TRAFFIC NOISE ATTENUATION IN SELF-PROTECTED BUILDING ENVELOPS

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Abstract- This study assesses sound performance at building front façades as well as types of design configuration of the self-protected building envelops which are often exposed to a linear finite-length sound source (e.g. traffic noise). Impacts of noise attenuation at the surface level of the building façade are also dealt with. The study includes an evaluation of the architectural elements shaping the configuration of the façade as a means of self-protection for noise attenuation against traffic noise whereby the architects and engineers have neither the choice of averting such disturbing sources nor using natural buffers or man-made barriers to shelter buildings aligned at main streets. A theoretical background is rendered so as to clarify the concept of self-protected building envelops and their role in the traffic noise attenuation. Computer simulation of mathematical models are also applied to test the effect of the facade design, articulation and configuration of envelop on noise attenuation. However, design alternatives of simulated different front façades facing traffic noise are analyzed as case studies. This study concludes with some useful findings depicting the relationship between envelop configuration and noise attenuation in order to make the building more self-protected. A few general considerations are added at the end of the paper.

I. INTRODUCTION

The building envelops and their design configurations maintain comfortable in-doors environment which resist negative out-doors pollutants such as traffic noise nuisances. Undoubtedly, it is the role of a professional architect to protect building occupants from the disturbing noise through appropriate designs of such envelops. Special designs of front façade facing a main street can be adequately achieved. Even though, adding design treatments to the building envelop directly exposed to both direct and diffracted paths of sound waves can yield significant noise attenuation.

A brief theoretical background is furnished to indicate the concept of self-protected buildings and their design requirements as a means to shelter buildings from traffic noise on the one hand, while on the other two hypotheses are set forward to suggest applicable remedies to such polluting problem. Computer simulation of mathematical models is applied to test the validity of the given hypotheses using simulated cases of different façade designs. However, prediction methods, analysis of defined variables and mathematical equations are used to estimate the resultant noise attenuation values and their relationship to the design variables. This study also attempts to find some appropriate configurations for self-protected buildings through testing the efficiency of the articulation of façade design on the spread of sound waves.

Adequate design of a building envelop exposed to traffic noise and calculation of required surface area for the front façade yield maximum noise attenuation for a self-protected envelop which protect in-doors from sound transmission. The outcomes expected from the current study are of special interest to architects and engineers who are mainly concerned with design of self-protected building envelops and defining appropriate areas of front facades that are exposed to heavy traffic noise so as to reduce its negative impacts on the in-doors environment.

Results of this study also indicate that the increase of the protected surface area of a building façade subject to traffic noise which lies within the sound shadow zone achieves multiple attenuation effects, while in the meantime reduces the sound level transmitted inside the building. The design of the envelop configuration affects the difference between the direct and diffracted paths of sound caused by wall barriers and/or articulations which reduce the sound level at the front façade.

As stated above two hypotheses are formulated to test the relationship between noise attenuation of alinear finite-length sound source such as traffic noise, in addition to design variables of building envelops depending on configuration, articulation and ratio of front façade area exposed to nuisance sound sources. The intention, here, is to find suitable design remedies to make the building more self-protected against noise pollution. The research hypotheses are as follows:

Hypothesis I: Through changing the surface area of the front façade, the impact of noise attenuation affects its exposed surface and areduction of thesound level transmitted into the building is achieved.

Hypothesis II: Articulation and the configuration of a building envelop exposed to disturbing sound sources influence the paths of wave spreading and noise attenuation at the reception point on the front façade.

II. SELF-PROTECTED BUILDINGS

Self-protected buildings can be either exposed to direct sound sources or being in the nearby with no natural buffers (trees, hills, etc.) or man-made barriers (walls, buildings, etc.) that could separate those buildings from sound sources. Such buildings can be arranged with some design elements added to envelops, thus maintaining barriers to buffer the direct sound path.In the meantime, design elements can protect the less-resisting façade units (e.g. doors, windows) from sound effect.

Architects usually use such self-protected buildings in orderto attenuate the sound level that reaches the façade surface, especially in locations where it is impossible to avert a source of nuisance sound whether due to planning, economic or any other imposing factor. It is rather necessary to explore other means of self-protection to buildings exposed to noise pollution and study the design requirements for their adequate protection. This can be achieved by one or more of the following treatments:

1. Using solid façades with small voids and openings especially on parts of the buildings facing noise sources.
2. Using podiums especially in multi-storey and tower buildings so as to shelter the lower floors of the tower from direct sound waves (Dept. of Planning, Transp. &Infrast.,2012), (Fig. 1).
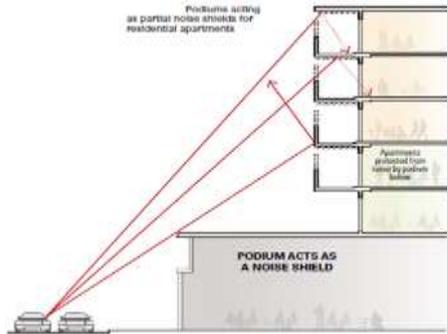

Figure 1: Podium in a multi-storey building works as sound barrier to the lower floors of the tower

3. Using arcades, balconies or corridors facing sound sources to maintain buffer zones that can be used for attenuating noise levels (Hossam El Dien & Woloszyn, 2014), (Fig. 2).
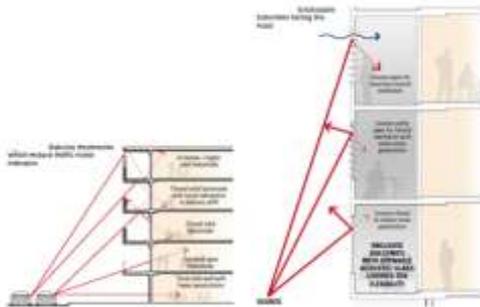

Figure 2: Arcades, balconies and corridors used as sound buffer zones

4. Using recessed façades and staggered floors for tall buildings exposed to sound canmake parts of the envelops protected especially as the buildings get taller, while other spaces can be allocated within the sound shadow zone of other parts of the multi-storey buildings (Dept. of Planning, Transp. & Infrast. 2012), (Fig. 3).
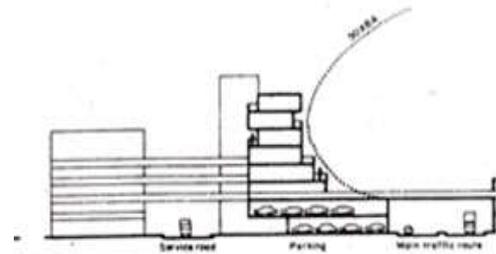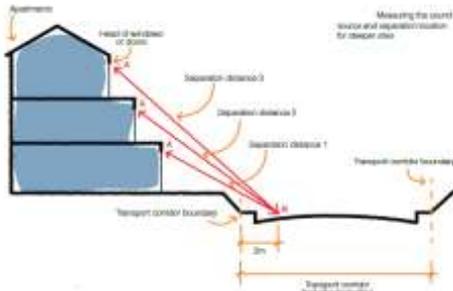
Figure 3: Recessedfaçades and staggered floors of tall buildings subject to sound

5. Minimizing the exposed area to sound at the front façade by choosing appropriate façade configurations.
6. Placing service rooms and semi-private parts of the dwelling facing the sound direction in order to protect the private parts beyond them, maintaining thus horizontal buffer for each floor and vertical sound proof between the floors, (The State Government of NSW, 2008), (Fig. 4).
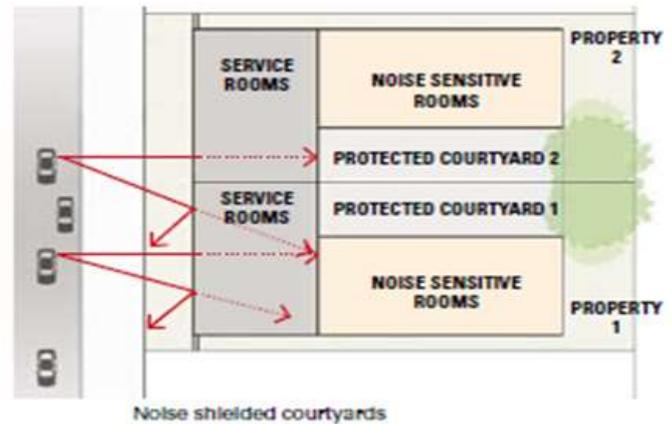
Figure 4: Placing semi-private parts of dwellings towards sound direction

7. Making use of the building design elements in order to achieve adequate self-protection.

Design elements for self-protected buildings:
A good building envelop contributes a reliable filter fornoise attenuation. Therefore, it is necessary to give serious attentions to the design of a building façade exposed to heavy sound through providing barriers as architectural elements. Among these elements are: wall barriers, balconies, front and courtyards, reduction of exposed façade area, maintaining an appropriate ratio between opening size and solid parts of the front façade that is subject to sound, in addition to building orientation with regard to the sound source direction.

1. *Wall Barriers;*are regarded among the self-protecting means that buffer direct sound paths from sources to the front façades. They include fences, curtain walls, louvers and balconies. Apart from their climatic protection advantages, they also function as sound proof agents (Vic Roads, 2003). Besides, such barriers can play a significant role in noise attenuation depending on their solidity, configuration and size areas (Gibbs, 1985). Wall barriers also

maintain sound shadows for areas lying behind them, that is due to the diffracted path which often happens at the top edge of the barrier (Environmental Protection Dept., 2003) (Fig. 5) or when the thickness of such barrier becomes wider than the wave length of the sound source, which in turn is affected by the difference between the diffracted and direct paths. This increases the impact of the noise attenuation value.
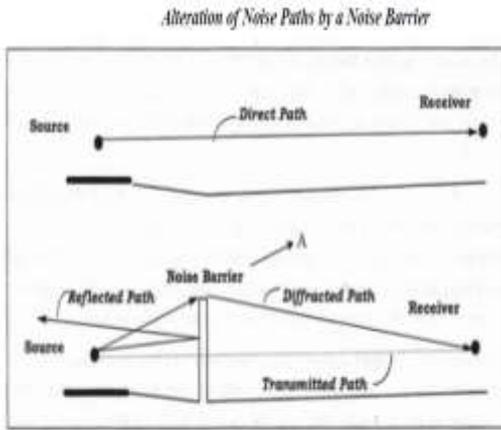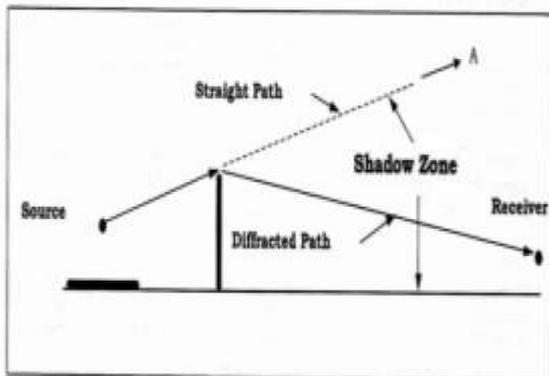

Figure 5: Barriers as buffers of noise waves

In case of thick masses of building and projections, such barriers can be of finite-length buffer for direct sound path originating from a source to the reception point at the front façade. This establishes a sound shadow zone forcertain parts of the building façade. Yet, they control the through sound transmission behavior due to the reflection and diffraction of noise paths originating from the source, (Dept. of Planning, Transp. & Infrast., 2012).

2. *Balconies;* are forms of semi-open extension to the in-doors. Opening onto the external environment through the façade skin, they render both out-door desired views as well as environmental protection. Balconies are also regarded elements of the building envelop, useful in hot climates, while serving as sound buffers (Mohsen, 1979).However, the edge top of the balcony parapet maintains a certain value of diffracted path that impacts noise attenuation due to the ensuing variables:

- The difference between the diffracted path at the parapet edgetop and the direct pathat thereception point on the façade skin
  (Fig. 6).
- The visual angle in between the façade center-point and the parapet corner edges.
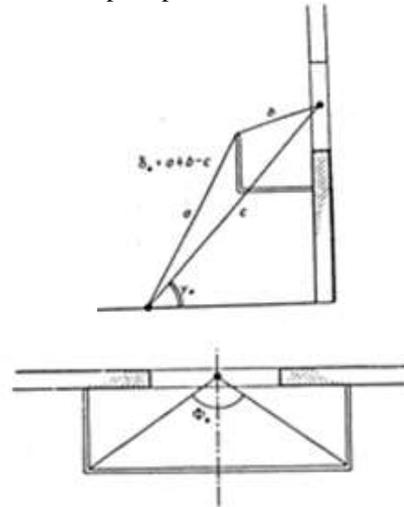- The incident angle of direct sound from the source to the receptionpoint.

Figure 6: Difference between diffracted and direct sound paths at balcony parapet edge

3. *Courtyards; are* open spaces surrounded by wall barriers or building masses to obtain in-doors functional and environmental requirements. In addition, they maintain the necessary privacy as well as sound protection within introspect buildings. Barriers and building masses yield good buffers to theinner courtyards (Fig. 7).
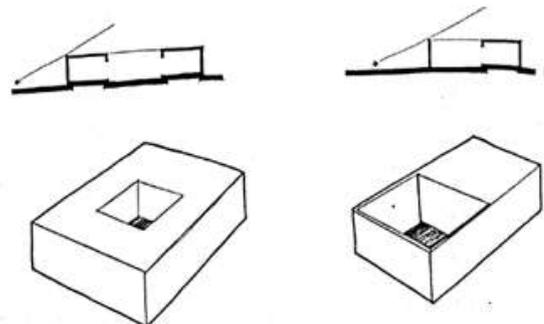

Figure 7: Wall barriers and building masses as sound buffers to inner courts

4. *Building orientation and plan tilting with regard to sound sources;* in urban settings, buildings are exposed to sound waves of different angles originating either from direct sources or reflected waves that are received from adjacent and opposite building masses. Therefore, the building orientation and its angle of plan tilting in relation to the sound source, impact the resultant noise attenuation at the reception point on the façade.

Computer simulation of mathematical models:
To test hypothesis I, four different designs of building envelops are chosen to be subject to a sound source. Despite

of an identical total projected length of each of the four buildings, the degrees of sound impact are different due to the façade configurations (i.e. front façade areas). Computer simulation of mathematical models is used totest the four case studies which are placed at an equal distancefrom afinite-length sound source, namely a linear source consisting of a set of point sources equidistant from each other (with constant equal distances between the points of the vehicular traffic that represents a main street sound source at 0.5m high above the ground level). While the source line represents the *X axis* of the measuring network of the mathematical simulation model, the *Y axis* represents the distance between the building façade and the street line (i.e. the sound source) (Fig. 8).
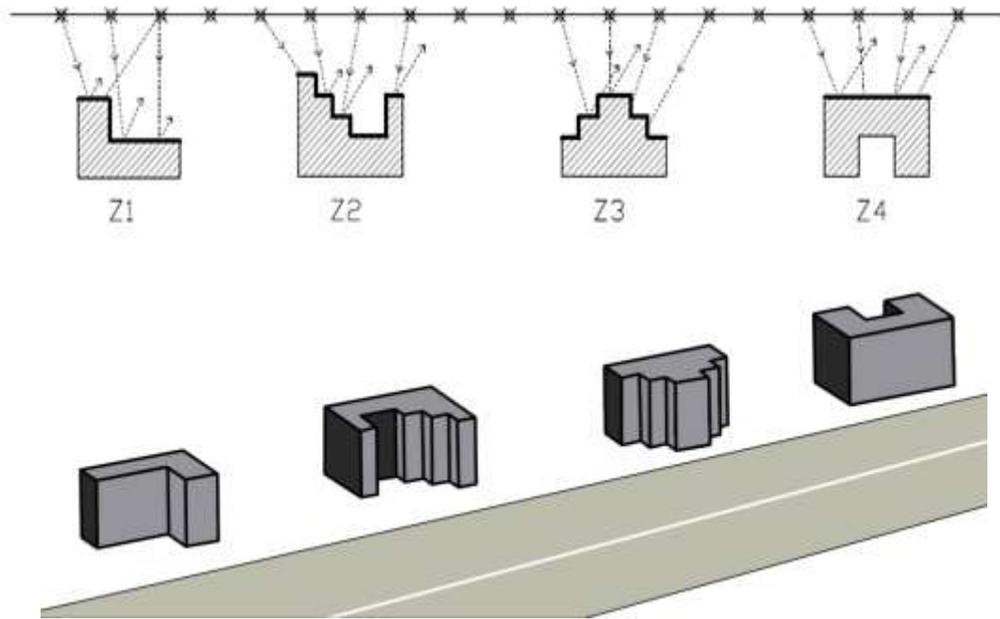

Figure 8: Design types of building envelops

HypothesisI constants:
- Sound reduction average of the façade at (40) decibel.
- Sound pressure level of the linear source (Lp) is (75) decibel.
- Sound absorption coefficient of the in-doors wall surfaces
  (α = 0.02).

Hypothesis I variables:
- Length of front façade parts of each model exposed to the sound source.
- Surface area of front façade exposed to source (K).
- Absorbing units of in-doors wall surfaces (A).

A. Application of mathematical equations to find values of defined variables

Calculated values of parameters are extracted from the geometrical analysis of the mathematical models. Then, they are used as variable values in equations to find the resultant impact of such variables on noise attenuation applied in the program (Table 1).

1. Calculation of the absorbing units of in-doors surfaces (Egan, 1988).
   A= (α)* S

Where
S = area of the interior wall surfaces.
A = absorbing units of the in-door surface.
α = coefficient of sound absorption.

2. Calculation of transmitted sound level in the interior space *(Lpi)* (Lewis, 1974).
   $$Lpi = Lp - NR + 10 \log \left(\frac{K}{A}\right)$$

Where
Lp = sound level of the linear source = (75) decibel.
K = surface area of front façade.
A = absorption units of in-doors surfaces.
NR = sound reduction of exterior wall = (40) decibel.

3. Calculation of façade attenuation values (Lewis, 1974).
   AT = Lp – L
   Where
   L = total sound level at the reception point on the front façade.
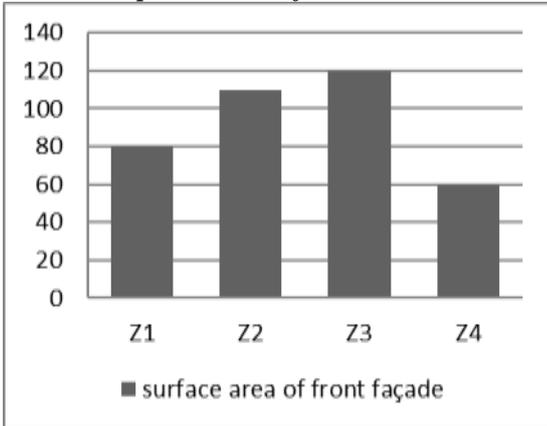   AT= façade attenuation values.
   Lp = sound level of linear source.

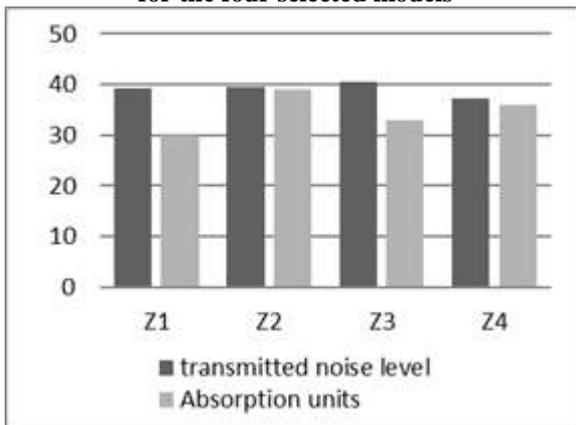| Model No	façade attenuation db	transmitted sound level db	Absorption units sabin	area of the interior surface m²	surface area of front façade m²	Length of front façade m
Z1	35.7	39.26	30	50	80	20
Z2	35.4	39.50	39	65	110	27.5
Z3	34.3	40.61	33	55	120	30
Z4	37.7	37.22	36	60	60	15

Table 1: Results of variables calculation from the program

Table 1 above clarifies how the length of front façade exposed to traffic noise maintains an increased surface area and thus causes a reduction of noise attenuation which in turn increases the level of transmitted sound into the building. It is observed, however, that the smaller the surface area is, the bigger its noise attenuation becomes and the lower level of transmitted sound into the building through the front façade results. Figures 9 through 13 represent outcomes of the computer analysis, as follows:
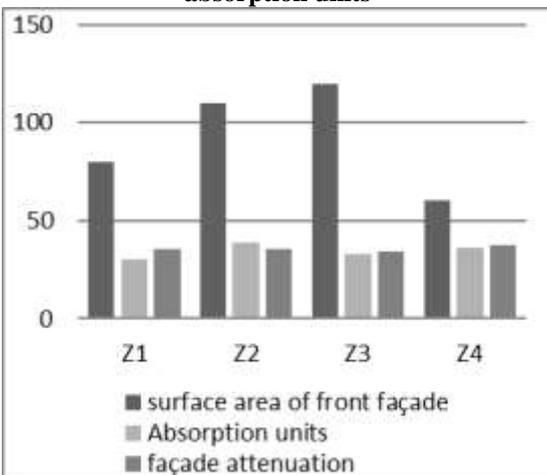
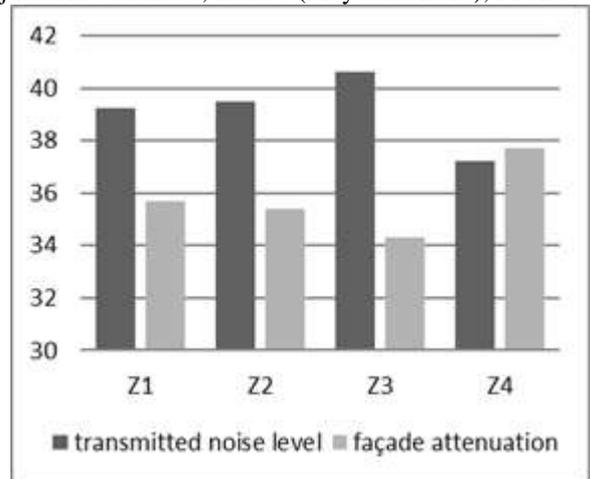***Diagrammatic representation of results:***

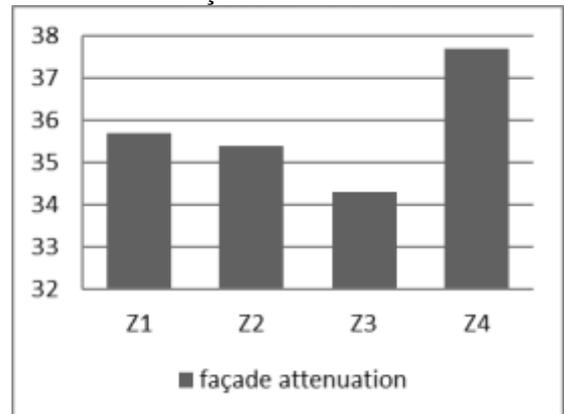**Figure 9: Comparison of surface area of front Façades for the four selected models**

Figure 10: Relation between transmitted sound level & absorption units

Figure11: Relation between surface area & absorption units with facade attenuation

Figure 12: Relation of transmitted sound level and front façade attenuation

**Figure 13: Relation of attenuation values for the four selected models**

III. CONCLUSIONS

1. A protected area lying within the sound shadow zone isobtained by using a recessed elevation exposed to sound, although the total surface area of the front façade isincreased. Comparing the two models (Z2) and (Z3), one discovers that (Z2) model is better because of the backward recessed parts of thefront elevation which increases the total surface area of the building façade as well as other parts lying within the sound shadow zone (Fig. 9).

2. An increase in the interior space area contributes better absorption of sound waves, thus reducing the level of transmitted sound into building and in the meantime increasing the attenuation value at the front elevation (fig. 12). Through comparing the four given models, one finds that:

   - By increasing the façade surface area exposed to noise in addition to reducing room absorption, the level of transmitted sound increases (Fig. 10).
   - The effect of changing the front surface area of a building exposed to noise is larger than the impact of the space absorption degree on the attenuation of the sound source (Fig. 11).

3. Testing the four selected models, one finds that the highest attenuation value is obtained in design (Z4) which has the least surface area exposed to the sound (i.e. unprotected) and the largest surface area of the back elevation opposite to the source direction. The lowest attenuation is achieved in model (Z3) due to the

increase of the exposed front elevation (i.e. unprotected) with no area lying within the sound shadow zone (Fig. 8).

To test hypothesis II, ten mathematical models of different designs of building masses and envelop configurations are chosen to be exposed to a linear finite-length noise source (e.g. traffic noise). Sections (perpendicular to the street elevations) of the ten building masses are drawn so as to maintain the mathematical models on the measuring network where the building site is allocated and the point of reception (A) is determined at the front façade by *X*, *Y* axes including its height above the ground and its distance from the sound source (S) (Fig. 14).
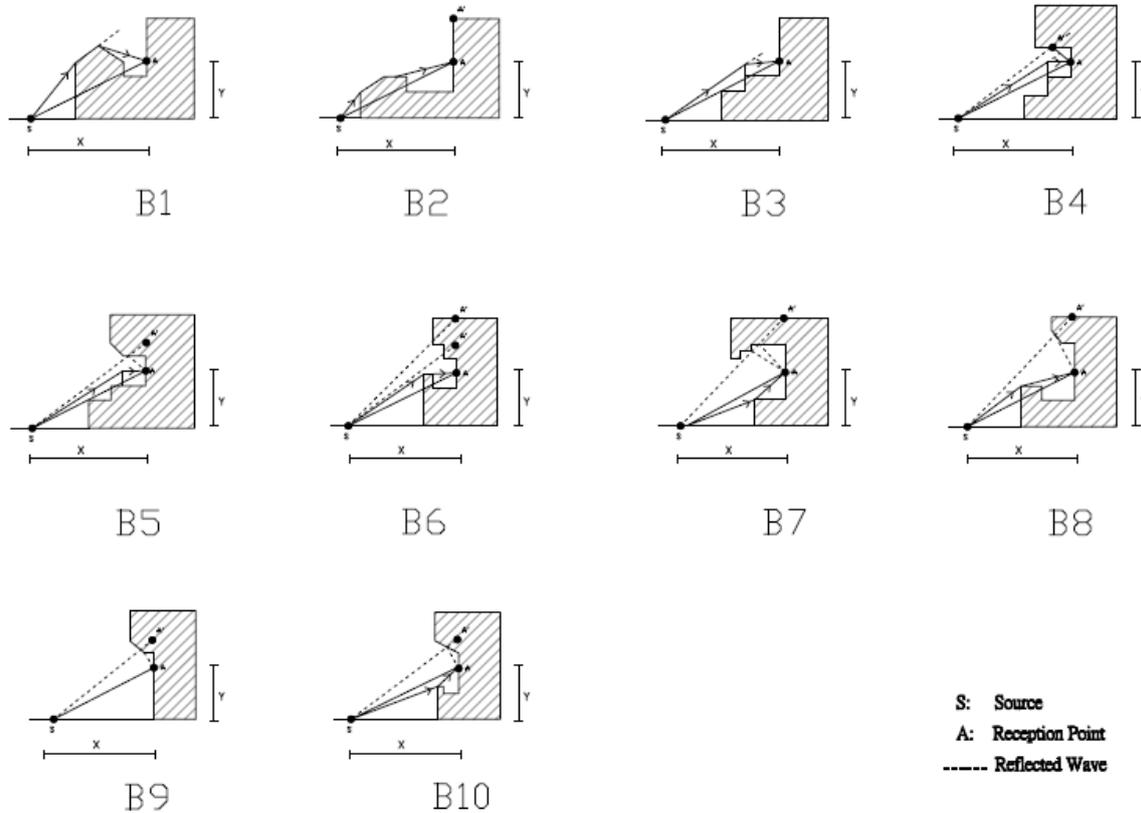
Figure 14: Design types of building masses exposed to traffic noise

IV. ANALYSIS

Testing the geometrical spreading paths of the sound waves reaching at the building, it is necessary to calculate the reflected sound waves paths in regard to the determined reflection points on the building surfaces facing the source. This can be achieved by using an image method to find the reception point (A). However, the surfaces of the exposed configurations are considered as reflecting mirrors to the reception point in order to determine the coordinates of such reflected point of the sound paths received from the source (S). It is feasible, thus to calculate lengths of paths received at the building barriers or balcony parapets placed in front of the reception point (A), including the direct and the diffracted paths from and by these barriers.

Hypothesis II constants:
- Height of reception point (A) from source location (S) at a constant value (y).
- Building height.
- Distance of reception point from source location at a constant value (x).
- Absorption coefficient of building surfaces = 0.02
- Power of sound source (w) = $10^{-4.5}$ watt.

- Direct sound level (LD = 46.6 decibel) at constant sound intensity and distance between source and reception point.

Hypothesis II variables:
- Values of reflected sound path (TR) from the façade due to its configuration.
- Values of diffracted sound paths from building façade due to its design, articulation and envelop configuration, affected by the difference between direct and diffracted paths (T).

Application of mathematical equations to find values of defined variables:

Calculated values of parameters are extracted from the geometrical analysis of the mathematical models. They are used as variable values in equations to find the resultant impact of such variables on noise attenuation applied in the program (Table 2).

1. Calculating the sound intensity at the source (I*s*) projected on the façade area of sound shadow:

$$I_s = \frac{w}{4\pi} = \frac{10^{-4.5}}{4\left(\frac{22}{7}\right)} = 2.5 * 10^{-6}$$

2. Calculating the reflected sound level using the ensuing equations entering the variable value (TR) that represents reflected sound paths measured from

geometrical spreading of sound waves of the mathematical models in question (Beranek, 1971).

LD = 120 + 10 log (ID)

$$IR = I_s (1-\alpha)/ (TR)^2$$

Where
IR = reflected noise intensity.
ID = direct sound intensity.
LD = direct sound level

Is = sound intensity at source = $2.5 * 10^{-6}$

TR= length of reflected sound paths measured from geometrical spreading of sound waves of each design model.

3. Calculating the total sound pressure level (L) at the reception point using the following equation (Beranek, 1971):

L = LD + LR

Where
LD = level of direct sound level.
LR = level of reflected sound level.

Following are the equations used in calculating the attenuation diffraction after adding the (T) values that represent the difference between the direct and diffracted sound paths obtained from the geometrical analysis of the models (Dept. of Transportation, 1988):

AT=10log (N) +13   if N > 1

$AT=13 N^{0.2}$ if $0.05 < N \leq 1$

$AT=5.01+35.7N+61.67 N^2$ if $0.03 < N \leq 0.05$

Where
N = Fresnel's number (variable value) that depends on the difference between the direct and diffracted sound paths that represent the noise attenuation value (Fig. 15) (Dept. of transportation).
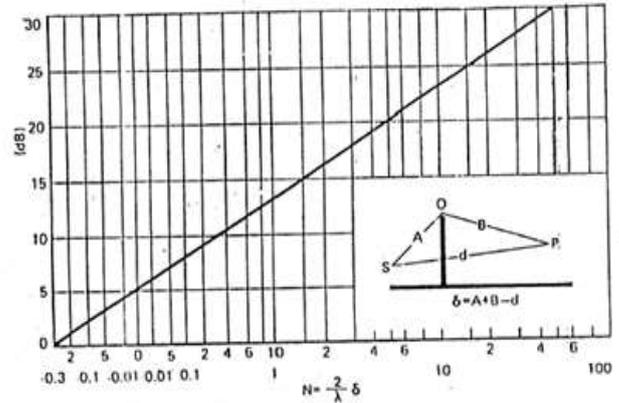

Figure 15: Relation between Fresnel's figure and attenuation of a wall barrier

4. Calculation of the total sound level after attenuation of diffraction from the building masses (Lp)

$$L_p = L - AT$$

Where
AT = attenuation of the diffraction from building masses barrier.
L = total sound pressure level received at the reception point of direct and reflected sound

.

| Model No	AT(db)	LP (db)	L (db)	LR (db)	TR (m)	T (m)
B1	26.224	20.375	46.6	0	0	3.56
B2	20.43	26.16	46.6	0	0	0.94
B3	15.61	30.98	46.6	0	0	0.31
B4	14.49	66.6	81.1	34.5	29.14	0.24
B5	15.75	65.56	81.31	34.71	28.45	0.32
B6	19.33	27.26	46.6	0	0	0.73
B7	15.01	70.26	85.27	38.67	32.06	0.27
B8	16.72	62.89	79.61	33.01	34.59	0.4
B9	0	80.87	80.87	34.27	29.92	0
B10	14.12	66.5	80.62	34.02	30.78	0.22

Table 2: Results of variables calculation from the program

Table 2 above clarifies values of sound path length reflected from the façade and diffracted from the wall barriers and masses lying in front of the reception point (A) at the front façade to indicate the effect of these paths on the total sound level after attenuation.
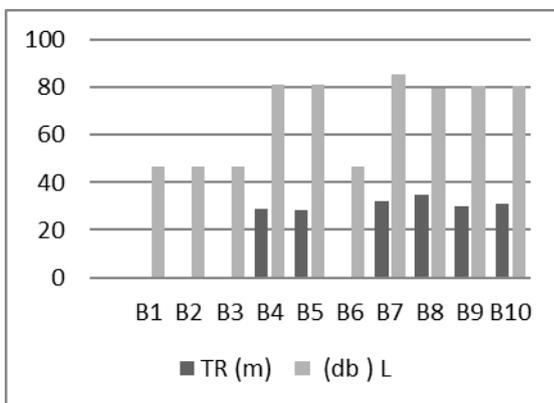
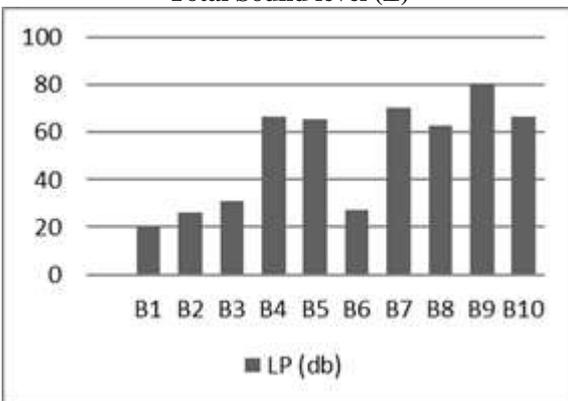V. DIAGRAMMATIC REPRESENTATION OF RESULTS
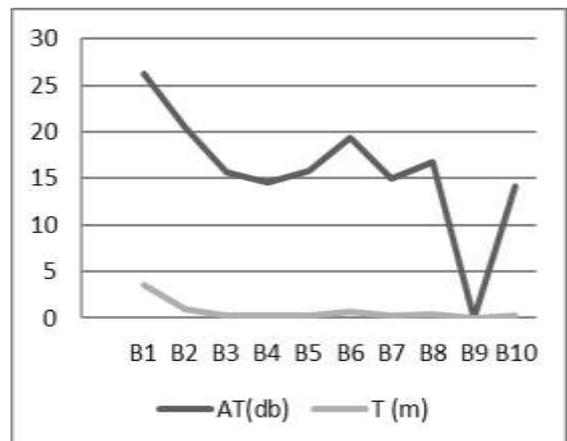
Figure 16: Relation of attenuation and difference between straight and diffracted path (T)
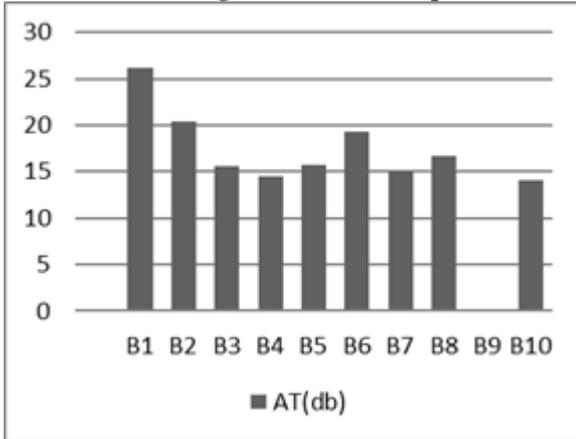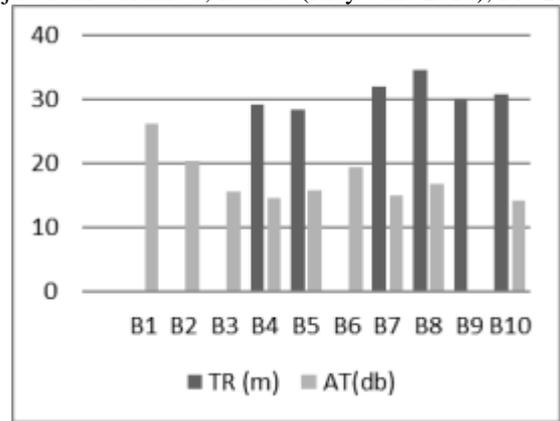

Figure 17: Comparison between attenuation diffraction values of the models
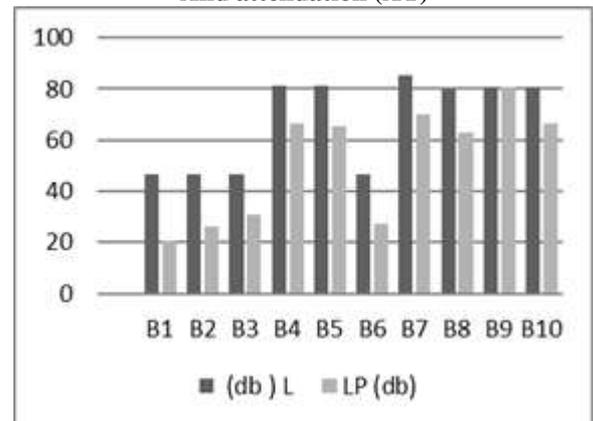

Figure 18: Effect of reflected sound path (TR) on the Total Sound level (L)

Figure 19: Comparison between values of sound level after attenuation (LP)

Figure 20: Relation between reflected sound path (TR) And attenuation (AT)

Figure 21: Relation between sound level before (L) and after (LP) attenuation diffraction

VI. CONCLUSIONS

1. The reception point (A) at the front façade receives direct sound from the source (i.e. traffic noise) and reflected sound from other existing mirroring surfaces, namely according to type of building configuration which increase the total value of the received sound level (L). Nevertheless, sound diffraction from top and around the building mass barriers lying in front of the reception point causes attenuation of the total received sound level due to the difference between the direct and diffracted sound paths (T) originated from the wall barriers or masses. The (T) value in turn, reduces the received sound level, and as the (T) value increases the attenuation value increases accordingly (Fig. 16).

2. No attenuation diffraction exists in model (*B9)* due to the diffracted sound path in front of the reception point. However, the direct and reflected sound increase the total received level of sound. Model (*B1)* represents the best configuration that achieves the highest value of attenuation diffraction (Fig. 17).

3. In model (*B6*), the reception point does not receive reflected path from the staggered configuration that lies on top of it due to the absence of reflected sound points received at it. Besides, good attenuation of the diffracted path is obtained due to the reduction of the received sound level (Fig. 18).

4. The impact of the reflected sound path from the building projection masses on top of the reception point represents an increase of the received sound as shown in the design models (*B4*), (*B7*), (*B5*), (*B8*), (*B9*) and (*B10*) respectively. The value of such level increases as much

as the reflected paths multiply as in model (*B7*) due to the staggered building masses which increase the reflected sound path towards the reception point, thus increasing the level despite of the attenuation difference caused by the diffracted sound path (Fig. 19).

5. The values of diffraction attenuation depend on the distance between the wall barrier or masses and the receptionpoint as well as the height in relation to the reception point height, but in case of equal heights of both the barrier top and the reception point, larger attenuation value is achieved even if it is less higher as shown in model (*B6*) compared with models (*B3*), (*B7*) and (*B8*) respectively (Fig.14).

6. Multiple reflected sound paths reduce the value of attenuation and increase the total sound level at the reception point (Fig. 20). However, the diffracted paths of building barriers and masses at the reception point reduce the value of the total direct and reflected sound level (L) which originates attenuation diffraction(AT). Thus, the total sound level after the diffracted attenuation (LP) becomes the lowest total direct and reflected sound level (L) (Fig. 21).

VII.   GENERAL CONSIDERATIONS

- Respecting certain sound design constraints pertinent to specifications of configuration and masses of barriers on the front façade does not mean ignoring the creative aspects of design. Such relevant constraints contribute co-efficient factors that help in increasing the efficiency of the barriers in maintaining functional and environmental requirements for the building. However, it is feasible to deal with such constraints in a flexible manner so that they may render the façade with design elements adequate enough to buffer noise and climatic effects, apart from other aesthetic and physical aspects such as louvers, balconies, arcades, curtain walls, etc. The latter elements function as a means of self-protection against sound, yielding thus a larger sheltered area to the building envelop which in turn balances the size and configuration of the barriers including climatic shelters especially to buildings directly exposed to heavy traffic noise.

- Make use of projected configurations, recessed and staggered façades in building envelops diffuse sound waves. In the meantime, it is recommended to avert inclined sound reflecting surfaces at windows and doors placed on the façade that is subject to traffic noise.

- Reduction of the building envelop area exposed to a disturbing sound source can be achieved through using articulated configurations on the external façade which reflects the sound waves originating from traffic noise.

- It is of high priority to study the effects of building corners from which attenuation diffracts the sound paths by choosing the highest difference between the diffracted and direct sound paths. This can be ultimately achieved by increasing the length of the diffracted path in order to decrease its sound intensity.

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