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The Multi-Coincidence Peak around 1000 Hz in Tyre/Road Noise Spectra

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ABSTRACT

Most frequency spectra of exterior tyre/road noise display a prominent peak in the range of 700-1300 Hz. This paper identifies and examines this peak, analyses its causes and suggests some noise reduction possibilities

The characteristics of some of the spectra are such that it would suggest the need to make an adjustment according to ISO 1996-2 for pronounced tonal components. This quite unfortunate concentration of noise emission is caused by a multitude of coinciding factors which are described in the paper.

It is argued that the causes for the phenomenon, termed *the multi-coincidence peak*, include characteristics such as tread pattern pitch, pipe resonances, tangential block resonances, belt resonances, the horn effect and road texture geometry. Elimination or modification of these frequency-concentrating factors, aiming at a mismatch of them, will be the key issue in order to effectively reduce tyre/road noise generation.

1. INTRODUCTION

When studying fairly recent measurements of tyre/road noise frequency spectra, it often appears that there is a rather pronounced predominance of the third-octave bands 800-1250 kHz. This is especially the case for car tyres and when looking at spectra that have been A-weighted. For some tyre/road combinations, the resulting peak around 1000 Hz is sufficiently pronounced to suggest the application of a tonal correction to the A-weighted level. Since tyre/road noise from car tyres is one of the most important contributions to noise exposure in today's society, arguably the most important one, this is something that is worth analyzing. The subject has been addressed in [1], but the following is an attempt to expand the analysis and discussion of this problem.

2. IDENTIFICATION OF THE SPECTRAL PEAK PROBLEM

It has been observed by many that traffic noise spectra display a prominence for the octave of 1000 Hz (however, in this study we mainly use third-octave bands), with the adjacent octaves also being of considerable strength. See Fig. 1 as an example. Traffic noise spectra are generally composed of contributions from a large number of vehicles passing by having a large variation in tyre equipment. They also pass-by at different speeds. These factors tend to smear out any potential narrowband or prominent third-octave band contributions over a range of third-octaves, as seen in Figure 1. Nevertheless, it is not uncommon to measure spectra with pronounced peaks, also in cases where vehicle and speed variations occur. See Figure 2 as an example.

An interesting feature is also, seen in both figures, that the peak characteristics of the spectrum are less prominent for trucks than for cars, even though the speed variation is much smaller.

Instead of studying traffic noise spectra, in which vehicles and speeds vary substantially and there is a mix of contributions of tyre/road noise and power unit noise (the latter is used as the term here for describing sources such as the engine, air intake, exhaust and transmission), one may look at pure tyre/road noise measurements made under controlled conditions, including a nominal speed. Such measurements are shown in Figure 3.

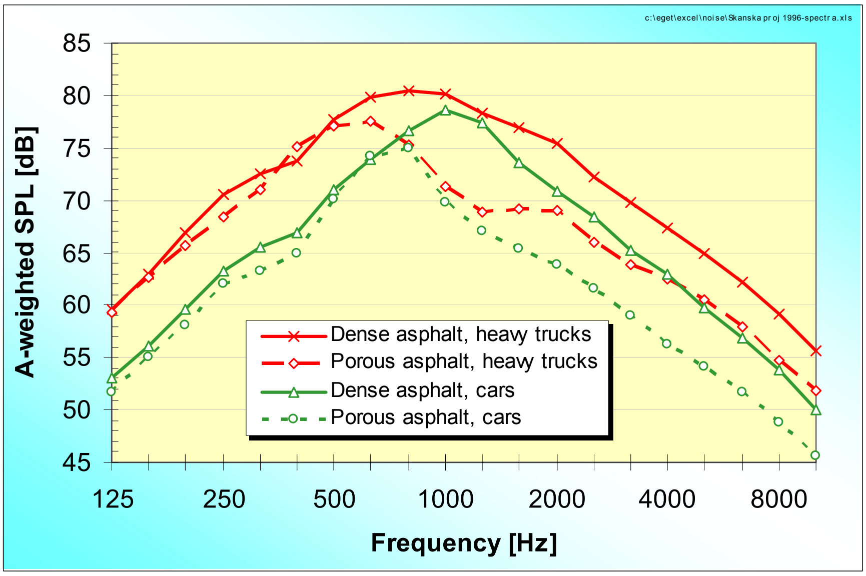


Figure 1. *Third-octave band spectra of traffic (vehicle) noise measured with the SPB method on a dense asphalt concrete surface and on a porous asphalt concrete surface. Speeds: 80-120 km/h for > 100 cars, 70-90 km/h for > 50 trucks.*

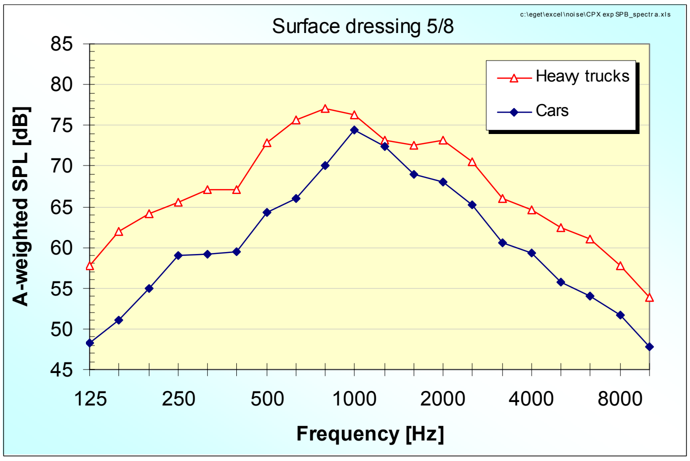


Figure 2 (above). *Traffic (vehicle) noise spectra measured with the SPB method on a surface dressing 5/8. Speeds: 80 km/h (cars), 70 km/h (trucks). From [2].*

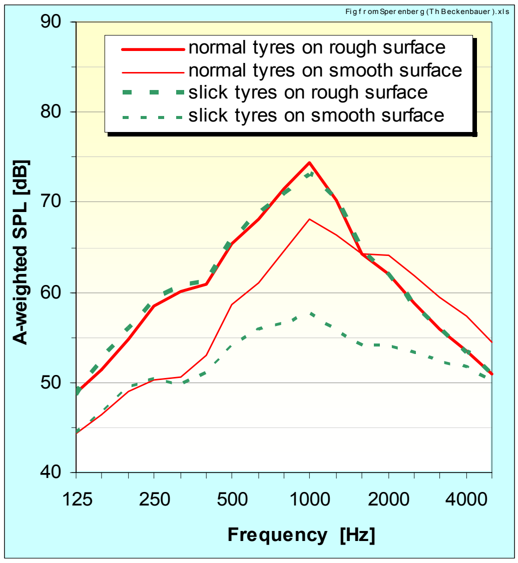


Figure 3 (right). *Tyre/road noise spectra measured with the coast-by method, figure processed from [3]. Two car tyre sets: "slicks" (2 different pattern-less tyres) and "normal" (12 normal summer-type tyre types); on a rough surface (surf dressing 5/8 on top of SMA 0/8) and on a smooth surface (ground cement concrete).*

Measured spectra on a large number of tyres (about 50) are shown in Figure 4. These were made in a cooperation project between the Technical University of Gdansk (TUG) in Poland and the Swedish National Road and Transport Research Institute (VTI). The surface on the left part was an imitation of an actual ISO 10844 surface, which is smooth-textured. It appears in the figure, that most tyre/road noise frequency spectra display a broad but pronounced peak in the range of

700-1300 Hz. Despite a wide range of tyre types, it is amazing how similar the spectral shapes are and how the sound concentrates around a peak at 800-1000 Hz. The chosen road surface should emphasise tyre differences here, but still the spectra are similarly shaped. The "peaky" nature of the spectra shown here is by no means uncommon; for example, the TINO project showed a possibly even more pronounced spectral peak [4]. The right part of Fig. 4 shows the same thing as the left part but when rolling on a very rough-textured surface.

In Figure 5, the spectra with the two most pronounced peaks have been picked-out. It better shows how sharp these peaks can be. Figure 6 is based on exactly the same data as the left part of Figure 4 but the A-weighting has been removed in order to show the spectral shapes with linear weighting (i.e., no weighting). Figure 6 is based on the same measurement as Figure 5, but analyzed in 1/12-octave bands (for field measurements narrower bands than third-octave are hardly justified due to the frequency distortion by the Doppler effect, but in this case the measurement was made on a laboratory drum facility). The figure shows that the "peakiness" of the spectra is not due to one or a few tonal components, but to a prominence of several components concentrated in the same range (bandpass-like noise); something which is typical of tread patterns efficiently randomized.

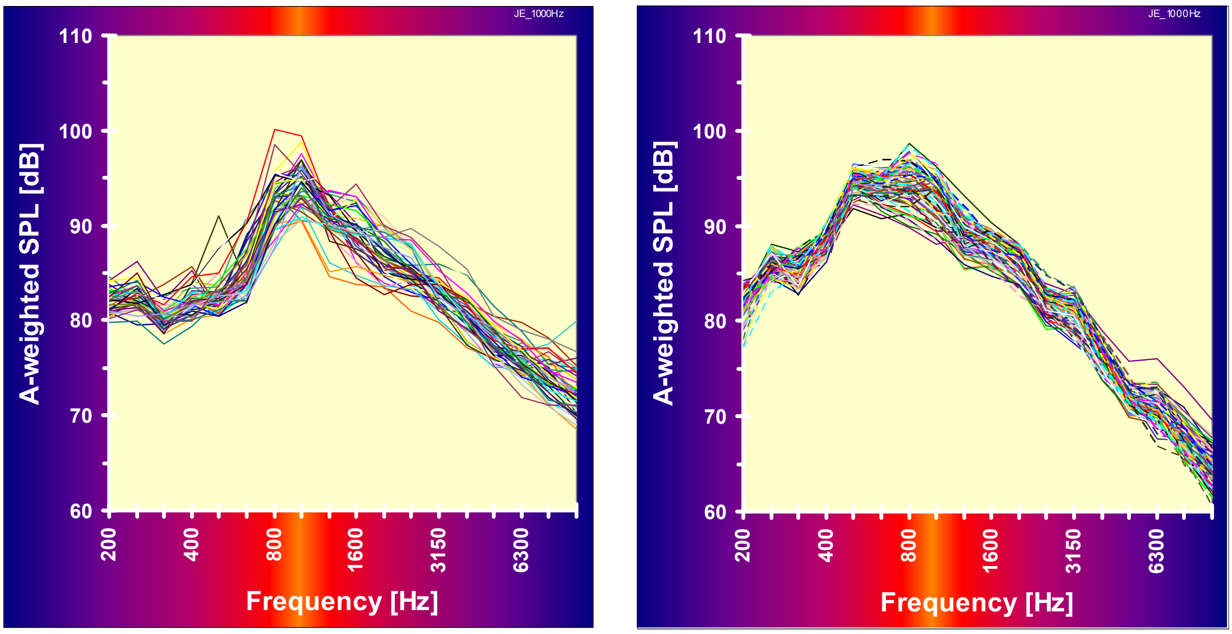
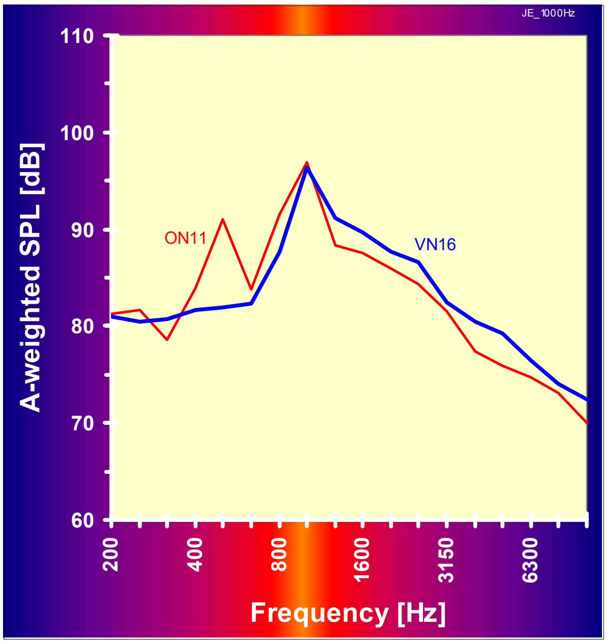
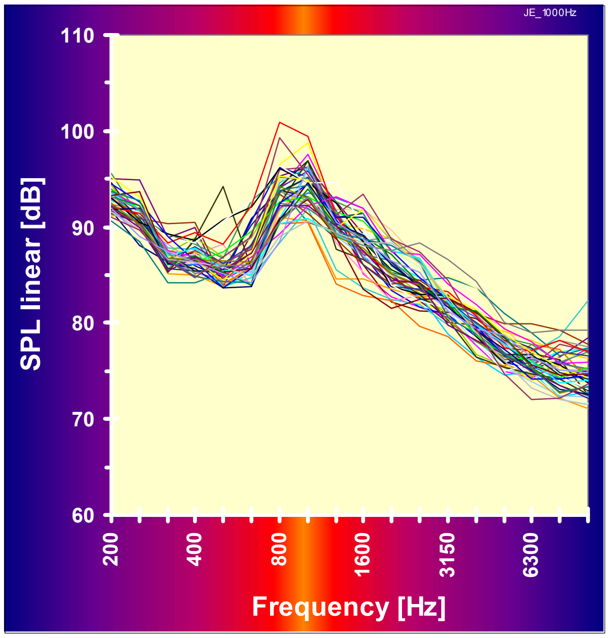


Figure 4. *Left part (4a): Third-octave band spectra obtained in TUG/VTI project for 50 different car aftermarket tyres running on the TUG drum with the ISO replica road surface at 90 km/h. Right part (4b): The same as 4a but for a rough-textured surface dressing (APS4, see [1]).*

3. POTENTIAL EFFECTS AND NEEDS FOR ITS REDUCTION

What detrimental effects might this have on the subjective impact of the sound? First, it must be acknowledged that much effort has already been spent by the tyre industry in reducing the tonal components, especially those which are caused by the periodic nature of the tread patterns.





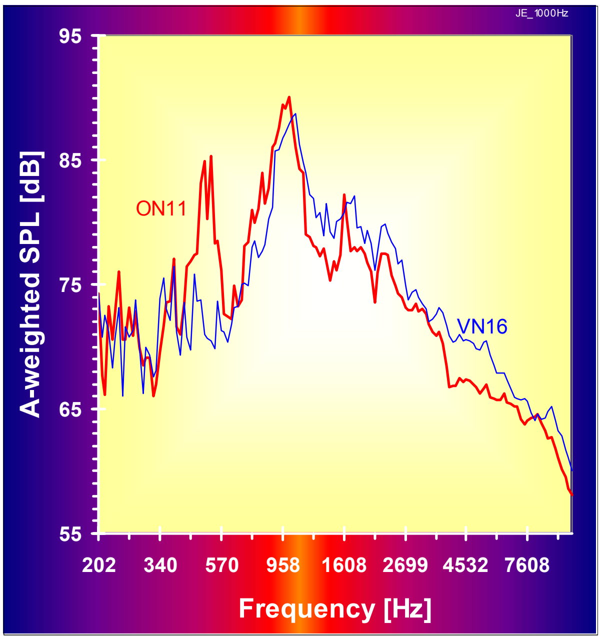


Figure 5 (upper left). *Third-octave band spectra from Figure 4a, obtained for two tyres running on the TUG drum with the ISO replica road surface at 90 km/h.*
Figure 6 (upper right). *The same as Figure 4a, but with a linear frequency weighting of the spectra.*
Figure 7 (left). *The same as Figure 5, but analysis in 1/12 octave band spectra.*

A patent was awarded to Michelin already in 1929 for a variable pitch tread pattern and it was noted by the middle of the 20th century that some tyres emitted a very objectionable tonal and "singing" sound; one truck tyre type was even nick-named "Singing Sam" for this reason, see Fig. 7.23 in [1]. Tyre manufacturers have tried now for decades to "randomize" their tread patterns to avoid the creation of pronounced tonal components. A comprehensive treatment of the randomization process is given in chapter 10.6 in [1]. It is the common view nowadays that at least for light vehicle tyres, the randomization is sufficiently effective in order to practically eliminate the tonality of tyre/road noise (exceptions occur).

However, the figures above suggest that a new spectral concentration has occurred. According to [1], there are indications that this spectral concentration is more evident on modern than old tyres. The new (?) spectral concentration does not result in exactly "tonal" sound, since the periodic component of the tread pitch has been spread out over a certain range of frequencies, but it features a prominent and rather narrow peak in the spectrum. In fact, the characteristics of some of the spectra in Figure 4a are such that it would suggest the need to make an adjustment according to ISO 1996-2 (published 1987, still in force) for pronounced tonal components. The spectra for two of these tyres are shown in Figure 5. See further section 27.2 in [1].

What can one expect from the subjective impact of such "peaky" spectra? First, it can be noted that according to "the critical band theory", the loudness of bandpass noise increases rapidly when the bandwidth narrows down to the critical bandwidth, which at 1000 Hz is around 150 Hz. The spectra in Figure 5 seem to approach this condition. However, a recent study indicates that narrow bandpass noise is not as objectionable as purely tonal noise and the critical band theory could not be confirmed, so the issue still seems somewhat open [5]. See also [14].

4. SUMMARY OF OBSERVATIONS

Traffic noise spectra composed of a mix of vehicle pass-bys at a range of speeds generally show a clear dominance for the 800-1250 Hz third-octave bands; sometimes shifted one or at most two bands down or upwards. Mostly, truck noise spectra are broader than car noise spectra. When studying *tyre/road noise* at a particular speed, most tyres and road combinations show a prominent peak, very frequently at 1000 Hz but it may also be shifted within the range 630-2000 Hz. This is particularly the case for car tyres, but in many cases also for truck tyres; see Figs. 1-2 in this paper and Figs. 159 and 172 in [3]. However, for truck tyres the peak is usually at about two third-octave bands lower frequency than for car tyres (the peak is within 500-1000 Hz), a relation car-truck which coincides with the difference in tyre tread pitch. From this fact, one might be tempted to speculate that the peak is due to the tread pattern geometry and resulting impact frequencies. But this could at most be only a partial reason, since the peak frequency relation between car and truck tyres is the same also for patternless car and truck tyres.

Beforehand, one may think that the peak would be more pronounced in cases where the road surface has a smooth texture as opposed to a rough texture, since it is known that tyre pattern effects are very important in such cases and require randomization efforts in order to avoid tonal noise. However, surprisingly, this is not generally the case; the peak may be equally prominent for a slick tyre running on a rough-textured surface. It may also be surprising to some that on a porous road surface there is generally also a peak; although a little displaced to a lower frequency (Figure 1). The reason is that the sound absorption has a sharp frequency dependence in the mid-frequency range and may effectively "cut away" most of the acoustic energy in the range 800-1600 Hz, leaving the 630 or 800 Hz bands as remnants of the original peak feature. Thus, one may say that the effect of a new porous surface is to shift the peak in frequency from about 1000 to about 600-800 Hz, at the same time as its peak level is reduced. One may clearly distinguish between the rather soft "bandpass noise" character of the tyre/road noise emission on a porous surface, and the more intrusive bandpass noise at higher frequencies on a dense surface.

It should be pointed out that truck tyre/road noise is only slightly higher than that of car tyres, for similar speeds and similar number of tyres, despite the greater widths of and much higher loads carried by truck tyres [6]. In fact, it is possible to find heavy trucks carrying 10-20 tons GVW that emit lower tyre/road noise than some high-performance cars with wide tyres [6]. Further, on some surfaces, an average of a wide selection of truck tyres was found to emit about the same tyre/road noise per tyre as an average of a wide selection of car tyres, despite carrying a load 5-7 times that of the car tyres (compare Figs. 142 and 158 in [3] but compensate for differences in speed and number of tyres). Many people would have difficulty in realising this. The reasons for this unexpected fact have never been analysed. However, this author suggests that it may at large be due to the fact that for truck tyres, the peak is shifted to lower frequencies, not coinciding so well with the maximum of the A-weighting curve. It may also be due to a somewhat less pronounced peak character; for example due to higher belt stiffness and larger excitation/contact points in the tyre/road interface (see below).

5. POTENTIAL CAUSES FOR THE MULTI-COINCIDENCE PEAK

This quite unfortunate concentration of noise emission in one of the most sensitive regions for the human hearing seems to be caused by a *multitude* of *coinciding* factors. Therefore, this author suggests using the term "*multi-coincidence peak*" for this phenomenon. The factors responsible for this may be found among the following effects or mechanisms.

A-weighting: When considering the impact on humans (loudness, annoyance), using the A-weighting curve is standard procedure. This gives the highest weight to frequencies 1000-5000 Hz. A comparison of Figures 4a and 6 shows the effect of the A-weighting. One may conclude that the A-weighting does not constitute a major cause for the peak, but it somewhat amplifies it.

Tread pattern pitch: Tyre tread patterns are often constructed to have a pattern periodicity of around 20-40 mm for cars and 45-65 mm for trucks. The former will give a fundamental impact frequency of 500-1500 Hz at highway speeds; the truck tread pitch will give about 40 % lower fundamental frequencies. This creates the tread impact mechanism, but also affects some air displacement mechanisms [1].

Pipe resonances in longitudinal grooves: Pipe resonances in longitudinal grooves through the contact patch will have frequencies within 900-2000 Hz [1]. Unpublished data from a senior tyre researcher known to this author suggest that the pipe resonance is pronounced as long as there is not much airflow through the pipe and around the tyre, but when there is substantial airflow, like on a rotating drum pulling air along its circumference, the pipe resonance may more or less disappear. However, this author and Prof Ejsmont have been unable to verify this; on the contrary some recently measured data (unpublished) suggest a very significant pipe resonance.

Pipe resonances in lateral grooves: Lateral grooves, closed at one end, may have resonances within the same range as given above. Such grooves are shorter but this is compensated for by their nature as $\lambda/4$ resonators versus $\lambda/2$ resonators for longitudinal grooves open at both ends.

Helmholtz resonance: The Helmholtz resonance, important for air resonant mechanisms (see 7.1.16 in [1]), will be most important within 1000-2500 Hz.

Tangential tread block resonances: Tread block elements may have tangential resonance frequencies within the 800-3000 Hz range [7]. Crossbars in the tread with a longitudinal dimension typical of a tread block show a resonance at around 750 Hz according to Paper 2 in [8].

Belt resonance: The belt resonance is generally around 600-1300 Hz, see 7.1.7 in [1].

The horn effect: The horn effect is most prominent at coast- or pass-by conditions in the range 600-2000 Hz, although the peak frequency depends very much on the location of the sound source in the horn geometry [9, 10]. If one assumes a source location of about 100 mm from the centre of the contact patch, which is not unlikely for a sound generation frequency around 800 Hz [1], the horn amplification may peak at such a low frequency as about 1000 Hz.

Road surface texture geometry: For a common surface which has chippings up to 11 or 16 mm, the peak in the texture spectrum will occur at 16 or 20 mm texture wavelength, which gives an excitation frequency of 800-1000 Hz at 70 km/h and 1000-1250 Hz at 90 km/h [1]. This texture spectrum peak is not very pronounced, except on porous surfaces, but should supply an excitation which reasonably well fits the other resonances, not the least create a stronger excitation to the belt resonance(s). This may explain much of the spectral peak for slick tyres on rough-textured roads. On the other hand, generally, a rough texture tends to reduce tread pattern resonances and thus to reduce tonality and pattern-related narrow-band spectral peaks, since it presents an irregular surface against which the tread pattern elements impact (and vice-versa). However, a rough texture for the latter purpose will do its job better if its spectral content is mismatched from that of the tread pattern.

Texture-to-sound transfer properties: The texture-to-sound transfer properties of tyres, as a response to a rough texture impact, suggests that a car tyre acts as a low-pass filter with a cut-off at around 1000 Hz [11].

6. POTENTIAL REDUCTION MEASURES

By looking at individual tyres in Figure 4, one can see that there is a large variation in how prominent the peak is; which means that one can affect it by tyre design. Likewise, one can see that the choice of road surface also affects the peak. Tyre and road designers must cooperate in optimization of the tyre/road contact here since both road and tyre properties are crucial. The ambition should be (1) to mismatch the effects mentioned above in terms of peak frequency as much as possible and (2) to reduce the various peaks and resonances in amplitude and (3) to try to move the peaks out of the most sensitive range for the human hearing; i.e., to lower frequencies. However, the latter is a little risky; since albeit it may work well for the A-weighted overall level, increased low frequency content is undesirable for noise immission indoors.

A possible way to positively affect the multi-coincidence peak seems to be to increase belt stiffness, but decrease contact stiffness. For example, in [12] it is shown that decreased contact stiffness may reduce the peak. Other evidence comes from [13]: In a large project aiming at producing a new tyre noise model, a comparison between tyre/road noise on two special surfaces was made. The baseline was a smooth hard surface on which sandpaper had been glued. The other surface was the same but with a rubber sheet added between the sandpaper and the base surface. Rubber thickness was 5-10 mm and its stiffness was 2.4 N/mm^2. This reduced the mechanical impedance (stiffness) of the surface. The effect was a rather dramatic decrease of the 1000 Hz peak, resulting in 3 dB(A) overall noise reduction. See also a discussion in 11.13 in [1].

Thus, it seems that a softer tyre/road contact, with softer tyre tread as well as road surface, seems to affect the peak in a positive way.

As suggested above, to reduce noise emission effectively, the R&D engineers should concentrate on reducing or moving the peak. For example, for tyre VN16 in Figure 5, if the three bands at 800-1250 Hz were reduced by 5 dB each, the overall A-weighted level would be reduced by about 3 dB, whereas if the next three bands (1600-2500 Hz) would be reduced by 5 dB, the overall reduction will be only one-fourth of what would be obtained by working on the 800-1250 bands. A practical existing application of dramatically affecting the multi-coincidence peak is a porous road surface designed for the most favourable sound absorption at 800-1250 Hz, which provides a noise reduction having an emphasis on the multi-coincidence peak.

7. CONCLUSIONS

It is strange that tyre and road construction has resulted in such a concentration of major noise generating and influencing mechanisms in the range of 700-1300 Hz. It is even probable that recent developments in tyre design, dictated by other concerns than exterior noise, has tended to increase the concentration. Elimination or modification of these frequency-concentrating factors, aiming at a mismatch of them, will be the key issue in order to reduce tyre/road noise generation and is a challenge facing both tyre and road engineers in the near future.

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