A combined approach for CPX tyre hardness and temperature correction

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ABSTRACT

In order to investigate the acoustic properties of road surfaces, the measurement method as specified in ISO/DIS 11819-2 (Close-ProXimity method CPX) is currently under development. The most important influence factors respectively sources of uncertainty of these measurements are temperature influences and the shore A hardness of the test tyre. At present, these influence factors are corrected via an air temperature as well as a tyre hardness correction, whereat the rubber hardness of the tyre is measured in laboratory. In this paper, the general temperature influence on the tyre hardness, the tyre temperature behaviour during test runs and a combined approach of (tyre) temperature and tyre shore A hardness correction is presented.

Keywords: Tyre/Road Noise, CPX method, temperature correction, tyre hardness correction
I-INCE Classification of Subjects Number(s): 11.7.1, 13.2

1. INTRODUCTION

With increasing noise emissions due to growing road traffic, the need for appropriate noise protection is a major challenge in Europe. The possibilities range from noise reduction at the source, i.e. tyre/road noise, to noise barriers and noise protection windows.

In the context of tyre/road noise, ISO/DIS 11819-2 (Close-ProXimity method CPX) [1] is currently under development. Its scope is the determination of the influence of different road surfaces on the sound emission due to road surface texture induced tyre vibrations and air pumping effects. A crucial item in the application of this standard is a high reproducibility and repeatability of the measurements. Therefore, different influence factors on the noise emission of the tyre have to be taken into account.

During the development of the standard, two major influence factors on tyre/road noise have manifested: on the one hand, temperature has a considerable effect on the noise emission, whereat air, road surface and tyre temperature seem to be prevailing candidates for correction terms. On the other hand, the hardness of the measurement tyre, determined as shore A hardness, also has an definite influence on tyre/road noise. In the next sections, the influences of these variables on the noise emission will be discussed.

2. TEMPERATURE DEPENDENCE OF TYRE SHORE A HARDNESS

The hardness of the rubber compound of the measurement tyre has an unneglectable influence on the dynamic behavior of the tyre and thus on its vibrations and noise radiation. Whereas a linear relationship of tyre/road noise and shore A hardness according to

$$L_{CPX}^{shoreA} = L_{CPX} - \alpha \cdot (H_A^{T_{ref}} - H_A^{ref}) \quad (1)$$

with H_A^{Tref} the shore A hardness of the measurement tyre at T_{ref} = 20°C and H_A^{ref} the reference shore A hardness (e.g. 66 shore A units for the P1 tyre ASTM SRTT) seems to be a viable approach for the correction of CPX levels due to changes of shore A hardness, values for α vary in literature from 0.10 to 0.30 dB(A)/shoreA [2, 3] for the ASTM SRTT and may even be dependent on the road surface type.

Furthermore, the hardness of the tyre rubber is temperature dependent. To determine the changes of

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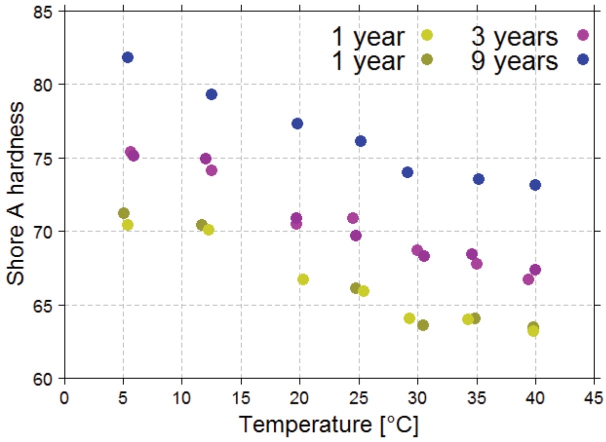

Figure 1 – temperature influence on shore A hardness of five different ASTM SRTT tyres; age of tyres is color-coded, their hardness increasing with increasing age

shore A hardness due to different tyre temperatures, hardness measurements were conducted for five different ASTM SRTT tyres of different age (two of age one year, two of age three years, one of age nine years) and hardness. The tyres were placed in a climatic chamber, where the ambient temperature was varied between 5 and 40°C. At selected temperatures within this range, the tyre hardness was measured. Before each hardness measurement, the temperature was held constant for at least 2 hours for the tyres to reach an equilibrium temperature.

Results of these measurements are shown in Figure 1. From this, it can be seen that a linear correlation is a good estimation over a wide range of temperatures. Also, the slope of this trend is similar for all tyres within the uncertainty of the shore A hardness measurements. Thus, when determining the shore A hardness of the measurement tyre, temperature corrections can be applied according to

$$H_A^{T_{ref}} = H_A^T - \beta \cdot (T - T_{ref}) \tag{2}$$

with β being -0.25 shoreA/°C. Coefficients of determination are above 0.90 for all five tyres.

3. AIR, ROAD AND TYRE TEMPERATURE

When correcting the CPX levels for temperature variations, currently the air temperature is used as variable in [4], whereat also a linear correction model is used. As suggested in [5, 6], the correction factor may be dependent on road surface type as well as on the measurement speed. The air temperature is thereby used as it is easily measurable, and good correlations can be found for single measurements.

As was shown in the previous section, tyre hardness is significantly changing within the common temperature range during CPX measurements. Therefore, it can be assumed that also the dynamic behavior of the tyre changes significantly and tyre vibrations and thus sound emission is changing. In the physical tyre/road system, it can be concluded that relevant changes of material properties only occur for the tyre (with the possible exception for special road surfaces as e.g. poroelastic pavements). From this, the conclusion is drawn that the only temperature-dependent parameter relevant for tyre/road noise emission is the tyre hardness. Thus, tyre temperature seems to be the most sensible parameter for temperature corrections.

Now the question arises of the correlations between air, road surface and tyre temperature as to determine whether the tyre temperature can be derived from air temperature measurements. The relation between air and surface temperature is discussed e.g. in [7, 8]. There, the influence of the surface albedo and the solar radiation are considered, also heat transfers into the soil and air as well as temperature influences due to evaporation of moisture are incorporated. As a consequence, a good correlation of air and surface temperature may only occur for e.g. a constant albedo, cloud amount or even degree of latitude. Also, as the albedo of common road surfaces varies between approx. 0.05 and 0.40 depending on surface type and age [9], strong differences in the correlation of air and road surface temperature may occur for different surface types under otherwise constant environmental conditions.

Concerning the heat transfer from the road surface into the tyre (and vice versa), the dependencies are more complex. When driven on a rough surface, heat is exchanged between the road surface and the tyre. Also the contact patch is heated due to the friction of the rubber on the road surface texture, as well as the tyre is heated due to tyre flexing and may be cooled due to the air flow around the tyre. This last effect may be dependent on the construction type of the CPX trailer, most prominently if an open or closed trailer design is used. Also, for open CPX trailers solar radiation may additionally heat up the measurement tyre.

4. INFLUENCE ON TYRE/ROAD NOISE

In order to further investigate the temperature and shore A hardness effects on tyre/road noise emissions, CPX measurements were performed on two days on a highway section of 1 km length in Austria. Repeated measurement runs with a measurement speed of 80 km/h were carried out with four different ASTM SRTT tyres (two of age one year, one of age three years, one of age nine years with a shore A hardness at 20°C ranging from 67 to 77 shore A units), and air temperature as well as road surface and tyre surface temperature was measured. The latter two were acquired with infrared thermometers, where the tyre temperature sensor was oriented towards the tyre tread pattern.

Overall A-weighted sound pressure levels were determined with time constant "fast" over the whole section. Air temperatures varied from 20 to 28°C during the measurements, road surface temperatures from 23 to 40°C. The distributions of the sound pressure levels at the rear microphone position are shown in Figure 2; each box represents a single measurement run. Please note that, for the sake of simplicity and without loss of generality, all following calculations are presented for the front microphone data only.

As expected, the differences in temperature and tyre yield large deviations in the resulting mean (as well as median) sound pressure levels ranging from 99.6 to 101.3 dB(A). The medians of sound pressure levels range approx. 0.5 dB(A) within one tyre set.

For further analysis, the sound pressure levels were averaged over the whole measurement section. Under the assumption that the relevant road surface parameters did not change within the two measurement days, deviations in sound pressure level originate only from unwanted measurement influences as temperature and tyre. Therefore, correction functions shall be found to compensate for the variations.

In total, three different approaches will be pursued and analyzed: first, the hardness and temperature correction functions as defined in [4] will be evaluated with a preceding total hardness correction according to (2) ("standard" method). Second, a multivariate linear regression analysis will be performed on the measured data set with H_A^{Tref} and air temperature as independent variables ("hardness/air temperature" method). Third, as the tyre surface temperature during the measurements is known, the tyre hardness during the measurements will be calculated by transforming (2) to

$$H_A^T = H_A^{T_{ref}} + \beta \cdot (T - T_{ref}) \quad (3)$$

and subsequently a linear regression analysis will be performed with the actual shore A hardness during the measurement as sole independent variable ("tyre temperature" method, which, although

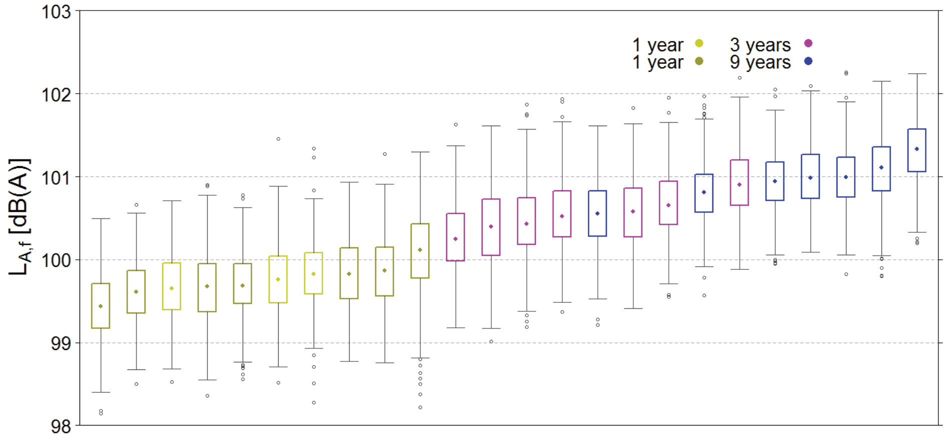

Figure 2 – distribution of uncorrected measured sound pressure values of the single measurement runs; the age of the tyres is color-coded in the figure

Table 1 – evaluation of hardness and temperature correction functions

method	model parameters	median L_{CPX}	lower quartile L_{CPX}	upper quartile L_{CPX}	residual standard error	R^2
standard	-0.092 dB/°C 0.20 dB/shoreA	99.7	99.3	99.8	N/A	N/A
hardness / air temperature	-0.052 dB/°C 0.13 dB/shoreA	99.8	99.7	100.0	0.22 dB(A)	0.85
tyre temperature	0.13 dB/shoreA	100.0	99.9	100.2	0.22 dB(A)	0.85

only dependent on one variable, implicitly includes shore A hardness and temperature effects). It should be noted that the first and second variant of these calculations may be seen as equivalent if the multivariate regression model yields the same coefficients as are selected from [4, 5] (-0.092 dB/°C, 0.20 dB/shoreA for dense asphalt concrete and a measurement speed of 80 km/h). Also, it should be noted that during the two days of measurements, weather conditions and especially cloud amount and therefore solar radiation were constant. Therefore, all results have to be interpreted with regard to section 3.

Table 1 compares the different correction approaches for the test measurement section. All measurement runs were corrected according to the three approaches and statistics calculated on their results. L_{CPX} levels vary by 0.3 dB(A) with a interquartile range of 0.3 to 0.5 dB(A). Here, it should be kept in mind that, as these results show repeated measurements of the same road section, low variations of L_{CPX} levels indicate superior correction methods. Residual standard errors as well as the coefficients of determination show a high model quality.

Interestingly, there are significant differences in the model parameters for the "standard" and "hardness/air temperature" approach, which, in regard to the median L_{CPX} levels, seem to partly balance one another out for the median values. Larger differences occur for the quartile values of the "standard" and "hardness /air temperature" methods: especially for the lower quartile value, an asymmetry can be found (originating either from the lower quartile or median value). This can be also seen in Figure 3. Where the "tyre temperature" and "hardness / air temperature" methods show comparable spans in interquartile box as well as whisker ranges, the "standard" method reveals a broader variation. The similar spans and skewness of the "tyre temperature" and "hardness / air temperature" methods are to be expected, as both regression models are based on the same data set.

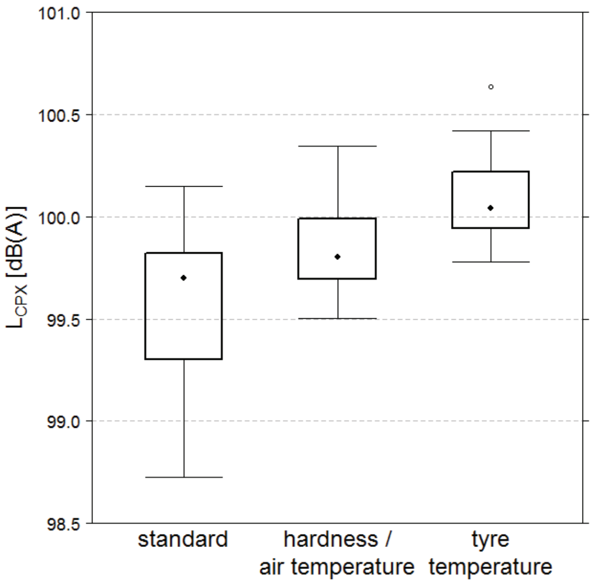

Figure 3 – distribution of corrected L_{CPX} values, evaluated for the three different model methods

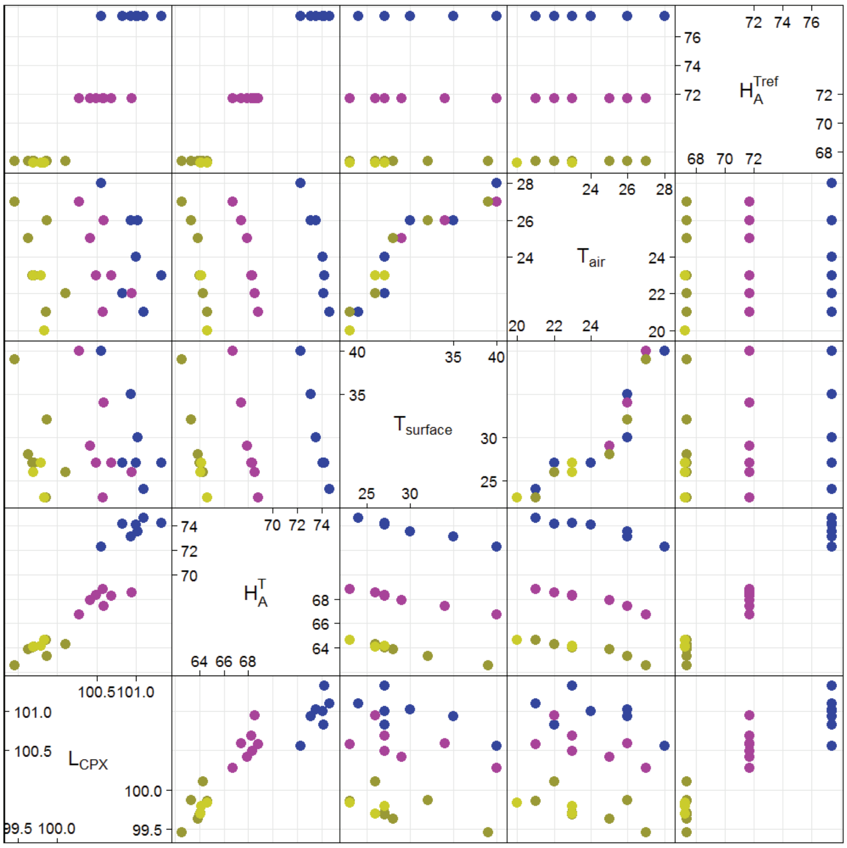

Figure 4 – scatter plot matrix of CPX sound pressure levels and relevant independent variables; the four measurement tyres are color-coded

In addition, in Figure 4 a scatter plot matrix of uncorrected L_{CPX} levels versus the independent variables shore A hardness during the measurement (which is for each tyre separately directly linked to the tyre surface temperature), road surface temperature, air temperature and shore A hardness at reference temperature is displayed. When examining the correlation of air and surface temperature, one can see that there are apparent deviations from linearity. This is, as discussed in section 3, to be expected. Air and surface temperature show direct correlations to H_A^T for each tyre individually, whereas air temperature again slightly deviates from linearity. For lower temperatures, the question arises if the strong linearity of road surface temperature and tyre temperature (displayed as actual shore A hardness during the measurement) is maintained.

Another interesting finding is the direct correlation of L_{CPX} and H_A^T. Where especially for the three newer tyres with lower H_A^T values a linear relationship between the two variables seems appropriate, the oldest tyre significantly alters the slope of the linear regression. Here, the measurement results obtained with the oldest tyre may be questioned. As 9 years of age, various effects may have altered the physical properties of the tyre leading to unknown influence factors on tyre/road noise emission. As the usage of tyres of such age is dissuaded, the results may be discarded here. With this, the calculations of Table 1 are repeated on the data subset and shown in Table 2.

Where there is no large deviation in median CPX levels for the three models, the interquartile ranges are significantly lowered for all methods. Also, residual standard errors as well as coefficients of determination exhibit a better performance of the regression models. Maybe most interestingly, there is a distinct change in slope for the L_{CPX} vs. tyre hardness correlation.

5. CONCLUSIONS

In this paper, results of different approaches of correction methods for the tyre/road noise influence factors temperature as well as tyre shore A hardness are discussed. The aim of this work is to minimize the influence of these variables on CPX measurements as to restrict deviations of CPX levels solely on road surface influences.

Table 2 – evaluation of hardness and temperature correction functions with limited tyre sample

method	model parameters	median L_{CPX}	lower quartile L_{CPX}	upper quartile L_{CPX}	residual standard error	R^2
standard	-0.092 dB/°C 0.20 dB/shoreA	99.8 dB(A)	99.7 dB(A)	99.8 dB(A)	N/A	N/A
hardness / air temperature	-0.054 dB/°C 0.19 dB/shoreA	99.6 dB(A)	99.6 dB(A)	99.8 dB(A)	0.16 dB(A)	0.88
tyre temperature	0.20 dB/shoreA	100.1 dB(A)	100.1 dB(A)	100.2 dB(A)	0.15 dB(A)	0.89

The three different methods show comparable performance indicators, although leading to a final spread of the CPX level of approx. 0.5 dB(A) (5% - 95%) resp. 0.2 dB(A) (25% - 75%). The two methods "hardness / air temperature" and "tyre temperature" exhibit low residual standard errors, as well as high coefficients of determination. At the same time, it should be noted that the interquartile ranges of these two methods do not overlap. The reason for this lies in the nonlinear correlation of measured air and road surface resp. tyre temperature, which is explained by solar radiation effects. It is expected that this difference may be even more significant for measurements with changing cloud amount or measurements on surfaces with variable albedo. Also, for low road surface temperatures, due to tyre flexing and friction effects of the rolling tyre, the linear correlation found between tyre and road surface temperature may significantly change. It is the intention of the authors to further pursue research on this topic. Also, the authors would like to ask other working groups to verify the presented findings.

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