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A NEW APPROACH FOR THE EVALUATION OF THE RELATIONSHIP BETWEEN ROAD TEXTURE AND ROLLING NOISE

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The available literature on tyre/road noise focuses mainly on the estimation of broadband CPX and SPB levels from road texture data, regardless of the spectral content of noise. Moreover, while traditional AC and SMA road surfaces have been widely studied during the past decades, a lack of knowledge on rubberized road surfaces still remains. This work addresses the issue of the influence of road texture on rolling noise, measured according the CPX method on different experimental rubberized road surfaces, which use crumb rubber to modify the properties of pavements. The results are analysed in one-third octave bands. Correlation coefficients were calculated for every couple of texture and CPX band on each surface, and tyre influence was also taken into account using a simple tyre envelopment model already available in literature.

Results show that the correlation coefficient of different pavements follows a similar pattern for different kind of pavements, with two distinct zones of correlation, relative to the different sound generation processes involved in rolling noise, but also highlights some differences among road surfaces, especially for high frequency noise.

Keywords: road texture, rolling noise, CPX, low noise road surfaces, rubberized road surfaces

1. Introduction

The different generation mechanisms make traffic noise a remarkably complex phenomenon: the sources are the power unit, composed by engine, gearbox and cooling system, the profile aerodynamics and tyre/road noise, also known as rolling noise.

While engine noise is the main source up to 35 km/h, for higher speeds propulsion noise is negligible over noise due to tyre/road interaction. For heavy vehicles, like lorries, the contribution of propulsion noise cannot be neglected even at higher speeds. For speeds higher than 120 km/h, the contribution of aerodynamic noise becomes dominant. Therefore, from 35 km/h to 120 km/h, the main noise source is rolling noise [1].

Tyre/road noise is a mixture of airborne and structure-borne phenomena, and its generation mechanisms can be classified according to the medium in which the generation process occurs [1].

Airborne mechanisms are generally related to noise at frequencies higher than 1 kHz, and are caused by the compression and expansion of the air trapped in the tread of the rolling tyre. These mechanisms are collectively known as air pumping; other airborne processes involve pipe and Helmotz resonances.

Structure-borne mechanisms are tyre vibrations caused by the impact of the tyre against the irregularities of the road surface. Radial vibrations of the tyre belt are caused by irregularities of the surface which deform the tread or by tread elements hitting and leaving the road surface. Tyre vibrations generate mainly low frequency noise. Other structure-borne phenomena not related to vibrations are the stick and slip and stick and snap mechanism. The former is caused by a relative motion of the tyre treads with respect to the road surface, while the latter is present when the grip of the tyre on the road is too strong [1].

In this work, rolling noise was measured with the CPX protocol defined by ISO 11819-2 [2] and using the reference tyre SRTT proposed by ISO/TS 11819-3 [4], therefore, the effects of tyre properties such as rubber type, tread pattern, tyre pressure and diameter will not be investigated, despite their influence on acoustical emission [3]. In this way, any relevant differences between two road surfaces are due to road surface properties, such as road texture, defined by ISO 13473-2 [5] Mean Profile Depth (MPD) defined by ISO 13473-1 [6] was not analysed since it is not suitable for a complete description of rolling noise [3].

ISO 13473-2 [5] defines road texture as the deviation of a pavement surface from a true planar surface, caused by the random nature of the disposition of the surface elements and their superficial roughness.

Macrotexture groups texture with wavelength from 0.5 mm to 50 mm, which is the same order of size as tyre tread elements, while megatexture groups wavelengths that range from 50 mm to 500 mm, that represents the same order of size as the tyre/road interface [1].

Due to the complexity of tyre/road interaction, modelling of rolling noise is mainly based on a phenomenological approach that uses statistical means to predict the characteristics of road texture that may induce a favourable effect on rolling noise. Other approaches, such as FEM and BEM modelling have been successful, although they are mainly based on slick tyres, therefore excluding noise due to tyre tread pattern [7].

Sandberg [1] highlighted that only the lower range of macrotexture (< 5 mm) and the texture wavelengths between 50 and 80 mm have a significant influence on rolling noise: the former group regulates airborne processes, and texture levels in this range are negatively correlated with high frequency noise, while the latter is positively correlated with low frequency noise, caused by tyre vibrations.

In a similar fashion, ISO 13473-5 [8] proposes texture level of the 63 mm octave band as an indicator of rolling noise, while Losa et al. [3] have developed a model that estimates broadband CPX levels using texture level between 16 and 63 mm, positively correlated with noise emission, and the texture level between 2 and 4 mm band, which is on the contrary negatively correlated with noise.

Recent works [9, 10] have underlined that the evaluation of texture spectrum is not sufficient to determine the acoustic properties of road surfaces, but the asymmetry of the profile also plays an important role. It is important therefore to distinguish between *negative texture*, i.e. a pavement surface characterised by deep valleys, and *positive texture*, dominated by high peaks. Negative texture results in a decrease of rolling noise, while positive texture is more aggressive from an acoustical point of view [10].

In fact, in its presence, tyre local pressure is more evenly distributed, and air is less compressed by the impact of the tyre tread on the road surface. A more even pressure distribution reduces structure-borne mechanisms, while the lower compression of air within the cavities between tyre and road surface leads to a reduction of airborne mechanisms [9]. Different envelopment algorithms can be found in literature, based on empirical considerations, such as von Meier's approach [11], or physical solutions of the tyre/road contact, such as the model proposed by Hamet and Klein [10].

2. Methodology of the study and characteristics of the test sites

In the present work, the acoustical and texture properties of three different rubberized road surfaces were analysed and compared to a traditional road surface. Acoustical properties were measured with the CPX protocol protocol described by Licitra et al [12] and based on ISO 11819-2 [2]. while road texture was measured with a laser triangulation sensor, as described in Section 2.1.

Each test site was divided in segments of length equal to three times a whole tyre circumference. For each site, the mean noise and texture spectra and their standard deviation was calculated, and, as shown in Section 3.1, their analysis can bring about interesting considerations on the relationship between road texture and rolling noise on rubberized surfaces.

Texture spectra were reported in dB, according to the definition reported in ISO 13473-2 [5], where the texture level L_{tx} is defined as 20 times the decimal logarithm of the RMS value of the profile amplitude a over a fixed reference value a_0 equal to 10^{-6} m:

$$L_{tx} = 20 \log \frac{a}{a_0} \tag{1}$$

A second part of the study involves the calculation, for each road surface, of the correlation coefficient between each couple of CPX and enveloped texture one-third-octave bands. Tyre envelopment was calculated using Von Meier's algorithm, which imposes a limitation on the second difference of the profile, which cannot exceed the value $d^* = 0.54$ mm^{-1}, chosen in order to simulate the elastic response of an average tyre [11].

Rubberized road surfaces are built using hot asphalt mixes containing crumb rubber as a modifier, in order to improve the properties of the binder. Licitra et al. [13] reported that rubberized road surfaces constitute an efficient noise reduction method, since broadband traffic noise is 8 – 10 dB(A) lower than traditional asphalt concrete pavements.

In the wet process, historically named *Asphalt Rubber* (AR), crumb rubber is blended with liquid asphalt cement (AC) before mixing AC with the aggregate; in general, the percentage of crumb rubber used in this process is roughly equal to 1% of the total weight.

In the dry process, crumb rubber is added to the hot aggregate, usually in the range of 1-3% of the weight of the total mixture before adding the AC [12]

Measurements were performed on four different sites located on the MeBo highway that connects the two South Tyrol cities of Meran and Bolzano, in northern Italy. The first two sites, named DR1 and DR2, are two rubber asphalts mixtures with a common grading curve, manufactured according to the *dry* process with a percentage of crumb rubber (1.4% for DR1 and 1.1% for DR2). AR2 is a rubber asphalt mixture, whose production is based on the *wet* process. The last road pavement analysed, named in this work AC12, is a dense asphalt concrete 0/12, used as reference surface representing a standard Italian pavement. The characteristics of the test sites are summarised in Table 1.

Table 1: Road surfaces

Road surface and grading		Air voids %	Process	Length [km]	Paving date
DR1	Gap graded 0/12	9.93%	Dry (1.4%)	2.6	2016, July
DR2	Gap graded 0/12	2.93%	Dry (1.1%)	1.3	2016, September
AR2	Gap graded 0/16	10.28%	Wet	1.1	2015, April
AC12	DAC 0/12	5.17%	--	0.9	2015, March

2.1 Measurement of rolling noise and road texture

The tyre adopted for the measurements is the SRTT tyre, reference tyre proposed by the ISO normative. Temperature and hardness normalisations are also performed in accordance with ISO 11819-2 [2], which reports reference temperature of 20 °C and reference hardness equal to 66 Shore A. Since the roads tested are part of a highway, the reference speed adopted for noise measurements is 100 km/h. Noise measurements are analysed in one-third-octave bands.

Road profile measurements were carried out using a self-built laser triangulation profilometer.

According to ISO 13473-2 [5], which classifies the mobility of profilometers as slow if the maximum speed of measurement is lower than 60 km/h, the device used in this work is as a *contactless* profilometer with a slow mobility, due to the sampling rate of the profile sensor equal to 32 kHz. In fact, in order to obtain a sampling interval of 0.5 mm, it can be calculated that the maximum measuring speed is 57 km/h.

The profilometer combines the output of the laser sensor, a piezoelectric accelerometer that measures the vertical displacement of the laser sensor and a rotary encoder that measures the distance travelled. Road profile measurements and CPX measurements were performed at the same time, thus ensuring the perfect alignment of signals.

The calculation of macrotexture and megatexture levels of the enveloped profile is performed according to the third method described in ISO/TS 13473-4 [14], which suggests performing a Discrete Fourier Transform of the profile signal, followed by a transformation of the narrow band spectrum to a one-third-octave band spectrum. The flowchart of the complete process is represented in Figure 1.

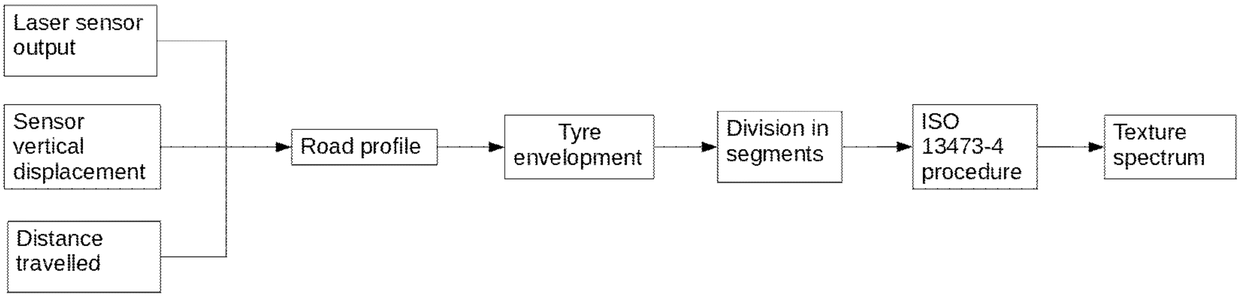

Figure 1: flowchart for road texture spectral analysis

3. Results

3.1 CPX and enveloped texture spectrum

CPX and enveloped texture spectra are shown in Figure 2. Although rubberized road surfaces present higher texture levels than the reference AC12 surface, their noise levels are generally lower, especially for frequencies higher than 800 Hz, indicating a more efficient suppression of air pumping processes.

The higher mean texture level calculated for AR2 is possibly due to the larger maximum aggregate size, equal to 16 mm, compared with both the DR surfaces and AC12, which have a maximum aggregate size of 12 mm.

Different kind of road pavements seemingly have a different relationship between noise and road texture: the higher texture levels measured on the AR2 surface lead to an increased low frequency structure borne noise and a lower high frequency airborne noise compared to the other road surfaces.

The opposite situation is present on the reference surface AC12, which produces lower structure-borne noise, but higher airborne noise compared to AR2.

The two DR surfaces show an intermediate behaviour between AR2 and AC12.While the noise differences between AC12, AR2 and DR1/2 can be qualitatively explained by road texture, considering the current literature concerning influence of road texture on rolling noise [1, 3], the same reasoning does not apply for DR1 and DR2.

The lower CPX noise levels recorded at high frequencies on the DR1 surface compared to DR2, despite texture levels of DR2 are slightly higher, show that suppression of air pumping processes depends on road texture only on first approximation.

Since DR1 and DR2 share the same grading curve, the lower airborne noise generated by DR1 could be explained considering the higher air void percentage of DR1 compared to DR2.

As suggested by Losa et al. [15], in fact, the percentage of air voids shows a linear negative relation with CPX levels.

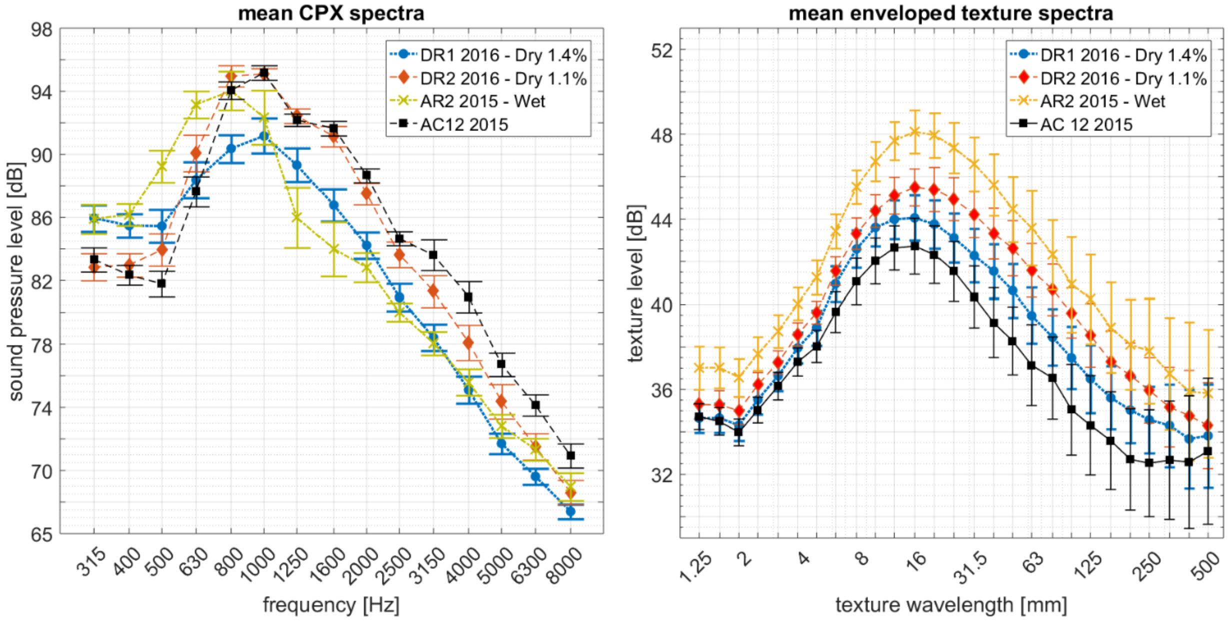

Figure 2: CPX noise levels (left) and enveloped texture levels (right). Error bars are equal to one standard deviation of segment measurements.

It can be concluded that, despite the higher structure-borne noise, rubberized surfaces are more efficient at suppressing airborne noise, which is the main component of rolling noise from 1 kHz onwards.

3.2 Correlation coefficient

The correlation coefficients for each road surface are shown in Figure 3 Despite the differences, it is quite easy to identify two distinct well correlated zones, similar to the isocorrelation pattern observed by Sandberg [1]. On every road surface, low frequency noise is positively correlated to road texture, while at frequencies higher than 1 kHz noise and road texture show generally a negative correlation, especially at wavelengths shorter than 20 mm.

Despite some differences, possibly due to the different construction processes and other properties whose influence could not be determined in this work, such as percentage of air voids, it is interesting to notice that the positively correlated zone shows a similar behaviour on all the road surfaces tested: the highest positive correlation is found at a wavelength equal to 25 mm, well correlated with noise at 500 Hz, for all the road pavements analysed.

The correlation pattern of negatively correlated zones shows more variability with road surfaces: while for AC12 the value of correlation is minimum at a wavelength equal to 1.25 mm and frequency of 8000 Hz, the lowest correlation for AR2 is found at 2.5 mm, for 1250 Hz, although a negative correlation is still evident at higher frequencies. The two DR surfaces also show a different response at high frequencies; in fact, for the DR1 road surface, the best negative correlation (-0.8) is found around 8 mm and 4000 Hz, although the negatively correlated area extends to the adjacent noise bands and to the texture wavelengths from 1.25 to 20 mm. For DR2, instead, the minimum value of the correlation coefficient is equal to -0.72 and is placed at 12.5 mm, for noise at 1600 Hz, although a good negative correlation is present between 1.25 - 25 mm and 2000 Hz one-third-octave bands.

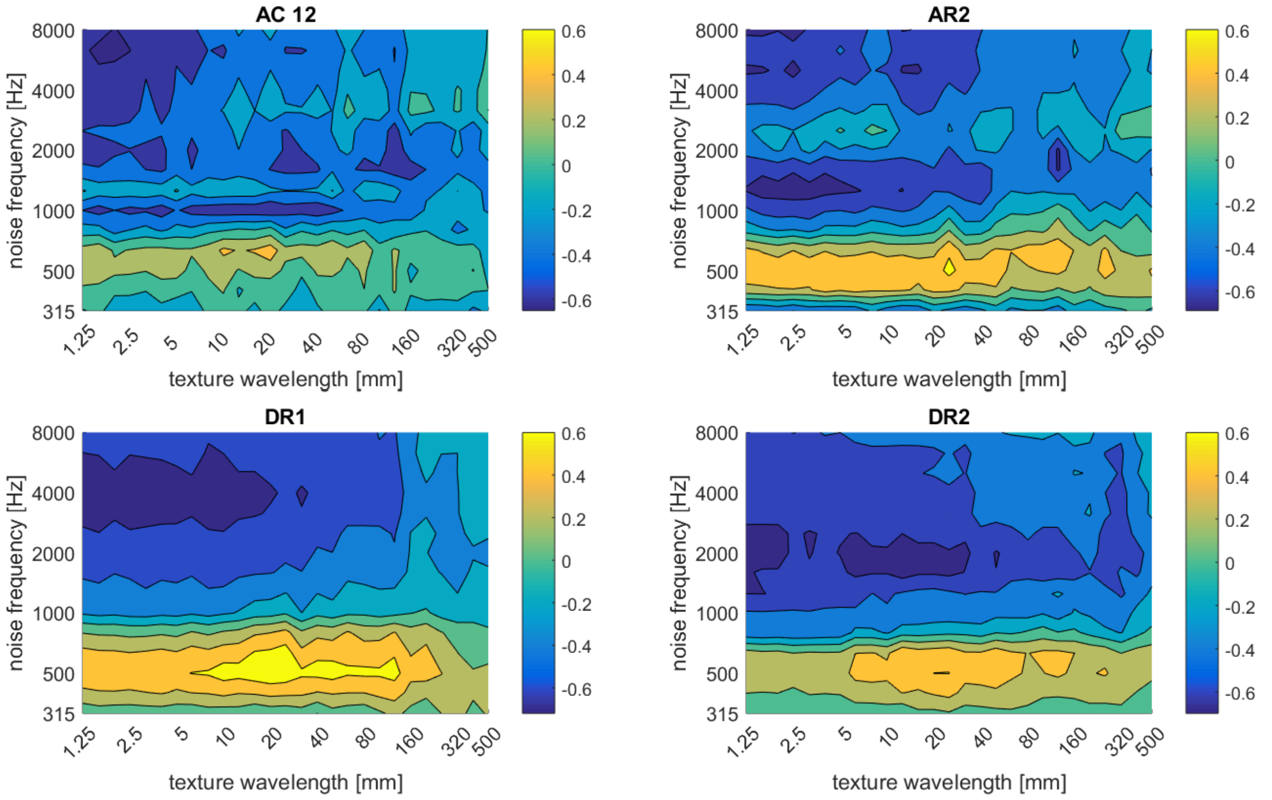

Figure 3: Correlation coefficient between CPX and texture levels one-third-octave bands

These differences in the correlation pattern could result in a preliminary choice to consider only the relationship between low frequency noise, represented by the 500 Hz band and the well-correlated enveloped texture band centred at 25 mm; despite its low relevance on broadband emission, its study could improve knowledge on structure-borne noise emission.

4. Conclusions

In order to evaluate the influence of road texture on rolling noise for rubberized surfaces, measurements of road texture and rolling noise were performed on 4 different road surfaces, namely two *dry* surfaces (DR1 and DR2), one *wet* surface (AR2) and a reference dense asphalt concrete (AC12).

The correlation coefficient of each couple of noise and enveloped texture one-third-octave bands was also calculated, and the isocorrelation curves were analysed for each road surface.

A strong positive correlation was found for all sites at 500 Hz and 25 mm: this could prove meaningful for the development of a global tyre/road noise model, although more research is needed to exclude that the phenomenon is due to tyre rather than road surface properties; moreover, the differences in high-frequency correlation patterns currently prevent the elaboration of a generic model valid for every road surface. However, the similarity of the two *dry* surfaces could indicate the possibility of performing cluster analysis on large samples of noise and texture measurements on these road surfaces.

These differences among correlation patterns could also be explained by analysing other parameters, such as air void percentage and grading of the aggregate. A similar model was developed by Losa et al [13], although it has not been tested on rubberized surfaces. Simple road texture measurements cannot evaluate these properties, but more invasive techniques are required, such as road asphalt core sampling.

The higher texture levels of the *wet* road surface resulted connected to higher structure-borne noise and lower airborne noise, while *dry* surfaces show a behaviour that presents intermediate characteristics between the *wet* surface and the reference surface AC12.

More research is required to understand the differences between DR1 and DR2, which interestingly present different correlation patterns at high frequency. This could be due to the different air void percentage, which could in turn be connected to the different percentage of crumb rubber in the aggregate.

Another aspect that requires further investigation is the comparison of the results obtained by the application of a different tyre envelopment algorithm, based on physical approaches like the model proposed by Hamet and Klein [10].

Future steps of research could include Principal Component Analysis, performed to find principal components of texture bands, thus reducing the number of independent variables to correlate with rolling noise and the division of the data sets of each road surface in a training and test set, on which perform modelling of tyre/road noise phenomena.

Finally, from a qualitative point of view, it is possible to conclude that, despite the higher levels of low frequency structure-borne noise recorded, rubberized surfaces are more efficient at suppressing high frequency airborne noise, whose impact on broadband CPX noise is more relevant than the former.

In fact, in order to evaluate acoustic efficiency of rubberized pavements, A-weighting of noise must be taken into account: since the bands from 1 kHz to 5 kHz yield zero or positive correction, their influence on broadband A-weighted noise is greater than the low frequency bands which are present a negative A-weighting correction. This makes the laying of rubberized asphalts a generally positive noise mitigation action.

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