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Uncertainty in the CPX method (ISO 11819-2/3) and its implications for pavement evaluation

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ABSTRACT

The close-proximity method, defined in International Standard ISO 11819-2, is frequently used for assessment of the acoustic performance of pavements. Road authorities refer to this standard when defining acoustic requirements in contracts with road builders. The method is proposed as a base for the acoustic classification of pavement types currently under development in the CEN organization. This and other applications may have legal consequences in case of noncompliance.

It is therefore essential that the accuracy of the method and the spread in performance of reference tyres is well understood. Even more relevant is that the interpretation of test results in terms of compliance yes/no is based on an unambiguous definition frame. In this paper the results of an analytical (according to Guide 98) and the statistical (according to ISO 5725) will be discussed and compared against each other. Recommendations for improving accuracy will be presented. Next the interpretation of test results in an approval system will be discussed in terms of true and false positives or negatives and the role of pre-knowledge will be explored.

Keywords: CPX, road pavement I-INCE Classification of Subjects Number(s): 52.3

1. INTRODUCTION

The acoustic quality of the road pavement is an important influencing factor in the generation of road traffic noise. For speeds above 50 km/h it is regarded as the most important factor, above the quality of the vehicle and tyre and driving style. In a growing number of situation, the control of traffic noise by the local or national authorities is pursued by the application of a noise reducing pavement.

Consequently the acoustic performance of a pavement is included in the tendering and contracting of road works. The compliance of the delivered products is then often tested on base of general accepted Close Proximity Measurement (CPX). In order to be able to interpret possible failure of the product on base of the test result, the influence of the accuracy in the method on the compliance testing shall be known. A test result exceeding the pre-defined requirement can be caused by too low quality of the product, but can also be a consequence of the limited accuracy in the CPX method.

A second issue for the manufacturer of a pavement is the spread normally attributed to a specific type. Compliance testing based on the characteristic average value will already cause a chance of failure of 50%.

It is the combined effect of normal spread in product quality and limited accuracy in results of CPX tests that defines the threshold values that have to be met.

The objective of the study was to understand the nature of the uncertainty of the CPX method, to estimate the spread in acoustic performances of pavements of the same type and to evaluate the combined effect of the uncertainty and the intrinsic spread when defining limit values in the procurement of pavements.

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1.1 Product variation

The manufacturing process of road pavements is of a different nature than that of most modern day manufactured products. While the latter are produced under perfect conditions from components that show minimal variation, road pavements are manufactured in unsheltered conditions from material that originates from a nearby quarry and is mixed at plants sometimes more than 100 km away from the pavement section. Understandable, such products will exhibit a variation in surface texture and in acoustic absorption and thus in acoustic performance. In the design process one adapts to these local conditions, but still a non-controlled variation in acoustic performance remains. One can approach the spread by a normal distribution specifying it with an average value and a standard deviation. A range of two standard deviations around the average value cover 68% of the elements.

From the data found in the QUESTIM project (6) It can be estimated that the standard deviation in acoustic performance is about 0,5 to 1,0 dB (depending om the type of surface). The data presented in Figure 1 present the case with a standard deviation of 1,0 dB.

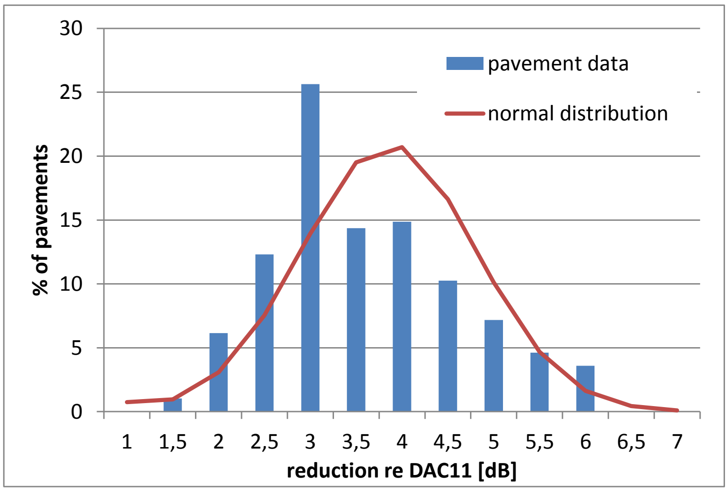

Figure 1 – Distribution of acoustic quality for 195 semi dense SMA8 pavements, measured in new condition. Acoustic quality defined as measured reduction with SPB for cars rel. to DAC 11. The standard deviation is 1,0 dB (source M+P).

It must be acknowledged that even when the manufacturers follow strict quality criteria referring to material composition, void content and bitumen fraction, a spread in acoustic quality is inevitable and shall be included in the implementation of a pavement evaluation procedure.

2. CLOSE-PROXIMITY METHOD (CPX)

2.1 Principle

The Close-Proximity Method, often referred to as CPX method, determines the acoustic performance of a pavement by measuring the sound level of a standard tyre rolling on that surface under standard conditions of speed and load. This method is presently in the final phase of standardization as ISO 11819-2 (1). The test tyres are also subjected to standardization and a draft is issued far balloting by ISO (2).

The principle and all the important influencing parameters are defined in the standard on a functional basis. The actual configuration of the measurement system can be chosen. Since measurement of the rolling noise in the wheel track is mandatory and measurement of both wheel tracks is preferred the majority of the systems are two wheeled versions, with a track width of about 1,8 m. Two examples are presented in Figure 2.

Figure 2 – Picture of two-wheeled versions of the CPX method, both covered and non-covered.

2.2 Sources of uncertainty in results

Both covered and non-covered systems are being used, covered having the advantage to be less sensitive to environmental background noise (for instance due to passing trucks), non-covered with the advantage of measuring in a semi anechoic environment, with less disturbing reflections.

The applicability of the method requires that the conditions under which the tests may be performed exhibit a certain margin, even if such conditions affect the final result. Most relevant in this respect are the speed during the measurements, the temperature and the condition of the test tyres. In the processing of the results, correction formulas are applied to compensate for those effects as good as possible. Nevertheless due to these and other variations in the test configuration and test conditions, the results of the testing of an identical object will differ when measurements are repeated with the same device and staff but on another day, or when measurements are being reproduced by another device and staff.

An additional aspect, not covered by this definition of uncertainty or precision, is that the CPX result is regarded to be representative for the effect of the road surface on the noise emission of the traffic as is determined with the Statistical Pass-By method (SPB) standardized in ISO 11819-1 (3). Although one assumes a strict relation, the relation exhibits a residual variance that cannot totally be explained.

2.3 Methods to estimate uncertainty

The compliance testing is done on base of the CPX method. As every measurement method, the CPX exhibit a specific accuracy. One can evaluate accuracy with an analytical or a statistical approach.

An analytical approach was followed according to the GUM (Guide to the Expression of Uncertainty in Measurement) (4), in which an uncertainty budget is determined, based on the allowed variations in the standard and the effect of non-controllable parameters. It can be assumed that the test results of the CPX method can be represented by a normal distribution. The average of an infinite series of measurements is interpreted as the “real” value. The uncertainty is defined by the distribution of test results around that average. Two times the standard deviation of this distribution presents the uncertainty with 95% coverage.

A statistical approach according to ISO 5725 (5) in which the accuracy is determined on base of repeated comparison of different systems (Round Robin Test). Accuracy is defined as *precision* in terms of both repeatability and reproducibility. In addition to this *trueness* is defined as the deviation between the average of the test results in the Round Robin Test and an accepted true value.

2.4 Uncertainty with analytical approach

The analytical approach is based on investigating the sources of uncertainty, estimating the contribution and next adding them up taking in to account a weighting factor. This procedure is followed in ISO 11819-2 for the CPX method and in ISO 11819-3 for the reference tyres.

Table 1 – Uncertainty budget for the CPX method. Data obtained from uncertainty clauses in (1) and (2)

Source of uncertainty	Sensitivity coefficient	No enclosure	enclosure
Allowance in procedure	1	0,20	0,20
Uncertainty in measuring equipment	1	0,30	0,30
Influence of environmental conditions	1	0,30	0,30
Influence of back ground noise	1	0,20	0,10
Effect of unwanted reflections	1	0,10	0,20
Variation in P1 reference tyre (11819-3)	1	0,38	0,38
Standard uncertainty		0,64 dB	0,64 dB

Since the CPX method is used in this respect for a not-to-exceed test, the 95% coverage probability is found by multiplying the standard uncertainty with a factor of 1,65 resulting in an expanded uncertainty with standard reference tyre P1 of 1,1 dB.

2.5 Uncertainty with statistical approach

The uncertainty defined on base of a statistical approach distinguishes the repeatability in a narrow sense (direct repetition), in a wider sense (same equipment and staff but repeated over a longer time period), the reproducibility and the deviation between the test results and a true value (trueness).

From several comparisons, both within CPX systems, between CPX systems and between CPX results and SPB results, one can obtain an impression of the values of these uncertainty quantities. We present data from a Round Robin Test performed in 2012 in which two CPX systems from M+P and a system from DRD participated. In this test all systems were equipped with their own tyres. As a comparison a reference tyre set was also included in order to understand the effect of system and the effect of the tyre. Tests were done on a series of five different surfaces, both porous and dense. The results are presented in Table 2.

The trailer influence indicates the net effect of system, equipment and allowances in measurement procedure. The residual standard deviation indicates the variation due in case of repeated measurements.

Table 2 – Results of Round Robin test on eight 2-wheeled CPX systems (8). Comparisons were done with varying tyre sets and with one reference tyre set. All figures in [dB].

Source of variance	SRTT reference	SRTT
Trailer	0,25	0,39
Residual	0,21	0,29
TOTAL	0,32	0,49

The results are in good accordance with the data of Table 1. The small difference can be explained by the fact that the Round Robin Test was done on a single day, so environmental conditions were more or less the same.

If the Table 1 result is corrected for the absence of environmental variance then a standard uncertainty of 0,56 dB results. The standard deviation in the test results for the reference tyre set of 0,32 is comparable to the standard uncertainty corrected for variance in P1 in table 1. The slightly lower results of the Round Robin test can also be explained by the fact that in that case over two tyres is averaged, while the table 1 values refer to the general case of a single tyre.

More specific data on repeatability is presented in Figure 3. The top graph presents results of tests done directly after each other. Average difference is <0,1 dB , the bottom presents repeated tests over a five year period with the same CPX system (but tyres were changed in this period). After correcting for aging of the surface with a best fitting 2nd order function, a residue of <0,2 dB remained. A comparable test of DRD over a five yr. period showed a residue of 0,2 dB.

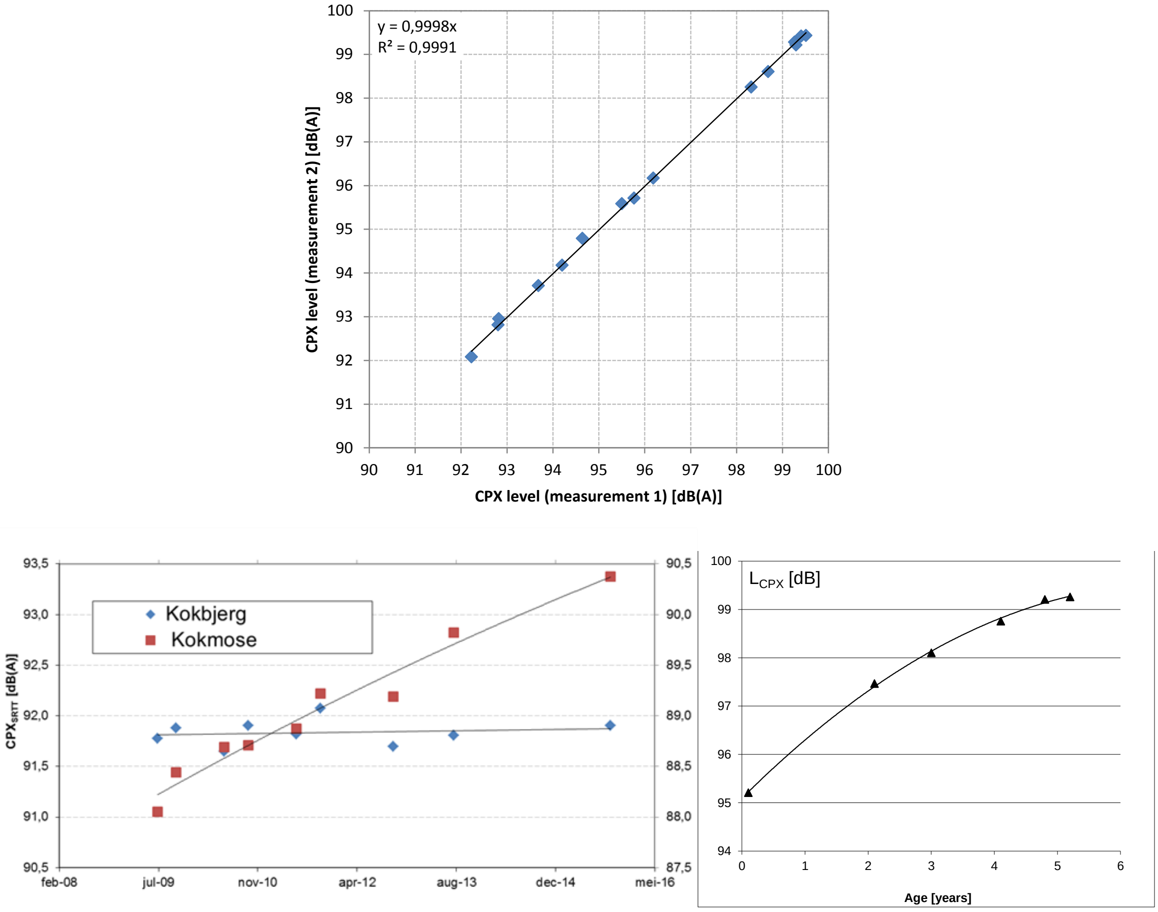

Figure 3 – Two examples of repeatability. Top: directly repeated measurements, average difference between consecutive runs is 0,07 dB. Bottom: repeatability over a period of five years. After compensating for the trend with a 2nd order polynomial function, a standard deviation of the residues of < 0,2 dB remained (source M+P and DRD)

2.6 Spread in reference tyre properties

From the CPX Round Robin Test (8) it was found that the tyres contribute significantly to the overall reproducibility. The properties of the reference test tyre P1 are defined in ISO 11819-3 (2) which is still a committee draft at this moment. The standard prescribes a certain tyre type SRTT, defined in an ASTM standard, but allows a certain freedom of wear and hardness variation. Although one can correct for hardness values deviating from the reference value, still a spread can be expected. In (2) the standard deviation in rolling noise level of the P1 tyre, after correction for hardness and temperature, is estimated to be 0,38 dB.

Within the framework of the quality assurance system of M+P, every year the reference test tyres in use are compared against each other. The Table 3 present the standard deviations in the test results over the years 2012 to 2015. The table corroborates the influence of the test tyre variation presented in Table 3.

Table 3 – Spread with population of SRTT tyres in use for CPX measurements. Tyres are replaced when hardness > 68 Shore unit A.

Year	Number of tyre sets	Standard deviation
2012	4	0,4
2013	5	0,3
2014	3	0,2
2015	4	0,4
Average		0,33 dB

2.7 Relation between CPX results and SPB results

The CPX method must be regarded as a proxy for the true value, being the effect of the road pavement on the sound emission of the actual traffic as being determined by the SPB method. The CPX system though has a number of practical advantages that makes it the preferred method for pavement monitoring and conformity checking (7). The accuracy in estimating the SPB value can be deducted from a comparison of CPX and SPB values assessed on the same pavement sections. From the CPX and SPB data bases available within the DRD and M+P the best fitting linear function and the standard deviation of the residues are calculated. The scatter diagram from the DRD data is presented in Figure 4.

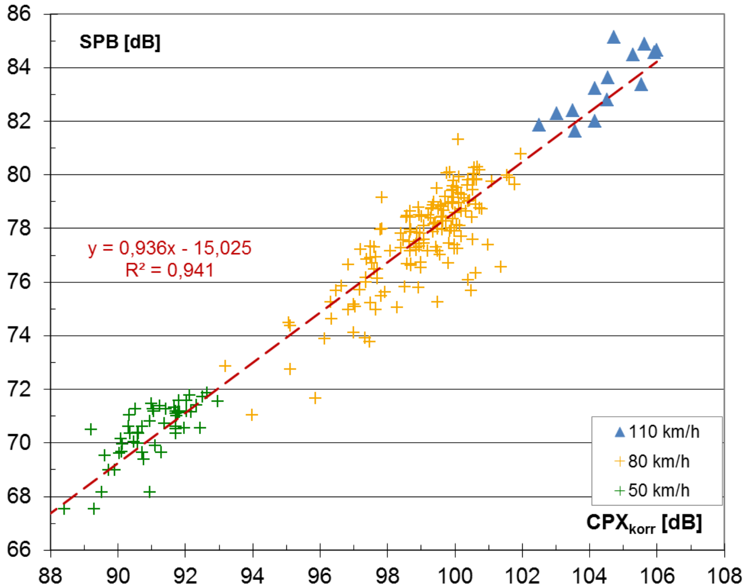

Figure 4 – Diagram of SPB results compared to CPX results found for that same section of road. Slope is 0,94, standard deviation of residues is 0,99 dB (source DRD)

The standard deviation of the residues is buildup of the standard uncertainty μ in the CPX results and SPB results together with the variation in the actual SPB-CPX relation. With an average value of the residues from the DRD and M+P data of 0,9 dB the summation is as follows:

$$(\mu_{SPB})^2 + (\mu_{CPX})^2 + (\mu_{CPX-SPB})^2 = 0{,}9^2 \quad (1)$$

The standard uncertainty in the estimation of the SPB level on base of a CPX level is found as follows:

$$\mu_{measuredCPX->SPB} = \sqrt{0,9^2 - (\mu_{SPB})^2} \quad (2)$$

From ISO 11819-2 a value for μ_{SPB} of 0,7 dB can be deducted, a value that is corroborated in the Round Robin Test, organized by BRCC in 2009 (9). With this 0,7 dB value the result of (2) becomes around 0,6 dB.

2.8 Conclusions on uncertainty

The presented data indicate that the standard uncertainty of the CPX Method and the variation within the SRTT tyre population is correctly assessed in ISO-11819-2 and 11819-3. The Round Robin Test of 2012 (8) supports these values (acknowledging that the effect of environmental conditions was exclude since all data were obtained at the same day) and indicates that two wheeled systems exhibit a slightly lower value of 0,5 to 0,6 dB and an expanded uncertainty at 95% coverage of 1,0 to 1,2 dB.

From the findings in paragraph 2.7 one can state that a CPX result can predict the true value (as expressed with SPB method) with a standard uncertainty of 0,7 to 0,8 dB. Accuracy at 95% coverage is then 1,4 to 1,6 dB.

3. Evaluation of pavement quality with CPX

3.1 Combined effect of product spread and measurement uncertainty

When applying repeated CPX measurements (by different systems and operators) on series of pavements of the same type, the resulting distribution of CPX values will exhibit a variation due to the combined variability of the acoustic performance of pavements within the same type and the limited uncertainty in the CPX measurement. The shaded area in Figure 5 presents the distribution of test results of such CPX method tests. The thick dotted line presents the relation between the acoustic quality of the surface and the “true” CPX test result. The arrow presents the accuracy of the CPX method. From it the thin dotted lines are estimated defining the range in which CPX results vary, given an acoustic quality of the surface.

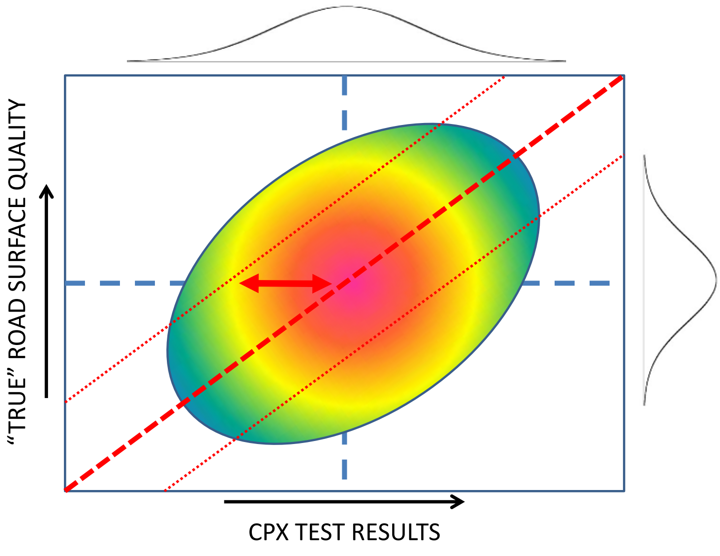

Figure 5 -Schematic illustration of the distribution of CPX test results of a series of pavements when also the spread in acoustic pavement performance is included (normal distribution indicated at the right side). The arrow indicate the accuracy of the CPX method. The thin dotted lines the spread, given a certain quality of the pavement.

3.2 Implementation of not-to-exceed CPX levels

When in a situation of measurement uncertainty and products variation, compliance value is defined in terms of a not-to-exceed CPX level, a situation will occur as is illustrated in Figure 6. Due to the uncertainty in the test result, pavements are accepted that are not meeting the requirements (indicated as false positives) and pavements are rejected that do meet the requirement (indicated with false negatives). The green areas indicate the evaluations that are correct. It is clear from the picture that a significant number of surfaces would be rejected falsely ("false negatives") primarily caused by the limited accuracy in the CPX method.

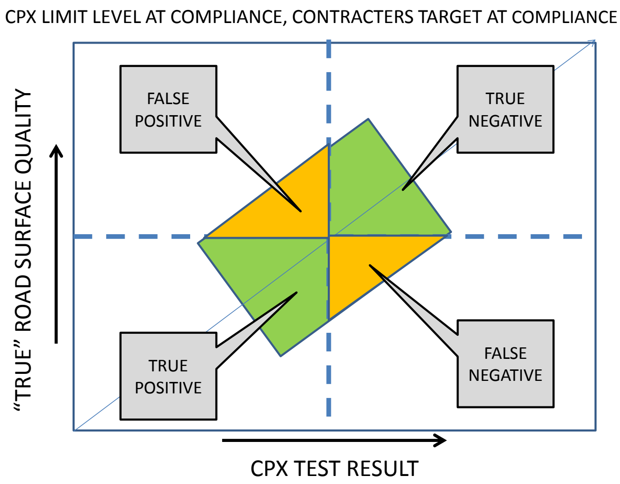

Figure 6 -Schematic illustration of the result of evaluation of pavements with a CPX method with limited accuracy

One could argue that thus the accuracy shall be included in the test requirement. This situation is illustrated in Figure 7 (left) in the shifted vertical line. Now the number of false negatives have decreased, but false positives have increased. Another reaction to measurement uncertainty could be that manufacturers improve the quality of their product. False positives and negatives and true negatives have decreased, but at the expanse of higher burden for the producers.

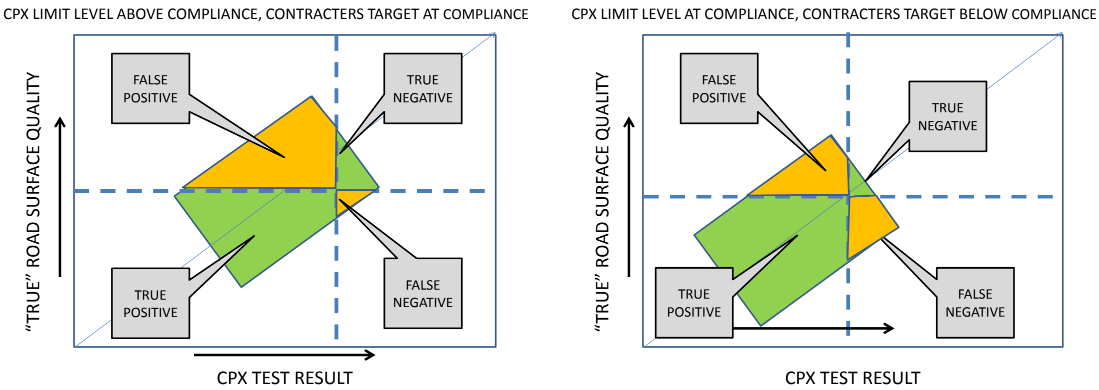

Figure 7 -Schematic illustration of the result of evaluation of pavements with a CPX method with limited accuracy. Left: CPX limit above compliance, contractors target at compliance. Right: CPX limit at compliance, contractors target below compliance.

Another solution might be improving the accuracy of the CPX method. This leads to the situation presented in Figure 8. The number of false rejections or approvals has been reduced. About 50% of the products is still rejected.

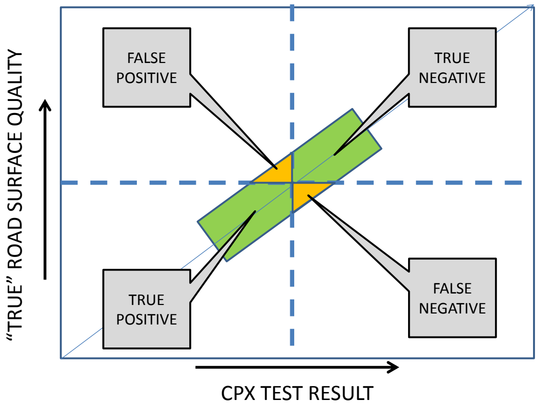

Figure 8 -Schematic illustration of the result of evaluation of pavements with a CPX method with improved accuracy

4. DISCUSSION

The ambition to incorporate the acoustic performance in the tendering of pavements cannot simply be realized by implementing the requested noise reduction in the contract and stipulating that proof is based on a similar CPX result. Not meeting the CPX test may indicate non-compliance, but may also be caused by inaccurate test results. Even if test results are accurate, a too low reading might fall within the normal product spread. A test requirement at the nominal value will have the effect that half of the products are rejected.

When CPX is regarded as a proxy for the noise reduction of traffic, as is measured with an SPB test, then the uncertainty in the prediction of SPB on base of CPX is to be included in the evaluation of the pavement.

It was found that accuracy of CPX and SPB measurements and CPX → SPB relation are about 0,5 to 0,7 dB (standard uncertainty). One cannot neglect uncertainty in the test. Compliance limits have to be defined such that occurrence of false positives and false negatives is balanced.

Including an uncertainty margin in the compliance test will reduce false negatives but increases false positives. The discussion is if this is a real problem. Product spread is always the case, also for the reference pavements. Indications are presented of standard deviations in the order of 0,5 to 1,0 dB. The reference value is often obtained from the average of a large number of reference pavements. Consequently about 50% of the reference pavements will not meet the reference value.

If applying a margin to the test limit does has no effect on the average value (as is illustrated in Figure 7-left) then the objective, namely a reducing surface with an average effect of – x dB is accomplished.

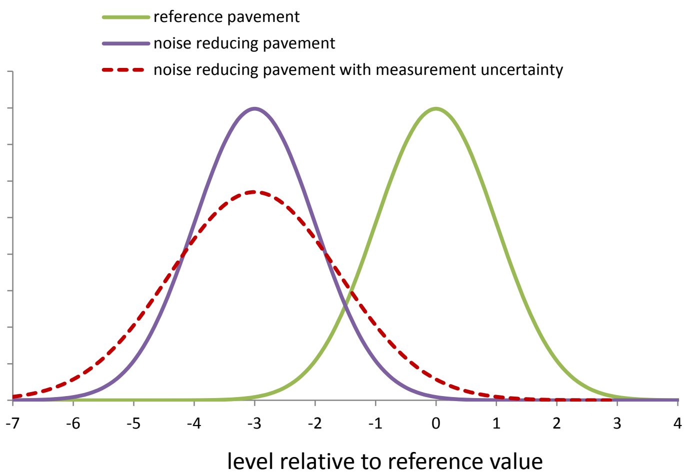

Figure 9 -Schematic illustration of the distribution of levels of a reference pavement and a noise reducing pavement (minus 3). The dotted line indicate the added effect of measurement uncertainty

In this margin the uncertainty of the test method and the spread in pavement properties shall be included. At the other hand, would it be positive to introduce an incentive to improve the product. One could therefor imagine a system with stepped bonus/malus/rejection interval as presented in Figure 10. The green interval indicates significant better than requested performance, rewarded with a bonus. The orange interval indicates an interval where non-compliance cannot be defined, but improvement is wished for and the red interval indicates performance beyond the uncertainty and product spread range and thus shall be regarded as non-compliant.

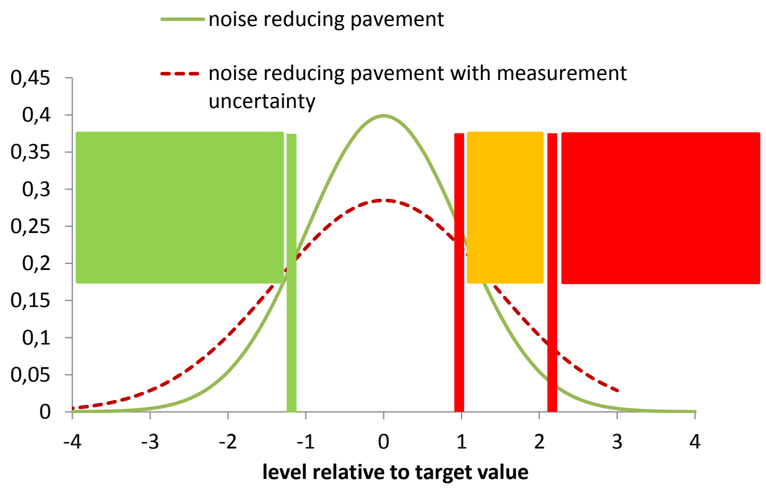

Figure 10 -Schematic illustration of the distribution of levels of a noise reducing pavement, taking into account measurement uncertainty and product spread, with bonus/malus intervals.

5. CONCLUSIONS

In the evaluation of acoustic properties of pavements in contracts, the uncertainty of the test method shall be taken into account. Not doing so, leads to a high fraction of false rejections. In addition the normal spread of properties in a pavement type cannot be neglected either. Defining the limit of a noise reducing pavement relative to the average value of the reference pavement results in improper rejection rates of 50%. We propose to include the uncertainty of the measurement method in the compliance testing of the pavement. In addition to that another limit can be set that includes also the spread in pavement properties. The range in between can be identified with by malus. To create an incentive for the producer to improve product performance a bonus area can be identified, when meeting the target level plus uncertainty.

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