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LINKING SPEECH CLARITY, REVERBERATION, AND DISTANCE FOR CLASSROOM DESIGN OPTIMIZATION

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ABSTRACT

Modern acoustic design for learning spaces often emphasizes reverberation time (RT) as a primary parameter; however, speech clarity (C50) is also important for ensuring speech intelligibility. Because RT can be calculated analytically and source-receiver distance is easily measurable, this study examines the relationship between C50, T30 and distance in classrooms with absorptive ceilings and backwalls. Measurements in nine university auditoria – spanning a range of room lengths and yielding 181 distinct observations across six octave bands – were analysed using Pearson correlations and regression models. An average empirical model for C50 was derived from source-receiver distance. These findings offer a practical tool for simplifying the acoustic design process without the need for complex 3D modelling.

Keywords: *speech clarity, reverberation time, Pearson coefficient.*

1. INTRODUCTION

In many acoustic designs, reverberation time (RT) is used as the main criterion for evaluating room acoustics. However, relying solely on RT does not capture all factors related to speech intelligibility [1], [2]. Speech transmission index (STI) that best describes this is often related to speech clarity (C50) [3], [4]:

$$C_{50} = 10\lg\frac{\int_0^{50} p^2(t)\mathrm{d}t}{\int_{50}^{\infty} p^2(t)\mathrm{d}t}\,\mathrm{dB} \tag{1}$$

Speech clarity provides insight into how well speech is conveyed within a space [5]. Given that RT can be calculated analytically using methods like the Eyring or Sabine formulas, it could be worth exploring a correlation between RT and C50, which may allow designers to estimate C50 without the need for complex 3D modelling, simplifying the design process and reducing costs.

A study from Campbell et al. [2] showed that for room with ceiling absorption RT varies very little, whereas C50 changes significantly. Different researchers introduced C50 calculation models using RT in [3] and [6]. Nijs and Rychtáriková in [7] and later Pelegrin-Garcia et al. [3] showed that incorporation of background noise level is crucial for correct estimation of speech intelligibility in real life conditions. It was stated that achieving good speech intelligibility in classrooms requires balancing the amount of absorption: too little causes high reverberation and poor clarity, while too much can reduce beneficial early reflections and lower U50, derived from C50 and background noise.

This paper examines the relationship between C50, RT and source-receiver distance with the aim of developing an alternative approach for estimating speech clarity in classrooms, auditoria, and other spaces where speech is a primary function. The current study included room acoustics measurements in 9 different classrooms in Riga Technical university.

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2. MEASUREMENTS

The measured rooms are university auditoria with regular rectangular shape. All rooms have mineral wool acoustic ceiling tiles and mineral wool panels on the back wall, a conventional design for teaching premises. The only exception is the 27 m long room, which had a sound reflecting glass cabinet. There are tables and wooden chairs. The walls to the corridor has protrusions to the outside, depth of 50-70 cm. Similar shape applies to the windows. This is to say that the rooms are not perfectly rectangular and have at least some degree of scattering. All rooms have an average ceiling height of 2.66 ± 0.05 m and width 5.78 ± 0.5 m, thus it is argued that these dimensions are similar for all rooms. The length of the rooms varies from 8.84 m to 27 m.
The measurements were done according to ISO 3382-1 [4] with a 15 s long exponential sweep. The measured impulse responses were processed to receive various acoustical parameters, including T30 and C50. All source-receiver positions were measured, so that the distances between sources and receivers are known. In 8 of the 9 rooms there were 3 sources and 5 to 10 individual receivers for each source. Only one room had a single sound source. In total there are 181 separate measurements.

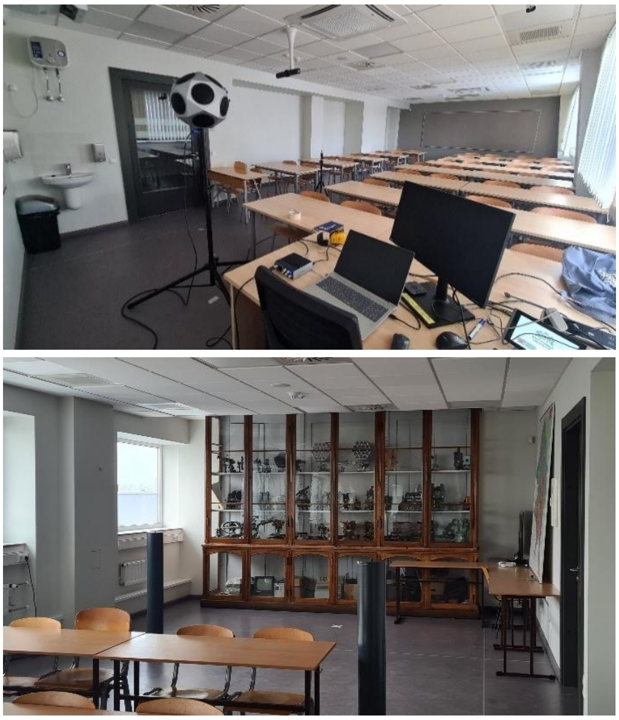

Figure 1. Top – view of the room 543, typical to all rooms; bottom – the glass cabinet in 27 m long room.

3. C50, T30 AND DISTANCE RELATION

Due to substantial amount of absorption, the T30 values vary between 0.4 to 0.8 s for all 6 octave frequency bands from 125 Hz to 4000 Hz, the mean is 0.55 s.
The resulting C50 values in 6 octave frequency bands were related to the source-receiver distance *d* and reverberation time T30. Later C50 was related to the multiplication of T30 and distance. Pearson correlation coefficient was calculated for (C50; *d*), (C50; T30) and for (C50; T30* *d*), which is shown in Tab. 1.

Table 1. Pearson correlation coefficient for C50.

f, Hz	125	250	500	1000	2000	4000
d	-0.36	-0.58	-0.72	-0.77	-0.81	-0.82
T30	-0.07	-0.39	-0.49	-0.56	-0.57	-0.63
T30**d*	-0.34	-0.57	-0.70	-0.77	-0.78	-0.80

A noticeable negative correlation between C50 and T30 is observed in the 500 to 4000 Hz frequency range, meaning that as reverberation time increases, speech clarity tends to decrease, and vice versa. This is a well known and expected correlation. The absence of such correlation at 125 and 250 Hz is expected, given that the variation in T30 values is limited to about 0.7 seconds at these lower frequencies. It is anticipated that measurements in more reverberant rooms would exhibit different correlation patterns.
A considerable negative correlation exists between C50 and distance—the farther the receiver is from the source, the lower the clarity. When T30 is multiplied by distance, the Pearson correlation coefficient is lower than that observed for distance alone. This suggests that in rectangular rooms with ceiling and backwall absorption and a ceiling height of approximately 2.7 m, C50 can be estimated based solely on the source-receiver distance. It is assumed that this is also applicable to rooms without backwall absorption.
A trend is observed at low to mid frequencies (125–500 Hz) where C50 values tend to increase at distances beyond 20 m – a pattern that is not seen at 1000 Hz and above. Notably, this effect appears only in the longest room, as the second-longest room measured 17.8 m. The presence of a glass cabinet in the longest room may contribute to the higher C50 values through additional reflections; however, it does not explain the absence of this trend at frequencies of 1000 Hz and above. Another possible explanation is the membrane absorption effect from the cabinet at lower frequencies.

4. REGRESSION ANALYSIS

Fig. 2 shows the plot of C50 against source-receiver distances for mid frequencies (500-1000 Hz). The average value between these middle frequencies is commonly used for simple acoustical design process. A simple linear regression, as well as the 2nd and 3rd degree polynomial models were fitted to C50 data for each frequency band. The RMS errors for each regression model are shown in Tab. 2. The 3rd order polynomial models show the smallest RMS error, which means the best fit for the data. Nevertheless, when approximating the 3rd degree models onto the data set, the extrapolated trendline shows abrupt and unnatural decrease of C50 values. It is anticipated that the decrease of C50 for a narrow and low room over long distances has an exponential nature and that the value should asymptote to a certain minimal value, similar to sound behaviour in ventilation ducts. The 2nd order polynomials also show a very good approximation for 125-500 Hz octave bands compared to the 3rd order model. So, it was decided to further use the 2nd order polynomial for C50 over distance approximation.
It was observed that the C50 distribution over distance follows similar trend for all 6 octave bands. Thus, to further assist in C50 estimation, an average C50 model between all octave bands was taken by averaging each polynomial coefficient. Tab. 3 shows the RMS errors for the average C50 model fitted to each frequency band and for the frequency-specific model. The average fit is still showing good approximation of the data, with a slight overestimation for the 500 Hz and minor underestimation for 1000 Hz.
The empirical C50-distance model for rooms with ceiling and backwall absorption is given as:

$$C_{50} = 9.65 - 0.8d + 0.02d^2 \qquad (2)$$

where d is source-receiver distance.

Table 2. RMS error for regression models order expressed in dB.

f, Hz	125	250	500	1000	2000	4000
1st	2.416	1.989	1.672	1.308	1.380	1.295
2nd	2.318	1.779	1.434	1.217	1.287	1.205
3rd	2.314	1.770	1.432	1.153	1.242	1.177

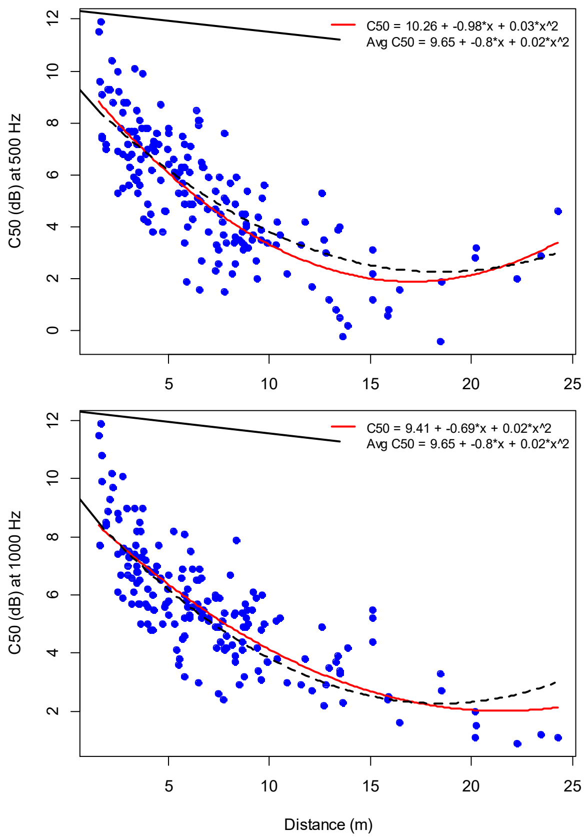

Figure 2. C50 relation to source-receiver distance and regression models for 500-1000 Hz.

Table 3. RMS error for regression models order expressed in dB.

f, Hz	125	250	500	1000	2000	4000
Avg	2.404	1.907	1.468	1.239	1.333	1.466
Spec	2.318	1.779	1.434	1.217	1.287	1.205

5. CONCLUSIONS

This study analysed the relationships among C50, T30, and source-receiver distance in university classrooms with acoustically absorptive surfaces. The results reveal a consistent negative correlation between C50 and distance, especially at mid to high frequencies, while T30 contributes less to the correlation, mainly due to absorptive nature of the rooms. The longest room showed that the speech clarity at 125-500 Hz tends to increase at distances over 20 m. Despite this fact, the overall trend supports the idea that C50 can be reliably estimated from source-receiver distance in such environments. Future work should expand the dataset to include rooms with different acoustic properties, reexamine the regression models, and validate the findings with independent data and k-fold cross-validation. For rooms with greater RT variability there should be a good negative correlation between C50 and RT. It is possible to include T30 into the regression analysis, probably using multiplication of T30 and distance as a predictor. This approach has the potential to streamline acoustic design by reducing reliance on detailed 3D modelling.

6. ACKNOWLEDGEMENT

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