MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Improvements in the CPX method and its ability to predict traffic noise emissions

Bühlmann, Erik[1]
Grolimund + Partner AG – environmental engineering
Thunstrasse 101A, CH-3006, Bern

ABSTRACT

Recent studies have provided for substantial improvements to measurements made by the Close-Proximity (CPX) method, intended for measurement of noise properties of road surfaces. These new findings were incorporated in the new standards published in 2017: the ISO 11819-2 (the CPX method) and Technical Specifications 11819-3 (about the reference tyres) as well as 13471-1 (about temperature corrections). This study, firstly, investigates the typical uncertainties associated with speed, ambient temperature and rubber hardness corrections. Secondly, the study evaluates to what degree the new standards improved the measurement method's repeatability by evaluating measurements that were undertaken on the same road surface at different times. Thirdly, the paper assesses the method's ability to predict the effect of road surfaces on roadside traffic noise by analysing the relationship with statistical pass-by measurements (SPB) undertaken on a large number of road surfaces within the same time frame. The study shows that the repeatability of CPX-measurements could be significantly improved by the new ISO standards, while some uncertainties associated with the properties of the test tyres remain. The study, moreover, provides evidence that overall and spectral road side traffic noise emissions can be reliably predicted by the CPX-method.

Keywords: Tyre/road noise, Measurement methods, Road surfaces
I-INCE Classification of Subject Number: 13, 72

1 INTRODUCTION

For speeds of 30 km/h and above the road surface is regarded as the most important influencing factor regarding the generation of road traffic noise [1]. Consequently, the acoustic quality of a road surface has become an important input factor in noise emission modelling. Low-noise road surfaces have become one of the preferred measures to reduce excessive traffic noise in many countries, because of their substantial noise reduction potential and area-wide effect, see e.g. [2, 3]. In many cases, the acoustic performance of a road surface is subjected to success monitoring or acoustic conformity testing (e.g. in cases where the noise reduction by a road surface is specified in construction tenders and contracts). In such cases, the Close Proximity

---

[1] erik.buehlmann@grolimund-partner.ch

(CPX) method is often used to test the conformity with the demanded values. The advantages of the CPX method are that it is both cost-effective and capable of evaluating the acoustic pavement characteristics along entire road sections. This gives the CPX method a real advantage over the Statistical Pass-By method (SPB) [4] which evaluates the acoustic properties of road surfaces in a cross-section by measurement of statistical noise emissions of vehicle pass-by's. Recent pre-normative studies have provided for substantial improvements of the CPX method. These new findings were incorporated in the new standards published in 2017: the ISO 11819-2 [5] (about the CPX method), the ISO/TS 11819-3 [6] (about the Reference Tyres) as well as the ISO/TS 13471-1 [7] (about Temperature Corrections). Because of the CPX method's high degree of standardisation (i.e. involving controlled measurements using a well-defined system and sets of test tyres) the method is thought to bring advantages regarding measurement repeatability. The fact that CPX measurements cannot be undertaken in entirely controlled environments, however, introduces a certain degree of measurement uncertainty. Moreover, there remain questions regarding the degree that the CPX test tyres are capable of predicting the noise emissions of a statistical tyre and vehicle fleet on a specific road surface.

The objectives of this study are, firstly, to review the CPX method's main influencing factors and to estimate the typical uncertainties associated with the correction schemes specified in the ISO standards; secondly, to assess the repeatability of the method; thirdly, to examine the method's ability to predict roadside traffic noise emissions on a particular road surface. The study concludes by making suggestions for further improvements of the method's repeatability.

2 MATERIALS & METHODS

2.1 The measurement principle

The CPX method is characterised by driving over a road surface at constant speed while continuously measuring the tyre/road noise emitted by standardised test tyres at two defined microphone positions 20 cm from the tyre. This can be done either with a one-wheeled or two-wheeled trailer (with isolated chamber(s) to shield the measurement from background noise e.g. from free flowing traffic) or at the tyre of the test vehicle itself. Reproducibility of the measurement is ensured by correcting the measured noise levels for the influence of the measurement system by a spectral free-field correction [see 5]. By applying a set of provided generic and semi-generic correction factors for speed, ambient temperature and tyre rubber hardness, the method ensures that the measured tyre/road noise values are corrected for the specific conditions during a measurement [see 5, 6]. As the magnitudes of these influences may vary for each tyre-pavement combination, every generic or semi-generic correction is subject to a certain uncertainty.

2.2 Reviewing the main influencing factors on CPX-measurement results and estimating the uncertainties associated with the correction schemes

Existing research on the topic suggests that the main influencing factors on CPX measurement results are driving speed and ambient air temperature during the measurements as well as tyre rubber hardness of the test tyres at the time of measurement [e.g. 8, 9, 10]. These influencing factors are evaluated and further discussed based on existing pre-normative research. The focus is, thereby, made on research that specifically relates to the test tyres P1 (for passenger cars) and H1 (for heavy vehicles) specified in ISO/TS 11819-3.

The corrections procedures required by the standards ISO 11819-2 and ISO 11819-3 aim at ensuring a high repeatability of the CPX-method. There, however, remains a degree of uncertainty for each of the correction procedures. This is especially the case when test conditions deviate considerably from the reference conditions defined in the standards. In a first step, the analysis investigates the degree of variation of these influencing factors and relates them to the correction factors provided in the standards. Secondly, the CPX measurement database of Grolimund + partner AG – environmental engineering (G+P), comprising a total of 8’382 km of measurement runs undertaken in the scope of monitoring measurements, is evaluated for typical variability in the test conditions. The database stores the recorded signals during each measurement run undertaken between 2008 and 2018 per road segment of 20 m. Thirdly, an estimate of the typical measurement uncertainties related to the correction schemes is given.

2.3 Repeatability tests

The repeatability of CPX measurements is assessed by comparing the measurement results on a range of test tracks undertaken at two different times within the same year. The underlying assumption is that the test track’s surface properties did not change during this period. In order to investigate the accuracy gains achieved by the ISO standards published in 2017, each of these measurements is evaluated, firstly, by applying the correction schemes of the 3rd Committee Draft (CD) of 2000 and, secondly, by using the correction schemes of the current ISO standards.

2.4 Correlation between CPX and SPB measurements

To evaluate the ability of CPX test tyres to predict the effect of a road surface for a statistical vehicle fleet, correlations between CPX and SPB measurements are established. The analysis investigates to what degree SPB maximum overall and spectral noise levels for passenger cars can be predicted based on CPX measurements with the tyre P1 by undertaking regression analyses.

3 RESULTS & DISCUSSION

3.1 Main influencing factors and estimated uncertainties of correction schemes

3.1.1 Driving speed

One of the most important influencing factors of CPX measurement results is the driving speed during the measurements. The ISO standard [5], therefore, requires measurements to be undertaken at a certain reference speed (in the case of Switzerland these are 50 on urban roads and 80 km/h on national roads). In practice, the exact reference speed cannot always be guaranteed. For such cases, the standard allows a correction for speeds that deviate by a maximum of ±15% from the reference speed on each road segment and by a maximum of ±5% over a tested road section. Schwanen et al. 2007 [8] investigated the speed coefficient of the CPX test tyre P1 on various road surfaces. An overview of the speed coefficients obtained in [8] is given in Figure 1.

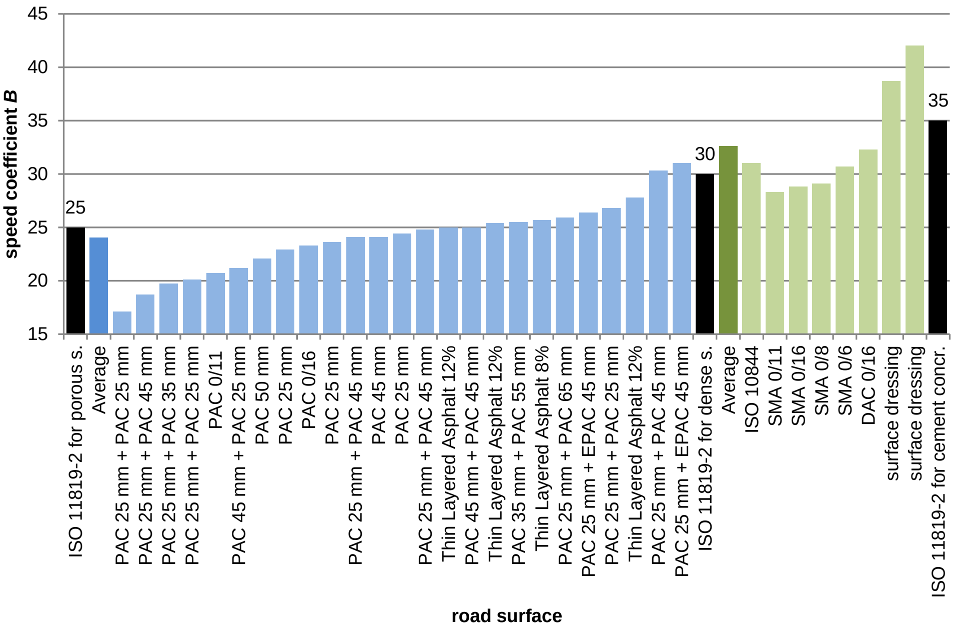

Figure 1 – Speed coefficients on different road surfaces obtained by Schwanen et al. 2007 for porous road surfaces (blue) and dense surfaces (green) in comparison with the speed coefficients B defined in the standard ISO 11819-2.

Figure 1 shows there is some degree of variation of the speed coefficient for different road surfaces within the same road surface category. ISO 11819-2 provides semi-generic speed coefficients *B* that shall be applied depending upon the road surface category (r), i.e. *B*=25 for porous asphalts, *B*=30 for semi-porous or dense asphalts as well as clogged porous asphalts, and *B*=35 for cement concrete surfaces. The speed correction is applied as follows:

$$C_{vref,\,\mathrm{r}} = -B \cdot \lg\left(\frac{v_{\mathrm{t},w,r,i}}{v_{\mathrm{ref}}}\right)\mathrm{dB} \qquad \text{Equation 1}$$

where v is the actual driving speed and v_{ref} is the reference speed, *B* is the speed coefficient and $C_{vref,\,\mathrm{r}}$ the correction for speed deviations from the reference speed v_{ref}. The true influence of speed on tyre/road noise is dependent upon the underlying noise generation mechanisms, each of which show a different speed dependency [11]. The predominance of certain noise generation mechanisms in turn is dependent upon the specific tyre-pavement combination. As a consequence, the speed coefficient can vary by as much as ±5 units from the speed coefficient *B* specified in [5] for a particular road surface within the same category (see Figure 1). In the worst case the speed correction introduces an uncertainty of around 0.5 dB where measurements are undertaken with the maximum allowed speed tolerance on a particular road segment (say at 42.5 km/h instead of 50 km/h). In view of this, measurements whenever possible are undertaken as close to the reference speed as possible to avoid unnecessary errors in the measurement results. In order to estimate the typical uncertainty associated with the correction for speed, the database of G+P for CPX measurements is evaluated regarding the distribution of driving speed during the measurements undertaken at reference speeds of 50 and 80 km/h (see Figure 2).

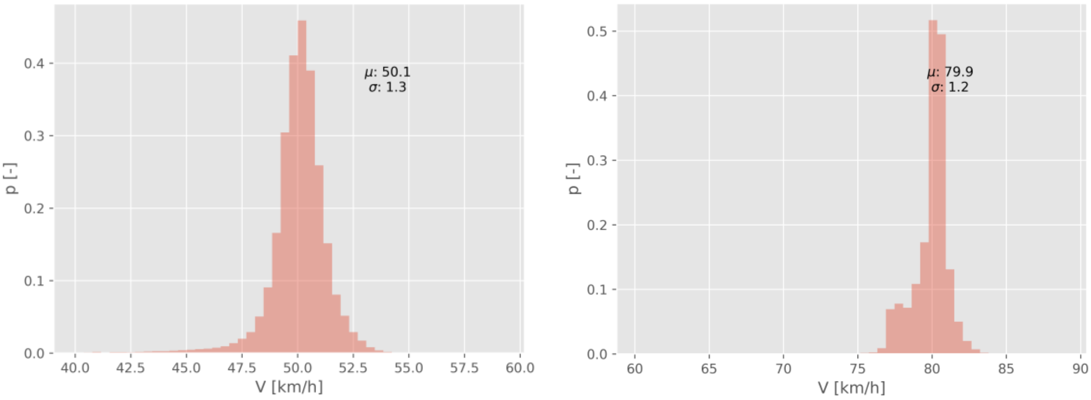

Figure 2 – Distribution of driving speed during 8'382 km of monitoring measurement undertaken by G+P at reference speed 50 km/h (left) and 80 km/h (right) together with mean μ and standard deviation σ.

As Figure 2 shows, the mean speeds during measurements undertaken by G+P are virtually at the reference speed. The standard deviations derived for measurements on urban roads (1.3 km/h) and for measurements on national roads (1.2 km/h) can be considered as reasonably small. When combined with the variation of the speed coefficients within the same road surface category, this would lead to a typical uncertainty associated with the speed correction of around 0.05 dB(A).

3.1.2 Ambient temperature

Another important influencing factor on CPX measurement results is the ambient air temperature during the measurement. Many authors found considerable temperature effects with noise levels decreasing up to 1 dB(A) per 10 °C rise in air temperature on dense asphalts, highlighting the need for temperature correction of measurement results [e.g. 10, 12, 13, 14, 15]. Reliable temperature correction of measured sound levels is therefore crucial. The working group ISO/TC43/SC1/WG27 compiled the temperature effects for the CPX test tyres P1 and H1 found in various studies. The resulting data compilation is shown in Figure 3.

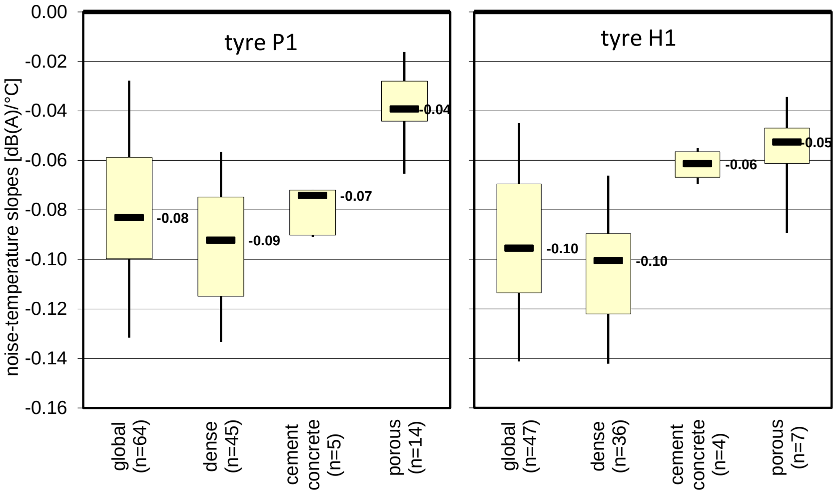

Figure 3 – Data compilation of noise-temperature slopes by ISO/TC43/SC1/WG27 for CPX test tyres P1 (left) and H1 (right) per road surface category

As illustrated in Figure 3, the temperature effects vary between different road surface categories, while only marginal differences between the two CPX test tyres P1 and H1 were found. Similar to the speed behaviour investigated in section 3.1.1, noise-temperature slopes vary for different road surfaces within the same category by as much as ±0.02 dB(A)/°C (distance of quartiles from median temperature effect). The reason for this variation is again, that the contributions of different noise generation mechanisms can vary depending on the specific tyre/road surface combination. These noise generation mechanisms in turn are not equally influenced by temperature. Within the temperature range allowed in [5] this would lead to a maximum error of 0.3 dB(A). Moreover, temperature effects vary also with speed [16]. The standard ISO/TS 13471-1 [7], therefore, provides speed dependent factors for each road surface category to correct for the influence of ambient air temperature during the measurement. The correction is made to a reference ambient air temperature of 20°C and is specified as follows:

$$C_{T,\mathrm{t}} = -\gamma_{\mathrm{t}}(T - T_{\mathrm{ref}}) \qquad \text{Equation 2}$$

where γ_{t} is the temperature coefficient for tyre t (either P1 or H1), in dB/°C; T is the air temperature during the CPX measurement, in °C; T_{ref} is the reference air temperature = 20.0 °C; $C_{T,\mathrm{t}}$ is the CPX level correction for temperature (T) for tyre t, in dB. While for dense asphaltic surfaces (such as DAC, SMA, TAL with air voids typically below 18 %, and surface dressings) $\gamma_{\mathrm{P1}}=\gamma_{\mathrm{H1}}=-0.14+0.0006\,v$, for cement concrete surfaces of all types $\gamma_{\mathrm{P1}}=\gamma_{\mathrm{H1}}=-0.10+0.0004v$ and for porous asphalts a factor of $\gamma_{\mathrm{P1}}=\gamma_{\mathrm{H1}}=-0.08+0.000\,4v$ is applied. Often it is not possible to carry out CPX measurements at the reference ambient air temperature of 20 °C. The database on CPX measurements of G+P was analysed regarding the distribution of ambient air temperatures occurring during the measurements. The results of this analysis are shown in Figure 4.

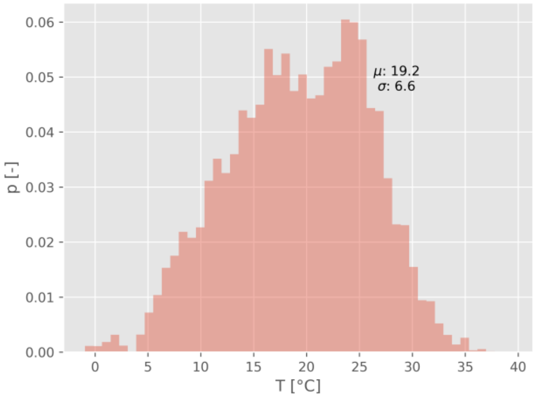

Figure 4 – Distribution of ambient air temperatures (T) in °C during 8'382 km of monitoring measurements undertaken by G+P together with mean μ and standard deviation σ.

According to Figure 4, the ambient air temperatures used for correction of CPX measurements are nearly centred on the reference temperature of 20 °C. The majority of measurements are undertaken at temperatures between 10 and 27 °C (i.e. within a range of 10 °C from the reference temperature), a limited number of measurements are also undertaken near the minimum and maximum temperature allowed by the ISO standard. When combining the typical temperature range with the variation of the noise-temperature slope within the same road surface category, this results in a typical uncertainty of 0.2 dB(A) for temperature correction.

3.1.3 Rubber hardness of test tyres

A third important influencing factor on CPX measurement results is the rubber hardness of the test tyres. Practical experience shows that test tyres can get significantly harder within a single measurement season [17]. This is why ISO/TS 11819-3 [6] includes a correction for tyre rubber hardness which was recently updated based on the results of [18]. The study provided a compilation of tyre-rubber hardness influence on CPX measurements based on various studies, which is presented in Figure 5.

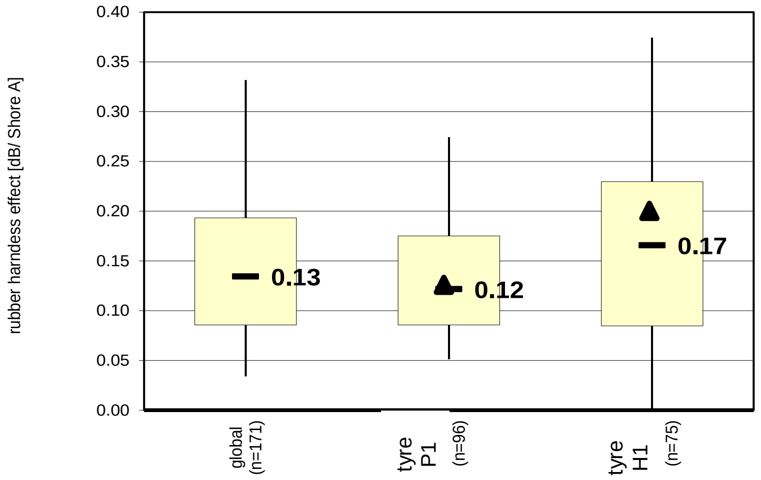

Figure 5 – Rubber hardness effect based on 12 datasets and 171 different relationships for P1 tyre and H1 tyre and the rubber hardness correction specified in the updated standard ISO 11819-3 (triangles), source [18].

The data compilation in Figure 5 shows a variability of the rubber hardness effect within the same tyre of ±0.05 for tyre P1 and of up to 0.12 dB/Shore A for tyre H1 (distance of quartiles from the standard correction factor). Within the rubber hardness range for CPX test tyres allowed in [6] this would lead to a maximum error of 0.35 dB for tyre P1 tyre and of 0.84 dB for tyre H1. The procedure for correcting for tyre-rubber hardness is specified as follows.

$$C_{HA,t} = \beta_t(H_A - H_{ref}) \qquad \text{Equation 3}$$

where β_t is the rubber hardness coefficient for tyre t ($\beta = 0.12$ for the P1 tyre and $\beta = 0.20$ for the H1 tyre in the updated version of ISO 11819-3), in dB/Shore A; H_A is the measured rubber hardness, in Shore A; H_{ref} is the reference rubber hardness = 66 Shore A; $C_{HA,t}$ is the CPX level correction for rubber hardness (H_A) for tyre t, in dB.

As the test tyres' rubber hardness increases at a rather fast rate during the measurement season even when stored at cool and controlled conditions, it is often not possible to carry out CPX measurements at the reference rubber hardness. The data base on CPX measurements of G+P is analysed regarding the distribution of rubber hardness of the P1 and H1 test tyres at the time the measurements. The dataset contains rubber hardness values for all measurements undertaken between 2013 (the year since tyre rubber hardness was systematically measured) and 2018. The results of this analysis are shown in Figure 6.

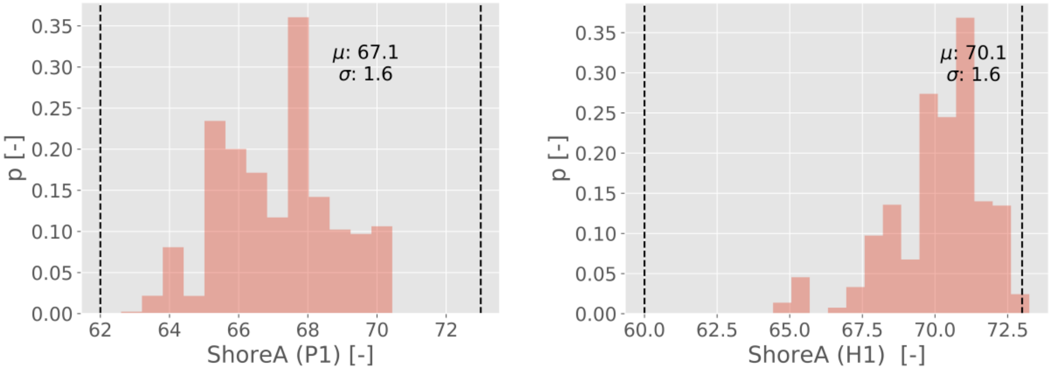

Figure 6 – Distribution of rubber hardness in Shore A of test tyres P1 (for passenger cars) and H1 (for heavy vehicles) during all monitoring measurement undertaken by G+P since 2013 together with mean μ and standard deviation σ. The dotted lines represent the tolerances allowed in the ISO standard.

Figure 6 shows that rubber hardness of the test tyres varied typically between 65 and 70 Shore A for tyre P1 and between 68 and 72 Shore A for tyre H1. The rubber hardness of both test tyres is not normally distributed around the reference rubber hardness. If this rubber hardness range is combined with the typical variation of the rubber hardness effect for the test tyre this results in a typical uncertainty for the rubber hardness correction of 0.2 dB for tyre P1 and of 0.7 dB for tyre H1.

3.2 Repeatability of CPX measurements

In this section the repeatability of CPX method is assessed by evaluating the difference of noise levels obtained from several separate measurement campaigns undertaken at different times within the same year (in most cases with deviating measurement conditions regarding speed, ambient air temperature and tyre rubber hardness). Data from 9 different road sections and from two different years (with different sets of test tyres) were incorporated in the analysis. The results from this practical repeatability test are shown in Figure 7, together with the measurement conditions (driving speed v, ambient air temperature T, rubber hardness S) experienced during each of the measurements, while indicating the month the measurements were undertaken. Please note that the underlying assumption is that the test track's surface properties did not change during the period between the measurement pairs. As all measurements displayed in Figure 7 were undertaken on low-noise road surfaces, this evaluation can be considered something like a worst case scenario, as the acoustic properties of low-noise road surface often vary over the cross-section of the wheel track (reducing repeatability if measurement runs do not take place in the exact same lateral position). Moreover, this type of surfaces can experience faster changes in the acoustic properties than other types of surfaces.

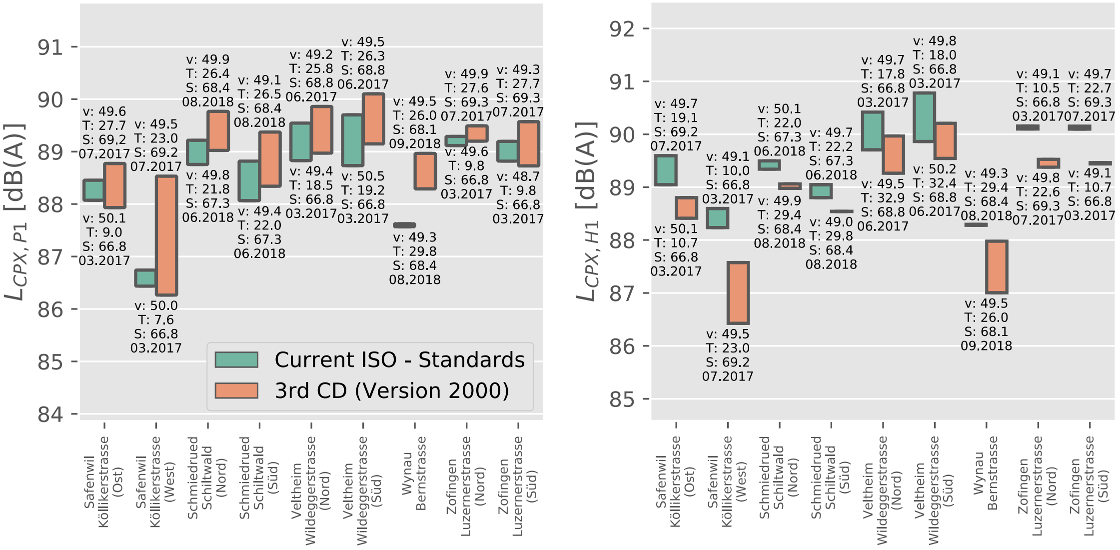

Figure 7 – Difference in $L_{\mathrm{CPX,\,P}}$ (left chart) and $L_{\mathrm{CPX,\,H}}$ (right chart) for measurements undertaken at two different times within the same year (see labels for measurement conditions). Measurements were evaluated according to the correction schemes of the current ISO standards (green) and the correction schemes of 3rd CD of 2000 (red).

As Figure 7 shows, the repeatability of CPX measurements was significantly improved by the correction schemes of the ISO standards published in 2017. This first evaluation yielded a repeatability of 0.45±0.3 dB for tyre P1 and of 0.35±0.3 dB for tyre H1 under the current ISO standards. Hence, the repeatability could be improved by 0.5 dB (down from 0.95 dB) for tyre P1 and by 0.10 dB (down from 0.45 dB) for tyre H1 if compared with the correction schemes of the 3rd CD dating back to the year 2000.

3.3 Remaining uncertainties

3.3.1 Lack of spectral correction approaches

It is known that the temperature effects and the influence of driving speed vary over the noise spectra [e.g. 8, 7]. To a lesser degree this is also the case for tyre rubber hardness influence [18]. Correction should, therefore, ideally be made based on spectra. Currently available data, however, are not sufficiently consistent to introduce frequency-dependent correction schemes in standardisation at this moment. For this reason, the current ISO standards prescribe that the same correction factors are applied for all frequencies. As more data on the spectral influences becomes available, a spectral correction may further reduce uncertainty of the CPX method, ultimately leading to improved repeatability of the method.

3.3.2 Acoustic conformity of test tyres

In study [18] the acoustic conformity of CPX test tyres with the same rubber hardness was tested on a drum in the laboratory. The study revealed that the standard deviations of noise levels for the P1 tyre are rather small and homogeneous over the noise spectrum and lay near the expected measurement uncertainty. Tyre P1 is designed to be used for various tests in the automotive industry. To ensure comparability of these tests, the tyre is made available in the long-term to car manufacturers with nearly unchanged rubber compounds. This leads also to a satisfactory acoustic conformity of the tyre. The study indicated, however, that for the H1 tyre the variation of spectral noise levels was considerably larger in some of the third-octave bands. This variability can only partially be mitigated when tyres of the same production batch are used. In contrast to tyre P1, the H1 tyre is a market tyre. According to information from tyre manufacturers, it is a normal procedure for tyre manufacturers to adapt the rubber compounds during the lifespan of a product line. In order to improve the repeatability of measurements with the H1 tyre, one should conduct conformity tests (ideally with several tyres and then select the most conformant one) before replacing a reference tyre. Alternatively, a procedure may be developed to correct for this. More research is planned on this topic with the aim of addressing the conformity issues of the H1 tyre in the near future.

3.4 Reliability in predicting road-side noise levels

To assess the ability of CPX test tyre P1 to predict the effect of a road surface for a statistical vehicle fleet of passenger cars, regression analysis for a total of 110 pairs of CPX and SPB measurements derived on a total of different road surfaces and road sections at 50 km/h was undertaken. The obtained correlations between $L_{\mathrm{CPX,P}}$ and $L_{\mathrm{SPB,P}}$ for overall noise levels (L_{AFmax}) is shown together with the 95% confidence intervals in Figure 8. It needs to be highlighted that the measurements included in the sample were not undertaken with the aim of establishing a correlation model and that all measurements were selected for display (i.e. without checking deviations for free field conditions required in [4]; these requirements are often difficult to meet for test sites in urban areas).

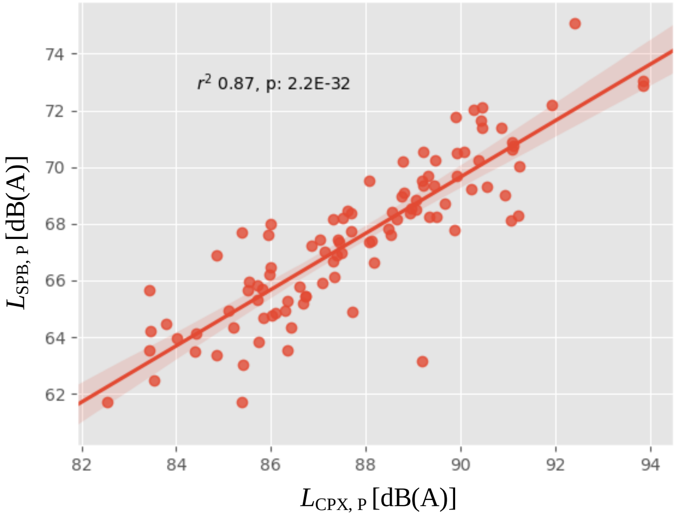

Figure 8 – Correlation between overall noise levels obtained for the CPX tyre P1 and those obtained from SPB measurements for passenger cars at 50 km/h.

Figure 8 shows that with a correlation coefficient of 0.87 overall noise levels between the two methods CPX and SPB correlate relatively well. The regression analysis was repeated for spectral noise levels shown in Figure 9.

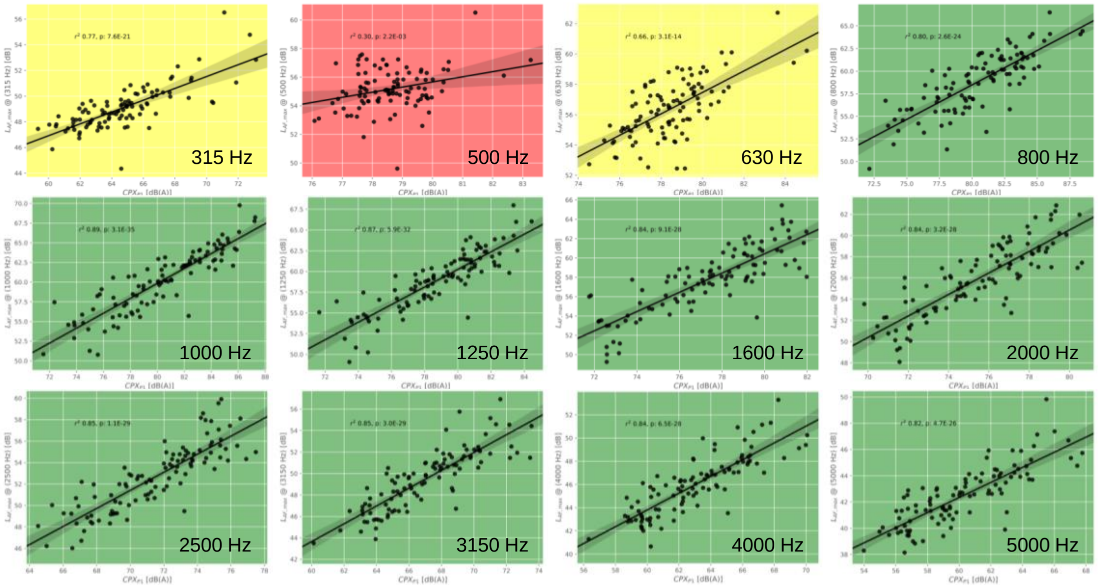

Figure 9– Correlation between spectral noise levels obtained from CPX measurements for tyre P1 (x-axis) and those obtained from SPB measurements for passenger cars (y-axis) displayed together with the 95% confidence intervals.

As Figure 9 shows, the spectral noise levels between CPX and SPB measurements correlate relatively well for most third-octave bands with correlation coefficients of 0.80 and higher (green plots). This is not equally true for third-octave bands of 325 Hz, 500 Hz and 630 Hz (yellow and red plots). The reason for this may be that these third-octave bands coincide with the block pattern frequencies specific to the P1 tyre. Tyre related noise generation may vary between different tyres and, hence, may not be identical for tyres of the statistical vehicle fleet. From the regression analysis provided in Figure 8 and Figure 9 it can be concluded that CPX measurements are suitable for predicting the road side effect of road surfaces even when spectral noise levels are to be considered, for instance as input data in modern noise emission models where spectral corrections for the properties of the road surface are required.

4 CONCLUSIONS

This study investigated the typical uncertainties associated with the correction schemes of the CPX method, its repeatability as well as the method's ability to predict the effect of road surfaces on roadside traffic noise. When applying the correction schemes of the current ISO standards, it was found that tyre variation in the rubber hardness correction contributed most (up to 0.7 dB) to the uncertainty of measurement results. While the typical uncertainty associated with the correction of temperature influence (up to 0.2 dB) is less significant and the typical uncertainty for the correction of the speed influence (up to 0.05 dB) is close to negligible, if larger deviations from the reference speed are avoided. Based on the limited practical repeatability test provided in this study, a repeatability 0.45±0.3 dB was determined for the CPX method. The study, moreover, provided evidence that overall ($R^2 = 0.87$) and spectral ($R^2 > 0.80$ for most third-octave bands) road side traffic noise emissions can be reliably predicted by the CPX method. In order to further increase the repeatability and reproducibility of the CPX method, the author advises refining the rubber hardness correction for test tyres (e.g. in establishing separate correction factors for different road surface categories) and to establish a procedure to address the acoustic conformity issues of the H1 tyre.

5 ACKNOWLEDGEMENTS

The author is grateful to Felix Schlatter for performing data analysis and for preparing and designing the illustrations of this paper.

6 REFERENCES

1 E. Bühlmann, S. Egger, E. Hammer and T. Ziegler, “Basic information for assessing noise effects at speed limit 30 km/h” (in German), VSS2012/2014, Bern, Switzerland (2017).

2 H. Bendtsen, J. Kragh and E. Nielsen, „Use of noise reducing pavements - European experience”, Hedehusenen, Denmark (2008).

3 S. Steiner, E. Bühlmann and E. Hammer, „Milestones in establishing low-noise asphalts as a widely used, effective and durable noise abatement measure in Switzerland”, Proc. EURONOISE, Crete, Greece (2018).

4 ISO 11819-1, “Acoustics — Measurement of the influence of road surfaces on traffic noise — Part 1: The Statistical Pass-By method”, ISO, Geneva, Switzerland (1997).

5 ISO 11819-2, “Acoustics — Measurement of the influence of road surfaces on traffic noise — Part 2: The close-proximity method”, ISO, Geneva, Switzerland (2017).

6 ISO/TS 11819-3, “Acoustics — Measurement of the influence of road surfaces on traffic noise — Part 3: Reference tyres”, ISO, Geneva, Switzerland (2017).

7 ISO/TS 11819-3, “Acoustics — Measurement of the influence of road surfaces on traffic noise — Part 3: Reference tyres”, ISO, Geneva, Switzerland (2017).

8 W. Schwanen, H.M. van Leeuwen and A.A.A. Peeters, „Acoustic optimization tool – RE3: Measurement data Kloosterzande test track”, Report M+P.DWW.06.04.8, Vught, the Netherlands (2007).

9 E. Bühlmann and T. Ziegler, “Temperature effects on tyre/road noise measurements”, Proc. INTER-NOISE 11, (2011).

10 E. Bühlmann E., S. Egger, P. Mioduszevski and U. Sandberg, “An in-depth look at the tire rubber hardness influence on tire/road noise measurements”, Proc INTER-NOISE 18, Chicago (2018).

11 U. Sandberg and J.A. Ejsmont, “Tyre/Road Noise Reference Book”, Informex, Kisa, Sweden (2001).

12 D. Lodico and P. Donavan, “Evaluation of temperature effects for on-board sound intensity (OBSI) measurements,” TRB 2012 Annual Meeting (2012).

13 M. Bueno, J. Luong, U. Viñuela, F. Teran and S.E. Paje, „Pavement temperature influence on close proximity tire/road noise,“ Applied Acoustics 73, 829-835 (2011).

14 F. Anfosso-Lédée and Y. Pichaud, “Temperature Effect on Tyre-Road Noise,“ Applied Acoustics 68 (2007).

15 A. Kuijpers, “Temperature Effects on Tyre/Road Noise and on Tyre Stiffness,” M+P bv memo to ISO Working Group 27, M+P.WG27/2002/2/ak (2002).

16 E. Bühlmann, U. Sandberg, P. Mioduszewski, “Speed dependency of temperature effects on road traffic noise”, Proc INTER-NOISE 15, San Francisco (2015).

17 E. Bühlmann, S. Schulze and T. Ziegler, “Ageing of the new CPX reference tyres during a measurement season”. Proc INTER-NOISE 13, Innsbruck, Austria (2013).

18 E. Bühlmann, P. Mioduszewski, U. Sandberg, „An in-depth look at the tire rubber hardness influence on tire/road noise measurements”, Proc. INTER-NOISE 18, Chicago (2018).