Influence of the tyre impedance on CPX level used to evaluate tyre/road noise

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ABSTRACT
For traffic noise studies CPX measurements are used to evaluate the noise-reduction of a road surface. CPX measurements as described in ISO/DIS 11819-2 are carried out at microphone positions close to predefined tyres at constant speed. The dominant CPX sound source is the tyre’s rolling noise as a result of tyre/road interaction, which - apart from the acoustic properties of the road surface - is mainly determined by the properties of the tyre.

To ensure continuous quality and comparability of CPX measurements, the variation of acoustically relevant properties of the reference tyres must be taken into account to reduce measurement uncertainties. Thus, to ensure comparability, the standard ISO/TS 11819-3 specifies shore hardness values to be checked at regular intervals and compared with normative values. According to our experience in CPX-measurements, determining the Shore hardness of the tyres is not sufficient to describe the reference tyres’ acoustically relevant properties. So, as an additional parameter the mechanical admittance (mobility) of different reference tyres was measured and compared to their Shore hardness and CPX levels on different road surfaces.

Based on these results, conclusions are drawn about the usability of the tyre mobility to increase the quality and comparability of CPX measurements.

Keywords: Tyre/Road Noise, Tyre Aging, CPX (Close-Proximity) Measurement Method.
I-INCE Classification of Subjects Number(s): 11.7.1, 52.3.

1. INTRODUCTION
The rubber hardness of the measurement tyres can affect CPX results. Rubber hardness is the resistance of the tyre rubber based on the depth of penetration and can be measured with a type A durometer. According to the latest ISO standards for CPX measurements (1, 2) a tyre tread hardness correction should be applied to compensate the impact of tyre ageing on the noise emission. The rubber hardness is known to change with time, so if the CPX tyres are in use, tyre hardness shall be measured at regular intervals (1, 2). Studies show value of 0.15 dB per Shore A for SRTT and 0.19 dB per Shore A for Avon AV4 tyres on ISO road surface (3). Other studies show values up to 0.3 dB per Shore A (4). To better understand tyre aging results of tyre mobility measurements are shown. Based on these measurements simulations of the rolling noise will be done and results will be compared to results from CPX measurements.

2. TEST OBJECTS
CPX measurements are carried out to assess and monitor the acoustic properties of road surfaces. The current study was carried out to better understand tyre aging and further improve repeatability. At
the beginning of the study a choice of tyres was made with the objective to get a cross section of ages and tread hardness. 11 CPX tyres (six Uniroyal SRTT tyres and five Avon AV4 tyres) were selected, manufactured between 14th week in 2014 and 42th week of 2006.

All tyres have already been used for CPX measurements, and have a mileage of approximately 2000 km up to 5000 km. After they have been discarded for measurements, they were stored under varying temperature conditions of approximately 8 °C to 20 °C, depending on the season.

3. PERFORMANCE MEASUREMENTS

3.1 Tyre tread depth

The tread depth was measured with the procedure specified in ISO/TS 11819-3 (2). Initial tread pattern depth shall be 8.0 (±0.5) mm for SRTT and 10.0 (±0.5) mm for Avon tyres. Tread pattern wear shall be a maximum of 1.0 mm in comparison to the initial tread depth. The relation between the measured tread pattern depth and the tyre age is shown in Figure 1.

![Figure 1](image1.png)

Figure 1 – Tread pattern depth vs. tyre age.

The selected tyres show good correlation between age and tread pattern depth. This means that the older tyres have a higher mileage than the younger ones.

3.2 Tyre tread hardness

The shore hardness measurements were also carried out according to ISO/TS 11819-3 (2). Figure 2 illustrates the positions where shore hardness was measured. The Technical Specification differs between two mandatory (red) and three optional (yellow) positions. The measurements were executed at all positions. For all measurements a Type A durometer was used. The tires were stored at least 24 hours before the measurements in the laboratory at around 21 °C to 22 °C.

![Figure 2](image2.png)

Figure 2 – Measurement positions for shore hardness: Uniroyal SRTT (left) and Avon AV4 (right).

The statistical relation between the measured rubber hardness and the tyre age is shown in Figure 3.
In the figure a good correlation between tyre age and rubber hardness is shown for both types of tyres. The hardness of the oldest tyres exceeds the requirements of the ISO standard.

These results are similar to those described in (3) and (4) and build the background for the tyre tread hardness correction. The weak point of this correction is, however, that it is based on a statistical model. The shore hardness itself is only one changing parameter within tyre ageing. Although this statistical model seems to be accurate for the data available up to now it can neither be ensured that it will work for all CPX tyres being used in different conditions nor is it possible to draw any conclusions about the real acoustic behavior of the tyres (compare to chapter 4).

Measuring the acoustic and vibrational properties, respectively, directly could however create a direct link from the tyre’s age to its acoustic behavior. Therefor we propose measurements of the tyre mobility and simulations of the rolling noise.

3.3 Tyre mobility

The tyre mobility is the ease with which the tyre is stimulated by an exciting force. High mobility values imply good vibrational excitation of the tyre in the respective frequency range. An exciter (shaker) was used with an attached impedance probe to perform mobility measurements. The probe allows the simultaneous measurement of the applied force $F$ and acceleration $a$ caused by the vibrational excitation. The signals of both channels have been converted to mobility. As excitation signal a band-limited white noise was used (15 Hz to 4 kHz). The signal quality was checked against the determined coherence, being close to 1. The tyres were mounted on rims and the rim is suspended by a hub. Tire and rim were not charged with any load. This test setup enables that tyre vibrations can propagate unaffected. The shaker was suspended by a crane so that the impedance probe can be positioned vertically to the tyres. The pre-load of the sensor changes the tension of the tyre torus and therefore the mobility spectra. Thus a standardized pre-load of 2.0 (± 0.01) kg was defined and adjusted with a scale. The test setup used is shown in the following figure.
Before performing the measurements the tyres were stored at least 24 hours in the laboratory at around 20 °C, so that a homogenous temperature distribution can be assumed. The tyre inflation pressure was set to 200 kPa. The mobility of each tyre was measured at 4 positions. The measuring positions were determined in a uniform manner starting at the valve. All other positions were obtained by rotation counterclockwise by 90°. The measurements were performed at the middle of the tread pattern. In the following figures exemplary results of the tyre mobility measurements are shown (average values). The mobility is plotted as a function of frequency. For both types of tyres characteristic mobility curves are found, see Figure 5.

In the frequency range up to 300 Hz the circumferencial modes are found. In the higher frequencies axial modes a superposed to the circumferencial waves and the tyre’s vibrational characteristics are comparable to a plate.

4. CPX-MEASUREMENTS

Acoustic near field measurement according to ISO 11819-2 (1) were carried out with all 11 tyres. As test site a section of the motorway A 99 in the area of Munich was chosen with four different consecutive road surfaces. The road surfaces are described in Table 2.
Table 2 – Road surfaces of the test site

<table>
<thead>
<tr>
<th>Track</th>
<th>Type</th>
<th>Denotation</th>
<th>Length, m</th>
<th>Age, years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stone mastic asphalt</td>
<td>SMA 8</td>
<td>800</td>
<td>unknown</td>
</tr>
<tr>
<td>2</td>
<td>Porous asphalt</td>
<td>PA 8</td>
<td>1200</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Porous asphalt</td>
<td>PA 8</td>
<td>1500</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>Thin layer asphalt</td>
<td>TL 5</td>
<td>2600</td>
<td>8</td>
</tr>
</tbody>
</table>

The measurements were carried out at a speed of 80 km/h. Before each measurement the tyre was brought to operating temperature by driving for at least 20 min at speeds up to 100 km/h. Each time a test tyre was changed the microphone positions were checked. The measurements were executed within two successive days. The temperatures were measured continuously. The average air temperature was 13 °C (between 7 °C and 16 °C). The average road surface temperature was 12 °C (between 5 °C and 17 °C). The test tyres inflation was checked in advance and set to 200 kPa in cold condition.

At the chosen test site regularly CPX measurements have been carried out. As an example of such a timeline, results are shown as follows. The past results are presented with blue bars, the current results (Track age 8 years) are shown in gray gradations, depending on the tyre age.

![Figure 6 – CPX results for SRTT tyre at thin layer surface. The gray bars show the results for different tyre ages measured within two days.](image)

It can be seen, that the level difference for tyres of a different age (gray) are in the same range as the differences due to ageing of the road surface (blue).

In Figure 7 CPX results vs. tread rubber hardness is presented.
The Figure shows different results for the two different surfaces (Porous Asphalt and Thin Layer Asphalt). The summary of the statistical results found for the studied tyres and surfaces is presented in Table 3.

Table 3 – Statistical results

<table>
<thead>
<tr>
<th>Track</th>
<th>Denotation</th>
<th>SRTT</th>
<th>( R^2 )</th>
<th>Avon AV4</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SMA 8</td>
<td>0.09 dB/Shore A</td>
<td>0.75</td>
<td>0.05 dB/Shore A</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>PA 8</td>
<td>0.01 dB/Shore A</td>
<td>0.04</td>
<td>0.12 dB/Shore A</td>
<td>0.92</td>
</tr>
<tr>
<td>3</td>
<td>PA 8</td>
<td>-0.03 dB/Shore A</td>
<td>0.28</td>
<td>0.14 dB/Shore A</td>
<td>0.98</td>
</tr>
<tr>
<td>4</td>
<td>TL 5</td>
<td>0.12 dB/Shore A</td>
<td>0.94</td>
<td>0.12 dB/Shore A</td>
<td>0.84</td>
</tr>
</tbody>
</table>

The results show level-corrections up to 0.14 dB per Shore A to account deviations from reference hardness of 66 Shore A. Compared to older studies, some show values of the same range (3) other show values up to 0.3 dB per Shore A (4). Nonetheless the correction value which must be applied dependents on the road surface and some results do not show a good correlation between sound level and tyre hardness at all.

This fact is unfavorable in practice. For daily application a correction independent of the surface would be of advantage. To ensure continuous quality and comparability of CPX measurements, the variation of acoustically relevant properties of the reference tyres must be taken into account to reduce measurement uncertainties. According to our experience in CPX-measurements, determining the Shore hardness of the tyres is thus not sufficient to describe the reference tyres’ acoustically relevant properties.

The mechanical mobility can be used as a parameter to solve the above mentioned problem since it is a direct descriptor for the vibrational behavior of the tyre. The data of the mobility measurements can be used to perform rolling noise simulations to assess the difference of tyre-road noise due to tyre ageing directly. Such simulations are described in the following chapter.

5. Simulations

5.1 Model description

The simulation framework is based on a dynamic tyre model and a tyre-road contact model as described in (6). Starting point is a reference configuration of a 205/55R16 slick tyre which is modelled using a waveguide finite element (WFE). The simulation framework combines FE modelling of the cross-section with a waveguide model for the circumference, resulting in a unique eigenvalue problem for each of the circumferential wave orders. The total tyre response is then given by the summation of the individual contributions over the frequency range of interest. Tyre-road interaction
is modelled using a non-linear 3D approach which accounts for the alternating relation between contact forces and tyre vibrations and small-scale roughness effects. Three-dimensional scans of the road surface and the tyre geometry are used as input data. Contrary to the approach presented in (6), no tread patterns and small-scale roughness related damping effects are included in the simulations. Based on the velocity field of the rolling tyre, a half-space BEM approach as described in (7) is used to model the sound radiation from the tyre.

5.2 Mobility

The tyre input data for the reference tyre is identical to the one presented in (7): the tyre mesh consists of 20 solid elements for the tread and 46 shell elements for the sidewalls and belt. The tyre circumference is discretized in 512 elements. The rim and the air cavity are not explicitly modelled, but their effect is included by blocking the tyre motion at the bead and including the pre-tension due to inflation. Bulk material data was provided by the tyre manufacturer. Due to the complex viscoelastic properties of rubber and the necessary reduction of multiple material layers into single shell or solid elements material input data is further adjusted to give a good match to measured mobilities (8). From the reference tyre, a younger and an older tyre are obtained by an adjustment of the Young’s modulus of the tread layer (-20 % younger, +50 % older) and the stiffness of the additional contact springs (-5 % younger, +10 % older). The latter represents the small-scale road/tyre tread interaction in the contact modelling (cf. (6)). The choice of a younger and older version of the reference tyre is based on the fact that the original mobility measurements were performed for a tyre which was already several months old at the time of the measurements.

In Figure 8 mobility results for SRTT tyres of different age are presented (measured data). Aging generally causes a decrease of the tire mobility and a slightly increase of the mode frequencies.

![Figure 8 – Comparison of mobility spectra for SRTT tyres of different age](image-url)

In Figure 9 the simulated input mobility is shown.
Figure 9 - Simulated input mobility on tread center line for the three differently aged tyres. The comparison of the measured and the simulated mobilities show a good fit for both the absolute mobilities as well as the frequencies of the modes. The differences for younger and older tyres are for measurements and simulations comparable, as well.

Differences in the high frequency range are a consequence of different boundary conditions for the excitation. The measurements are conducted with a circular contact point \( r = 10 \text{ mm} \) and a preload of 2 kg, whereas in the simulations the mass-less excitation acts on a 16 mm \( \times \) 16 mm square.

5.3 Rolling noise

For all tyres, the inflation pressure is 200 kPa, and rolling is simulated for a driving speed of 80 kmph and a static load of 3200 N. The road roughness profile for simulatons is based on a scan of ten lateral tracks of the surface, which was investigated for the rolling noise measurements as well (Thin layer asphalt). Rolling is calculated for six full tyre revolutions of which the last two are evaluated, resulting in a frequency resolution of 5.6 Hz. The sound radiation is evaluated as mean sound pressure at 321 points on a half-sphere of radius 1 m around the contact point between tyre and road and converted to the mandatory CPX positions. The total A-rated sound pressure level is calculated for the third-octave bands from 100 Hz to 2.5 kHz.

Figure 10 - Simulated third-octave band rolling noise spectra for the three differently aged tyres. Spectra are distance-corrected to match the distance tyre-microphone in the CPX-measurements. Total levels: 101.1 dB(A) (younger), 101.9 dB(A) (reference), and 103.4 dB(A) (older)
In Figure 11 the results of the CPX measurements are presented.

![Figure 11](image)

Figure 11 – CPX measured third-octave band tyre-road noise spectra for the three differently aged tyres. Total levels: 100.3 dB(A) (95 weeks), 100.8 dB(A) (177 weeks), and 100.7 dB(A) (353 weeks)

The simulation show differences up to 2 dB between the youngest and the oldest tyre for rolling noise on the Thin Layer Asphalt (Track 4), whereas the differences are smaller for measured data. However the spectral levels at 500 Hz and 1000 Hz coincide very well. It has to be kept in mind, that the whole track length of the investigated thin layer asphalt is more than 2 kilometers long while the texture measurements for the simulations are just 2 m long. This means that some deviation between measurement and calculation can be accepted due to inhomogeneity of the road surface texture. With regard to the differences between measured and simulated mobility the results are yet satisfactory. Tyre usage seems to outweigh over tyre age and has to be considered.

6. CONCLUSIONS

For traffic noise studies CPX measurements are used to evaluate the noise-reduction of a road surface.

CPX measurements as described in ISO/DIS 11819-2 are carried out at microphone positions close to predefined tyres at constant speed. The dominant CPX sound source is the tyre’s rolling noise as a result of tyre-road interaction, which - apart from the acoustic properties of the road surface - is mainly determined by the properties of the tyre. To ensure continuous quality and comparability of CPX measurements, the variation of acoustically relevant properties of the reference tyres must be taken into account to reduce measurement uncertainties. Thus, to ensure comparability, the standard ISO/TS 11819-3 specifies shore hardness values to be checked at regular intervals and compared with normative values. According to our experience in CPX-measurements, determining the Shore hardness of the tyres is not sufficient to describe the reference tyres’ acoustically relevant properties. The results of this study show level-corrections up to 0.14 dB per Shore A to account deviations from reference hardness of 66 Shore A. Nonetheless the correction value which must be applied dependents on the road surface and some results do not show correlation between sound level and tyre hardness at all.

As an alternative process the mobility of different reference tyres was measured. Based on the results rolling noise simulations were done. Comparing spectral data form measurements and simulation results shows that both coincide quite well. The acoustic ranking was the same for both measurements and calculations and changes in the spectra are comparable. Based on these results, further studies will been taken to increase the quality and comparability of CPX measurements based on tyre mobility measurements.

REFERENCES

2. ISO/TS 11819-3. Acoustics - Measurement of the influence of road surfaces on traffic noise - Part 3:


