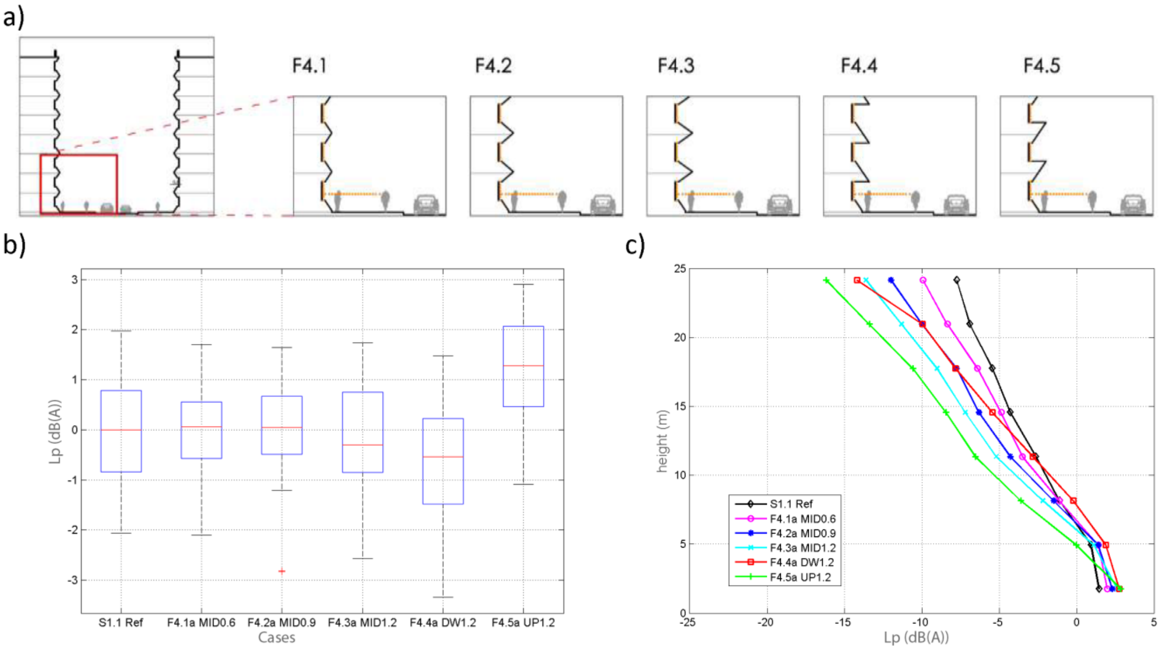

Figure 8: Sequence F4_Triangular prominences on façade. (a) Cross section and geometries considered in the sequence. (b) Noise exposure for pedestrians. The sidewalk area examined is 4.5m next to façade. (c) Average exposure at windows. Reference case S1.1 is included.

The addition of triangular irregularities on the façades has little effect for the road traffic noise exposure of pedestrians (Figure 8b). However, a strong reduction in façade exposure relative to the reference case is observed (Figure 8c). This effect becomes most pronounced at higher storeys. The specific shape of the triangles is important, and gives rise to variations of up to

6.2dB(A) in the upper floor's window and a reduction of 8.4dB(A) relative to the reference case (S1.1). However, a small increment in noise exposure is found on the lower windows. Noise decreases when the triangles become larger (F4.1, F4.2, F1.3).

The down-vertex case (F4.4) reduces pedestrian exposure with 0.5dB(A) (Figure 8b). However, this is the most disadvantageous case in this sequence for façade exposure at the first storeys due to the specific inclination promoting reflections towards the window (Figure 8c).

The Up vertex case (F4.5) increases pedestrian exposure with 1.5dB as the shape promotes early reflections towards the pedestrians. Nevertheless, it is the most advantageous case along the façades as it simultaneously shields part of the window and avoids the reflection towards the window.

Sequence F5: SHIELDED INCLINED WINDOWS

In this section, the idea of self-shielded windows is explored (Figure 9a). The windows are put in an inclined position, similar to a roof window. The façade, including windows, then forms a sawtooth shape. Two cases are considered and compared to the reference case S1.1

- F5.1_Shielded windows inclined at 40 degrees
- F5.2_Shielded windows inclined at 55 degrees

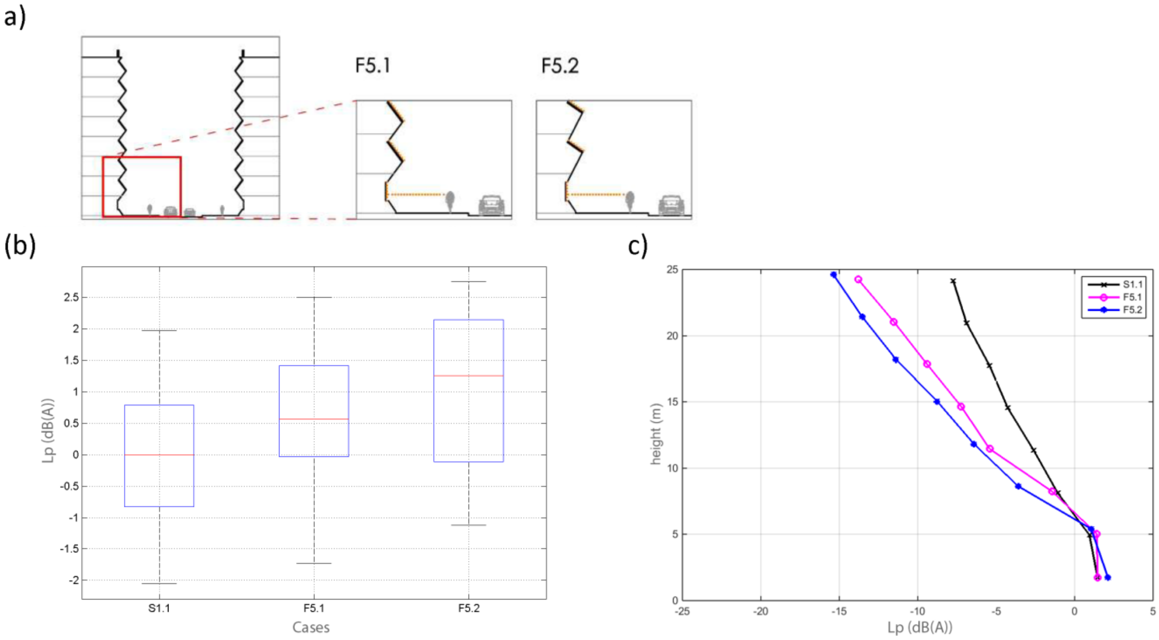

Figure 9: Sequence F5_Shielded inclined windows. a) Cross section and geometries considered in the sequence. (b) Noise exposure for pedestrians. The sidewalk area examined is 4.5m next to façade. (c) Average exposure at windows. Reference case S1.1 is included.

An important positive effect, becoming more pronounced with height, is noticed in façade exposure (Figure 9c). However, a small increment on pedestrian exposure is observed due to the inclined surfaces facing down towards the sidewalk (Figure 9b). There are no positive effects for ground and first floor windows.

Shielded windows inclined at 40 degrees (F5.1), reduces up to 6.1dB(A) on the upper window. A slight increment of 0.7dB(A) is found averaged over the pedestrian area, as shown in Figure 9.

Increasing the inclination of the windows to 55 degrees (F5.2), reduces an additional 1.5dB(A), reaching a total reduction of 7.6dB(A) on the seventh-floor window. However, an increment of 0.7dB(A) is achieved on pedestrian exposure.

Sequence S1: LOW BARRIER SHAPE

Small geometrical changes in a low barrier next to the source are modelled in this sequence (Figure 10a). Four cases are shown and compared to the reference case S1.1.

- S1.1_Reference case (without barrier)
- S1.2_Vertical low barrier
- S1.3_30˚ inclined low barrier
- S1.4_0.26m vertical lamina added on the top of the inclined low barrier.

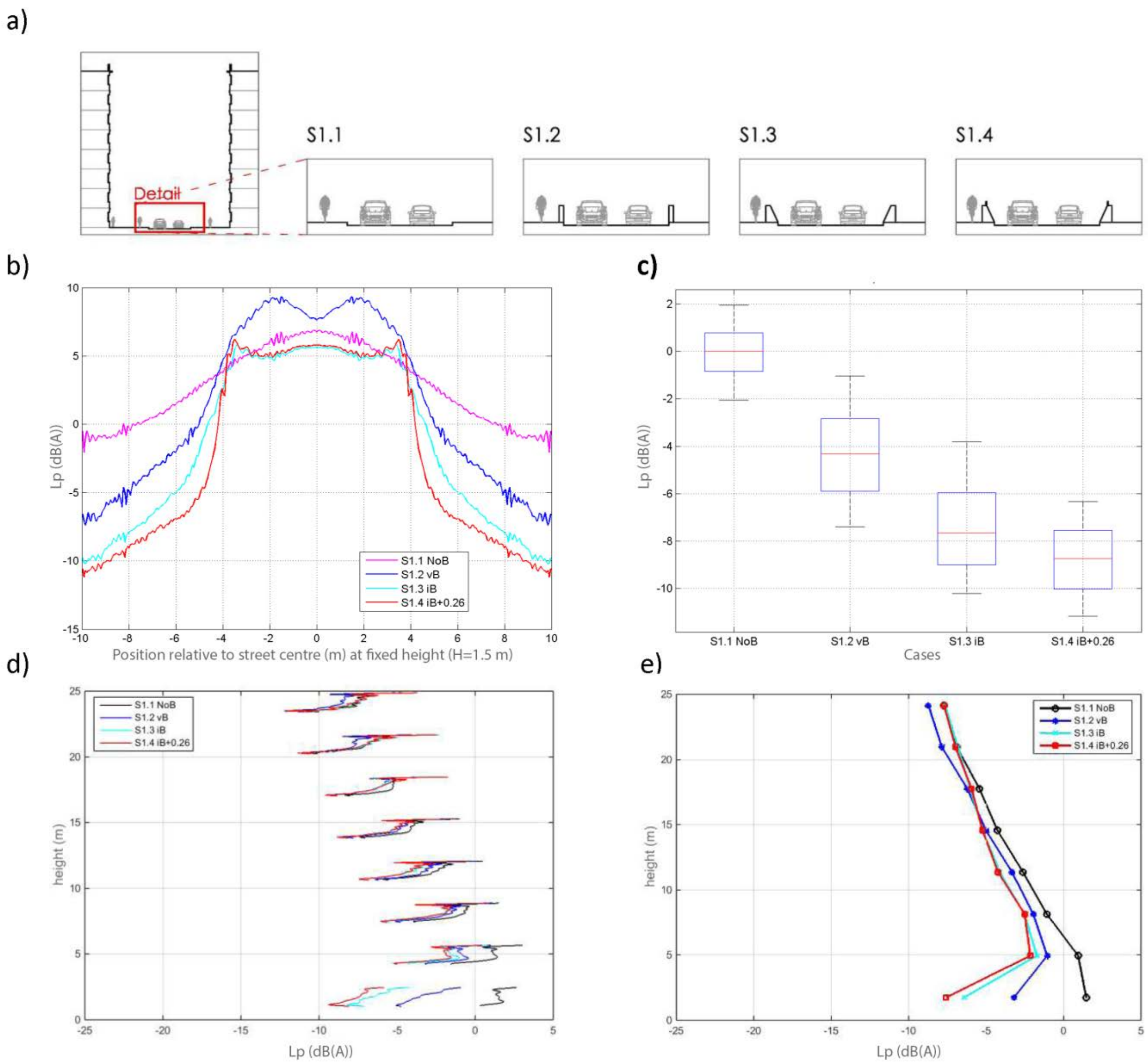

Figure 10: Sequence S1_Low barrier shape. (a) Cross section and geometries considered in the sequence. (b) Noise exposure along the street width. (c) Noise exposure for pedestrians. The sidewalk area examined is 4.5m next to façade. (d) Noise exposure along windows. (e) Average exposure at windows. Reference case S1.1 is included.

Low-height barriers show a big effect on the noise exposure of pedestrians (Figure 10b), while little effect is observed along the façade, except for the first floors (Figure 10d).

In the vertical low barrier case (S1.2) the median value is reduced with 4.3dB(A) for pedestrians (Figure 10c). This shielding effect confirms previous assessments [10], but tilting the low barrier seems even more interesting, additionally reducing 3.4dB(A) for pedestrians and achieving a total reduction of 7.7dB(A) relative to the absence of such a barrier (S1.1). Inclinations of 10˚, 20˚, 30˚ and 40˚ were studied as well. A 30˚ inclined low barrier is found to be the most beneficial for the current canyon dimensions.

The addition of a small vertical lamina on the top of the inclined low barrier reduces additionally the median value with 1.1dB(A), giving total median reduction of 8.8dB(A) related to the case without barrier (S1.1) (Figure 10c). Differences up to 10dB(A), can be found close to the façades (Figure 10b). Note that in the current simulations, the small lamina is assumed to fully prevent transmission through it just like for the low-height barrier itself.

The addition of a low barrier slightly affects the noise levels along the façade (Figure 10d), but the inclination of such a low barrier achieves a significant reduction on the window exposure, amounting from 9dB(A) at ground floor up to 1dB(A) at the 4th floor. The effect on the last two floors is insignificant: sound travels directly to these storeys without being shielded by the barriers. It is important to note that the low barriers are modelled in 2D, the latter being equivalent to an infinitely long barrier. In a real urban setting, the solution will not be that effective as the barrier needs interruptions to allow the pedestrians to cross the street.

Sequence S2: GREEN ABSORPTION ON A VERTICAL LOW BARRIER

Different green wall absorption treatments on a vertical low barrier are analysed in this sequence (Figure 11a). Five cases are discussed and opposed to the low vertical barrier without absorption (S1.2).

- S2.1_Absorption on the receiver side
- S2.2_Absorption on the receiver side and top
- S2.3_Absorption on the source side
- S2.4_Absorption on the source side and top
- S2.5_Absorption on the source side, top and receiver side

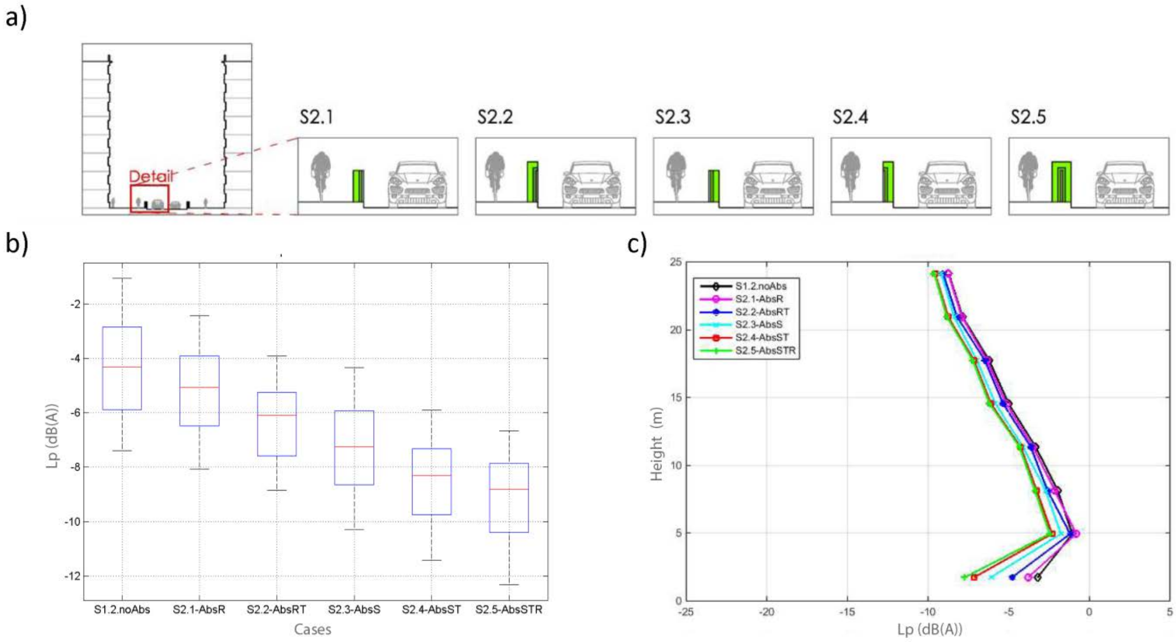

Figure 11: Sequence S2_Green absorption on a low vertical barrier. (a) Cross section and geometries considered in the sequence. (b) Noise exposure for pedestrians. The sidewalk area examined is 4.5m next to façade. (c) Average exposure at windows. Case with the low vertical barrier without absorption (S1.2) is included.

Results show an important effect in the pedestrian zone (Figure 11b). However, only a slight effect is observed along the façade (Figure 11c). Furthermore, they demonstrate that specific application of absorption on the faces of such a barrier is important.

The addition of a low vertical barrier with frequency-dependent absorption, provided by a realistic green wall substrate, leads to a reduction in pedestrian exposure of at least 5dB(A) (Figure 11b). Different absorption positions give additional reduction within a margin of 4dB(A), reaching a maximum reduction relative to the no-barrier case (S1.1) of nearly 9dB(A) with all faces absorbing (S2.5). Absorption on the source side only (case S2.3) additionally reduces more than 2dB(A) compared to the case with absorption on the receiver side (case S2.1). The addition of absorption on the top of the low barrier reduces additionally 1dB(A) for pedestrians, despite the small surface of 0,66m; this can be observed in both cases where top absorption is added: S2.1-S2.2 and S2.3-S2.4.

It can be concluded that absorption on the source side of a low-height vertical barrier, placed in a street canyon, is most advantageous. This demonstrates the importance of absorbing direct sound from the source. The least effective is the case with absorption on the receiver side, however, still leading to a level reduction of 5dB(A) relative to the case without a barrier (S1.1).

Sequence S3: DEPRESSED ROAD

Different geometries on a 1.7m depressed road are analysed in this sequence (Figure 12a). Five cases are shown and compared to the reference case S1.1

- S3.1_No barrier
- S3.2_Vertical low barrier on the sidewalk edge
- S3.3_Inclined low barrier on the sidewalk edge
- S3.4_Inclined retaining walls and vertical low barrier on the sidewalk edge
- S3.5_Inclined retaining walls and inclined low barrier on the sidewalk edge

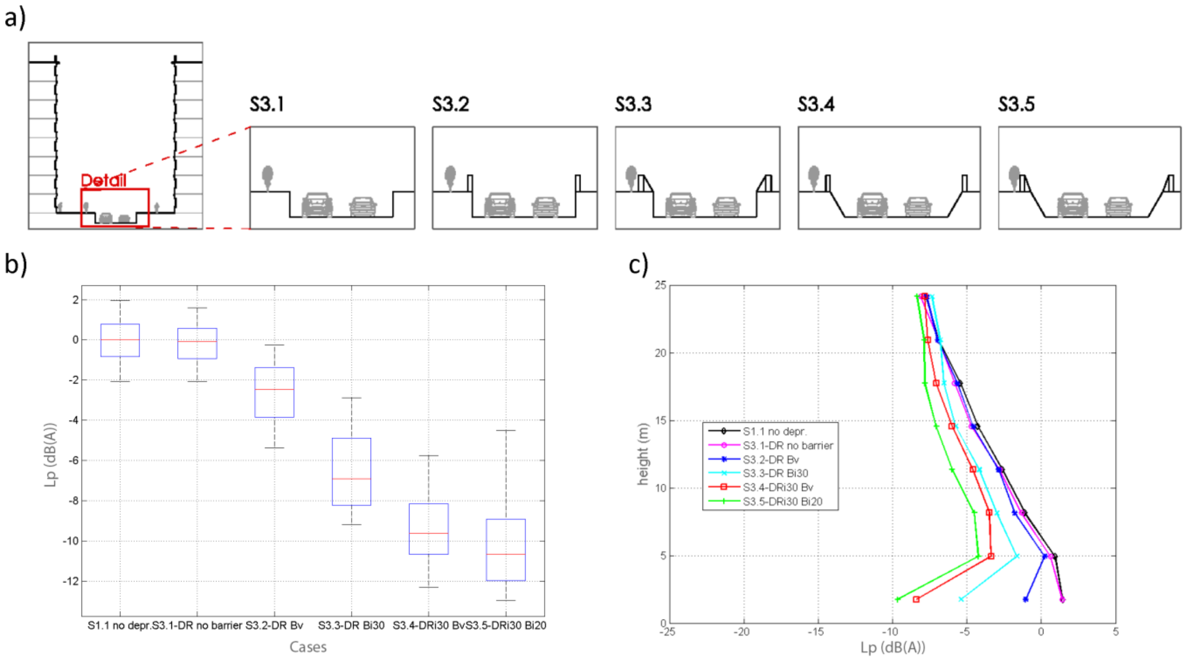

Figure 12: Sequence S3_Depressed roads (-1.7m). (a) Cross section and geometries considered in the sequence. (b) Noise exposure for pedestrians. The sidewalk area examined is 4.5m next to façade. (c) Average exposure at windows. Reference case S1.1 is included.

Results show a high effect of introducing small barriers along a depressed road for both pedestrians (Figure 12b) and façade receivers (Figure 12c), especially on lower floors.

The inclination of the low barrier on the sidewalk edge (S3.3) is again highly efficient as it additionally reduces 4.4dB(A) for pedestrians and at the ground floor (relative to a vertical barrier at the edge, S3.2) and around 2dB(A) along the rest of the façade. Little effect is observed in the last floors.

A depressed road (S3.1) practically does not affect neither pedestrian nor façade noise levels compared to non-depressed roads. Depressed roads with a barrier on the sidewalk edge (S3.2, S3.3) show a slight reduction below 1dB(A) compared to non-depressed cases (S1.2, S1.3). On the other hand, depressed roads allow inclining the road retaining walls (S3.4) which gives additional 2.7dB(A) reduction for pedestrians; a higher reduction of 3.8dB(A) is achieved when the low barrier on the edge is inclined at 20 degrees (S3.5). An impressive total noise reduction for pedestrians of 9.6dB(A) in case S3.4 and 10.7dB(A) in case S3.5 is predicted. Furthermore, a large reduction in façade exposure is achieved in case S3.4 from 9.8dB(A) at GF (but only

0.7dB(A) at the 6th floor), and in case S3.5 from 11.1dB(A) at GF (to 2dB(A) at the upper floors). However, the inclination of the retaining wall has the disadvantage that it reduces the useful surface of the street.

Furthermore, a parallel sequence with absorbing material on the retaining walls has been calculated. It demonstrates the usefulness of absorption on a vertical retaining wall next to the road, reducing additionally from 4dB(A) in case S3.3 to 7.5dB(A) in case S3.2. However, the addition of absorption on the inclined retaining wall is no longer efficient as they additionally reduce noise with less than 1dB(A) for both pedestrian and façade receivers. This is consistent with the findings in Sequence S2.

Sequence S4: TWO LEVEL STREET

Different cases of a two level street are analysed in this sequence (Figure 13a). The road is placed 3.0m below the pedestrian zone. There are parking spaces at both sides of the road. Five cases are compared to the reference case (S1.1)

- S4.1_No barrier
- S4.2_Vertical low barrier on the sidewalk edge
- S4.3_Inclined low barrier on the sidewalk edge
- S4.4_Inclined walls and vertical low barrier on the sidewalk edge
- S4.5_Inclined walls and inclined low barrier on the sidewalk edge

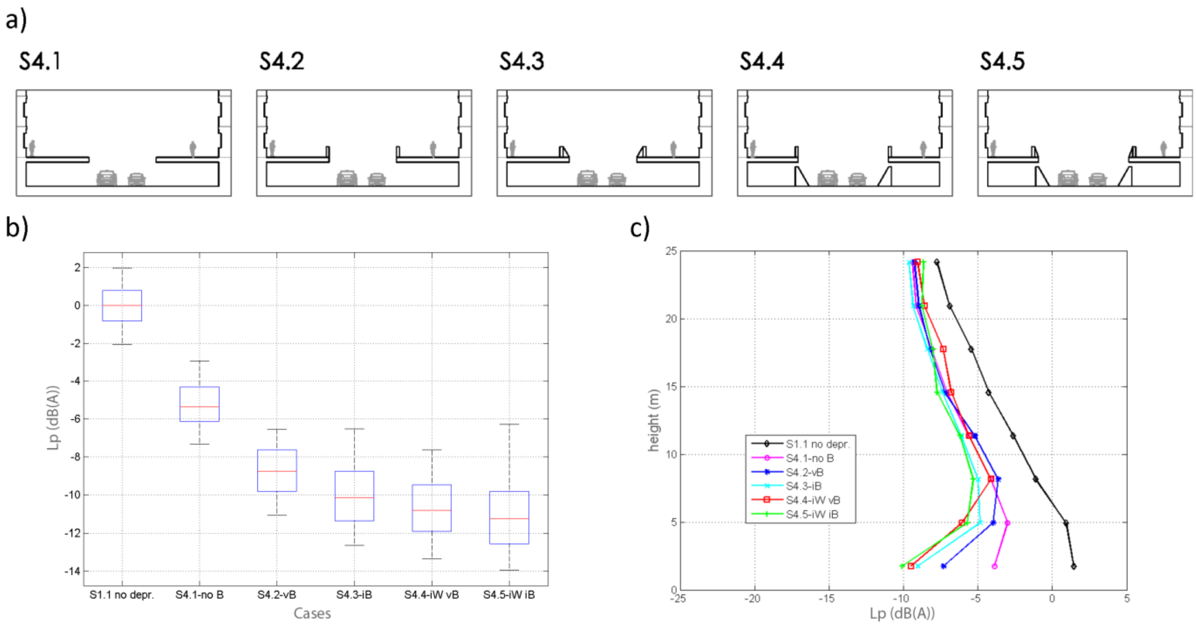

Figure 13: Sequence S4_Two level street. (a) Cross section and geometries considered in the sequence. (b) Noise exposure for pedestrians. The sidewalk area examined is 4.5m next to façade. (c) Average exposure at windows. Reference case S1.1 is included.

A second level road has an important positive effect for pedestrians (Figure 13b) and along the whole façade (Figure 13c). However, the cases in this sequence mainly affect noise levels in lower storeys. A maximum reduction of 11.3dB(A) is found for pedestrian exposure, and 11.5dB(A) reduction averaged over the ground floor window. This is in contrast to the previous sequence (S3), where lowering the road shows practically no difference in noise exposure. The parking spaces lower the pedestrian exposure with 5.3dB(A) and the average noise levels with 6dB(A) in ground floor window (related to the case S3.1 in the previous sequence with the road lowered also at -3m). Furthermore, the addition of a vertical low barrier on the edges (S4.2) additionally reduces the median value with 3.5dB(A). The reduction is 4.8dB(A) when the low barrier is inclined (S4.3), reaching a total reduction of 10.1dB(A). Nevertheless, the addition of an inclined wall next to the road (S4.4, S4.5) in this sequence has little advantage, in contrast to the previous sequences. The case with inclined barriers on sidewalk edge (S4.3) can be considered as efficient since it provides pronounced noise reduction for both pedestrians and along the façades.

4. CONCLUSION

The numerical results presented in this work indicate that urban canyon shape has an important influence on road traffic noise levels for directly exposed receivers. Furthermore, it was found that building geometry mainly influences noise levels along the façades whereas geometrical changes next to the source have a higher relevance for pedestrians and at the windows of the lower floors.

Redirecting the first noise reflections towards the open top end of the canyon was shown to be important when aiming at reducing the noise exposure. This requires inclination of geometries along the façade and especially next to the source. Furthermore, small geometrical changes show to be a powerful architectonic tool to reduce noise in an existent canyon. Inclined low barriers can serve as street furniture, increasing utility of the urban space. Inclined geometries are more or less equivalent to the correspondent vertical ones with absorption. Addition of absorption to an inclined element does not seem to bring additional noise reduction.

The general building shape (F1) can be important for road traffic noise levels at pedestrians. Flat upwardly inclined and concave façades redirect the first noise reflections towards the exit of the canyon, reducing the reverberation, and as a consequence they show less noise exposure at the same position in the street. Additionally, they behave rather similar in various absorption scenarios, while the shapes providing higher reverberation strongly depend on the building material. Flat downwardly inclined façades are least interesting.

The setback of the first floors of a building (F2) has a positive influence along façades. No important reduction is found for pedestrians at the same position relative to the road. However, the possibility to walk somewhat further from the road guarantees lower averaged noise levels.

Balcony design (F3) has a great influence on the façade noise levels. A combination of measures is most advantageous: inclining the balcony ceiling and ledge in upper storeys and adding absorption on the ceilings up to the 3rd floor significantly reduces the average noise levels along windows in upper floors (up to 12.9dB(A)).

The addition of triangular prominences on the façade (F4) has a strong influence on the façade exposure, especially at the upper floors. A reduction up to 8.4dB(A) is predicted. The up vertex case is most advantageous for façade receivers, as it simultaneously shields part of the upper window and at the same time avoids reflections towards the lower window.

Self-shielded windows (F5) provide important noise reduction along the façade. Reduction up to 7.6dB(A) in the upper floors is achieved. Reduction is proportional to the angle of inclination. No positive effect is found for the pedestrian exposure.

Low barriers next to the source (S1) should be preferably inclined, additionally reducing 3.4dB(A) for pedestrians, yielding a total road traffic noise reduction of 8.8dB(A) with a small vertical lamina on its top. No important effect is observed along the façade except for lower storeys.

Absorption treatments on a vertical low barrier (S2) show a remarkable effect on the whole façade and large reductions for pedestrians. The addition of absorption on the source side of the vertical low barrier is more efficient than on the receiver side. The most advantageous case includes absorption on the source side, top and receiver side of the low barrier. However, the efficiency of this case is similar to a small inclined barrier without absorption.

A depressed road (S3) is highly efficient if its retaining walls are inclined. The median value is reduced by 10.6dB(A) for pedestrians. Large reductions are also found on the first floors. The addition of absorption on the inclined retaining walls is only efficient if they are vertical.

Positioning the road at a second level (S4) has a strong beneficial effect for the sound pressure levels to which pedestrians are exposed and along the façade. A reduction up to 11.3dB(A) is predicted for pedestrians and up to 11.5dB(A) at the ground floor window.

Note that the current numerical simulations have been performed in two dimensions (using street cross sections), assuming that there is no variation along the third dimension and that a coherent line source is modelled. Especially in the case of low-barriers, the necessary interruptions (for safety reasons) are not included and could significantly deteriorate their performance. 3D aspects of building façade design have not been analysed or exploited either.

This numerical study shows that noise reduction in a street canyon can be achieved by geometrical street design. This implies that sound waves are affected during propagation, although sources and receivers are located in the same reverberant space. This study aimed at quantifying the effect of a number of non-trivial ideas purely from the viewpoint of noise reduction, neglecting other building functions. Nevertheless, these results are of importance as changing canyon and façade shapes can be used as a tool in urban street design to mitigate road traffic noise exposure in future developments. This is of high relevance as road traffic noise is a persistent and main environmental problem in cities nowadays. Furthermore, the findings presented in this work offer a promising connection between street acoustics and architecture and urbanism, currently working independently. Consequently, architects and urbanists should take these conclusions into account for future planning.

5. APPENDICES

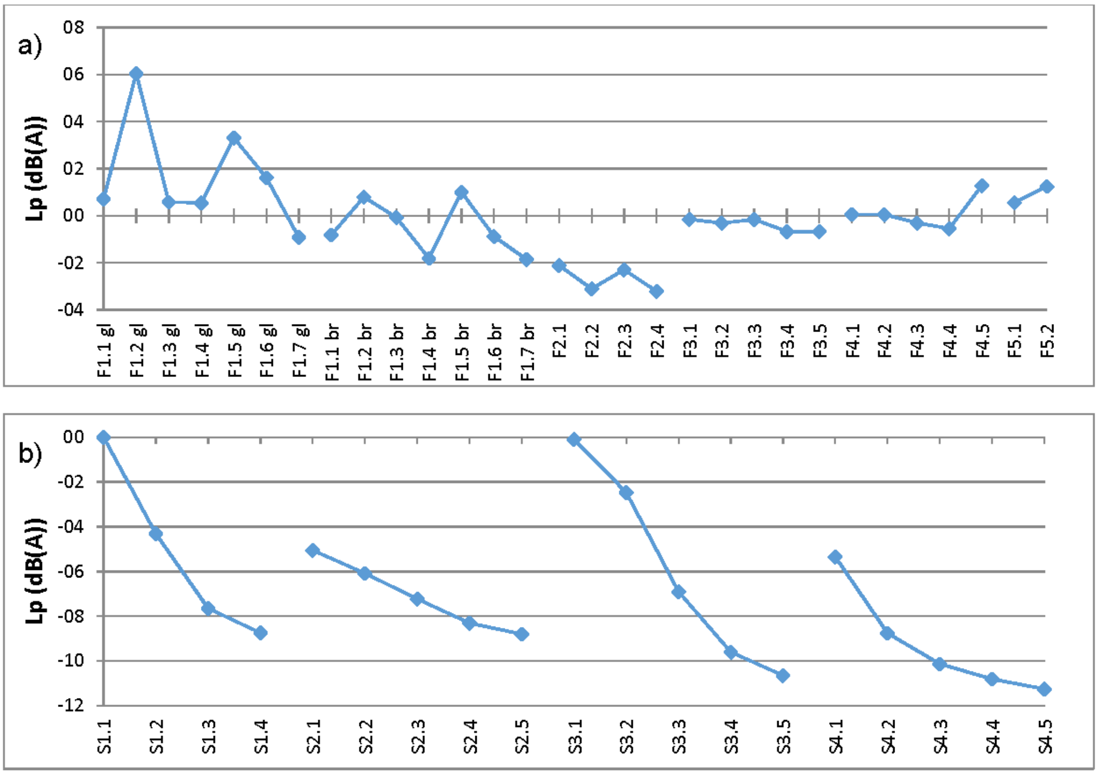

Figure 14: Pedestrian exposure in each case. (a) In façade geometry cases. (b) In Street geometry cases.

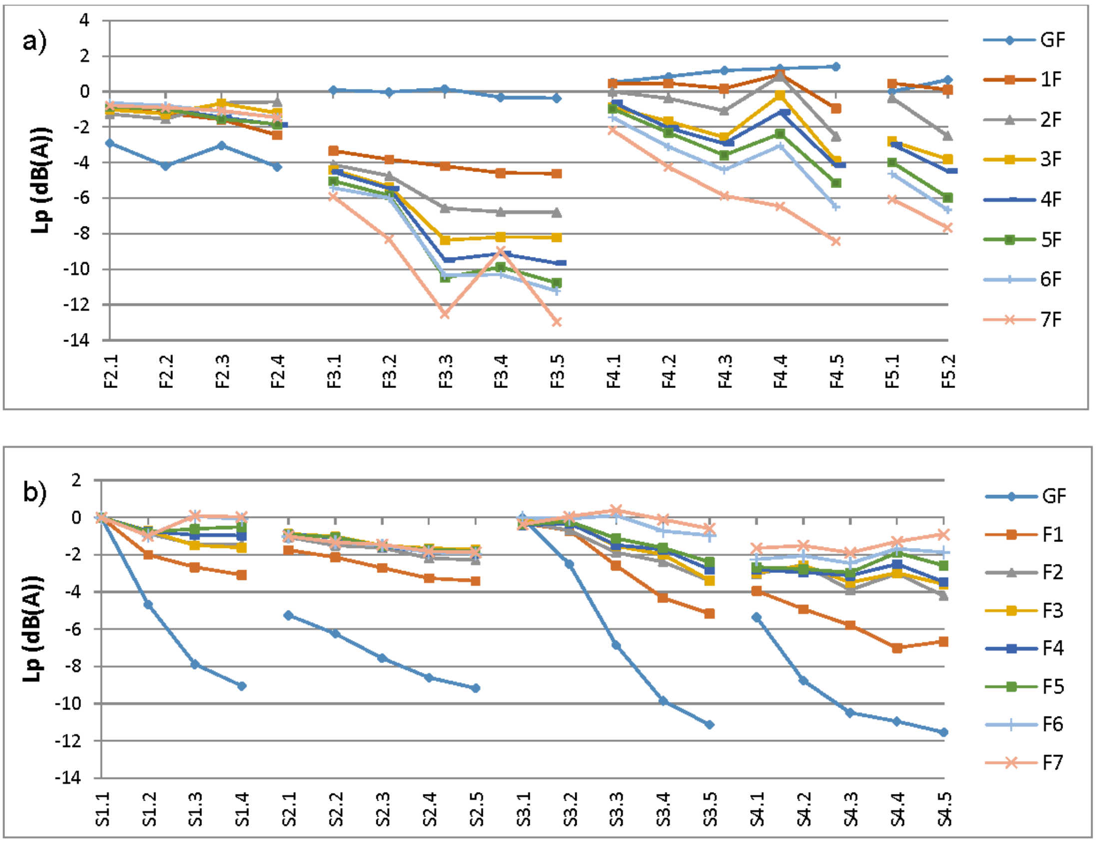

Figure 15: Average exposure at windows. (a) In façade geometry cases. (b) In Street geometry cases.

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