INTERNATIONAL CONGRESS ON ACOUSTICS
MADRID, 2-7 SEPTEMBER 2007

A NEW MODEL FOR ACOUSTIC DESIGN OF OPEN OFFICES

PACS: 43.55.Ka

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ABSTRACT
Noise control in open offices should aim to the reduction of the disturbance of speech and human activities. Applicable noise control methods are: room acoustical, architectural and layout design, team arrangement of workers and behavioural rules. Excellent room acoustical conditions can be obtained with high room absorption, high screens and shelves, and comfortable masking sound. The interaction of these means is complicated and it depends strongly on the distance from the speaker. The distraction caused by speech reduces with decreasing speech sound level and speech intelligibility.
Measurement method and recommendations for the acoustic target levels were presented in an associated paper. The aim of this study is to present a simple model for acoustical design of open offices. The model was based on measurement results of 15 very different open plan offices. The model takes into account room dimensions, ceiling and wall absorbers, furniture height, masking sound level and speech effort. The model calculates the A-weighted speech sound level and Speech Transmission Index at increasing distances from the speaker. Finally, the radius of distraction, r_D, and spatial decay of A-weighted speech, DL_2 are determined. The tool is freely available in the internet and it is very easy to use.

INTRODUCTION
Most office workstations are located in open plan and landscaped offices (open offices). In open offices, the most distracting noise source is speech and human activities [1]. The room acoustical design in open offices should aim to the reduction of the distractive speech noise. However, there are no general methods available for predicting the speech noise propagation in open offices. Room acoustical computer modelling has been found too heavy and slow method for practical design where principal effect of different interior designs on room acoustics should be answered immediately.

The aim of this study is to present a simple model for predicting speech noise propagation in open offices. In this paper, a model for predicting spatial decay of A-weighted speech, DL_2, and Speech Transmission Index, *STI*, is presented. The model describes spatial attenuation of speech noise at short and long distances from a speaker. The model is based on the experimental research results of Virjonen et al [2,3]. The model is described in more detail in an unpublished Ref. [4].

MATERIAL AND METHODS

Background
The model is based on sound propagation measurements in 15 very different open offices described in associated paper [3]. A-weighted speech level, L_S, Speech Transmission Index, *STI*, and other room acoustical parameters e.g. reverberation time, T_{20}, and Early Decay Time, *EDT*, along a straight line were measured. The measured T_{20} values were 0.32 - 1.15 s and the measured *EDT* values were 0.31 - 1.37 s.

During the measurement of Virjonen et al. [2], detailed information of the offices was collected, e.g. room geometry, absorption coefficients of the surfaces, dimensions and properties of screens and furniture and layout metrics. The room lengths were between 16 m and 70 m, room widths between 4 m and 45 m, and room height between 2.5 m and 5.9 m. The screen heights varied between 1.2 and 2.2 m.

The absorption coefficient estimations were based on material absorption databases since the most prominent surface materials could be identified. The ceiling absorption coefficients were between 0.1 and 0.8, the floor absorption coefficients between 0.1 and 0.4 and the wall absorption coefficients between 0.1 and 0.9.

The spatial decay of the A-weighted speech level per distance doubling, DL_2, was determined using the A-weighted speech sound levels measured at the distances of 4 - 32 meters away from the speaker. The measured A-weighted speech levels in the measurement line are presented in Ref. [2].

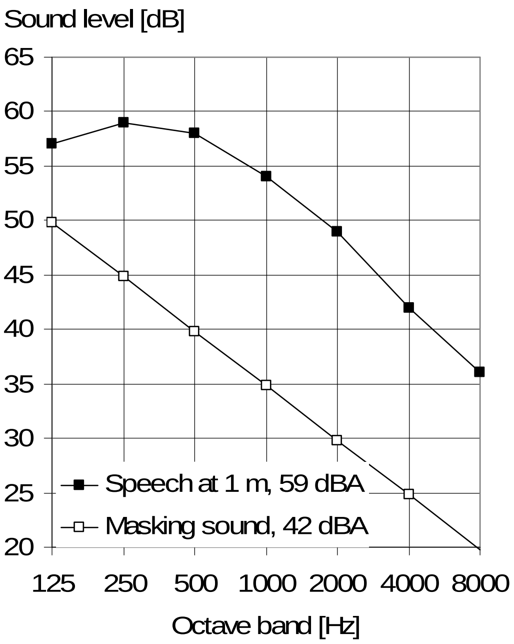
Model for the spatial decay rate of speech DL_2

The A-weighted speech level attenuated almost linearly with logarithmic distance in all offices. However, the attenuation was often two-pieced: smaller near the speaker, and growing after a certain distance. According to our analysis, the determination of DL_2 should start at a distance of 4 meters from the speaker. Therefore, the result parameters of the model should be the spatial decay of the A-weighted speech level per distance doubling, DL_2, and the A-weighted speech level at 4 meters from the speaker, L_{pS4m}. (Fig. 1)

The experimental data of Ref. [2] was analyzed using single and multi-variable linear regression analysis. No single parameter could predict DL_2 or L_{pS4m} properly. After several attempts, the multi-variable linear regression analysis produced acceptable empirical equations 2 and 3 for both DL_2 and L_{pS4m}. The selected input parameters of the model were room length, L, room width, W, room height, H, screen height, h, screen width, w, and average absorption coefficients, α, of floor, ceiling, walls and screens. An example of determining the input parameters is presented in Fig. 2.

Model for the radius of distraction r_D

Spatial decay rate of speech, DL_2, does not describe the speech privacy since it is unaffected by background noise level of room. Therefore, another parameter is needed. The most appropriate descriptor of speech privacy is *STI* since it is physically measurable and correlated with work performance.[5] The prediction of *STI* was based on speech-to-noise ratio, L_{SN}, and early decay time, *EDT*, as described in Ref. [6]. Spatial decay of *STI* was used to determine the radius of distraction which is determined as the distance where *STI* falls under 0.50. The limit was based on Ref. [5].



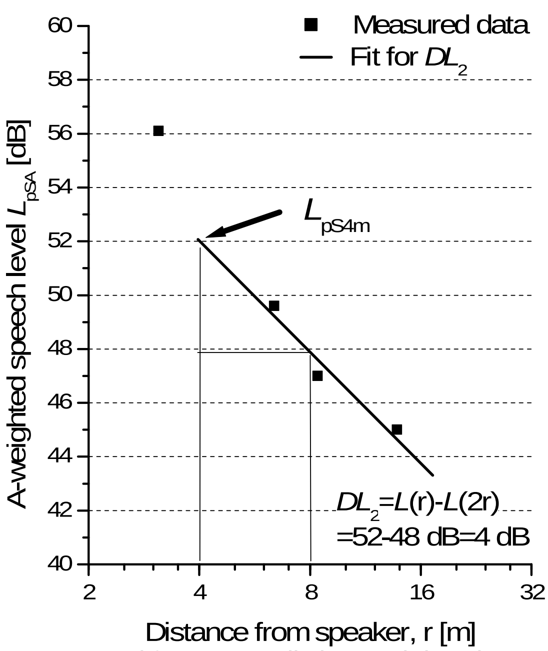


Figure 1.- Left: The speech and masking spectra used for *STI* predictions. Right: The determination of DL_2 and L_{pS4m}.

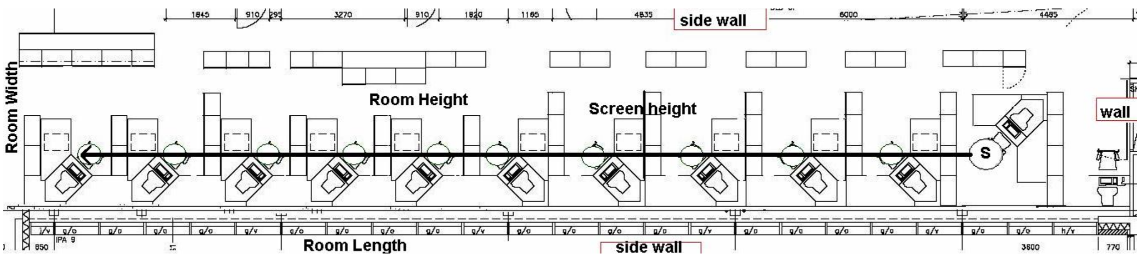


Figure 2.- An example of determining the input parameters, office nr. 11 in Ref. [3].

The calculation of A-weighted speech level is explained below. Background noise level is freely selectable. Typically, it is between 30 and 50 dBA in Europe. The value should be based on the HVAC design, if ventilation is the main noise source. If artificial masking system is used, the expected value is used, typically 40 ... 45 dBA.

The spectrum and level of the speech and the background noise must be considered in the determination of speech-to-noise ratio, L_{SN}. To simplify the calculations, the shape of the speech sound spectrum and the masking background noise are assumed to be constant (Fig. 1). The selected speech sound spectrum represents normal running speech [2]. The masking spectrum suggested by Beranek is used [7].

There is no simple method to calculate the *EDT* of complex rooms. In the measured open offices, the difference between T_{20} and *EDT* was small. Therefore, reverberation time was predicted using e.g. Sabine's equation: T=0.16V/A, where V is room volume [m^3] and A is total room absorption area [m^2-Sab].

PREDICTION MODEL

The prediction model is presented in Equations 1 - 3. The model is used to predict the spatial decay of the A-weighted speech level along a line at increasing distances from a speaker. The A-weighted speech level at distance r from the speaker, L_{pS}, can be predicted by

$$L_{pS}(r) = L_{pS4m} - 3.3DL_2\left(\lg(r) - \lg(4)\right) \qquad \text{(Eq. 1)}$$

where

$$L_{pS4m} = L_{pS1m} - 3.23h - 0.09W + 0.44\alpha_{horizontal} - 5.75\alpha_{ceiling} \qquad \text{(Eq. 2)}$$

and

$$DL_2 = 7\frac{h}{H} + 0.17\frac{L}{H} + 4.28\alpha_{ceiling} + 1.52\alpha_{horizontal} \qquad \text{(Eq. 3)}$$

The A-weighted speech level of normal speech in free field at the distance of 1 meter from the speaker, L_{pS1m}, is 59 dB. The horizontal absorption coefficient, $\alpha_{horizontal}$, can be estimated as an average of wall and screen absorption coefficients. The absorption coefficients of the ceiling, the floor, the walls and the screens can be estimated when the surface materials are known. The room length, L, is determined to the direction of measurement line. The average screen height, h, is the average height of shelves and screens.

Accuracy of the models

The prediction accuracy in the 15 open offices is presented in Figure 3. The average accuracy of L_{pS4m} predictions was -0.2 dBA with standard deviation of 2.2 dBA. The average accuracy of DL_2 predictions was +0.4 dBA with standard deviation of 1.4 dBA. The comparison of measured and predicted spatial decays are presented in Figure 4 for office nr. 11.

The accuracy of the model was also determined in individual measurement points. The average accuracy of the A-weighted speech level in individual offices was -5.5...+3.8 dB in the 15 open offices and the standard deviation was 0.6...3.5 dB (Table I). The average accuracy of the *STI* prediction was -0.12...+0.13 and the standard deviations were 0.01...0.09. The accuracies are acceptable for design purposes.

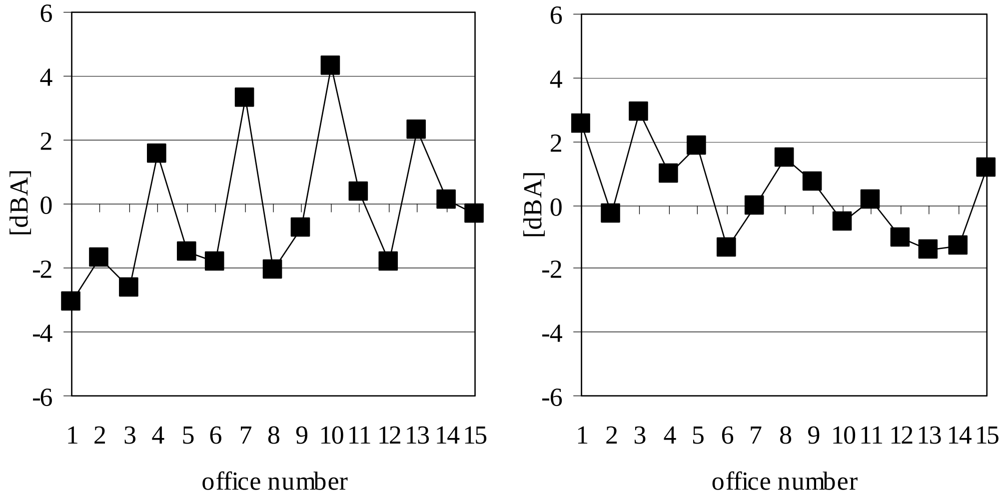


Figure 3.- The prediction accuracy of L_{pS4m} (left) and DL_2 (right) in 15 offices.

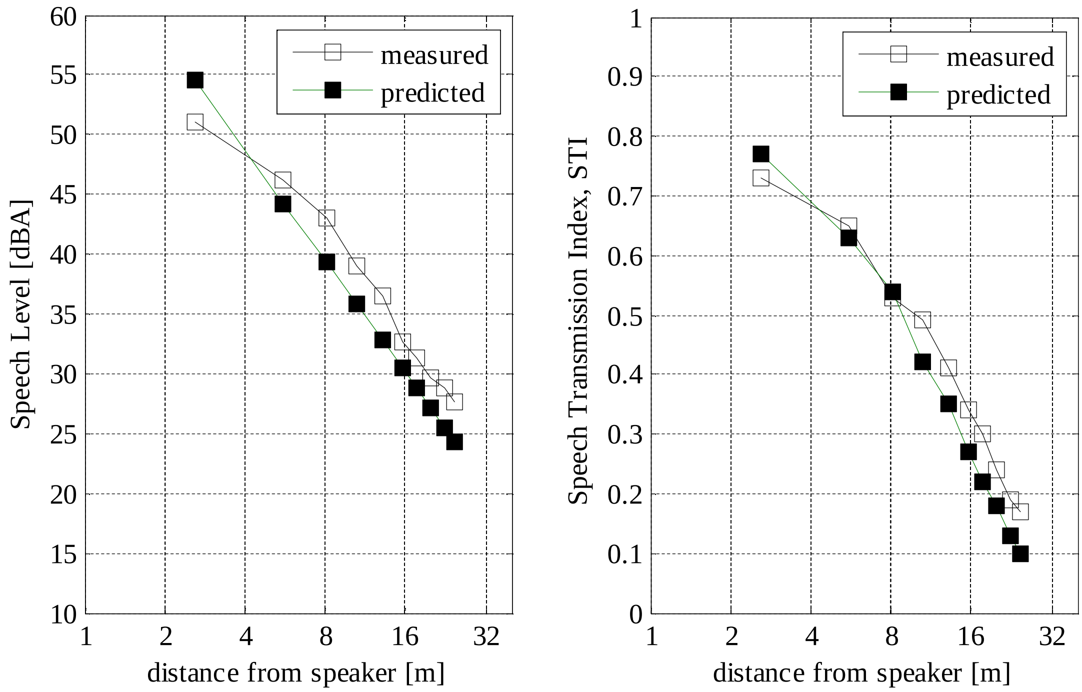


Figure 4.- Predicted and measured A-weighted speech level (left) and Speech Transmission Index (right) in the office nr. 11.

DISCUSSION

A new model was presented for designing of open offices. The model is based on empirical data. The modelled results may not be reliable if the room under design is significantly different from the open offices of this study. In the future, the determination of prediction accuracy should be based on other offices. Now, the same offices were used as source of the model and validation. However, we have strong preliminary evidence that the model gives the same accuracy in most of the typical open office designs as documented here.

The development has not been finished. The database of 15 offices lacks strongly damped offices where room height is small, screen height is high and absorption coefficients are high on ceiling, screens and walls. This configuration should result in DL_2>13 dB or more. The model cannot be used for the design of such offices until such offices have been measured and added to the present database.

INTERNET TOOL

The proposed model has been programmed into a JAVA applet which is freely available in the internet [8]. The applet has a simple interface for selecting the input parameters (Fig. 5). The room dimensions are selectable within reasonable ranges. A few typical surface materials for the walls, ceiling, floor and screens are selectable from list boxes. Speech effort and the masking sound levels are also adjustable. The spatial decays are presented graphically. The single number values DL_2 and r_D are given and they can be compared to recommendations of Ref. [3] which are also visible in the interface. The user can select display of either A-weighted speech level or Speech Transmission Index by radio button.

The internet tool has received positive feedback from acoustical designers, material manufacturers, students, end users, architects and interior designers. It is designed for all parties that are involved in the acoustic design of new or renovated open offices.

Table I.- The average and the standard deviation of the prediction accuracies of L_{pS} and *STI* in the 15 open offices. The number is averaged over all measurement points.

open office number	prediction accuracy of L_{pS} [dBA] average	prediction accuracy of L_{pS} [dBA] standard deviation	prediction accuracy of *STI* average	prediction accuracy of *STI* standard deviation
1	-3.8	1.3	**-0.12**	0.01
2	-1.2	0.6	**-0.09**	0.04
3	-4.4	1.9	**-0.12**	0.04
4	0.7	1.3	**0.01**	0.09
5	-3.3	1.3	**-0.11**	0.03
6	-1.9	1.1	**-0.02**	0.05
7	2.8	0.8	**0.02**	0.07
8	-4.0	3.1	**-0.06**	0.04
9	-5.5	1.2	**-0.06**	0.05
10	3.8	0.8	**0.05**	0.06
11	-2.3	2.1	**-0.04**	0.04
12	-2.8	1.9	**-0.04**	0.04
13	0.2	3.5	**0.05**	0.05
14	0.8	2	**0.09**	0.05
15	-1.2	1.2	**0.13**	0.05

ACKNOWLEDGEMENTS

This study was a part of national research programme MAKSI (Perceived and modelled indoor environment) funded by Tekes, National Technology Agency, Finnish Institute of Occupational Health and several participating companies. Thanks are due to the companies who let their premises at our disposal. Thanks are due to all researchers, consultants, architects and material manufacturers for good comments which helped us in the development of the internet tool.

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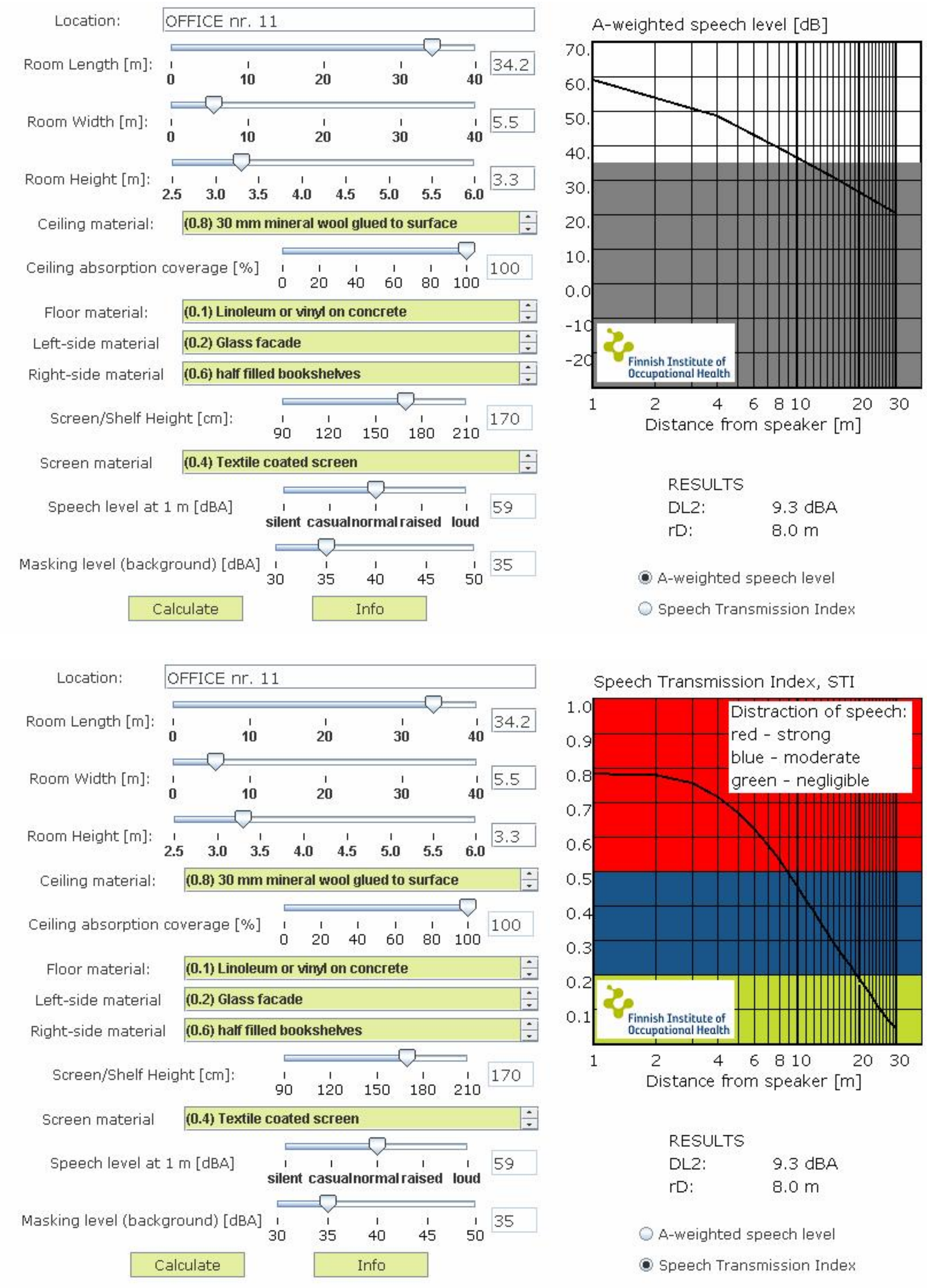

Figure 5.- Screen captures of the internet tool. Spatial decays of A-weighted speech level (top) and Speech Transmission Index (bottom)