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ESTIMATION OF THE STI PREDICTION ERROR OF THE TSTI AND E_{LIN}STI REGRESSION EQUATIONS

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Abstract: This paper presents the estimation of the *STI* prediction error, using *RT*, of the TSTI and E_{lin}STI regression equations. The *RT* values, at the central frequencies of the octave band, were experimentally determined for the amphitheater of the Niš Department of the Academy of Applied Technical and Preschool Studies. Using the Matlab and EASERA software packages, *STI* values were calculated. A comparison with the *STI* parameter values obtained using TSTI, E_{lin}STI and the proposed regression prediction equation was performed through statistical analysis. The first part of the paper presents the proposed prediction equations and explains their comparative statistical analysis. The second part of the paper presents the experimental results (in tabular and graphical form) and an analysis of the results, based on which a conclusion is drawn regarding the estimation of the *STI* prediction error of the TSTI and E_{lin}STI equations.

Key words: speech transmission index, reverberation time, prediction, error estimation.

1. INTRODUCTION

In contemporary scientific literature, a growing number of authors focus on the prediction of the Speech Transmission Index *STI* by establishing a functional relationship between Reverberation Time *RT* and *STI* [1 - 5]. The functional relationship is determined empirically based on the statistical analysis of acoustic parameters in a large number of rooms.

Tang and Jeung presented the results of testing the acoustic parameters *RT*, *STI*, and *RASTI* (Rapid Speech Transmission Index) and defined a regression equation of logarithmic form for the rapid estimation of *STI* in [2]. Galburn and Kitapci analyzed the accuracy of *STI* index prediction using *RT* and the signal-to-noise ratio (L_{SN}) in [3]. When formulating the prediction equation, the authors considered the characteristics of the diffuse sound field in two examined rooms. The results obtained from the prediction equations showed good agreement with the measured results. In [4], Escobar and Morilas acoustically analyzed multipurpose rooms. After determining objective and subjective parameters, they proposed a linear and a logarithmic regression equation for the prediction of *STI* and *RT*. Nowoświat and Olechowska analyzed six classrooms modeled using the ODEON software package, for which they developed a logarithmic equation for *STI* prediction [5]. A comparative analysis of the measured and predicted values confirmed the accuracy of the proposed prediction equations.

In this paper, the estimation of *STI* prediction error as a function of *RT* was performed of the regression equations TSTI (logarithmic) and E_{lin}STI (linear), proposed by Tang and Jeung in [2] and Escobar and Morilas in [4], respectively. The Reverberation Time, *RT*, was experimentally determined at the central frequencies of the octave band f_c ={250, 500, 1000, 2000, 4000} Hz for the amphitheater A2 of the Niš Department of the Academy of Applied Technical and Preschool Studies. Using the mathematical package Matlab and the acoustic parameter calculation package EASERA, *STI* parameters were calculated for each measurement position in the amphitheater. A new linear regression equation for prediction was proposed based on the calculated *RT* and *STI* values, VSTI. Subsequently, using the TSTI, E_{lin}STI, and VSTI regression equations, *STI* predictions were performed, and the error estimation *e* was calculated for all equations. A comparative analysis of the statistical parameters of *STI* prediction error estimation (mean value μ, standard deviation *SD*, and variance σ^2), draws conclusions about the error estimation of the TSTI and E_{lin}STI equations. The results are presented in a tabular and graphical form.

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The organization of this paper is as follows. In Section 2 the TSTI and E_{lin}STI equations for *STI* prediction are presented. Section 3 presents: the experiment, the results, and the analysis of the results. Section 4 is the conclusion.

2. TSTI AND E_{LIN}STI EQUATIONS FOR STI PREDICTION

Tang and Jeung published a paper in [2], in which they presented an analysis of the acoustic parameters *RT*, *STI*, and *RASTI* based on the results of numerous measurements in 18 classrooms (auditory rooms, computer labs, music rooms, and laboratories) from different locations in Hong Kong. In each classroom, they conducted at least 6 measurements. Their regression analysis covered 100 different correlation dependencies between *RT* and *STI*. After a detailed analysis, they proposed a logarithmic regression equation (referred to as the TSTI equation in the following text) for the rapid prediction of *STI*:

$$STI_T = a_T - b_T \cdot \log_{10}(RT) \tag{1}$$

The constants a_T and b_T were determined for the *RT* values at each of the central frequencies f_c.

Escobar and Morilas presented the results of acoustic analyses of 17 rooms (classrooms, conference rooms, and multipurpose rooms) in [4]. They measured: (a) objective parameters such as *RT*, *STI*, background noise, and the Definition Index (D_{50}), and (b) the subjective parameter Speech Transmission Index, which they used to predict the Subjective Intelligibility Scale (SIS) for the Spanish language. In their analysis, they used a linear equation (referred to as the E_{lin}STI equation in the following text) for the rapid prediction of *STI*:

$$STI_{E_{lin}} = a_{E_{lin}} + b_{E_{lin}} \cdot RT \tag{2}$$

The constants $a_{E_{lin}}$ and $b_{E_{lin}}$ were determined for the *RT* values at each of the central frequencies f_c.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1. Experiment

The experiment was conducted in the amphitheater A2 of the Niš Department of the Academy of Applied Technical and Preschool Studies and is explained in detail in [6]. For each measurement position, MP, in the amphitheater, the reverberation time, *RT*, values were experimentally determined, and the *STI* parameter values were calculated. The *RT* values from each measurement at every MP were used to predict the *STI* parameter in the regression equations. In this case, the Matlab software package was used.

STI prediction using the TSTI and ElinSTI equations was performed with the corresponding coefficients a_T and b_T, and $a_{E_{lin}}$ and $b_{E_{lin}}$, calculated in [2] and [4], respectively. The linear regression equation that has also been proposed for predicting *STI* parameters (referred to as the VSTI equation in the following text) is:

$$STI_V = a_V + b_V \cdot RT\ . \tag{3}$$

The regression constants a_V and b_V were also calculated here for each central frequency f_c.

The estimation of *STI* prediction errors regression equations are defined by:

$$e_T(f_c, n) = STI(f_c, n) - STI_T(f_c, n)\,, \tag{4}$$

$$e_{E_{lin}}(f_c, n) = STI(f_c, n) - STI_{E_{lin}}(f_c, n)\,, \tag{5}$$

$$e_V(f_c, n) = STI(f_c, n) - STI_V(f_c, n)\,, \tag{6}$$

where are: f_c – central frequencies of the octave band, $n = 1,..., N$ – measurement number, and *STI* – speech transmission index determined by measurement.

The comparative analysis of the precision of the prediction formulas, STI_T Eq. (1) [2], STI_{Elin} Eq. (2) [4] and STI_V Eq. (3) is based on the statistical parameters: μ_{e_T} , SD_{e_T} , $\sigma^2_{e_T}$, $\mu_{e_{Elin}}$, $SD_{e_{Elin}}$, $\sigma^2_{e_{Elin}}$ and μ_{e_V} , SD_{e_V} , and σ^2_{eV} respectively, and their mean values.

The experiment was performed for: MP = 20, M = 5 – the number of measurements per MP, and N = MP · M = 100 – the total number of measurements.

3.2. Results

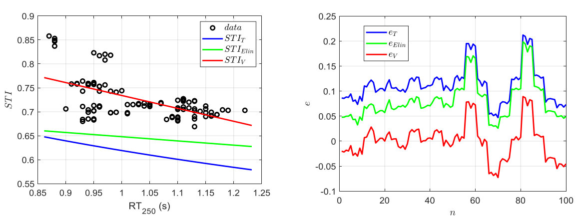
The estimation of *STI* prediction errors of the: a) TSTI and ElinSTI equations and b) VSTI equation, are presented in Tables 1 and 2, respectively. Graphical representations of the relationships: a) $STI = f(RT)$ and b) errors estimation *e*, at the central frequencies of the octave band $f_c \in \{250, 500, 1000, 2000, 4000\}$ Hz, are shown in Figures 1 – 3.

Table 1 – Estimation of STI prediction error of: a)TSTI and b) E_{lin}STI equations

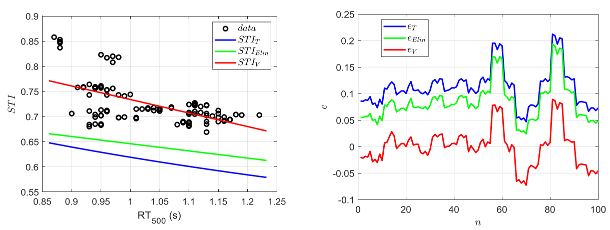
	TSTI equation					E_{lin}STI equation				
RT_{f_c}	a_T	b_T	μ_{e_T}	SD_{e_T}	$\sigma^2_{e_T}$	$a_{E_{lin}}$	$b_{E_{lin}}$	$\mu_{e_{E_{lin}}}$	$SD_{e_{E_{lin}}}$	$\sigma^2_{e_{E_{lin}}}$
RT_{250}	0.6191	0.4425	0.1119	0.0358	0.0013	0.736	-0.088	0.0809	0.0389	0.0015
RT_{500}	0.5895	0.4422	0.1382	0.039	0.0015	0.789	-0.143	0.0845	0.0370	0.0014
RT_{1000}	0.5868	0.4269	0.1304	0.0436	0.019	0.819	-0.174	0.0863	0.0362	0.0013
RT_{2000}	0.5851	0.4316	0.136	0.0385	0.0015	0.813	-0.172	0.0903	0.0363	0.0013
RT_{4000}	0.5665	0.4626	0.1364	0.0319	0.001	0.834	-0.218	0.1165	0.0355	0.0013
mean values			$\overline{\mu_{e_T}}$	$\overline{SD_{e_T}}$	$\overline{\sigma^2_{e_T}}$	mean values		$\overline{\mu_{e_{Elin}}}$	$\overline{SD_{e_{Elin}}}$	$\overline{\sigma^2_{e_{Elin}}}$
			0.1306	0.0378	0.0049			0.0917	0.03678	0.00136

Table 2 – Estimation of STI prediction error of VSTI equation

RT_{f_c}	a_V	b_V	μ_{e_V}	SD_{e_V}	$\sigma^2_{e_V}$
RT_{250}	1.0029	-0.269	0	0.0352	0.0012
RT_{500}	1.3581	-0.627	0	0.0349	0.0012
RT_{1000}	0.7236	0.0031	0	0.043	0.0018
RT_{2000}	1.5983	-0.8967	0	0.0301	0.0009
RT_{4000}	1.2523	-0.5898	0.1364	0.0319	0.001
mean values			$\overline{\mu_{e_V}}$	$\overline{SD_{e_V}}$	$\overline{\sigma^2_{e_V}}$
			0.0273	0.035	0.001

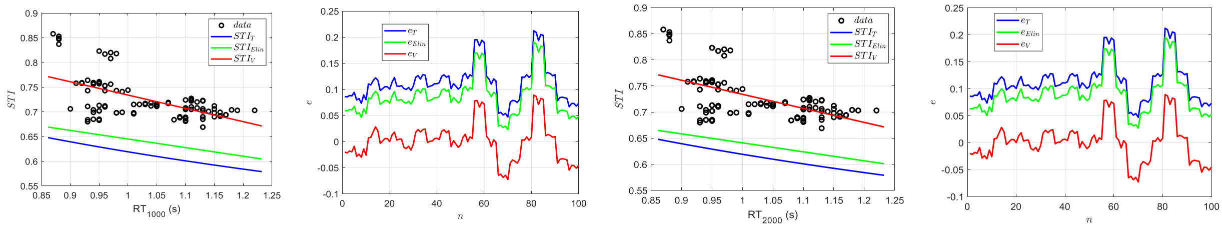


a)



b)

Figure 1 – Speech transmission index, STI, and error estimation, e, as a function of reverberation time, RT, for: a) fc = 250 Hz and b) fc = 500 Hz



c) d)

Figure 2 – Speech transmission index, STI, and error estimation, e, as a function of reverberation time, RT for: a) fc = 1000 Hz and b) fc = 2000 Hz

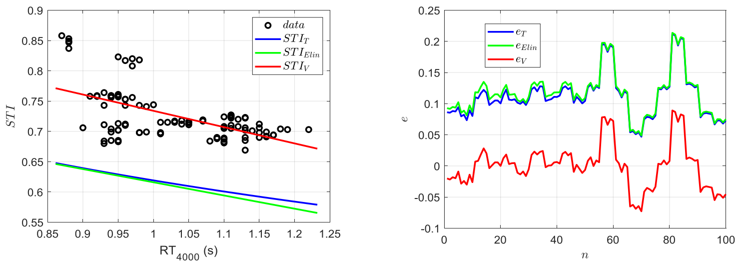


Figure 3 – Speech transmission index, STI, and error estimation, e, as a function of reverberation time, RT, for f_c = 4000 Hz

3.3. Analysis of Results

Based on the results shown in the Tables (1 - 2) and in Figures (2 – 4), the following conclusion is drawn:

- *On the estimation of the STI prediction error of the TSTI equation:*

a) The mean *STI* prediction error estimation for RT_f is $\overline{\mu_{e_T}}$ = 0.1306. The values of μ_{e_T} for RT_f are fairly consistent, except for RT_{250}: μ_{e_T} = 0.1119. This could indicate that the equation is better suited for lower frequencies;

b) The mean standard deviation of the error estimation for *STI* prediction for RT_f is $\overline{SD_{e_T}}$ = 0.0378. The value SD_{e_T} = 0.0319 for RT_{4000} is the lowest, indicating relatively lower variability in errors at higher frequencies. The highest value, SD_{e_T} = 0.0436 occurs for RT_{1000} which may suggest greater prediction inaccuracy for f_c = 1000 Hz;

c) The mean variance of the *STI* prediction error estimation for RT_f is $\overline{\sigma_{e_T}^2}$ = 0.0049. The higher variance for RT_{1000}, $\sigma_{e_T}^2$ = 0.019, may indicate greater unpredictability of errors in this range, suggesting that *STI* prediction using the TSTI equation is not reliable for this frequency band. Low variances for the other RT_f, $\sigma_{e_T}^2$ = (0.0013, 0.0015, 0.0015, 0.001), indicate stable and predictable errors.

- *On the estimation of the STI prediction error of the E_{lin}STI equation:*

a) The mean *STI* prediction error estimation for RT_f is $\overline{\mu_{e_{E_{lin}}}}$ = 0.0917. The values $\mu_{e_{E_{lin}}}$ increase from 0.0809 to 0.1165, with the highest values observed at higher frequencies: 2000 Hz and 4000 Hz. This is further confirmed by the largest deviation of this parameter at these frequencies: 0.0262. This indicates greater accuracy of the equation in predicting reverberation parameters at lower frequencies;

b) The mean standard deviation of the error estimation for RT_f is $\overline{SD_{e_{E_{lin}}}}$ = 0.03678. In the observed octave range, the prediction errors remain relatively constant: $SD_{e_{E_{lin}}}$ = 0.0389 ÷ 0.0355. A slight decrease in values with increasing frequency is noticeable, confirming the better accuracy of the equation, with small and stable errors, at higher frequency ranges;

c) The mean variance of *STI* prediction error estimation for RT_f is $\overline{\sigma^2_{e_{E_{lin}}}}$ = 0.00136. Low values of this parameter in the octave range: $\sigma^2_{e_{E_{lin}}}$ = 0.0015 ÷ 0.0013, indicate stable errors and confirm the greater precision of the equation at higher frequencies.

- *On the estimation of the STI prediction error of the VSTI equation:*

a) The mean *STI* prediction error estimation for RT_f is $\overline{\mu_{e_V}}$ = 0.0273. For *RT* on the first four octaves the equation is extremely precise because it is μ_{e_V} = 0. For RT_{4000} it is μ_{e_V} = 0.1364. This could mean that this equation is excellent for predicting *STI* for *RT* at $f_{c\in}$ {250, 500, 1000, 2000} Hz but not at f = 4000 Hz;

b) The mean standard deviation of the error estimation for RT_f is $\overline{SD_{e_V}}$ = 0.035. For RT_{250}, RT_{500}, RT_{2000}, and RT_{4000}, SD_{e_V} = (0.0352, 0.0349, 0.0301, 0.0319), respectively. All of these are low values, but for RT_{2000} and RT_{4000}, the values are lower than those for RT_{250} and RT_{500}. This indicates relatively low variability of the errors, meaning the errors are consistent and the equation provides stable predictions of *STI* for these RT_f values (even though for RT_{4000}, the error is μ_{e_V} = 0.1364). This is not the case for RT_{1000}: SD_{e_V} = 0.043 is the highest value;

c) The mean variance of *STI* prediction error estimation for RT_f is $\overline{\sigma^2_{e_V}}$ = 0.001. For RT_{250} and RT_{500} σ^2_{eV} = 0.0012, the variances are equal and low, which confirms the stability of the errors. The equation shows consistent accuracy at lower frequencies. For RT_{1000}, σ^2_{eV} =0.0018 is the highest value. This value indicates that the prediction errors for RT_{1000} are more spread out around the mean compared to the other frequencies. The variance for RT_{2000}, σ^2_{eV} = 0.0009, is the lowest, suggesting that the prediction errors are the most stable, least variable, and that the equation is very precise. The variance for RT_{4000}, σ^2_{eV} = 0.001, is slightly higher than for RT_{2000} but still low. This indicates that, despite the higher mean error for RT_{4000}, σ^2_{eV} = 0.1364, the prediction errors are consistent, not overly random or unpredictable.

- *On the comparison of the estimation of the STI prediction errors of the regression equations:*

a) The *STI* prediction error estimation: at frequencies f_c ={250, 500, 1000, 2000,} Hz, the TSTI and ElinSTI equations exhibit error estimates within the ranges: μ_{e_T} = 0.1119 ÷0.1389 and $\mu_{e_{E_{lin}}}$ = 0.0809 ÷ 0.0903. Specifically, at these frequencies, μ_{e_V} = 0, the VSTI equation's maximum accuracy for predicting *STI* is confirmed. At f_c = 4000 Hz: μ_{e_T} = μ_{e_V} = 0.1364, so their percentage difference, *PD*, is 0%, while for $\mu_{e_{E_{lin}}}$ = 0.1165 and μ_{e_V} , *PD* = -14.59 % (because it is $\mu_{e_{E_{lin}}} < \mu_{e_V}$). For the entire octave frequency range, the *PD* between $\overline{\mu_{e_T}}$ and $\overline{\mu_{e_V}}$ is 79.1%, while the *PD* between $\overline{\mu_{e_{E_{lin}}}}$ and $\overline{\mu_{e_V}}$ is 70.23%. Thus, the TSTI equation has a 79.1% higher error estimation than the VSTI equation, while the errors estimation of the E_{lin}STI equation are 70.23% higher than those of the VSTI equation. The VSTI equation demonstrates the highest accuracy;

b) The standard deviation of the estimation error: for different frequencies, the *PD* between the equations shows variations in precision. Namely, the TSTI equation is exact at 4000 Hz, like VSTI (*PD* between SD_{e_T} and SD_{e_V} is 0%), relatively precise at 250 Hz and 1000 Hz (*PD* = {1.676, 1.376} %, respectively). The error estimation increases at 500 Hz and 2000 Hz, and the *PD* amounts to 10.51

% and 21.818 %, respectively. For the entire octave frequency range, the *PD* between $\overline{SD_{e_T}}$ and $\overline{SD_{e_V}}$ is 7.41 % and between $\overline{SD_{e_{E_{lin}}}}$ and $\overline{SD_{e_V}}$ is 4.84 %. Thus, the TSTI and ElinSTI equations have higher standard deviations of error estimates than the VSTI equation in a global sense but have specific advantages at certain frequencies.

c) The variance of *STI* prediction error estimation: the TSTI and VSTI equations at f_c = 4000 Hz have the same error estimation, with an *PD* between $\sigma^2_{e_T}$ and $\sigma^2_{e_V}$, of 0%. At lower frequencies, f_c = {250, 500} Hz, the difference is more moderate, with values of 7.69% and 20%, while at f_c = {1000, 2000} Hz, the difference increases significantly, reaching 90.53% and 40%. For the ElinSTI and VSTI equations at f_c = {250, 500, 2000, 4000} Hz, the percentage difference between $\sigma^2_{e_{E_{lin}}}$ and $\sigma^2_{e_V}$ is *PD* = (20, 14.29, 30.77, 23.08) %, respectively. At 1000 Hz, the difference is -38.46%, which means the ElinSTI equation has a smaller error estimate. For the entire octave frequency range, the *PD* between $\overline{\sigma^2_{e_T}}$ and $\overline{\sigma^2_{e_V}}$ is 79.59%, and between $\overline{\sigma^2_{e_{E_{lin}}}}$ and $\overline{\sigma^2_{e_V}}$ it is 26.47%.

4. CONCLUSION

This paper presents the estimation of the *STI* prediction error, using *RT*, of the TSTI and ElinSTI regression equations at the central frequencies of the octave band $f_{c\in}${250, 500, 1000, 2000, 4000} Hz, through a comparison with the proposed linear regression prediction equation, VSTI. The metric for comparison is the error estimate, *e*, which is evaluated based on statistical parameters.

Based on the conducted comparative analysis of statistical parameters, it is concluded that for predicting *STI* in an acoustically treated amphitheater:

- The mean value of the error estimation of the TSTI and ElinSTI equations, 79.1% and 70.23%, respectively, are higher than the mean value of the error estimation for the proposed VSTI equation,
- The mean values of the standard deviations of the error estimation of the TSTI and ElinSTI equations, 7.41 % and 4.84 %, respectively, are higher than the mean value of the standard deviation of the error estimation of the proposed VSTI equation, and
- The mean value of the variance of the error estimation of the TSTI and ElinSTI equations, 79.59% and 26.47%, respectively, are higher than the mean value of the variance of the error estimation of the proposed VSTI equation.

The analysis of the errors estimation of other regression equations for *STI* prediction using *RT* will be the subject of further studies, aiming to improve the accuracy and reliability of the models for different acoustic conditions and types of spaces

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