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## MODELING OF SOUND PROPAGATION IN URBAN STREETS CONTAINING TREES USING MARKOVIAN TECHNIQUE

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**Abstract:** It is claimed that the trees may become a possible control method for noise in streets and hence contribute another step towards a sustainable environment. This paper examined the capability of an abatement scheme containing absorbent facades and trees in streets through a simulation model developed using the novel approach based upon Markovian techniques. The study showed that sound pressure level in a street containing trees relative to that in an empty street predicted by the Markov model was in good agreement with predictions obtained using commercial software, RAYNOISE model. Within the scope and assumptions in this study, it is shown streets containing trees and absorbent building façade result in sound reductions typically less than 1.5 dB. Hence trees in streets appear to have only a slight effect on sound attenuation, and thus make no significant contribution towards producing a sustainable environment in this respect.

**Keywords:** *Diffuse reflection, Markov process, Transition probability, Sound propagation, Noise control*

### 1.0 Introduction

A number of models of noise propagation in urban streets have been proposed based upon façade reflections which are diffuse (Ismail and Oldham, 2003). In addition to their aesthetical function, trees in urban streets will affect the sound field and should be considered in the model. The importance of the effect of trees as well as other obstacles can be seen from the work of Steenackers et al. (1978) who compared their theoretical expression for sound field drop in smooth streets with field measurements of the decay of sound from a point source located in the street channel. They suggested that the presence of these scattering objects in the street was probably the reason the apparent

coefficient of absorption for wider street is higher than for narrow streets. Kang (2000) has also suggested that diffusely reflecting façades and scattering objects including trees, street furniture etc. may be possible noise control method for sound in streets. However, current diffuse models generally assume that the street channel is empty and hence do not account for the effect of objects such as street furniture, vegetation or vehicles.

In this paper the application of a particular probability method, the Markov chain, which can incorporate the effect of trees will be employed. The method had been suggested by Gerlach (1975), Kruzin and Fricke (1982) and Alarcao and Bento Coelho (2003) in modelling of sound propagation in room. A Markov process involves consideration of states which change with time. The possible transitions between states can be described in terms of a probability or transition matrix where an element denoted by  $p_{ij}$  denotes the probability of a transition from state  $i$  to state  $j$ . The fundamental requirements for a Markov matrix are: i) All elements are non-negative and ii) The sum of each column is 1.

The results from the developed model were compared with the results obtained with a commercial hybrid ray tracing and image source model, RAYNOISE using the diffuse reflection option. The applicability of model to predict sound level for street containing trees are carried out through various abatement scheme and the results obtained compared with the results for a similar empty street.

## 2.0 Modelling Process

### 2.1 Transition probability

The trees are assumed as 'screens' and which scatter the sound in all directions. This is also the assumption made by previous researchers working in the fields of urban noise propagation (Leschnick, 1980; Kuttruff, 1982) when treating the obstacles. Therefore, the trees in the street are modelled as a simple screens aligned in the same direction as the façades. The screens are also assumed to absorb and transmit the sound. The degrees of transmission is simulated by employing a transmission factor, TF which is zero for full screening, one for no screening and values of TF between 0 and 1 relate to partially transparent screens. The configuration of the model is shown in Figure 1. The thickness of the trees is ignored. Both surfaces of the screen are divided into a small patches of the same size as those on surfaces  $I_T$  and  $J_T$ . Surface  $F1_T$  and  $F2_T$  have patches defined by  $f1_x=1,2,\dots,n_1$ , and  $f1_z=1,2,\dots,m_1$ , and  $f2_x=1,2,\dots,n_1$ , and  $f2_z=1,2,\dots,m_1$ , respectively. In order to simplify the mathematics, the dimensions of all surfaces are integer multiples of the patch size including the heights of façades and screens, can be expressed by the integer numbers,  $m$  and  $m_1$ , respectively. A grid based approach is adopted with the grid dimension equal to the patch size.

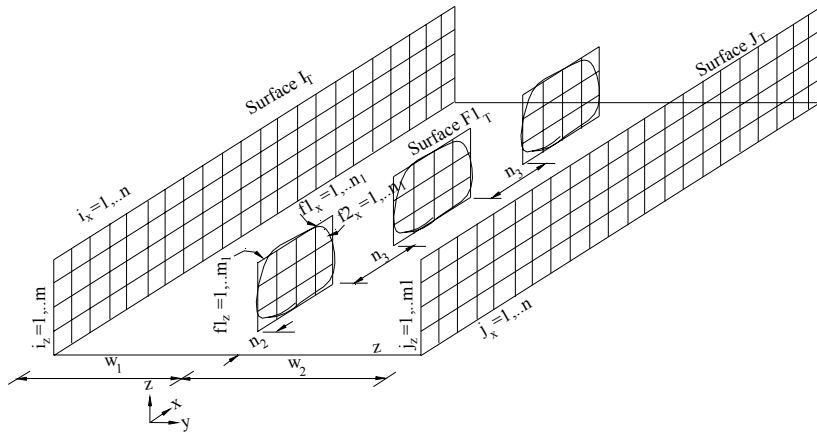


Figure 1: Trees are idealized as simple screen

The source is assumed to be located in the ground plane to avoid the need to consider the possible interference effects. This approach can be justified as the multiple diffuse reflections between facades can be expected to mask any interference effects. The initial radiation of sound is determined by the distribution to any patch on surfaces  $I_T$ ,  $J_T$  and  $F1_T$ . Each patch then is assumed to act as point sources, thus the size of these patches have to satisfy the condition that the distance between any two opposite patches is greater than five times the projected dimension of a patch. This requirement also applies to the distance between the source and any patch and the receiver.

The road is assumed to be specularly reflecting and reflections are taken into account by considering images of the facade and screen patches in the ground plane. The sound to a patch on surface  $J_T$  will have a direct path for radiation from surface  $I_T$  plus sound radiation from a patch on  $I_G$  reflected in the ground plane (Figure 2a),  $I_G$ ; The sound to a patch on screen  $F1_T$  will have direct path of radiation from surface  $I_T$  plus sound radiation reflected in the ground plane i.e. radiation from image in  $I_G$  (Figure 2b); Sound radiation from the patch on surface  $F1_T$  back to a patch on surface  $I_T$  can be direct or reflected in the ground plane. Sound reflected in the ground plane can be treated by means of an image patch on  $F1_G$  (Figure 2c).

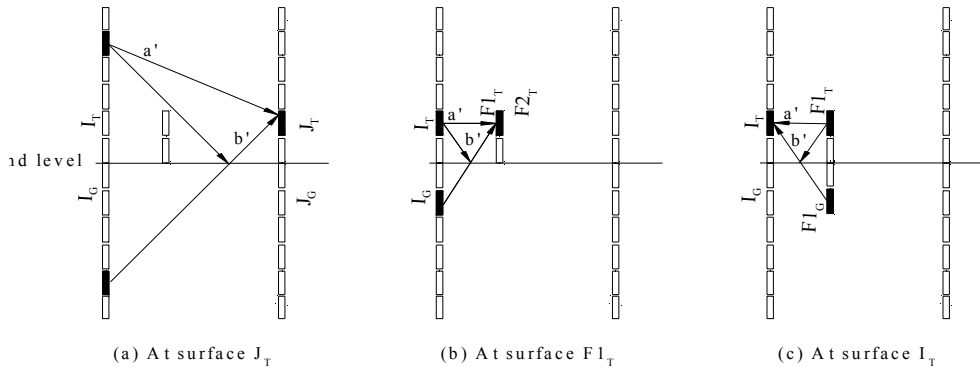


Figure 2: Sound radiated by 2 patches due to direct path (a') and ground reflection (b')

The multiple reflections between patches are modelled as a process of Markov in which the energy falling on a patch in street will be reflected and distributed to all the patches in the street according to their “visibility” with respect to the reflecting patch. This can be interpreted in terms of probability where the fraction of the reflected sound energy reaching a particular patch is equivalent to the probability of reflected energy reaching that patch. Transitions correspond to orders of reflection. The possible transitions between states can be described in terms of a probability or transition matrix.

The transition probability is equivalent to projecting the radiating patch onto a unit hemisphere centred about the radiating patch. The transition probability from patch j to patch i then can be calculated by;

$$P_{(i_x, i_z), (j_x, j_z)} = d\Omega_{(i_x, i_z), (j_x, j_z)} / 2\pi \tag{1}$$

Where  $d\Omega_{(i_x, i_z), (j_x, j_z)}$  is projected area forms a cone with solid angle defined as (Nosal, 1994 and Nosal et al., 2004);

$$d\Omega_{(i_x, i_z), (j_x, j_z)} = \frac{\Delta_x \Delta_z \cos \varphi_{(j_x, j_z)}}{d_{(i_x, i_z), (j_x, j_z)}^2} \tag{2}$$

$d_{(i_x, i_z), (j_x, j_z)}$  is the distance between the centre of patches i and j respectively,  $\Delta_x$  and  $\Delta_z$  are the patch dimensions in the x and z directions for surface I.

The transition probability matrix will consist of the following:

$$P = \begin{bmatrix} 0 & 0 & M_{I_T J_T} P_{I_T J_T} & 0 & P_{I_T F1_T} & 0 & 0 & 0 \\ 0 & 0 & M_{I_G J_T} P_{I_G J_T} & 0 & P_{I_G F1_T} & 0 & 0 & 0 \\ M_{J_T I_T} P_{J_T I_T} & 0 & 0 & 0 & 0 & 0 & P_{J_T F2_T} & 0 \\ M_{J_G I_T} P_{J_G I_T} & 0 & 0 & 0 & 0 & 0 & P_{J_G F2_T} & 0 \\ P_{F1_T I_T} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ P_{F1_G I_T} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & P_{F2_T J_T} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & P_{F2_G I_T} & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (3)$$

$P_{I_T J_T}$ ,  $P_{I_G J_T}$ ,  $P_{J_T I_T}$ ,  $P_{J_G I_T}$ ,  $P_{I_T F1_T}$ ,  $P_{I_G F1_T}$ ,  $P_{J_T F2_T}$ ,  $P_{J_G F2_T}$ ,  $P_{F1_T I_T}$ ,  $P_{F1_G I_T}$ ,  $P_{F2_T J_T}$  and  $P_{F2_G I_T}$  are the sub matrices due to radiation of sound between patches on surfaces indicated by their respective subscripts.  $M_{I_T J_T}$  and  $M_{J_T I_T}$  are masking matrices for the sound radiation from patches on surfaces  $I_T$  to  $J_T$  and sound radiation from patches on surfaces  $J_T$  to  $I_T$  affected by screening.

$M_{I_G J_T}$  and  $M_{J_G I_T}$  are masking matrices for the sound radiation from image patches on surfaces  $I_G$  to surface  $J_T$  and from image patches on surfaces  $J_G$  to surface  $I_T$  due to screening, respectively. Masking matrices contain masking coefficients determined using an integer and remainder approach based upon the area screened by the obstacles. The null sub-matrices relate to radiation between patches on the same surface and to the situations where radiation is not possible (e.g.  $I_T$  to  $F2_T$  and  $J_T$  to  $F1_T$ ).

The fraction of incident sound energy on surface  $I_T$  which radiates to surface  $J_T$  is determined by multiplying reflection coefficient by the transmission factor,  $(1 - \alpha_I)TF$ . However, because the TF will be incorporated into the masking matrix, only  $(1 - \alpha_I)$  can be seen, i.e.  $M_{I_T J_T} P_{I_T J_T} (1 - \alpha_I)$ . For the radiation of energy from patches on surfaces  $F1_T$  to  $I_T$  and from patches on surfaces  $F1_G$  to  $I_T$ , the fraction of energy is determined by  $(1 - \alpha_{F1}) \cdot (1 - TF)$  and subsequently, sub-matrices  $P_{F1_T I_T}$  and  $P_{F1_G I_T}$  are multiplied by  $(1 - \alpha_{F1}) \cdot (1 - TF)$ . The energy radiated from surface  $J$  to surface  $I$  and surface  $F2$  to  $J$  are determined in a similar way.

The processing time can be reduced by employing the principle of reciprocity with respect to the following sub-matrices;  $P_{J_T I_T} = P_{I_T J_T}$ ,  $P_{J_G I_T} = P_{I_G J_T}$ ,  $P_{J_G I_T} = P_{I_G J_T}$ ,  $P_{J_T F2_T} = P_{I_T F1_T}$ ,  $P_{J_G F2_T} = P_{I_G F1_T}$ ,  $P_{F1_T I_T} = P_{I_T F1_T}^T$ ,  $P_{F1_G I_T} = P_{I_G F1_T}^T$ ,  $P_{F2_T J_T} = P_{I_T F1_T}^T$ ,  $P_{F2_G I_T} = P_{I_G F1_T}^T$ ,  $M_{J_G I_T} = M_{I_G J_T}$ , and  $M_{J_T I_T} = M_{I_T J_T}$ .

$P_e$  can be expressed as ;

$$P_e = \begin{bmatrix} 0 & 0 & M_{I_T J_T} P_{I_T J_T} (1-\alpha_j) & 0 & P_{I_T F_{I_T}} (1-\alpha_j) & 0 & 0 & 0 \\ 0 & 0 & M_{I_G J_T} P_{I_G J_T} (1-\alpha_j) & 0 & P_{I_G F_{I_T}} (1-\alpha_j) & 0 & 0 & 0 \\ M_{I_T J_T} P_{I_T J_T} (1-\alpha_j) & 0 & 0 & 0 & 0 & 0 & P_{I_T F_{I_T}} (1-\alpha_j) & 0 \\ M_{I_G J_T} P_{I_G J_T} (1-\alpha_j) & 0 & 0 & 0 & 0 & 0 & P_{I_G F_{I_T}} (1-\alpha_j) & 0 \\ P_{I_T F_{I_T}}^T (1-\alpha_{F1})(1-TF) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ P_{I_G F_{I_T}}^T (1-\alpha_{F1})(1-TF) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & P_{I_T F_{I_T}}^T (1-\alpha_{F2})(1-TF) & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & P_{I_G F_{I_T}}^T (1-\alpha_{F2})(1-TF) & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (4)$$

The effective transition matrix  $P_e$  then can be used to obtain the distribution of sound energy from patches to patches during each transition order as follows;

$$E^{(q)} = E^{(q-1)} P_e = E^{(0)} (P_e)^q \quad (5)$$

q is order of transition and E is total energy.

### 2.2 Distribution of Sound Energy From Source to Patches

Before the Markov model can be run it is necessary to distribute the sound energy of a source to the patches which can then be regarded as sound sources, for example to a patch on surface  $I_T$  (Figure 3). The basic principle of the source energy distribution is that the fraction of energy from the source that is incident at each patch is the same as the ratio of the solid angle subtended by the receiving patch divided by the total angle into which energy from the source radiates. The normal intensity at the centre of a patch can be determined using the inverse square law which a point source at ground plane at  $(x_s, y_s, z_s)$  radiate hemispherical. The source properties (sound power spectrum) can be separated out from the geometry to obtain a source function, S. for example for patches on surfaces  $I_T$ ;

$$S_{(i_x, i_z)_T} = \frac{\cos \theta_{(i_x, i_z)_T}}{2\pi d^2_{s, (i_x, i_z)_T}} \quad (6)$$

Where  $d_{s,(i_x,i_z)_T}$  is the distance from the centre of a patch on surface  $I_T$  to the source and  $\cos \theta_{(i_x,i_z)_T}$  is the angle of incidence of a sound ray from the source to the centre of a patch on surface  $J_T$ .

The source to patch distribution function vector can be written as;

$$S = \left[ S_{I_T} \quad S_{I_G} \quad M_{S_{J_T}} S_{J_T} \quad S_{J_G} \quad S_{F1_T} \quad S_{F1_G} \quad S_{F2_T} \quad S_{F2_G} \right] \quad (7)$$

$S_{I_G}$ ,  $S_{J_G}$ ,  $S_{F1_G}$ , and  $S_{F2_G}$  is sub matrices corresponding to radiation from the source to image patches which are null matrices. Radiation from the source to  $F2_T$ ,  $S_{F2_T}$  is set to be zero because radiation to this surface is impossible.  $M_{S_{J_T}}$  is the masking matrix for sound radiation from source to patch on  $J_T$ . It can be determined by applying an integer and remainder method in the x and z directions.

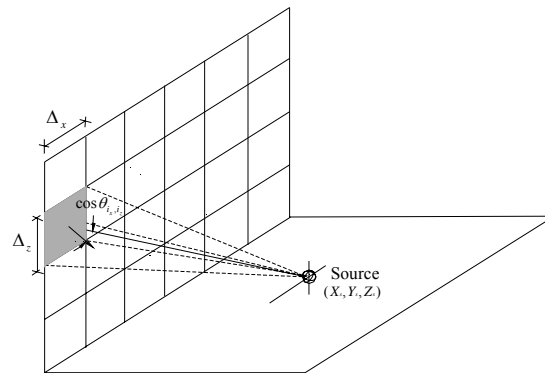


Figure 3: Distribution of sound energy from a source to a patch i.

2.3 Distribution of Sound Energy From Patches to Receiver

The radiation of sound reflected diffusely from a patch and image patch to a receiver can be treated in the same way. The intensity at the receiver due to radiation from a patch can be calculated using the inverse square law to yield a receiver function and distribution vector similar in form to Equations (6) and (7).

The distribution vector for sound energy from patches to a receiver can be written as follows;

$$R = \left[ R_{I_T} \quad R_{I_G} \quad M_{J_T R} R_{J_T} \quad M_{J_G R} R_{J_G} \quad R_{F1_T} \quad R_{F1_G} \quad R_{F2_T} \quad R_{F2_G} \right] \quad (8)$$

$R_{F2_T}$  and  $R_{F2_G}$  are equal to zero.  $R_{I_T}$ ,  $R_{I_G}$ ,  $R_{J_T}$ ,  $R_{J_G}$ ,  $R_{F1_T}$  and  $R_{F1_G}$  are the receiver to the centre of the patches on surfaces  $I_T$ ,  $I_G$ ,  $J_T$ ,  $J_G$ ,  $F1_T$ , and  $F1_G$ , respectively.  $M_{J_T R}$  and  $M_{J_G R}$  are the masking matrices due to the presence of the screen. The determination of the masking matrices is similar to the determination of the matrices for the case of radiation from the source to patches on  $J_T$ .

The total energy response at the receiver after  $q^{th}$  transition is determined using the following expression;

$$I_T = I_d + \sum_{j=1}^q E^{(q-1)} AR \quad (9)$$

Where  $A$  is absorption coefficient,  $E$  total energy,  $I_d$  is direct sound from the source and  $R$  is the receiver function.

The sound pressure level at receiver is given by;

$$SPL = 10 \lg 10 ( I_T / 10^{-12} ) \quad (10)$$

3.0 Comparison Between Results From Markov and RAYNOISE Models

The validity of the 3D Markov approach was checked with RAYNOISE model. The street length and width of 50m and 10m was employed (Figure 4). The point source was positioned at (5m, 2.5m,0m). Two screen arrangements of 4@1m x3m and 4@1m x10m were employed. The screen were assumed reflective with TF=0. In Raynoise model, the source emission angle was set at  $H_{min}=-180^\circ$  to  $H_{max}=180^\circ$  and  $V_{min}$  and  $V_{max}$  equal to  $0^\circ$  and  $90^\circ$ , respectively in order to ensure that the source radiates in a hemispherical way.



The ground was assumed to be fully reflecting with both the absorption coefficient and the diffusion coefficient set at 0. The facade absorption coefficient was set to 0.1 and the diffuse coefficient,  $d$  was set to 1 to obtain diffuse reflections. The calculation was carried out using 300,000 rays the triangular beam option and 12 reflections.

The sound pressure level in a street containing reflective screens relative to that of the sound pressure level for the street without screens obtained from the 3D Markov and RAYNOISE models is shown in Figure 5. The results from both simulations show a very small effect (approximately a variation of -0.3 to 0.4 dB) and they are in agreement typically better than 0.2 dB (Figure 5).

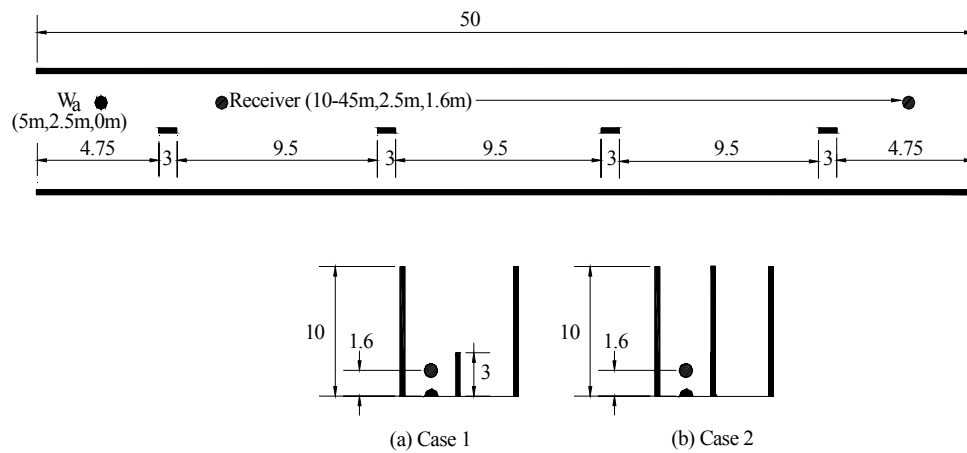


Figure 4: Street configuration

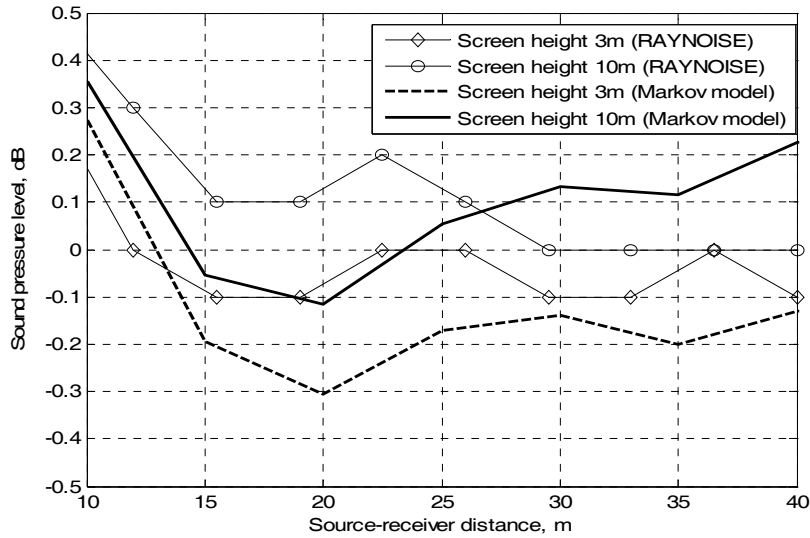


Figure 5: Comparison sound pressure level in a street with reflective screens relative to that of the street without screens obtained from the RAYNOISE and the 3D Markov models.

#### 4.0 The Effect of Trees and Absorption of Building Facades

The effect of trees were carried out by assuming that absorption coefficients of trees within 0.1 to 0.3. This is theoretically derived using equation  $\alpha = Gf^{0.5}$  where  $f$  is frequency and  $G$  is a constant within the range 0.001 and 0.002 (Toshio and Shinji, 1996). Trees with dense leaves are assumed with a Transmission Factor  $TF=0.25$ . Seven noise abatement schemes as shown in Table 1, consisting of various treatments to both facade surfaces and screen surfaces are investigated. Case I was intended to study the effect of untreated facades containing screen other than trees which is absorptive.

Table 1: Absorption coefficient and transmission factor for each abatement case

Case	Absorption coefficient				Transmission factor(TF)
	Façade 1	Façade 2	Screen face 1	Screen face 2	Screen
I	0.1	0.1	0.9	0.9	0
II	0.1	0.1	0.1	0.1	0.25
III	0.2	0.2	0.3	0.3	0.25
IV	0.3	0.1	0.3	0.3	0.25
V	0.4	0.4	0.3	0.3	0.25
VI	0.4	0.4	0.9	0.9	0
VII	0.4	0.4	0	0	1

Case II was used to investigate when screen consisting of dense leaves trees (TF=0.25) and with absorption coefficient 0.1. The sum of the absorption coefficient and the transmission factor must be less than 1 to ensure that the law of conservation is not violated. Case III was intended to investigate the effect when the absorption coefficient of façade is doubled and the screen of densely leaves trees have greater absorption. Case IV was similar to Case III but was aimed to investigate the effect of absorption concentrated on one side of facade. Case V was used to examine the effect when the absorption coefficient of façade in Case III is doubled. Case VI was similar with Case I with the building facades more absorptive. Case VII was used to examine the effect of the screen with a transmission factor of 1.

The results of each case were compared with that for the unscreened case with the absorption coefficient of both façades equal to 0.1. Figure 6 shows the sound pressure level variation relative to the unscreened case for source-receiver distances of 5m to 40m.

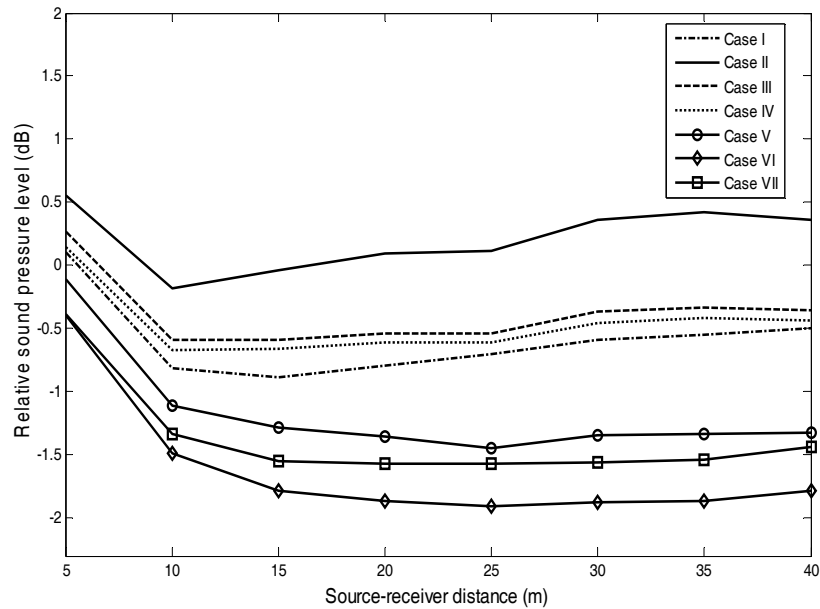


Figure 6 : Effect of building facades absorption and transmission factor (TF)

Abatement scheme with reflective façade and densely leaves of trees with low absorption increase the sound pressure level up to 0.5 dB. While abatement scheme with absorptive building facades and the densely leaves of trees with absorption coefficient 0.3 and TF=0.25 (Case V) reduced approximately 1.5 dB. The reduction is similar to abatement scheme with absorptive building facades i.e without any screen. However, reduction due to abatement scheme consisting strong screen absorptions for both building facades and screens (Case VI) is higher than abatement scheme in Case V with the difference is approximately by 0.4dB. Also the effect of reduction of absorption concentrated on one side of facades is similar to the effect with the distribution of absorber evenly on both facades.

### 5.0 Discussion

It has been found that the relative sound pressure level predictions obtained with the 3D Markov approach agreed with the RAYNOISE model predictions to within approximately 0.2 dB. This small difference suggests that 3D Markov processes produces results equivalent to those of the ray tracing algorithm. The results of investigations using both the 3D Markov model and RAYNOISE, the use of screens with a low absorption coefficient can result in a slight increase in the sound pressure level. The same trend with the dense leaves trees with low absorption coefficient. The

result is consistent with experiments using a scale model of sound propagation in a street containing pedestrian barriers with low absorption coefficient by Horoshenkov et al. (1999).

The reduction of up to 2 dB can be achieved when both the facades absorption are 0.4 and screens with high absorption coefficients of 0.9. When this screen replaced by dense leaves trees with coefficient of absorption 0.3, it does not have a significant effect on sound attenuation in the streets. The maximum sound attenuation predicted along the street along the street was less than 1.5 dB. Previous research by Kragh (1981) also found from his experimental investigation that the effect of a belt of trees near the roads was less than 1 dB. Tang and Ong (1988) also reported similar findings in their work on the simulation of the effect of road side trees in an urban canyon on the sound field at ground level using the Monte Carlo method. The sound reduction is also affected by the distribution of absorber on facades and it is better to concentrate absorption on one façade as suggested by Kang (2000).

## **6.0 Conclusion**

A 3D Markov model for the prediction of sound propagation in streets containing trees has been described. It has been shown that the sound pressure level relative to the sound pressure level for unscreened case predicted by the Markov model is in good agreement with predictions obtained using RAYNOISE model. This shows that Markov approach has the potential to predict the sound field in more complex environments. The technique could also be developed to investigate sound propagation through a region combining a low density of buildings as considered by Leschnick (1980) and Kuttruff (1982).

Within the scope and assumptions in this study, it is shown the abatement schemes containing trees with dense leaves and absorbent building façades result in sound reductions that are typically less than 1.5 dB. Hence the trees with dense leaves in streets appear to have only a slight effect on sound attenuation, and thus make no significant contribution towards producing a sustainable environment in this respect. The results also suggest that any forms of screens with a low coefficient of absorption do not have a significant effect on sound attenuation in the streets and may actually result in a slight increase in noise level.

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