Analyzing tire-road noise influences based on component level measurements

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Introduction

The World Health Organization (WHO) has defined road traffic noise as the most severe environmental impact in urban areas worldwide [1]. In a similar vein, the German Federal Environment Agency (UBA) reached the same conclusion for Germany [2]. As tire-road noise identified as the primary source of noise [3], further investigations in this area are needed. The UBA conducted a study to assess the robustness of UN tire legislation R117 [4]. For this, 60 tires according to R117 were measured and compared to the type approval (TA) results from the tire label. The difference between those two measurements is shown in Figure 1.

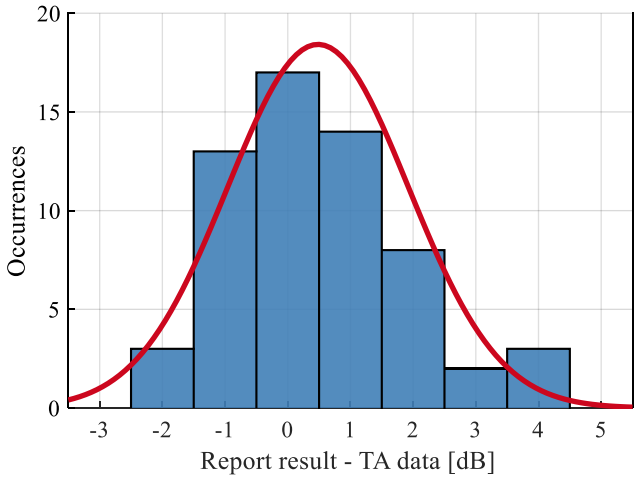

Figure 1: Difference between reproduced measurements and type approval result [4]

The figure illustrates that 16 out of the 60 tested tires have a deviation of 2 dB or more. Ideally, these measurements should be reproducible under identical conditions. This prompts the question of which parameters are not well defined in the R117. For example, temperature, the wheel load or the inflation pressure have defined values/ intervals in the regulation. An additional factor that can vary is the test vehicle on which the tire is mounted. According to [5], for passenger cars, the vehicle has an influence of up to 7 dB. In order to eliminate this problem of vehicle dependency, a systematic investigation of the influence of several parameters on tire-road noise on an adapted tire test rig is carried out.

Approach

In the following, the measurement setup, the adaption of the tire test rig and the sound power calculation are evaluated. Additionally, the parameter variation is explained. The measurement setup consists of six microphones in the near field of the tire [6]. One motivation for this setup is the usability on a full vehicle for conducting validation measurements. Additionally, as CPX-measurement positions from the close proximity method [7] were taken, this leads to the opportunity in comparing the measurements conducted with CPX-measurements. The tire test bench used is an outer drum with the diameter of 100”, usually used for tire dynamic analysis. As the test bench is not an acoustic test bench, an acoustic capsule was built.

For each measurement, sound power is determined based on the microphone data, in accordance with the guidelines outlined in ISO 3740 [8]. This process consists of multiple steps to ensure accuracy and reliability. First, background noise is classified by lifting the tire off the drum and measuring the noise emitted by the drum alone. The difference between this noise and the sound recorded during tire-drum contact is analyzed. The results consistently indicate a difference of more than 10 dB, confirming the suitability of the test bench for the parameter study. Following this, the accuracy class is determined, with class 2 being selected due to its low sensitivity to background noise levels. An essential aspect of the final calculation is the definition of the characteristic source dimension. This is defined as the contact patch. The source is adjacent to two reflective planes: one formed by the test bench panel and the other by the ground including the drum.

The study examines nine different tires, all with a 17” rim diameter. These include six summer tires, two winter tires, and one all-season tire. Within the summer and winter tire categories, the same tire model and make were used but with different dimensions. The selected tires have two different widths and three distinct load indices. Each tire was tested under three different inflation pressures, four wheel loads adjusted according to the load index to ensure consistent stress conditions, and ten velocities. Therefore, a total of 120 measurements were conducted for each tire.

To provide an overview of the conducted measurements, Figure 2 presents the frequency spectra for all tires under a specific set of conditions, including a fixed inflation pressure, wheel load, and velocity. The data is displayed in 1/3rd octave bands covering the frequency range from 100 Hz to 5 kHz. The color bar represents the sound power level in dB(A), calculated according to the procedure described above. Each row corresponds to one tire. The tire notation follows a structured format: the first part indicates the tire type, where "W" represents winter tires, "S" denotes summer tires, and "AS" refers

to all-season tires. This is followed by the tire width, while "LI" specifies the load index. A numerical identifier is included at the end to assign a unique designation to each tire.

The results reveal that all tested tires exhibit the characteristic frequency spectrum of tire-road noise. The maximum sound power levels occur at frequencies above 1 kHz, while noise levels decrease at both lower and higher frequencies. Within the overview provided in Figure 2, it is evident that the winter tires (first and last rows) reach their peak noise levels at higher frequencies, specifically around 2.5 Hz. With increasing the speed, the frequency band of the maximum sound level moves slightly, the overall level increases, but the shape of the spectra remain the same.

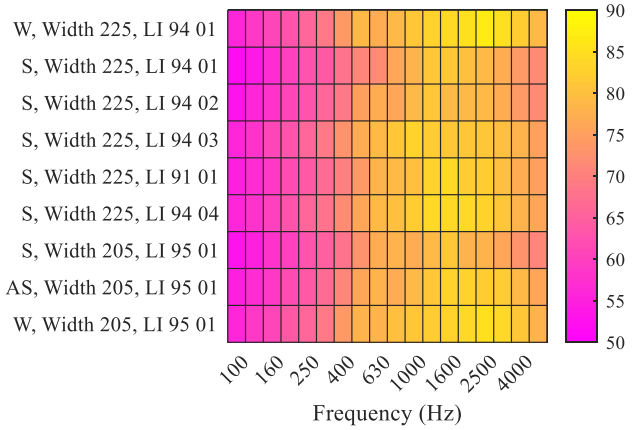

Figure 2: Overview of all tires measured

As a result from the measurement campaign as mentioned above, several parameters can be investigated. In the following, the influence of the speed, the wheel load as well as the drum surface is examined.

Parameter Study

In the beginning, the speed-dependency on the measurements conducted is evaluated as this is the factor influencing the tire road noise the most [5]. The relationship between the velocity and the sound level is across literature defined as

$$L = A * \log(v) + B \qquad \text{[dB]} \qquad (1)$$

Where A represents a speed-dependent parameter and B represents the speed-independent term [5; 9].

To assess whether the test rig accurately represents the expected behavior of tire-road noise, the dependency of sound level on velocity is analyzed and presented in Figure 3. To avoid excessive redundancy in the graphical representation, the results are shown for a single tire under one specific test condition across all measured velocities. The measurement points are shown as blue crosses with a fitted logarithmic curve. Additionally, 95%-prediction bounds are visible in magenta. The measurements meet the relationship defined in Equation (1). The $\mathrm{mean}(R^2)$ equals to 0.9933 and the RSME is at 0.7 dB. Furthermore, the observed variance of 25 dB over a velocity range of 90 km/h is consistent with findings reported in the literature [10], further supporting the validity of the test rig for investigating tire-road noise behavior.

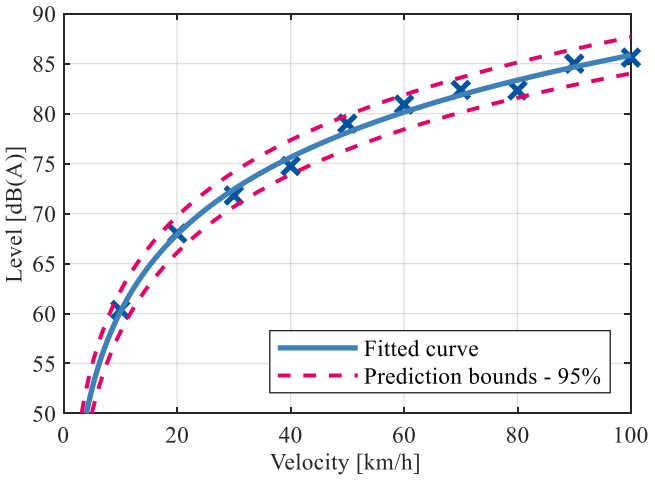

Figure 3: Dependency on the velocity

In addition to the overall noise level, parameters A and B from Equation (1) can be analyzed in more detail. The average values across all measurements for each tire are presented in Figure 4. This procedure is valid due to the high correlation in the regression model as mentioned above. Parameter A, shown in Figure 4 in red, represents the velocity-dependent component of Equation (1). This means that A corresponds to the sound level gain in dB when multiplying the velocity a factor of ten.

The measured values for the parameter A align well with literature data in terms of both amplitude as well as frequency spectrum. Frequencies below 1 kHz are strongly associated with radial mechanical vibrations, which fall within the documented range for parameter A of 20 to 30 dB(A) [11]. Frequencies around 1 kHz are generated by a combination of mechanical vibrations and aerodynamic effects [12]. The observed peak for the parameter A for the 1 kHz as well as the 1.25 kHz 1/3rd octave band exceeds 25 dB(A), but is still lower than values reported in the literature [9; 11]. A potential explanation for the higher literature values is the absence/ reduction of force excitations due to the smooth surface of the test bench drum. Additionally, the high variance in this range can be attributed to the influence of multiple overlapping mechanisms [13]

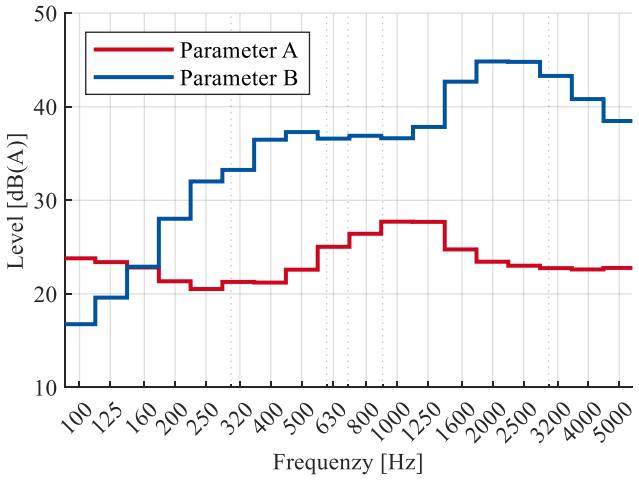

Figure 4: A- and B-parameter from Equation (1)

Parameter B, shown in Figure 4 in blue, represents the constant component associated with resonance frequencies [11]. These include pipe resonances, which typically occur between 500 Hz and 3 kHz, as well as Helmholtz resonances and the horn effect, which are mainly observed between 1 and 2 kHz [14]. These resonance effects are clearly distinguishable in Figure 4 due to the raising values in the higher frequency range. A logarithmic modeling approach for the influence of velocity on tire-road noise provides a physically accurate approximation when accounting for the frequency-dependent parameters A and B.

In addition to the dependency on speed, the influence of wheel load can also be analyzed based on the conducted measurements. The results are presented for a single tire under a specific test condition, with a fixed inflation pressure and velocity. These findings are illustrated in Figure 5. As previously mentioned, the investigated wheel loads were defined based on the wheel load factor to put all tires, even when having different wheel load factors, under the same stress. The selected load levels correspond to 40 %, 60 %, 80 %, and 120 % of the nominal wheel load determined by this factor. They are shown in Figure 5 in petrol, orange, green and blue respectively.

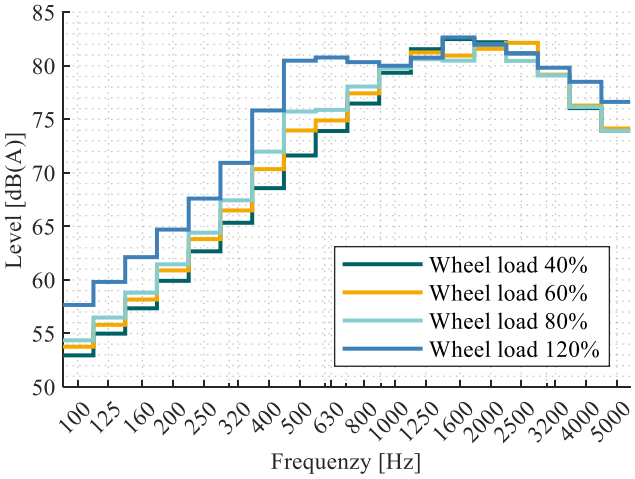

Figure 5: Wheel load dependency

The results show a linear increase in sound levels in the lower frequencies below 500 Hz, which can be attributed to the torus cavity resonance [5] and to the intensified sidewall vibration [15; 16]. Higher load leads to a larger contact patch, which further amplifies mechanical vibrations [17; 18]. It is clear that the blue curve (representing the highest wheel load) reached values above 80 dB(A) at 500 Hz where as the lower wheel loads show this behavior from 1 kHz upwards. Additionally, changes in resonance behavior and air-pumping, along with reduced air volume and increased compression, shift sound power levels from the 1 to 2 kHz range to lower frequencies between 500 Hz and 80 Hz, as well as to frequencies above 3 kHz [19].

Previous studies, such as [20], have investigated the impact of inflation pressure and tire load on sound emissions. The findings indicate that when the inflation pressure is adjusted in accordance with the load, the sound level increases by approximately 1 to 2 dB per twofold increase in load. However, when the inflation pressure remains unchanged, as represented in Figure 5, the increase in sound level ranges from approximately 0.7 to 1.5 dB per doubling the load. In Figure 5, this comparison can be made by analyzing two pairs of wheel loads: 40 % versus 80 % in the first pair and 60 % versus 120 % in the second pair. When considering only the maximum sound levels, this trend is not clearly reflected in the measurements for this specific tire. Notably, the maximum sound level recorded for the 40 % wheel load condition is close to that of the 120 % wheel load condition. A more detailed analysis of 1/3rd octave bands, particularly at lower frequencies, reveals that the trend described in [20] is clearly observable. In fact, the difference exceeds 1.5 dB in certain frequency ranges, highlighting a more pronounced effect than suggested by previous studies.

The impact of the drum surface on tire-road noise is analyzed by comparing two measurements of the same tire under identical conditions but with different surface textures. This comparison is illustrated in Figure 6. The measurement conducted on corundum paper is represented in violet, while the measurement performed on a 3D-printed road surface replica is shown in grey.

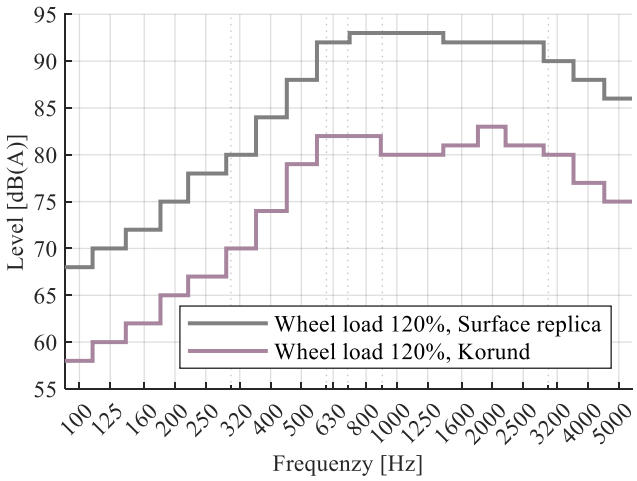

Figure 6: Test rig surface influence

The results indicate only minor shifts in the maximum level range, occurring between 630 Hz and 2.5 kHz. The broad frequency range can be attributed to the high wheel load, as discussed previously. Overall, the spectral characteristics remain largely unchanged, with a general increase of approximately 10 dB observed across all analyzed 1/3rd octave bands. Previous studies have reported surface-related noise variations of up to 10 dB [5], indicating that the results presented here align with the upper boundary found in the literature. This is reasonable given the substantial differences between the two surfaces. The corundum paper provides a very smooth surface with minimal texture, resulting in lower interaction with the tire. In contrast, the road surface replica closely mimics actual road textures, leading to a stronger interaction between the tire and the surface and, consequently, higher noise levels.

Summary & Outlook

Within this paper, several parameters that influence tire-road noise have been investigated on a tire rest rig. A total of nine

different tires were examined under three inflation pressures, four wheel loads, and ten velocities, with six microphones positioned in the near field of the tire. The sound power was calculated based on the acquired microphone data, allowing for a detailed analysis of the influencing parameters. Regarding velocity dependence, the well-established logarithmic relationship between sound level and speed was confirmed within the test rig environment. The logarithmic parameters A and B exhibited trends consistent with findings in the literature. Additionally, increased wheel loads resulted in a broader frequency range with elevated sound levels, extending towards lower frequencies. These results emphasize the necessity of considering inflation pressure adjustments when evaluating the correlation between tire load and noise emissions. Furthermore, an initial investigation into the effect of drum surface variations was conducted. The findings suggest that the utilized test rig is generally suitable for parameter studies on tire-road noise. However, to fully assess its applicability, comparative measurements on a full vehicle setup are required.

Future research will involve a more in-depth analysis of additional tire and surface parameters, such as absorption characteristics, as well as expanding the dataset through further measurements. Ultimately, these investigations will serve as the foundation for a predictive model of tire-road noise. The results indicate that a comprehensive approach incorporating tire properties, surface characteristics, and driving dynamics is essential and should be addressed using combinatorial optimization techniques. Since the accuracy of predictive models is highly dependent on frequency range and the underlying physical mechanisms, further refinement of the conducted measurements is necessary. For validation purposes, additional experiments using the same setup must be performed on a test track to ensure the transferability of findings to real-world conditions.

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