Assessing the Repeatability and Reproducibility of In Situ Measurements of Sound Reflection and Airborne Sound Insulation Index of Noise Barriers

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Introduction

In situ measurements of sound reflection and airborne sound insulation of noise barriers are usually done in Europe according to CEN/TS 1793-5 [1]. This method have been substantially improved during the EU funded QUIESST project [2], [3]. In the frame of the same project, an inter-laboratory test has been carried out in order to assess the repeatability and reproducibility of the newly developed method when applied to real-life samples [4]. These values of repeatability and reproducibility are presented here, both in one-third octave bands and for the single-number ratings.

Organization of the Inter-Laboratory Test

The measurement method is fully described in refs. [2] and [3]. Actually the newly established measurement method is too new and too complex to attempt a mathematical model or even to specify the different components of an uncertainty budget according to the GUM [5], therefore it was decided to assess the uncertainty through an inter-laboratory test (ILT) [4].

Name	Country
Austrian Institute of Technology	Austria
Bundesanstalt für Straßenwesen	Germany
Centre Scientifique et Technique de Bâtiment	France
Research and Development Centre in Transport & Energy Foundation	Spain
Katholieke Universiteit Leuven	Belgium
Laboratoire Régional des Ponts et Chaussées de Strasbourg	France
Rheinisch-Westfälische Technische Hochschule Aachen – Institute of Technical Acoustics	Germany
University of Bologna	Italy

Table 1: Participating laboratories.

It was also decided:

- to involve eight European laboratories, each responsible for providing a complete measuring equipment and two skilled operators to apply the new method on the selected test sites;
- to set up two test sites in different European countries where to build the test samples;
- to keep as the first test site the Grenoble site already used in the former ADRIENNE project [6];
- to set up different samples, flat and non flat, sound absorbing and sound reflecting; some of them are representative of the European market, some others are designed to check critical aspect of the method;
- to have a supervising panel, composed by an expert of this kind of in situ measurement from UNIBO and an expert of statistical analysis from TNO.

Overall, 8 European laboratories measured in a blind inter-laboratory test 13 samples placed on 2 test sites: Grenoble (France) and Valladolid (Spain).

The participating laboratories are shown in table 1 (in the following each laboratory will be identified by a letter). A general view of the test sites is shown in Figures 1 and 2.

Figure 1: The Grenoble test site. East side.

Figure 2: The Valladolid test site.

Measurement Results

Table 2 reports the single number ratings for sound reflection. Table 3 reports the single number ratings obtained for the sound insulation of the acoustic elements. Table 4 reports the single number ratings of sound insulation across the posts on the Valladolid test site. Figures 3 and 4 shows an example of the results obtained on the Valladolid test site.

Sample	Laboratory							
	A	B	C	D	E	F	G	H
1	0	0	0	0	0	0	0	0
2	7	7	7	7	7	7	6	7
3	8	8	8	8	8	8	8	7
4	0	0	0	0	0	0	0	0
5	16	15	12	16	15	12	16	15
6	11	-	-	11	-	-	9	8
7	8	9	8	8	8	8	8	9
8	3	3	4	4	3	4	3	6
9	5	6	5	5	4	6	5	7
10	3	3	3	4	3	3	3	5
11	3	3	4	4	2	3	3	4
12	7	8	7	9	6	6	6	7
13	2	3	3	2	2	2	2	4

Table 2: Single number ratings DL_{RI}, in dB, for sound reflection. Samples 1 to 6: Grenoble. Samples 7 to 13: Valladolid.

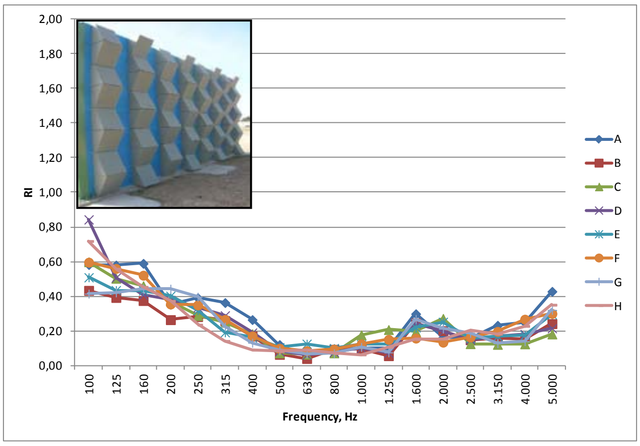

Figure 3: ILT results for sound reflection, in one-third octave bands from 100 Hz to 5 kHz, for sample 7 on the Valladolid test site.

Sample	Laboratory							
	A	B	C	D	E	F	G	H
1	-	52	51	51	-	54	52	54
2	38	39	39	40	40	40	39	38
3	-	51	-	51	-	53	51	54
7	33	33	34	33	36	35	33	38
8	51	51	-	53	53	56	-	55
9	25	24	24	25	-	28	24	27
10	-	63	-	61	61	65	-	64
13	-	55	-	55	62	62	-	-

Table 3: Single number ratings $DL_{SI,E}$, in dB, for airborne sound insulation across acoustic elements. Samples 1 to 3: Grenoble. Samples 7 to 13: Valladolid.

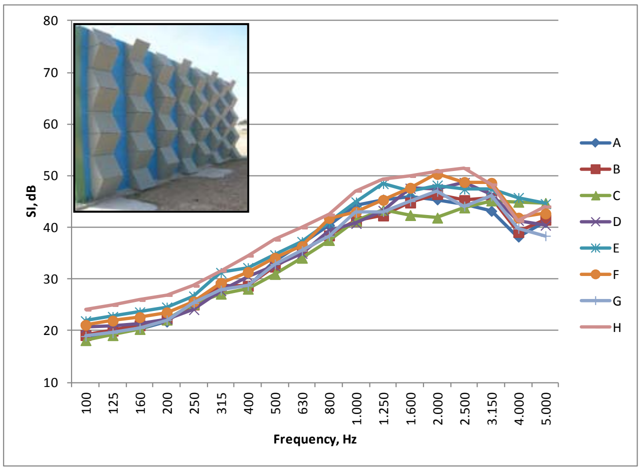

Figure 4: ILT results for airborne sound insulation across acoustic elements, in one-third octave band from 100 Hz to 5 kHz, for sample 7 on the Valladolid test site.

Sample	Laboratory							
	A	B	C	D	E	F	G	H
7	24	23	24	24	27	26	24	27
8	23	23	23	22	24	24	23	23
9	24	23	24	24	26	27	24	24
10	19	19	19	17	22	23	20	19
13	22	22	22	20	-	21	22	21

Table 4: Single number ratings $DL_{SI,P}$, in dB, for airborne sound insulation across posts, obtained in Valladolid.

Repeatability and Reproducibility

The statistical analysis has been carried out using **non-rounded** values, also for the single number ratings, in order to avoid to add another contribution to the final uncertainty.

According to ISO GUM [5], the accuracy of measurement is the closeness of the agreement between the result of a measurement and a true value of the measurand, where "measurand" stands for a well-defined physical quantity.

In the context of the present inter-laboratory test, there are:

- 247 measurands for sound reflection, namely the 18 $RI(f)$ plus the DL_{RI} for each of the 13 samples;
- 152 measurands for airborne sound insulation of the acoustic elements, namely the 18 $SI(f)$ plus the $DL_{SI,E}$ for each of the 8 measurable samples;
- 95 measurands for airborne sound insulation across posts, namely the 18 $SI(f)$ plus the $DL_{SI,P}$ for each of the 5 measurable samples.

Their true values are unknown, however. Therefore, what can be determined are the repeatability and the reproducibility of the measurement procedure.

The **repeatability** ***r*** is the random variation under constant measurement conditions. It is the best approach to quantify the variability under homogeneous conditions. It is worth noting that separate repeatability values can be calculated for each of the one-third octave bands as well as for the single number rating. As the single number rating is a sort of weighted average of the respective one-third octave band values, it could be expected that the single number rating repeatability is smaller than any of the repeatability values of the constituent one-third octave bands.

The **reproducibility *R*** is the random variation under changed conditions of measurement. Again, it is possible to calculate this value for the separate one-third octave band values as well as for the single number rating, where the reproducibility for the single number rating is probably smallest.

In this paper *r* and *R* are expressed as 2 x s_r and 2 x s_R, respectively, where s_r is the standard deviation of measurements on one and the same object taken under similar conditions briefly after each other, while s_R is the standard deviation of measurements on one and the same object under different conditions. This is called an **expanded uncertainty** measure.

With this choice, the interval [*M* – *R*; *M* + *R*], where *M* is the value of a single measurement, gives a 95% lower and upper bound for the true value of a single measurement taken by a randomly chosen laboratory. As in the ILT it has been shown that an inter-laboratory variation does exist, **reproducibility** and not repeatability should be chosen to declare the 95% confidence interval of a measurement.

The adopted statistical model can handle random variation that depends on experimental factors. For example, for the single number rating of sound reflection it is:

$$DL_{RI,ijk} = L_i + e_{1,ij} + S_k + e_{0,ijk} \qquad \text{[dB]} \qquad (1)$$

where

$DL_{RI,ijk}$ is the measurement of laboratory *i* (i=1,…,8) on the *k*-th sample (*k*=1,…,13) at location *j* (*j*=1,2);
S_k is the true value of $DL_{\mathrm{RI,ijk}}$ for the *k*-th sample (k=1,…,13);
L_i is the effect of laboratory (*i*=1,…,8);
$e_{1,ij}$ is the random variation between the 16 measurement sessions (8 labs x 2 sites);
$e_{0,ijk}$ is the residual (random) variation.

$e_{1,ij}$ can be calculated by studying the eight differences in location mean values, one for each laboratory. It is assumed that the $e_{0,ijk}$ are identically and independently distributed normal variables with means 0 and variance σ^2_{0k}. So the random error within the sessions depends on the sample.

For the calculation of repeatability and reproducibility, it has been found better to isolate the random variation of sample 4, which is much larger than the others. The intervals for the various standard deviations, as well as for repeatability and reproducibility are shown in Table 5.

It is worth noting that *R* and *r* give the expanded uncertainty of DL_{RI} from measurements **before rounding** off. Denoting a single measurement before rounding with *M*, the two values round(*M* – 1,62) and round(*M* + 1,62) can be taken as defining a rounded **conservative** 95% confidence interval for the true value of a measurement. The interval is called conservative, because the upper bound in table 5 is used. It is therefore likely that the interval is too wide.

Parameter	**95% credible interval**	
	min	**max**
s. d. session/laboratory	0,22	0,62
s. d. all samples excl. sample 4	0,44	0,62
s. d. sample 4	0,97	3,01
Reproducibility (*R*)	1,08	1,62
Repeatability (*r*)	0,88	1,23

Table 5: 95% credible intervals for standard deviations, reproducibility and repeatability of DL_{RI}, in dB.

Using the same underlying statistical model, the reproducibility and repeatability in one-third octave bands have been calculated. The results are visualized in figure 5. The plot of *R* and *r* values shows medians and 95% credible intervals.

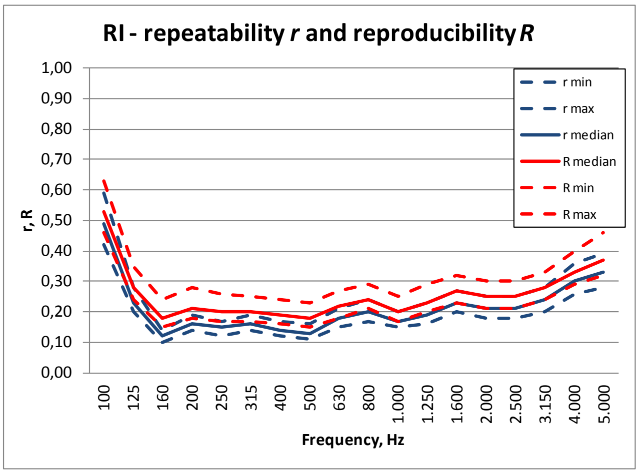

Figure 5: Repeatability (r = 2s_r) and reproducibility (R = 2s_R) of the sound reflection index, *RI*, in one-third octave bands.

For airborne sound insulation the adopted statistical model is similar. The sound insulation data for acoustic elements have been modelled with a separate random error for sample 13, which is much larger than the others. A study of pair wise differences revealed between-laboratory differences between RWTH and CSTB laboratories and the others.

The intervals for the various standard deviations, as well as for repeatability and reproducibility are shown in Table 6.

Denoting a single measurement before rounding with *M*, the two values round(*M* – 2,61) and round(*M* + 2,61) can be taken as defining a rounded **conservative** 95% confidence interval for the true value of a measurement.

Parameter	95% credible interval	
	min	**max**
s. d. session/laboratory	0,07	0,67
s. d. all samples excl. sample 13	0,77	1,24
s. d. sample 13	1,85	12,93
Reproducibility (*R*)	1,62	2,61
Repeatability (*r*)	1,54	2,48

Table 6: 95% credible intervals for standard deviations, reproducibility and repeatability of $DL_{SI,E}$, in dB.

Using the same underlying statistical model, the reproducibility and repeatability in one-third octave bands based on the random error of the barriers excluding sample 13 have been calculated. The results are visualized in figure 6. The plot shows medians and 95% credible intervals.

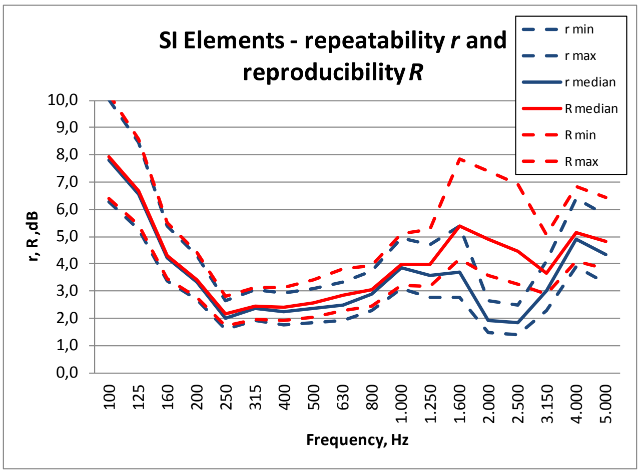

Figure 6: Repeatability (r = $2s_r$) and reproducibility (R = $2s_R$) of the airborne sound insulation index, *SI*, for the acoustic elements, in one-third octave bands.

The sound insulation data measured across posts in Valladolid have been modelled as before. A study of pair wise differences revealed between-laboratory differences between RWTH and KUL laboratories and the others. The intervals for the various standard deviations, as well as for repeatability and reproducibility are shown in Table 7.

Parameter	95% credible interval	
	min	**max**
s. d. session/laboratory	0,08	0,61
s. d. all samples	0,46	0,80
Reproducibility (*R*)	1,03	1,83
Repeatability (*r*)	0,92	1,60

Table 7: 95% credible intervals for standard deviations, reproducibility and repeatability of $DL_{SI,P}$, in dB.

Denoting a single measurement before rounding with *M*, the two values round(*M* – 1,83) and round(*M* + 1,83) can be taken as defining a rounded **conservative** 95% confidence interval for the true value of a measurement.

Using the same underlying statistical model, the reproducibility and repeatability in one-third octave bands based on the random error of the samples excluding sample 13 have been calculated. The results are visualized in figure 7. The plot of *R* and *r* values shows medians and 95% credible intervals. The most striking differences in the plot are those in the 3150 Hz - 5000 Hz one-third frequency bands, for which there is a difference of 0,5 dB to 1 dB between reproducibility and repeatability.

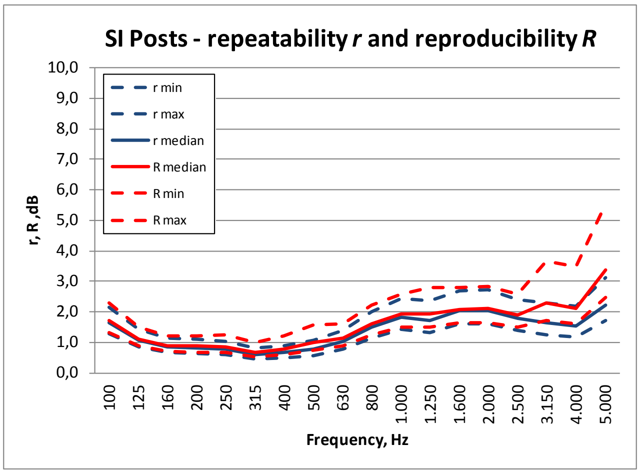

Figure 7: Repeatability (r = $2s_r$) and reproducibility (R = $2s_R$) of the airborne sound insulation index, *SI*, for the acoustic elements, in one-third octave bands.

References

[1] CEN/TS 1793-5: Road traffic noise reducing devices - Test method for determining the acoustic performance - Part 5: Intrinsic characteristics - In situ values of sound reflection and airborne sound insulation

[2] QUIESST D3.3: Noise reducing devices acting on airborne sound propagation – Test method for determining the acoustic performance – Intrinsic characteristics – In situ values of sound reflection under direct sound field conditions. (`http://www.quiesst.eu`)

[3] QUIESST D3.4: Noise reducing devices acting on airborne sound propagation – Test method for determining the acoustic performance – Intrinsic characteristics – In situ values of airborne sound insulation under direct sound field conditions. (`http://www.quiesst.eu`)

[4] QUIESST D3.5, Inter-laboratory test to assess the uncertainty of the new measurement methods for determining the in situ values of sound reflection and airborne sound insulation of noise reducing devices under direct sound field conditions. (`http://www.quiesst.eu`)

[5] ISO/IEC Guide 98-3, Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement

[6] `http://acustica.ing.unibo.it/Researches/barriers/adrienne.html`

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