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REDUCTION OF THE HORN EFFECT FOR CAR AND TRUCK TYRES BY SOUND ABSORBING ROAD SURFACES

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Abstract
Sound absorption of porous road surfaces leads to reduction of tyre/road noise by up to 6 dB(A) or more. The effect is larger than may be expected at first sight, from elimination of sound waves reflected by the road only. Experiments show that the increased radiation of rolling noise by the tyre/road geometry (the horn effect) must be taken into account when predicting the noise reduction by a sound absorbing road surface, in order to explain the magnitude and specific frequency dependence of the reduction. The horn effect has been experimentally determined for both passenger car and truck tyres. A model for the absorption effect has been built on these results and validated against a large set of rolling noise measurement.

Keywords: road, tyre, absorption, horn effect.

1 Introduction

Within the ongoing development of silent road surfaces, sound-absorbing porous road surfaces have been very successful when it comes to obtaining high noise reduction. In the Netherlands, porous asphalt concrete is now the standard surface on motorways: in 2016, the entire highway network will consist of single layer porous asphalt concrete (ZOAB). In locations with severe noise pollution, double layer porous asphalt concrete is applied as a countermeasure, obtaining noise reductions of 5 to 6 dB(A) or more. Researchers and road builders are working hard to obtain porous surfaces that have high noise reduction, in combination with durability and prolongation of acoustic properties over time.

On the local road network, porous asphalt concrete is not so effective since it's noise reduction is less for lower vehicle speeds. The relatively large stone size (usually 11 or 16 mm) causes high texture variations. Double layer porous asphalt concrete is constructed with a top layer of smaller stones, but it is too expensive to be applied on local roads in a cost effective manner. A solution is found in thin porous surface layers, generally consisting of, 2-6 mm stones in a layer of 25 to 40 mm thickness. These surfaces have low texture roughness, but some of the sound absorption is sacrificed due to the lower void content. Nevertheless, they exhibit relatively high noise reduction values of 4 dB(A).

Up until now, it is not well understood why these thin layers work so well acoustically, having relatively low sound absorption values (less than 50%). Also, the large-scale application of single and double layered porous asphalt concrete on the motorways requires a better understanding of the influence of the sound absorption of the road surface on the rolling noise emission. An optimal design, after all, will lead to a higher reduction of road noise pollution at lower cost.
A need arises, therefore, for a model to predict the noise reduction of road surfaces based on their sound absorption. Using this model, the optimal sound absorptive surface can be designed for each specific application.

The SPERoN consortium, which consists of Chalmers University, Müller-BBM and M+P (see www.speron.net) has developed an acoustic model optimization tool based on their hybrid SPERoN model (Statistical Physical Explanation of Rolling Noise).

Using this tool, the rolling noise levels and frequency spectrum for passenger car and truck tyres can be predicted for any road surface, defined by it's surface parameters: texture profile, sound absorption curve, flow resistance and mechanical impedance (surface flexibility). The model distinguishes between different noise generating mechanisms, such as tyre vibrations, airflow-related processes and frictional components.

The influence of sound absorption on the emitted rolling sound power has been researched by M+P within the EU FP6 project SILENCE. This work has resulted in a model that predicts the reduction of rolling noise based on the sound absorption spectrum, in 1/3-octave frequency bands. The layout of this model has been previously presented [1] and is now part of the SPERoN model.

Up until recently our model lacked thorough validation for truck tyres. Given the goals described above, especially the application on the highway network, requires a model that works good for both passenger car and truck tyres.

This paper presents the improvements that have been made since the first release of our model. Extensive work has been done at the end of last year up until recently to increase the model accuracy using measurement results and statistical analyses. The main focus has been to research the horn effect for truck tyres and to optimize and verify the model parameters against a large set of rolling noise measurements.

2 Influence of sound absorption on tyre/road noise

2.1 Sound absorption destroys the horn effect

In many sound propagation models, e.g. [2], the sound absorption of the road surface is taken in to account by introducing the finite acoustic impedance of the surface into a ray tracing approach: the sound path from a point source to the receiver point is modeled using a direct sound path and an indirect sound path reflected by the road surface (see Figure 1, left). The acoustic impedance can be calculated as a complex quantity by using impedance models [3][4] based on surface parameters such as void content, layer thickness, etc. Advanced propagation models also take Fresnel weighting into account when modeling the reflection on the road surface.

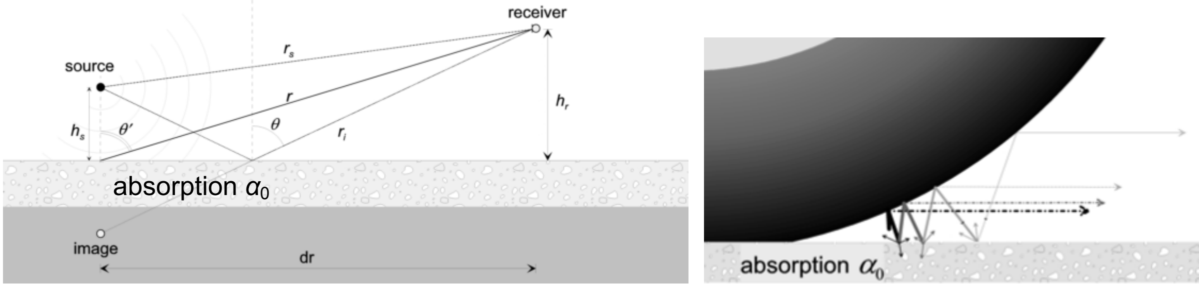


Figure 1 – Sound propagation over an absorptive surface; left: single point source to receiver, right: multiple reflections of noise within the tyre horn

While this approach is correct for noise sources above a sound absorptive surface in general, the influence of absorption on the tyre/road noise emission is somewhat more complicated. Sound is radiated by the tyre, mostly from the area close to the tyre/road contact patch. This sound source is very close to the road surface, therefore it cannot be regarded as a simple point source and the single-ray approach is not valid.

The right-side image of Figure 1 shows a different view on the sound path; sound emitted from the tyre/road contact is reflected multiple times between the road surface and the tyre tread before it propagates further to the receiver. The tyre/road geometry is actually in the shape of a horn, with the tyre/road contact patch at its mouth. This horn shape causes a much larger radiation efficiency of the emitted tyre/road noise than in free field. This increased radiation efficiency is referred to as the horn effect [5][6].
Note that the multiple reflection approach is illustrative, but the acoustics of a horn is better described from an acoustic impedance matching point of view, as is done in musical acoustics, for example. This is, however, outside the scope of this paper.

Sound absorption works very efficiently in counterbalancing the horn effect, since one side of the horn is no longer fully reflective. Imagine drilling holes in one side of the bell of a trumpet: that would seriously affect it’s volume.

Figure 2 shows the result of laboratory measurements of the horn effect, using a passenger car tyre. Sound is measured inside the horn using two microphones: one is placed close to the beginning of the horn at 10 cm from the contact patch centre, a second is placed 5 cm more to the outside. The measurement is performed twice: once with the tyre in position and once without the presence of the tyre. The difference between both measurements is the amplification caused by the presence of the tyre, which is the “horn effect”.

The solid lines show the horn effect measured on fully reflective concrete floor; it is clear that the horn effect leads to amplifications up to 8 dB(A) between 800 and 1250 Hz. Then the tyre was placed over a plate of sound absorbing foam material, with absorption values of > 80% for frequencies above 500 Hz. The results are shown as dashed lines. The reduction of the horn effect by the absorbing material ranges up to 12 dB around 1 kHz.

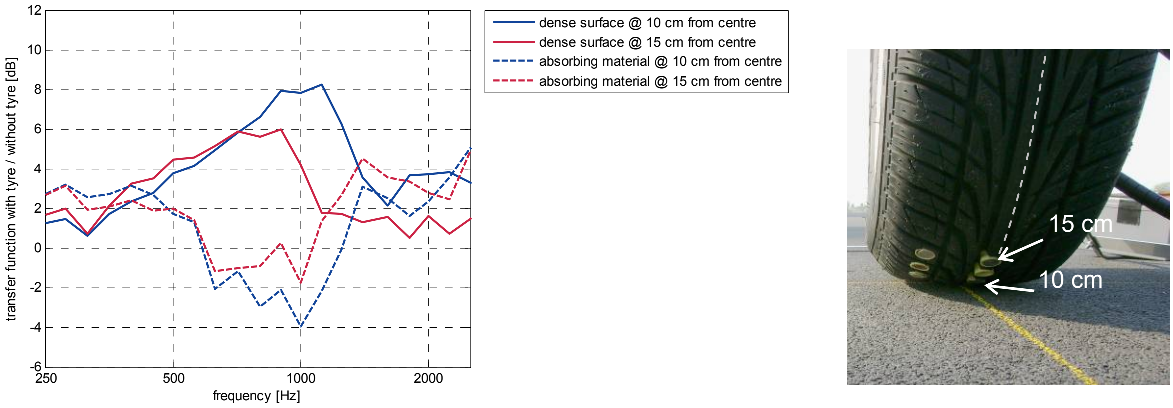


Figure 2 – Lab measurement result of the horn effect on a dense surface (solid lines) and on a plate of sound absorbing material (dashed lines); blue lines show results close to the tyre/road contact patch centre (the mouth of the horn), red lines are measured more outward

2.2 Frequency shift

From experience with noise measurements on porous asphalt surfaces, it has been shown that a frequency shift occurs between the measured sound absorption spectrum and the actual noise reduction spectrum. Sound absorption at a particular frequency causes a reduction of the emitted noise, but at a slightly higher frequency.

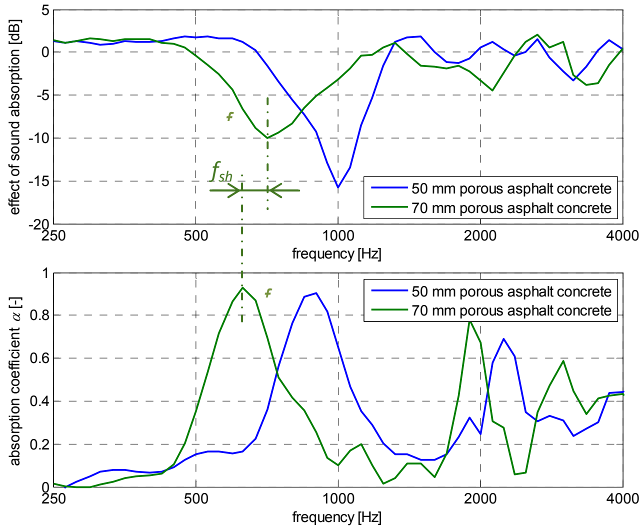


Figure 3 – Noise reduction occurs at a slightly higher frequency than the measured sound absorption; top: influence of sound absorption, measured on two different porous asphalt concrete surfaces with respect to dense asphalt; bottom: sound absorption curve, measured with the Extended Surface Method

The top graph in Figure 3 shows the attenuation of rolling noise measured on two porous asphalt surfaces of different thickness. The attenuation is determined by the horn effect, measured using the method described above, on these porous surfaces to the results on a dense asphalt concrete surface: a negative value means a reduction of rolling noise with respect to the dense surface, which ranges up to -15 dB(A) at 1 kHz.
The bottom graph shows the sound absorption spectrum for both surfaces, measured with the Extended Surface Method [7]. It is clear that the minimum in the upper graph, which is the frequency at which the highest noise reduction occurs, is shifted upward in frequency by approximately 10 – 15% with respect to the peaks in the sound absorption curve.

A satisfactory explanation for this frequency shift phenomenon has not yet been found. However, acoustic impedance models [3][4] also predict a frequency shift when combined with a single ray propagation model from point source to receiver, like in Figure 1 (left). The shift is much smaller, however, than found from actual rolling noise measurements.

3 Prediction model for the effect of sound absorption

A mathematical model has been developed to predict the effect of sound absorption on the rolling noise emission. This model has been incorporated in the SPERoN model framework, which has been presented earlier in [1]. In this paragraph, the measurements used for the development of the model are first explained. Then the model layout and it's different components are described.

3.1 Measurement campaign

3.1.1 Rolling noise measurements

The mathematical model for prediction of the effect of sound absorption is built on the rolling noise measurements that were performed during the development of the SPERoN model. This measurement campaign consisted of rolling noise measurements for 13 passenger car tyres and 15 truck tyres on 41 different road surfaces, including many varieties of sound-absorbing surfaces.

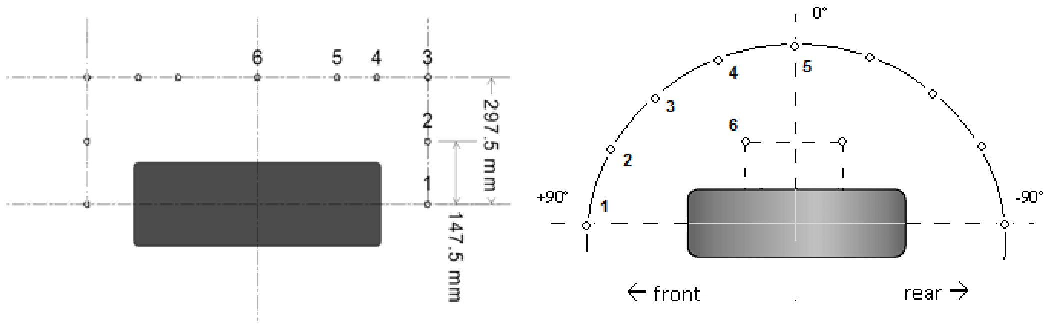


Figure 4 – Definition of receiver positions for passenger car tyre (left) and truck tyre (right)

The rolling noise measurement setup consisted of a rolling noise measurement trailer, similar to the standardized CPX measurement setup. Instead of the usual CPX microphones, however, an array of 11 microphones was built around the rolling tyre (see Figure 4). For the estimation of the sound power spectra only the first six microphones, in the front half of the sound field, are used.

3.1.2 Horn effect measurements

A dedicated, stationary measurement set-up was developed and used to measure the horn effect on a variety of porous asphalt surfaces. The measurement technique makes use of the reciprocity principle, which means the positions of the noise source (the tyre) and the receiver are interchanged: the horn effect is determined by placing microphones inside the tyre horn and using a movable noise source to measure the transfer from each of the source positions to each of the receiver positions used for the rolling noise measurements. A picture of this measurement set-up is given in Figure 5.

Two microphones are used: one quite close to the contact patch and a second somewhat more towards the end of the “horn”. It is assumed that these two positions represent a fairly good average of the entire sound field inside the horn.

Figure 5 – Measurement set-up for determining the horn effect for truck tyres; left: noise source aimed at the tyre; right: microphones inside the tyre horn

3.2 Model components

3.2.1 Background and calculation formula

The model aims to predict the effect of sound absorption on the sound power level emitted by the rolling tyre. A method was developed to estimate the sound power level from the close proximity measurements, using a weighted average over the different microphones. This method is described in more detail in [1] and [8].

Following this approach, our prediction model calculates the average effect of sound absorption over two source positions s and six receiver positions r, corresponding to the microphone positions used for the measurements. The effect of sound absorption with respect to a dense, non-absorbing road surface $\Delta L_{p,\alpha}$ is then calculated as a function of frequency f by using equation (1):

$$\Delta L_{p,\alpha}(f) = \tfrac{1}{12}\sum_{s=1}^{2}\sum_{r=1}^{6} A_{s,r} \cdot H_{horn,s}(f)\cdot \alpha_{eff}\left(f/f_{sh,r,s}\right), \qquad (1)$$

where A is the amplitude factor in dB, H_{horn} is the horn effect frequency weighting factor, ranging from 0 to 1, α_{eff} is the “effective” sound absorption, and $f_{sh,r,s}$ is the frequency shift factor (see § 2.2). Each of these parameters is further explained below.

3.2.2 Horn effect frequency weighting

As was explained in § 2.1, the horn effect causes amplification of the sound emitted by the tyre. This amplification is strongly frequency-dependant: for low frequencies the wavelength of the sound is much larger than the dimensions of the tyre; therefore the radiation efficiency is low. At high frequencies, the radiation efficiency was also found to be quite low. During the SILENCE project, results from BEM modeling of a smooth tyre on a reflective surface have shown a similar decrease in radiation efficiency at high frequencies.

It is important to incorporate this frequency dependence in the prediction model, since it explains why sound absorption is especially effective in the mid frequency range, around 1 kHz for passenger cars and at somewhat lower frequencies for trucks. Figure 3, for example, shows that an absorption coefficient of 0.9 at 630 Hz leads to a maximum noise reduction for car tyres of 10 dB, whereas an equal absorption coefficient of 0.9 at 850 Hz leads to a reduction of up to 15 dB.
To take into account this strong frequency dependence, a frequency weighting factor H_{horn} is taken into account. This factor has been established from the horn effect measurements for passenger car and truck tyres, averaged over several reflective road surfaces, and is given in Figure 6 for both source positions.

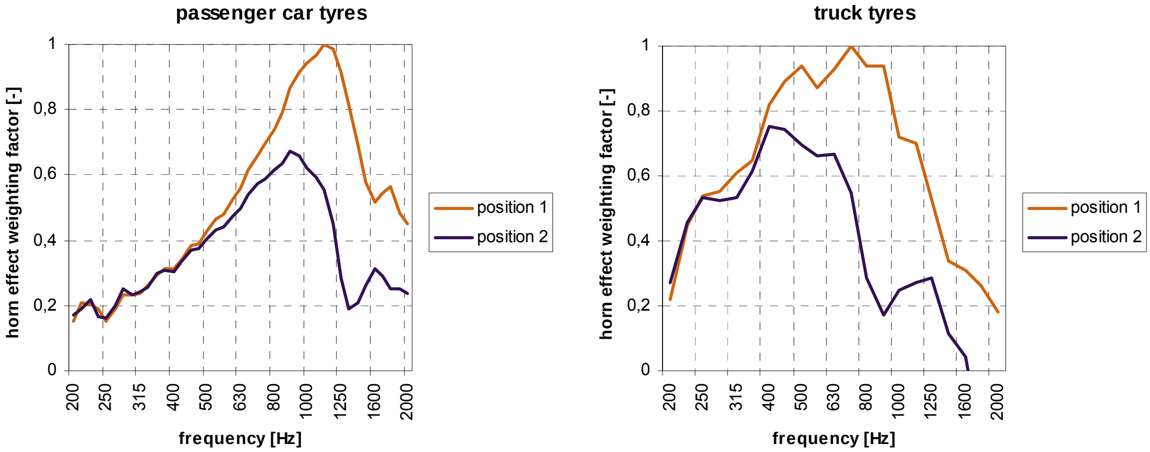


Figure 6 – Horn effect averaged over three different dense surfaces for a passenger car tyre (yellow lines) and for a truck tyre (blue lines), close to the contact patch (position1, left) and more to the outside (position 2, right)

3.2.3 Effective absorption curve

The noise reduction depends, of course, on the sound absorption coefficient α. It was shown before, however, that a non-linear relation exists between the noise reduction $\Delta L_{p,\alpha}$ at a certain frequency and the actual sound absorption coefficient α. The sound absorption, α_0, as it is usually defined and measured, is therefore translated into an "effective" sound absorption, α_{eff}, using the green curve depicted on the right. It has been shown in [1] that using this effective sound absorption curve significantly improves the prediction accuracy of the model.

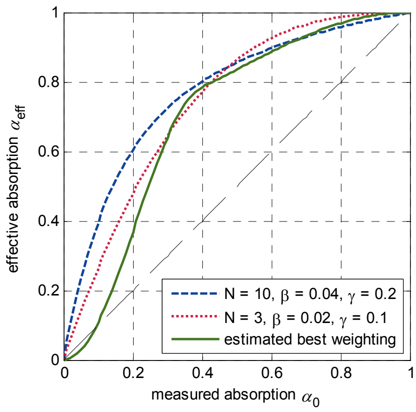


Figure 7 – Effective absorption curve

3.2.4 Estimating remaining parameters

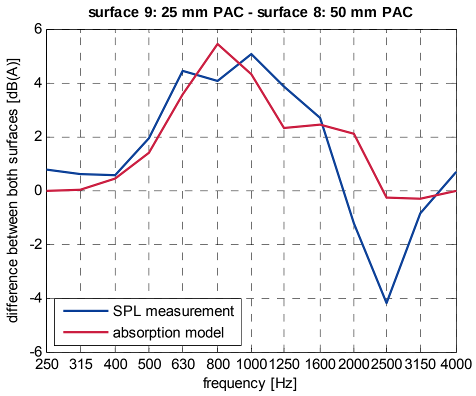
As was mentioned in § 2.2, the frequency shift factor found when comparing the frequency spectra from the rolling noise measurements to the measured sound absorption curves is larger than found from acoustic impedance models. The frequency shift factor, f_{sh}, has therefore been established by comparing the horn effect measurements on several absorptive surfaces to the sound absorption measurements. Finally, the amplitude factor *A* determines the overall amplitude of the noise reduction, in dB. As a first estimate, we take it to be equal to the maximum amplification value found from the horn effect measurements, which is approximately 12 dB for both passenger car and truck tyres.

4 Validation

The accuracy of our model has been validated against the rolling noise measurements. It would be straightforward to compare the model prediction for any absorptive surface to that for a dense surface and see if the predicted noise reduction is also found from the measurements. However, the difference in rolling noise between these two surfaces is not only the sound absorption; the surface texture and flow resistance will also be very different.

We have chosen, therefore, to compare each porous asphalt surface to all other porous asphalt surfaces that have a top layer of the same stone size and comparable void content. In the set of 41 measurement surfaces, 9 porous surfaces with 4/8 mm stone size were found, each of which can be mutually compared in pairs. Also, 4 surfaces with 8/11 mm and 6 surfaces with 2/6 mm stone size were available. In total, 62 pairs of “comparable surfaces” could be found.

Figure 8 below shows two examples of such a comparison. The left graph shows two porous asphalt surfaces of 25 and 50 mm thickness, therefore having very different sound absorption spectra. The blue line shows the difference between the sound power level spectrum measured on both surfaces at 80 km/h, whereas the red line shows the difference between the noise reduction spectra predicted by our model. It is clear that the 25 mm surface exhibits higher sound power levels around 630 – 1250 Hz and lower noise levels around 2,5 kHz. The first effect is well predicted by the absorption model, whereas the lower values around 2,5 kHz are not. The right graph shows another example, comparing two double-layer porous asphalt concrete surfaces, one of 70 mm and one of 50 mm thickness.



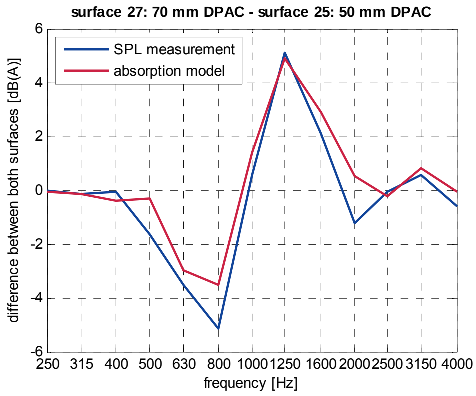


Figure 8 – Comparison of surface pairs: each graph shows the difference between two surfaces from measurements (blue lines) and predicted by the absorption model (red lines)

To validate our model for all 62 surface pairs, we have used single-number criteria. We choose to use different criteria. First, we compare the overall dB(A) levels found from the rolling noise measurement against the overall dB(A) effect found from our model. These results are however dominated by the middle-frequency range, which has the largest influence on the overall level. Furthermore, errors at the low frequency range could be compensated by opposite errors in the high frequency range.

We choose, therefore, to also use an alternative criterion which equally weighs the difference between the model and measurement over the entire frequency range. To do so, we use the standard deviation of the difference between both spectra. That means, we subtract the model spectrum from the measurement spectrum and take the standard deviation over the values for each frequency band.

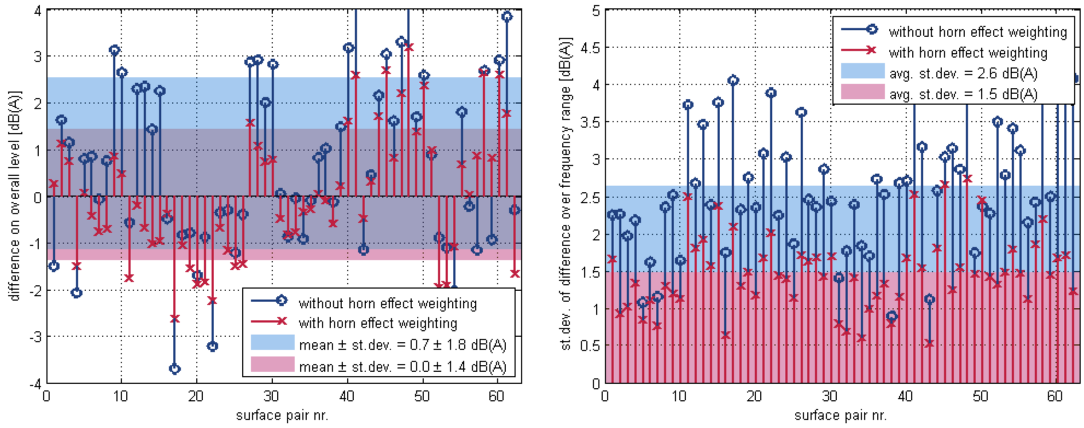


Figure 9 – Model accuracy for passenger car tyres, expressed as a difference between noise measurements and model prediction on an overall dB(A) level (left) and as a standard deviation over the whole frequency range (right)

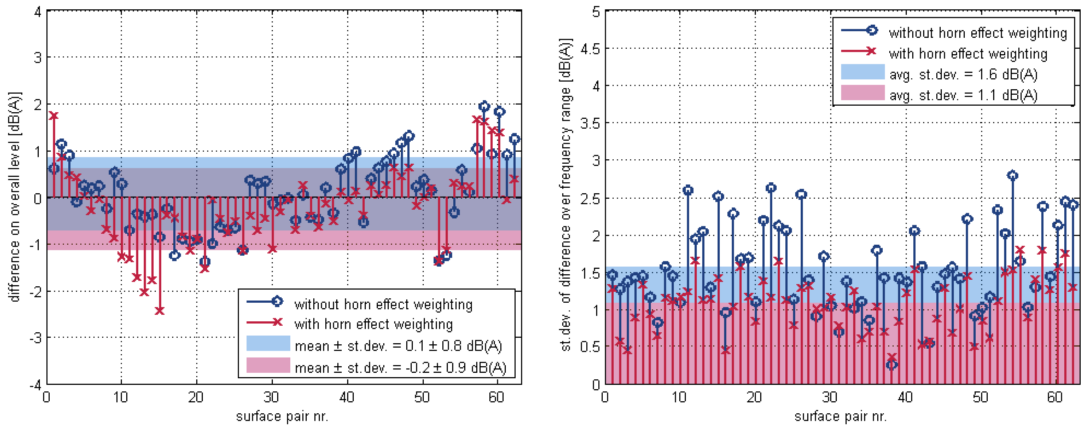


Figure 10 – Model accuracy for truck tyres, expressed as a difference between noise measurements and model prediction on an overall dB(A) level (left) and as a standard deviation over the whole frequency range (right)

Figure 9 shows the result of both methods: the left graph shows the first criterion, a difference on dB(A) level, for each surface pair. The right graph shows the standard deviation of the spectral difference over the entire frequency range.
In both graphs, the blue points show the model without using the H_{horn} weighting curve (or $H_{horn}(f) = 1$ for all frequencies), so the frequency dependence caused by the horn effect is not taken into account. The red points show the full model, including the horn weighting.

The average error over all surface pairs is indicated using the blue and red shades. It is clear from both graphs that incorporation of the frequency weighting curve in our model leads to significantly better predictions. The model predicts the influence of absorption on an overall dB(A) level with an accuracy of 1.4 dB(A) for car tyres and 1 dB(A) for truck tyres. The average accuracy over the frequency range is 1.5 dB(A) for car tyres and 1.1 dB(A) for truck tyres (all values are standard deviations).

This is the total error of the comparison, however, which also includes measurement errors in rolling noise and sound absorption measurements, for both surfaces. Besides, differences between surfaces not explainable by sound absorption, such as different in surface texture and flow resistance, are not taken into account.

5 Conclusions

A prediction model for the influence of sound absorption on tyre/road noise has previously been developed. Further improvements of the model have recently been made by including a horn effect frequency weighting curve for truck tyres. Also, the model parameters have been reevaluated in a more extensive and coherent way than before.
It has been shown that the horn effect causes an increase of radiation efficiency especially in the middle frequency range (around 1 kHz). The larger dimensions of the truck tyre cause an increase of the horn effect in the lower frequency range (315 to 800 Hz).
A validation of the model accuracy against a large set of rolling noise measurements on 20 different porous asphalt surfaces has been performed. It is shown that including the specific frequency dependence of the horn effect causes a significant increase in the accuracy of model predictions.

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