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On the declaration of the measurement uncertainty of airborne sound insulation of noise barriers

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ABSTRACT

The declaration of the results of a measurement cannot be considered complete if not accompanied by a clear and realistic declaration of the measurement uncertainty. Airborne sound insulation of noise barriers makes no exception. It is measured in the laboratory under a diffuse sound field (EN 1793-2) and in situ (EN 1793-6) in a direct sound field. The uncertainty in laboratory conditions can be assessed referring to ISO DIS 12999-1; the uncertainty in field conditions can be assessed referring to the outcomes of the QUIESST project. This paper shows how these findings should be used to derive the so called expanded uncertainty of the results, both in one-third octave bands and for the single-number ratings. An approach to presenting and interpreting the results consistent with the ISO GUM is given. The differences from the previous practice are highlighted, in particular when the classification into categories of the barrier under test for the purpose of CE marking (EN 14388) is concerned. Some ideas for the future updates of the relevant standards are proposed. For the first time, it is shown how to deal with measurement uncertainty of airborne sound insulation of noise barriers.

Keywords: Noise Barriers, Sound Insulation, Uncertainty

1. INTRODUCTION

Airborne sound insulation of noise barriers is routinely measured in the laboratory under diffuse sound field conditions. For example, the European standard EN 1793-2 [1] specifies how to assess the sound insulation performance of noise barriers which can reasonably be assembled inside the testing facility described in EN ISO 10140-2 and EN ISO 10140-4. Reverberant conditions can be found inside tunnels or deep trenches or under covers, but the great majority of installed noise barriers is exposed to a direct sound field coming from a road or a railway. In order to measure the airborne sound insulation performance of noise barriers under direct sound field conditions a new method has been developed, described in EN 1793-6 [2]. It can be applied in situ, i.e. on the site where the noise barrier is installed [3]. The measurement results of these two methods are comparable but not identical, mainly because the laboratory method uses a diffuse sound field, while the in situ method assumes a directional sound field. However, research studies suggest that a quite good correlation exists between the two methods [4]. Both methods give the measurement results in one-third octave bands and also as a single-number rating, based on a reference noise spectrum and rounded to integer values. In addition the single-number rating may be used to categorize products. Table 1 reports the categories specified

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in EN 1793-2 and EN 1793-6.

The use of the single-number rating is solely for the purposes of comparing the overall performance of noise reducing devices, irrespective of local conditions, traffic composition and road surface type. The use of categories is a further simplification over the single-number rating and as such should be regarded only as a rough indication of the average product performance. Nevertheless the airborne sound insulation category is an obligatory part of the CE marking declaration following EN 14388 [5]. Moreover this categorization has assumed the greatest importance on the market and often tenders are specified primarily in terms of it.

Table 1 – Categories of airborne sound insulation

EN 1793-2		EN 1793-6	
Category	Single-number rating, dB	Category	Single-number rating, dB
B0	Not determined	D0	Not determined
B1	<15	D1	<16
B2	15 to 24	D2	16 to 27
B3	25 to 34	D3	28 to 36
B4	>34	D4	>36

2. UNCERTAINTY

The declaration of the measurement results must be accompanied by the a clear and realistic declaration of the measurement uncertainty; see ISO GUM [6]. The declaration of the uncertainty and the related confidence level is now mandatory for all European test standards. For the diffuse sound field method, this declaration can be based on the reproducibility values for building acoustics, as EN 1793-2 is based on the ISO 10140 package; these values are reported in the draft international standard ISO/DIS 12999-1 [7]. For the direct sound field method, the declaration of the measurement uncertainty can be based on the reproducibility values obtained in the inter-laboratory test recently carried out in the frame of the EU funded QUIESST project [8]. In both cases, at the current knowledge it seems not possible to formulate a complete mathematical model of the measurement procedure; that's why the measurement uncertainty is assessed through the concepts of repeatability and reproducibility. It is worth recalling that the repeatability r is the random variation under constant measurement conditions: same measurement procedure, same operators, same measuring system, same location (laboratory), and replicate measurements on the same object over a short period of time The reproducibility R is the random variation under changed conditions of measurement: different locations (laboratories), operators, measuring systems, and replicate measurements on the same or similar objects.

Table 2 reports the standard deviation s_R of measurements in reproducibility conditions taken from ISO/DIS 12999-1, case A [6], and obtained in the QUIESST inter-laboratory test, measuring across the acoustic elements and across posts [8]. The value shown for the single-number rating in diffuse sound field conditions corresponds to case A of ISO/DIS 12999-1 with the corrective term C_{tr}. These data are plotted in Figure 1. In both cases of diffuse and direct sound field the standard deviation of reproducibility is assumed as standard uncertainty u of the measurand according to ISO GUM [6] and the reproducibility value R is calculated as the expanded uncertainty U:

$$R = U = k \times u = k \times s_R \quad (1)$$

where k is the coverage factor; its value depends on the distribution of the possible values of the measurand and on the confidence level [6]. A confidence level of 95% is the usual choice.

This is called an expanded uncertainty measure. With this choice, the coverage interval [M – R; M + R], where M is the value of a single measurement and R the reproducibility, gives a 95% lower and upper bound for the true value of a single measurement taken by a randomly chosen laboratory. As in the inter-laboratory test 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.

It is important to remark that the coverage interval should be assessed before rounding. Therefore single-number ratings are no more limited to integer values.

Table 2 – Standard deviation of measurements in reproducibility conditions

Frequency Hz	Diffuse sound field, case A, dB	Direct sound field, Acoustic elem., dB	Direct sound field, Posts, dB
100	3,0	4,0	0,8
125	2,7	3,3	0,5
160	2,4	2,1	0,4
200	2,1	1,7	0,4
250	1,8	1,1	0,4
315	1,8	1,2	0,3
400	1,8	1,2	0,3
500	1,8	1,3	0,4
630	1,8	1,4	0,5
800	1,8	1,5	0,7
1000	1,8	2,0	0,9
1250	1,8	2,0	0,9
1600	1,8	2,7	1,0
2000	1,8	2,5	1,0
2500	1,9	2,2	0,9
3150	2,0	1,8	0,8
4000	2,4	2,6	0,8
5000	2,8	2,4	1,1
Single n. rating	**1,4**	**1,3**	**0,9**

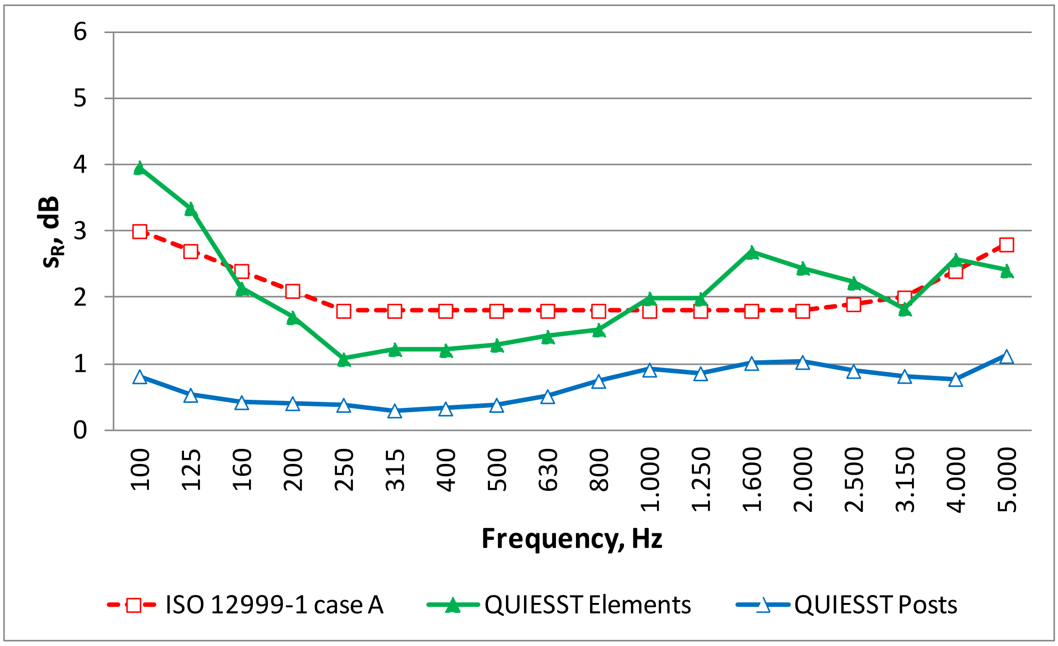

Figure 1 – Standard deviation of measurements in reproducibility conditions

3. CATEGORY ASSESSMENT AND DECISION RULES

3.1 A simple example

Until now the assignment of a product to a category have been done disregarding the uncertainty. For example, let's suppose that a noise barrier has a single-number rating of sound insulation before rounding of 25,7 dB. Rounding to an integer value gives DL_R = 26 dB; according to EN 1793-2 the noise barrier is said to be in category B3 for airborne sound insulation (see Table 1). In the light of uncertainty declaration, this is not correct and a les naïf assessment should be done.

Considering the standard deviation of reproducibility in laboratory conditions of 1,4 dB (see Table 1) and assuming a Gaussian distribution of DL_R values, the reproducibility of this values of the single-number rating DL_R at 95% confidence level is:

$$R(DL_R) = k_{95} \times s_R = 1{,}96 \times 1{,}4 = 2{,}74 \text{ dB} \quad (2)$$

At 95% confidence level this gives a coverage interval [23,0 – 28,4] dB, with a probability of being below the lower threshold value of 25 dB for category B3 equal to 31% (see Figure 2), i.e. the above assessment is wrong in about one case out of three.

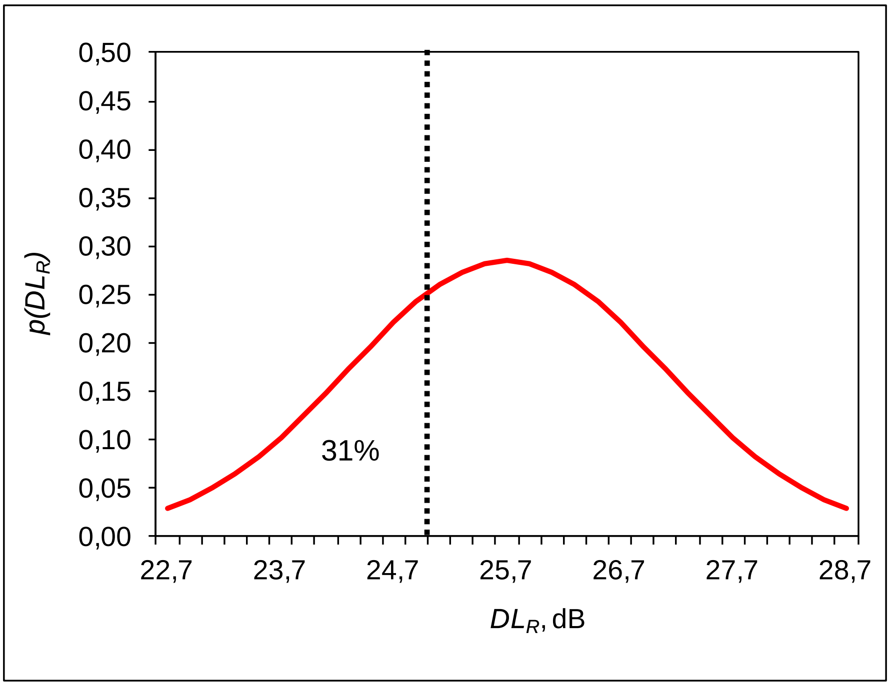

Figure 2 – Example of conformity assessment for the single-number rating of a measurement according to EN 1793-2. The dotted black line indicates the lower tolerance limit of category B3 in a diffuse sound field: 25 dB. The probability for a measurement result of being less than 25 dB is 31%

3.2 Decision rules

The above example is a particular case of conformity assessment, a process where ***decision rules*** are adopted before taking a decision on whether a values conforms to tolerance (threshold) limits or not. A decision rule specifies the role of measurement uncertainty in formulating acceptance criteria [9]. Acceptance limits and corresponding decision rules should be chosen in such a way as to manage the undesired consequences of incorrect decisions. There are a number of widely used decision rules that are applied when knowledge of a property of interest is summarized in terms of a best estimate and corresponding coverage interval; some of them are recalled in the following. It is worth noting that, even if categories in Table 2 are defined by a tolerance interval having lower and upper tolerance limits, T_L and T_U, for the sake of simplicity in the following the focus will be on the ***lower*** tolerance value T_L of each category; this is justified by the fact that one is usually interested in reaching the higher category possible, i.e. in passing the highest possible lower tolerance value.

3.3 Decision rule based on simple acceptance

The two interested parties, conventionally named "producer" and "user (or consumer)" of the measurement result, agree, implicitly or explicitly, to accept as conforming (and reject otherwise) a measured value y when it is inside the tolerance interval defined by the tolerance limit(s). With reference to a lower tolerance limit T_L (see Figure 3):

$$y \geq T_L \Rightarrow \text{acceptance} \tag{3}$$

This is a "shared risk" rule, i.e. the uncertainty is neglected and the producer and user share the consequences of incorrect decisions. The probability of assessing the wrong category can be as large as 50 %. This would happen if the measured value lays very close to the tolerance limit. In such a case about 50 % of the probability density function for the measurand would lie on either side of the limit separating two categories, so that whether the item is attributed to a category or the other, there would be a 50 % chance of an incorrect decision.

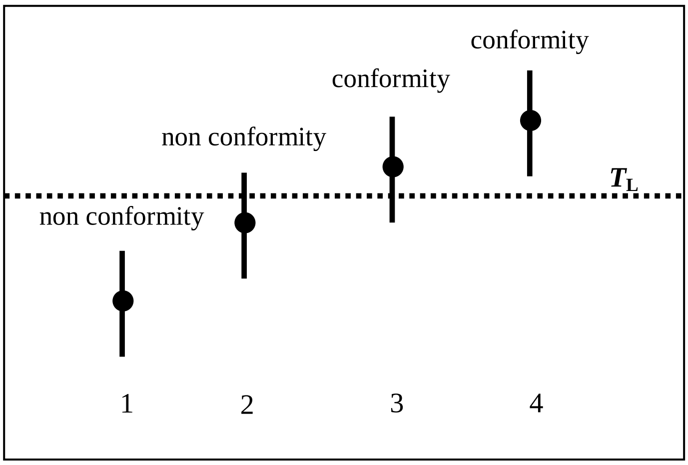

Figure 3 – Sketch of conformity assessment to an lower tolerance limit using the simple acceptance rule. The black circle indicates the best estimate of the measurand y and the black vertical line is the 95% coverage interval $y \pm U$

3.4 Decision rules based on guard bands

The risk of accepting a non-conforming value can be reduced by setting an acceptance limits A_L different from the tolerance limit T_L. The interval defined by T_L and A_L is called a *guard band*, and the resulting decision rule is called guarded acceptance or rejection.

The difference between a tolerance limit T_L and a corresponding acceptance limit A_L defines a length parameter w for a guard band. In many applications, the length parameter w is taken to be a equal to the expanded uncertainty for a coverage factor corresponding to a confidence level of 95%.

$$w = \left| A_L - T_L \right| = U = k_{95} \times u \tag{4}$$

Following the **stringent guarded acceptance rule**, the guard band is inside the tolerance interval and the measured value y is accepted as conforming only when it is inside the acceptance interval, i.e. when the measured value is inside the tolerance interval with its 95% coverage interval.

$$y - U \geq T_L \Rightarrow \text{acceptance} \tag{5}$$

Following the **stringent guarded rejection rule**, the guard band is outside the tolerance interval and the measured value y is rejected as non conforming only when it is outside the tolerance interval with its 95% coverage interval.

$$y + U \leq T_L \Rightarrow \text{rejection} \tag{6}$$

If the stringent guarded acceptance and rejection rules are assumed together an ambiguity interval exists: when the best estimate of the measurand y is inside the interval [T_L-U, T_L+U] no decision can be taken. Figure 4 shows the situation.

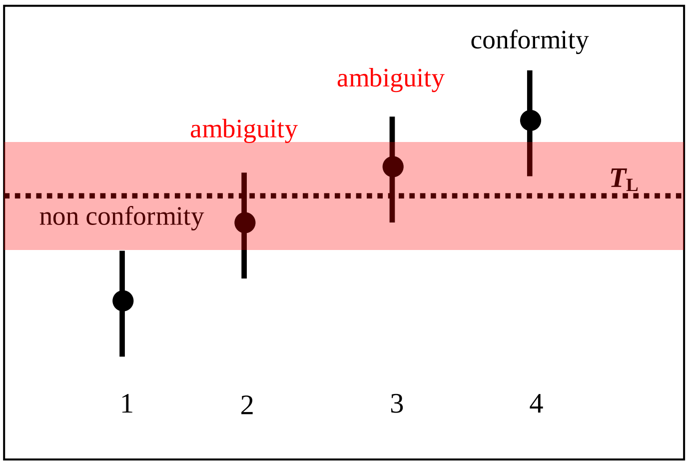

Figure 4 – Sketch of conformity assessment to an lower tolerance limit using both the stringent guarded acceptance and stringent rejection rules. The black circle indicates the best estimate of the measurand y and the black vertical line is the 95% coverage interval $y \pm U$. The shaded area is twice the guard band

Following the **relaxed guarded acceptance rule**, the guard band is outside the tolerance interval and the measured value y is accepted as conforming unless it is outside the acceptance interval, i.e. when the measured value is outside the tolerance interval with its coverage interval.

$$y + U < T_L \Rightarrow \text{rejection} \tag{7}$$

Following the **relaxed guarded rejection rule**, the guard band is inside the tolerance interval and the measured value y is rejected as non conforming unless it is inside the tolerance interval with its coverage interval.

$$y - U > T_L \Rightarrow \text{acceptance} \tag{8}$$

If the relaxed guarded acceptance and rejection rules would be assumed together a contradiction interval would exist: when the best estimate of the measurand y is inside the interval [T_L-U, T_L+U] it should be conforming (relaxed acceptance) and not conforming (relaxed rejection) at the same time. Figure 5 shows the situation.

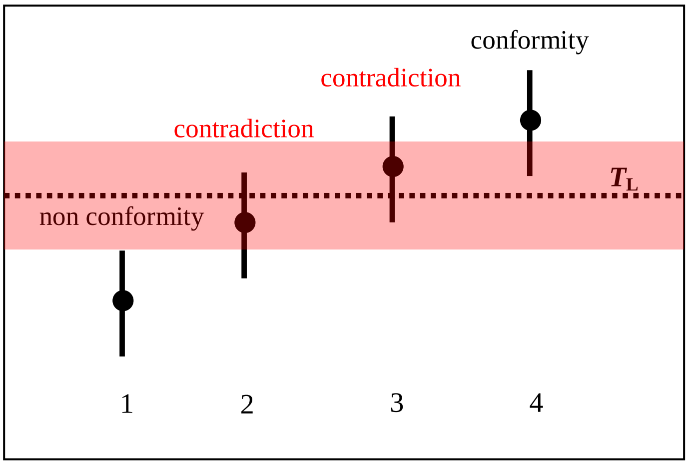

Figure 5 – Sketch of conformity assessment to an lower tolerance limit using both the relaxed guarded acceptance and relaxed rejection rules. The black circle indicates the best estimate of the measurand y and the black vertical line is the 95% coverage interval $y \pm U$. The shaded area is twice the guard band

4. CATEGORY ASSESSMENT REVISITED

As the declaration of the uncertainty and its confidence level are mandatory, the assessment of categories for airborne sound insulation must comply to this situation.

It is clear that the simple acceptance/rejection rules are inadequate, as the risk of a wrong decision is too high (see again the example of Figure 2), to not mention the fact that using these rules the uncertainty is practically ignored.

The stringent acceptance and rejection rules cannot be assumed together without leaving an ambiguity interval; for products having an airborne sound insulation single-number rating in this interval a clear statement for CE marking is not possible (Figure 4).

The relaxed acceptance and rejection rules cannot be assumed together without giving raise to contradictions; this is the worst situation in view of CE marking (Figure 5).

As the main purpose of the assignment of a sound insulation category to the noise barrier as a function of the single-number rating is the accomplishment of (a part of) the declaration supporting the CE marking, the best choice seems to be the combination of the stringent acceptance and relaxed rejection rules. For a lower tolerance limit T_L this combination of rules is (see also Figure 6):

$$y - U \geq T_L \Rightarrow \text{acceptance} \quad (9)$$

$$y + U < T_L \Rightarrow \text{rejection} \quad (10)$$

$$y - U < T_L \text{ and } y + U > T_L \Rightarrow \text{presumed rejection} \quad (11)$$

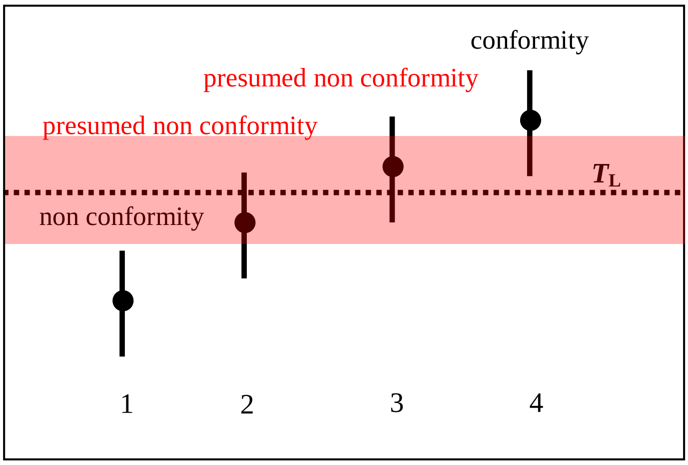

Figure 6 – Sketch of conformity assessment to an lower tolerance limit using the stringent acceptance and relaxed rejection rules. The black circle indicates the best estimate of the measurand *y* and the black vertical line is the 95% coverage interval $y \pm U$. The shaded area is twice the guard band

Applying this combination of rules to the example of Figure 2, it can be said that the measured value of a single-number rating of airborne sound insulation measured according to EN 1793-2 before rounding of 25,7 dB (26 dB rounded) is ***presumably non conforming*** to the lower tolerance limit of category B3 with a false acceptance probability of 31% at 95% confidence level. Therefore the investigated noise barrier should be assigned to category B2. This conclusion is different to the naïf conclusion based on the simple acceptance rule (26 > 25 dB then category B3) in use until now.

The same conclusions apply to values measured in situ under direct sound field conditions, of course with different lower tolerance limits for the categories (see Table 1). In this latter case a further difficulty adds: the reproducibility values obtained in the QUIESST inter-laboratory test are different for measurements across acoustic elements and across posts. It might be suspected that the magnitude of the uncertainty depends on the level of the measurand, introducing a further statistical complication, but knowing the situation found on the test sites it is more plausible that the test samples were not homogeneous (i.e. with localized strong leaks), giving rise to highly fluctuating values of airborne sound insulation in front of the acoustic elements. In all cases the categories should be different for measurements across acoustic elements and across posts.

4.1 Another example

Now let’s suppose that a noise barrier has a single-number rating of the sound insulation index measured in situ, according to EN 1793-6, across the acoustic elements of 31,0 dB before rounding.

Rounding gives the same value.

Considering the standard deviation of reproducibility of 1,3 dB (see Table 1) and assuming a Gaussian distribution of $DL_{SI,E}$ values, the reproducibility of this values of the single-number rating $DL_{SI,E}$ at 95% confidence level is:

$$R(DL_{SI,E}) = k_{95} \times s_R = 1{,}96 \times 1{,}3 = 2{,}55 \text{ dB} \tag{12}$$

At 95% confidence level this gives a coverage interval [28,5 – 33,6] dB, with a probability of being below the lower threshold value of 28 dB for category B3 equal to 1% (see Figure 7), i.e. the noise barrier under test is conforming to category B3 for acoustic elements at 95% confidence level, as the risk of a false acceptance is only 1%.

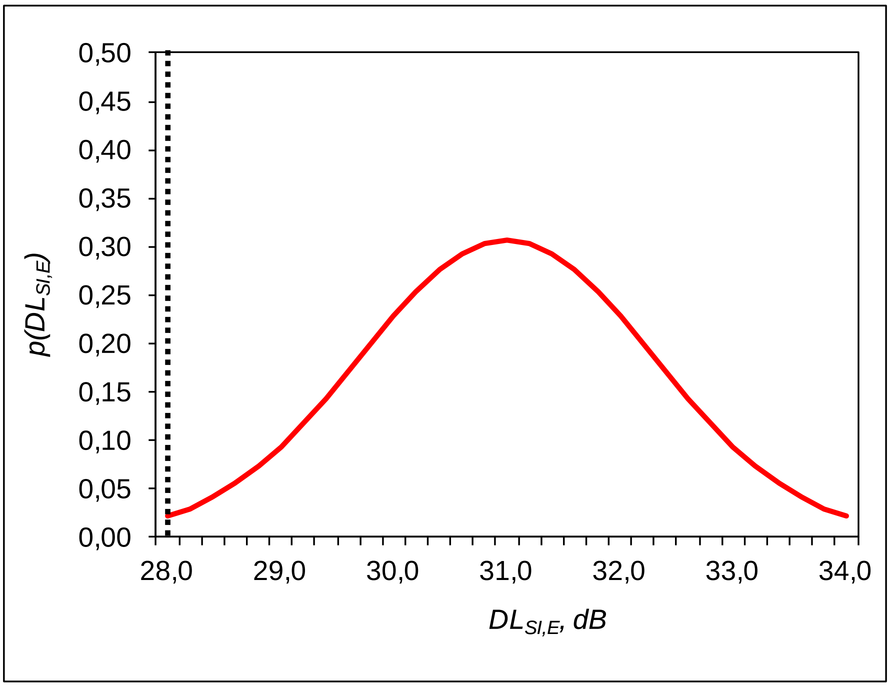

Figure 7 – Example of conformity assessment for the single-number rating of a measurement according to EN 1793-6. The dotted black line indicates the lower tolerance limit of category B3 in situ across acoustic elements: 28 dB. The probability for a measurement result of being less than 28 dB is 1%

Now let’s suppose that the same noise barrier has a single-number rating of the sound insulation index measured in situ, according to EN 1793-6, across posts of 28,5 dB before rounding. Rounding to an integer value gives $DL_{SI,P}$ = 29 dB.

Considering the standard deviation of reproducibility of 0,9 dB (see Table 1) and assuming a Gaussian distribution of $DL_{SI,P}$ values, the reproducibility of this values of the single-number rating $DL_{SI,P}$ at 95% confidence level is:

$$R(DL_{SI,P}) = k_{95} \times s_R = 1{,}96 \times 0{,}9 = 1{,}76 \text{ dB} \tag{12}$$

At 95% confidence level this gives a coverage interval [26,7 – 30,3] dB, with a probability of being below the lower threshold value of 28 dB for category B3 equal to 29% (see Figure 8), i.e. the noise barrier under test is presumably not conforming to category B3 at 95% confidence level and should be assigned to category B2 for posts.

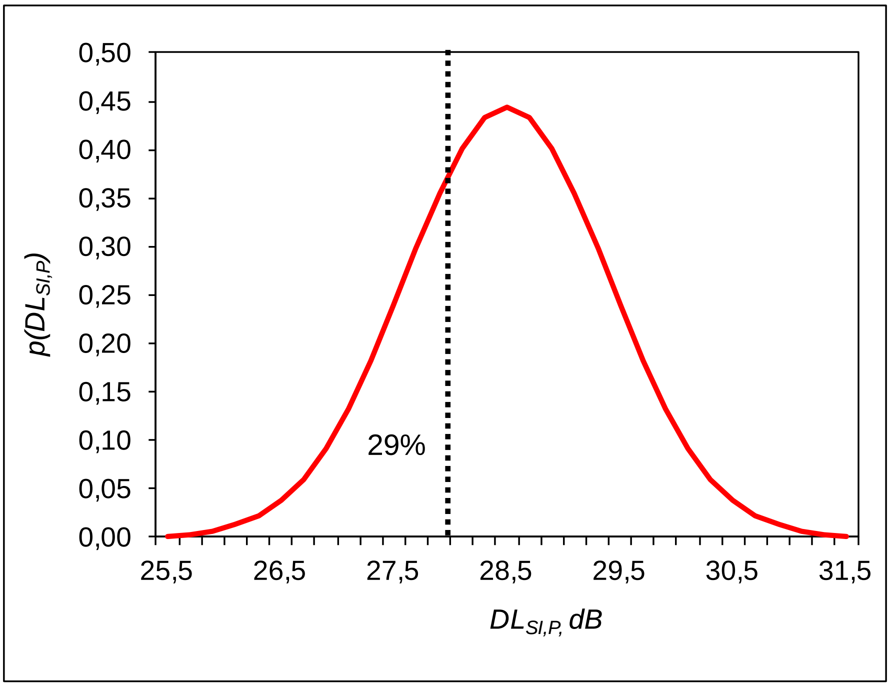

Figure 8 – Example of conformity assessment for the single-number rating of a measurement according to EN 1793-6. The dotted black line indicates the lower tolerance limit of category B3 in situ across posts: 28 dB. The probability for a measurement result of being less than 28 dB is 29%

5. PROPOSALS FOR FUTURE STANDARDS

In the light of the preceding considerations it is clear that the existing standards should be updated.

1. EN 1793-2 should be updated making explicit reference to the reproducibility values of ISO/DIS 12999-1.
2. EN 1793-6 should be updated with the reproducibility values coming from the QUIESST inter-laboratory test.
3. Both EN 1793-2 and EN 1793-6 should be updated with an improved procedure to deal with categories; two solutions are possible. The first one consists in introducing into an annex the above considerations on how to manage reproducibility, confidence levels, coverage intervals, etc. in order to correctly establish the airborne sound insulation category of a noise barrier. The combined stringent acceptance and relaxed rejection rules should be specified as the recommended decision rules in both standards. This will make the use of categories considerably more complicated. The second solution is simply to discard categories and to declare the results in terms of one-third octave bands values and single-number rating, plus of course the related uncertainty at 95% confidence level.
4. EN 14388 should be updated specifying that categories must be assessed keeping into account uncertainty and decision rules, as explained above, or alternatively stating that the single-number rating is the only quantity needed to assess the level of airborne sound insulation performance for CE marking.

6. CONCLUSIONS

The declaration of the measurement uncertainty and the related confidence level is mandatory in all European test standards. This has a deep effect on the rough classification of noise barriers in categories for airborne sound insulation based only on the value of the single-number rating.

Estimates of the standard deviation of reproducibility do exist, both for the diffuse field method (EN 1793-2) and the direct sound field method (EN 1793-6) and must be used.

The 95% credibility interval should be assessed before rounding the single-number rating.

The simple acceptance rule in use until now carries a high risk of incorrect decision and thus it should be replaced by better rules. In the light of the goal of the decision, i.e. the declaration of a performance level for CE marking, it seems reasonable to adopt the combination of the stringent acceptance and relaxed rejection rules.

This new decision procedure gives results different from those obtained ignoring the uncertainty. Moreover the procedure appears complex and requires some knowledge of statistics. A simpler alternative could be the elimination of the categories: the single-number rating will be directly the performance level.

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