The influence of road properties on tyre/road noise: an experimental approach

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Outline

- Introduction
- Tyre/road noise and road surface properties
- Tyre/road noise and road mixture properties
- Discussion
- Rundown and conclusions

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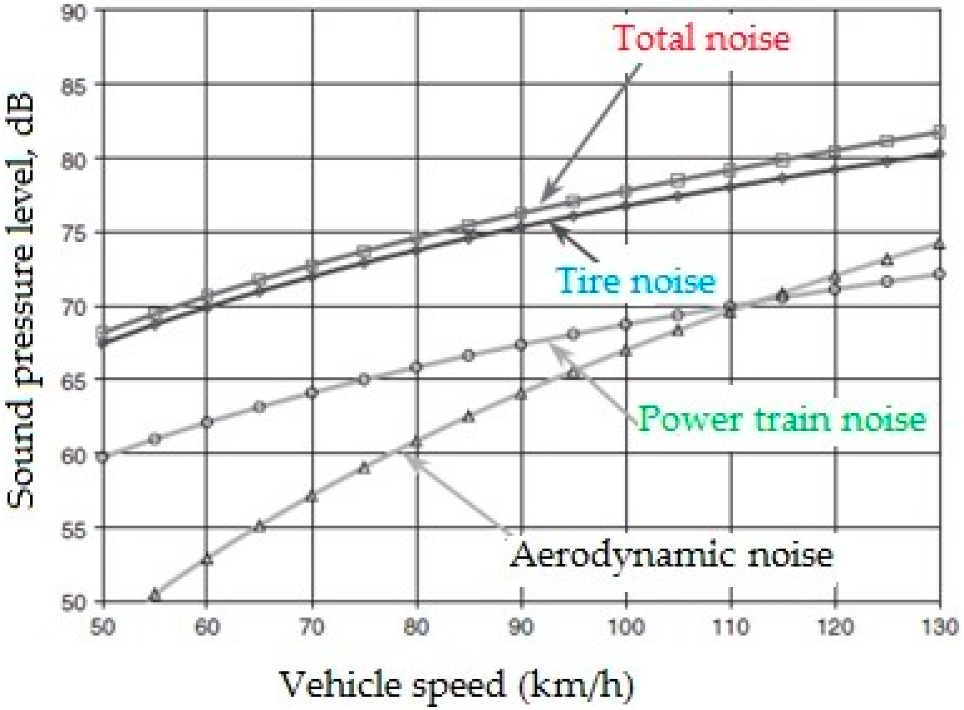
Road Traffic Noise (RTN)

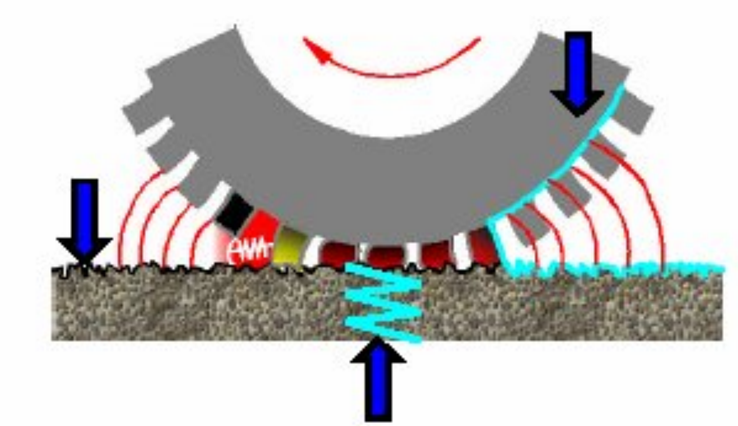
- Extremely complex and ancient problem;
- Can be divided in:
  - Propulsion noise;
  - Tyre/road noise;
  - Aerodynamic noise
- Contributions vary depending on:
  - Type and age of tyres;
  - Class and age of vehicles



Donavan, P., Rymer, B. Assessment of highway pavements for tire-road noise generation. In *Proc. of the Soc. of Auto. Eng. Noise and Vib.*, Grand Traverse, MI, USA, 3 May 2003

Tyre/road noise

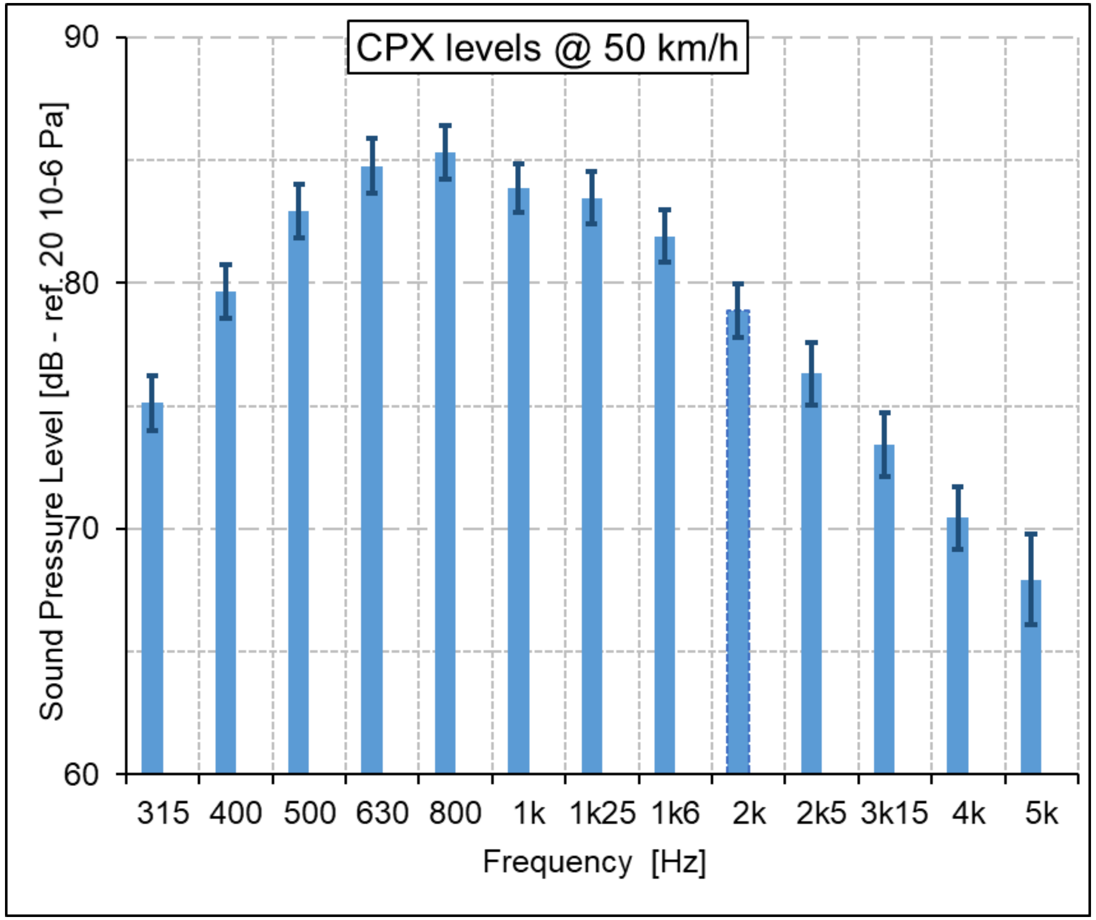
- Modelling is more and more important due to increasingly strict regulamentations on low-noise surfaces – **EU GPP**
- Divided roughly in two frequency ranges:
  - Low frequency noise (< 1 kHz): vibrodynamic noise
  - High frequency noise (> 1 kHz): aerodynamic noise
- Other phenomena:
  - Stick-slip, stick-snap;
  - Horn effect;
  - Tyre cavity resonances;
  - Tyre tread resonances



Dijkink, J. H., & van Keulen, W. (2004)

Tyre/road noise measurement

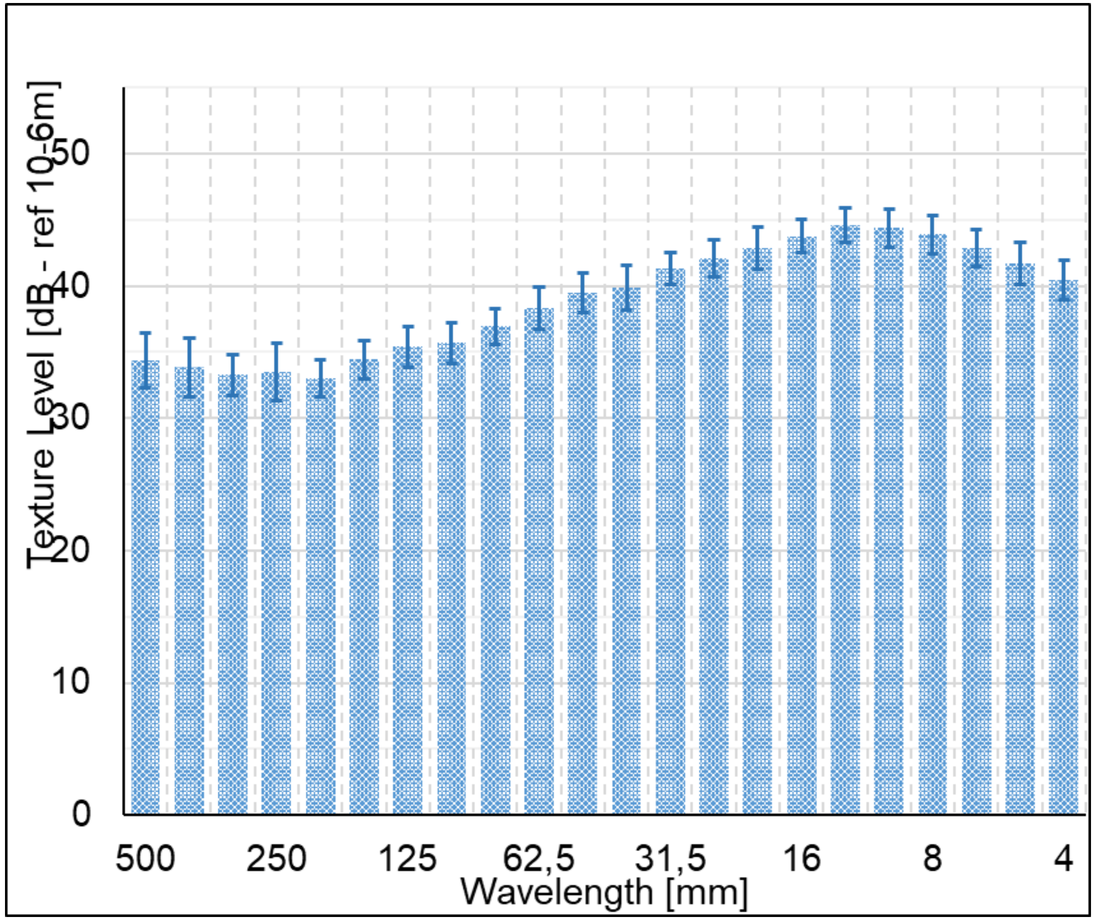
- Use of the Close Proximity Method (CPX) - ISO 11819-2:2017:
  - Standard Reference Test Tyre (SRTT);
  - Temperature and tyre hardness normalisations;
  - Fixed speed – logarithmic dependence of noise on speed: lots of runs needed!
- Two microphones, placed at 10 cm from the ground level and 20 cm from the tyre plane
- The mean spectrum in one-third octave bands is calculated for each surface



Road surface: road texture

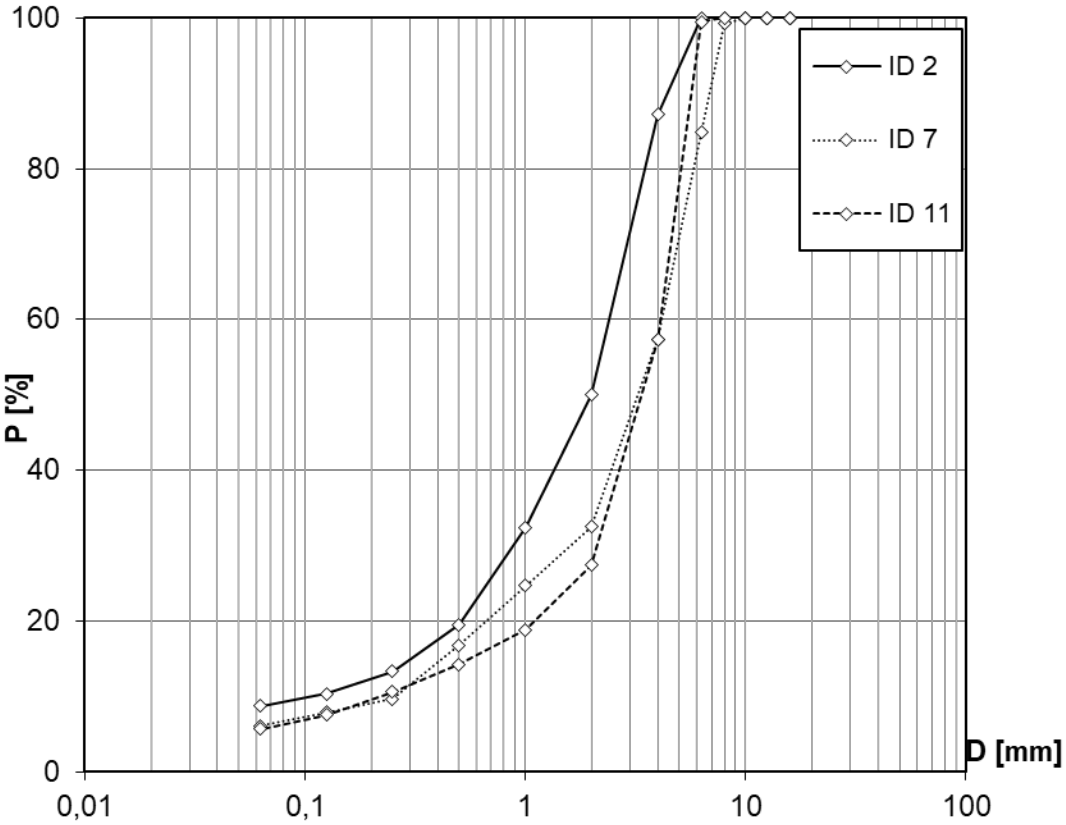
- Road surface is usually described in terms of its profile;
- Profiles can be measured using a laser triangulation sensor;
- From the profile, the texture spectrum is calculated in one third octave bands using fft
- Texture spectra are provided in dB:

$$L_{tx} = 20\log\left(\frac{a}{a_0}\right)$$



Road mix properties

- **Bitumen percentage (*B%*):** volume of bitumen to the total volume;
- **Voids in the mineral aggregate (*VMA*)**: intergranular space occupied by asphalt and air in a compacted asphalt mixture;
- **Grading curve *P*(*d*):** obtained sieving the sample through a set of sieves of different diameter *d*;
- **Fractal dimension[1] D_f**: $P(d) = \left(\frac{d}{d_{max}}\right)^{3-D_f}$



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1. Leonardi, G. (2010). Fractal dimension for the characterization of the porosity of asphalt concretes. *Archives of Civil Engineering*, *56*(4), 321-333.

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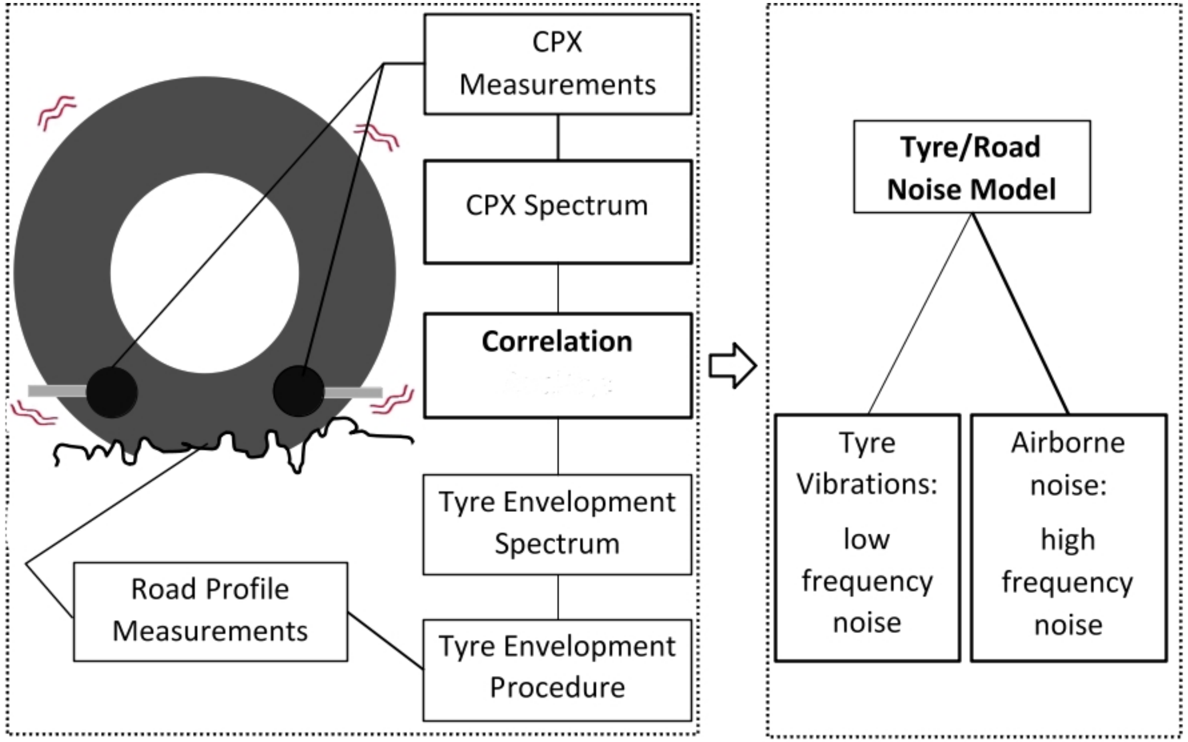
Methodology

- 10 different road surfaces
- Mean values for each profile;
- Envelopment profile: simulates tyre deformation due to the contact with road surface - derived from Goubert, L. & Sandberg, E. (2018);
- Correlation betwen noise and tyre envelopment spectra;
- Linear regressions between texture and noise bands

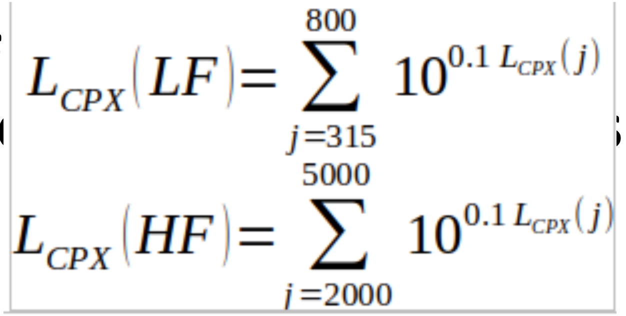


Del Pizzo, A., Teti, L., Bianco, F., Moro, A., Licitra, G. Influence of Texture on Tyre/Road Noise Spectra in Rubberized Pavements. Manuscript submitted for publication to *Applied Acoustics*

Results: correlation coefficient

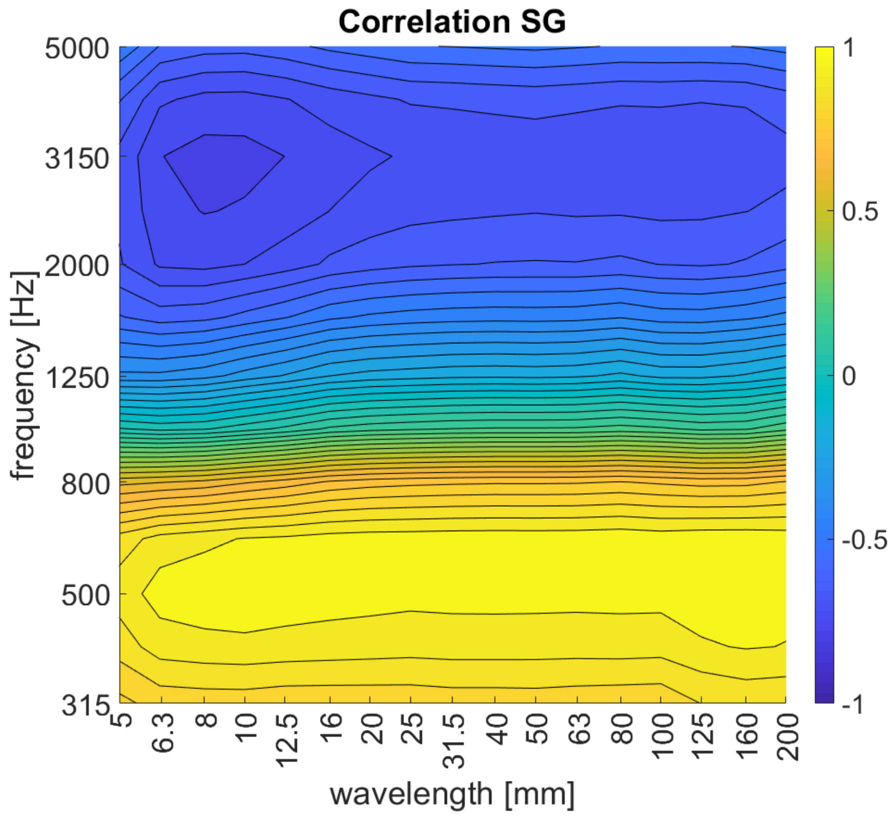
- High frequency region: negatively correlated with road texture (peak at 8 mm);
- Low frequency region: positively correlated with road texture (peak at 80 mm)

- **Consistency with previous studies!**
- **Low-f**
  frequ
  :

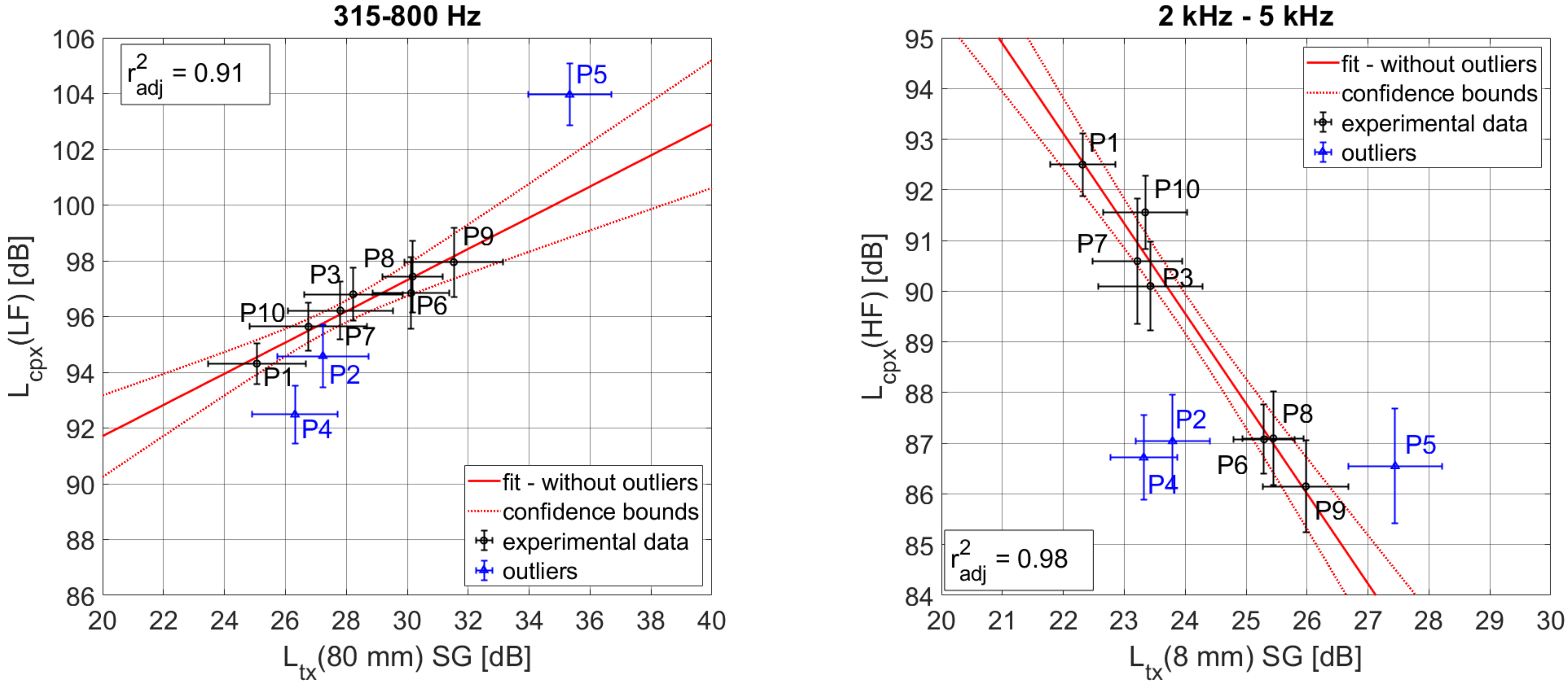


$$L_{CPX}(LF) = \sum_{j=315}^{800} 10^{0.1\,L_{CPX}(j)}$$

$$L_{CPX}(HF) = \sum_{j=2000}^{5000} 10^{0.1\,L_{CPX}(j)}$$

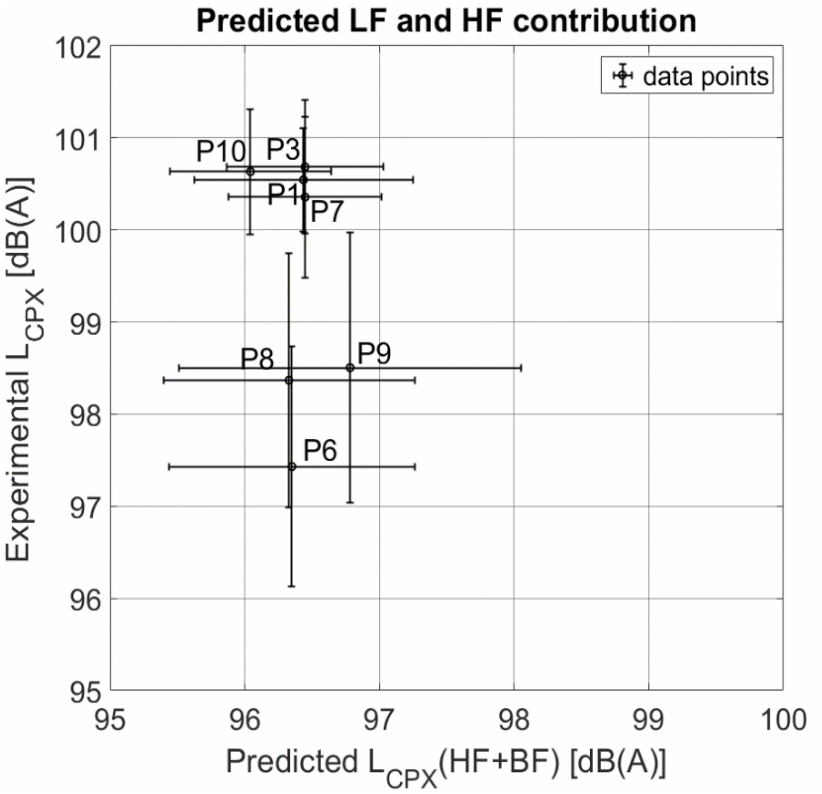


Results: linear regression



What about broadband levels?

- 315-800 Hz noise:
  - well correlated with 80 mm texture;
- 2000-5000 Hz noise
  - well correlated with 8 mm texture;
- Contribution of frequencies around 1 kHz is missing!
- Not able to forecast CPX broadband levels!



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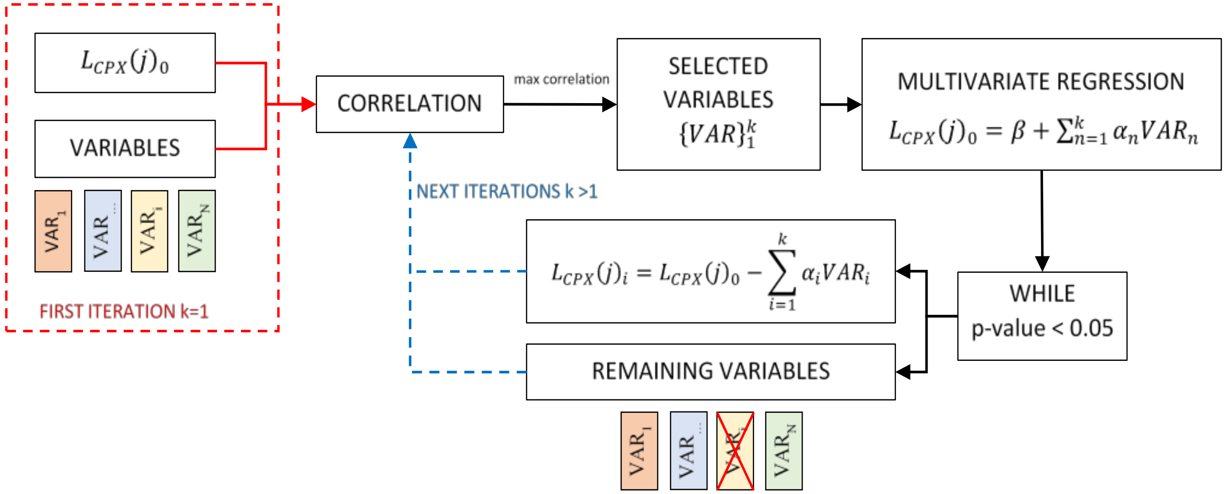
Methodology

- Measurements performed shortly after laying;
- CPX levels were calculated for:
  - 315-800 Hz
  - 1000-1600 Hz
  - 2000-5000 Hz
- volumetric and mixture parameters:
  - Aggregate size ***d*(*P*)** through which a percentage ***P*** passes and fractal dimension D_f: texture properties,
  - Bitumen percentage ***B%*** and voids in mineral aggregates ***VMA***: absorption properties



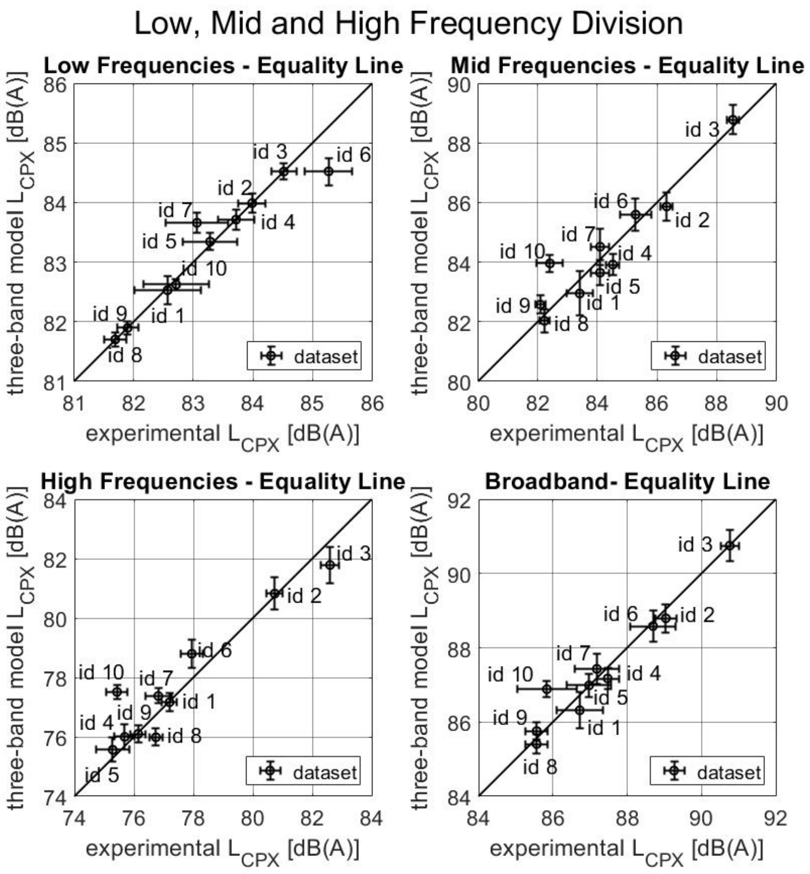
De Leon, G., Del Pizzo, A., Teti, L., Moro, A., Bianco, F., Fredianelli, L., Licitra, G., Modelling the Acoustic Performance of Newly Laid Low-Noise Pavements. Manuscript submitted for publication to *Transportation Research part D: Transport and Environment*

Results: significant variables

- Low frequency (315-800 Hz): ***B%***, ***VMA***, $\boldsymbol{D_f}$, $\boldsymbol{D}_{95}$
  - Tyre vibrations are connected to larger chip sizes!
- Middle frequency (1000-1600 Hz): ***B%***, ***VMA***, $\boldsymbol{D_f}$, $\boldsymbol{D_{45}}$
  - Smaller chip sizes are involved
- High frequency (2000-5000 Hz): $\boldsymbol{D_f}$, $\boldsymbol{D_{45}}$
  - No dependence from binder or void percentage

Results: linear regressions

Frequency range	RMSE [dB]	Adjusted R-squared
Broadband L_{CPX}	0.37	//
L_{CPX}(Low)	0.26	0.972
L_{CPX}(Mid)	0.63	0.912
L_{CPX}(High)	0.83	0.851



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Discussion

Road surface properties

- Measuring road texture is quicker, simpler and provides a spatial evaluation of the current state of a road surface;
- However:
  - Does not correlate well with noise around 1 kHz;
  - Tyre/road noise is peaked at 1 kHz.

Road mixture properties

- Road mixture properties are known before paving, therefore knowing their relation with tyre/road noise can lead to *acoustical* optimization of the mix design
- However:
  - Difficulties in monitoring its time evolution;
  - Cannot be performed on a whole profile, but only for on-spot measurements;
  - Issues regarding the reproducibility of test results[1]

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1. Pratico, F. G., Vaiana, R., & Moro, A. (2013). Dependence of volumetric parameters of hot-mix asphalts on testing methods. *Journal of Materials in Civil Engineering*, *26*(1), 45-53.

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Rundown…

- Tyre/road noise is the main source of road traffic noise, caused by tyre/road interaction;
- The CPX protocol is ideal for tyre/road noise measurements;
- Modelling was performed using road surface;
- Modelling using mixture and volumetric data can only describe the acoustic performance of newly laid surfaces

… Conclusions…

- Low frequency noise (vibrodynamic noise):
  - Long wavelengths (80 mm) and large chipping sizes (D_{95})
- Mid-frequency 1 kHz-1.6 kHz
  - No correlation with texture
- High frequency noise (aerodynamic noise)
  - Short wavelegnths (8 mm) and small chipping sizes (D_{45})
  - Contrary to literature, no dependence from void content (but is related to fractal dimension)

… Further developments

- Effects of crumb rubber added to the mix formula? We have found evidence they alter high-frequency mechanisms!
- Pavement stiffness?
- Physical modelling is not yet achieved!
    - Development of a internal tyre noise sensor;
    - Simultaneous measurements of:
        - Road texture,
        - Internal noise,
        - Tyre vibrations,
        - CPX levels;
    - Numerical modelling using spring-mass models;
    - Regression of data using shallow neural network techniques;

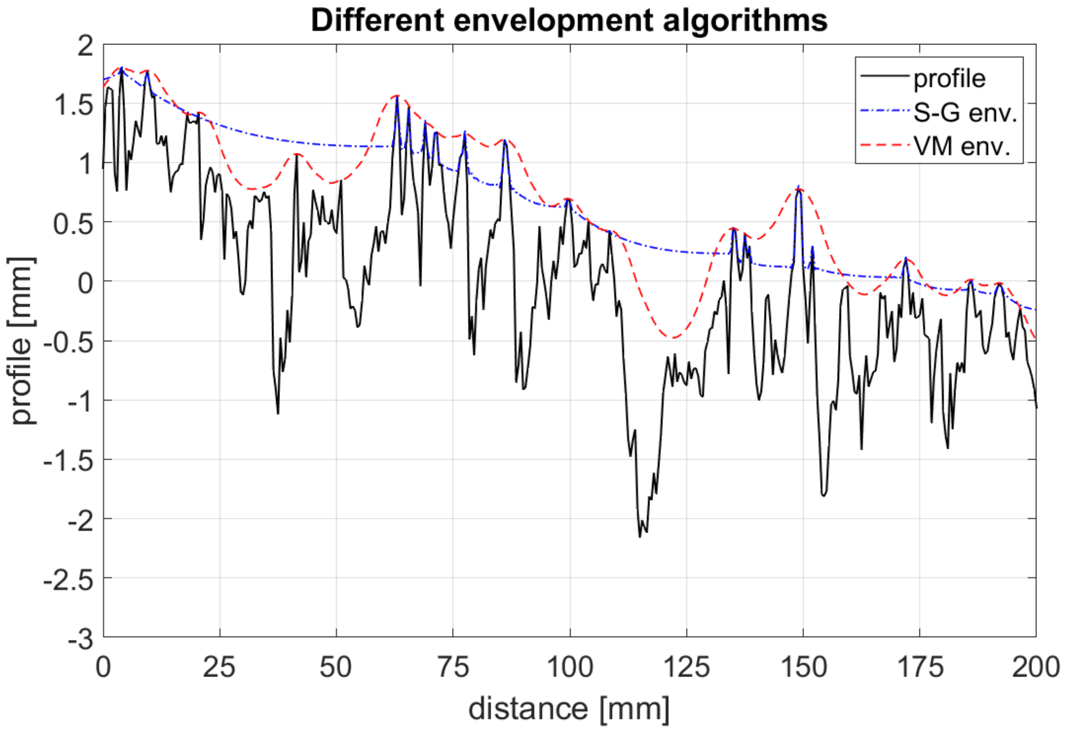
Related works (free-access and available upon request)

1. Del Pizzo, A., Bianco, F., Teti, L., Moro, A., Licitra, G. A New Approach for the Evaluation of the Relationship between Road Texture and Rolling Noise. In *Proc. of ICSV25*, 8-12 July 2018; Hiroshima, Japan.
2. Del Pizzo, A., Teti, L., Bianco, F., Moro, A., Licitra, G. Influence of Texture on Tyre/Road Noise Spectra in Rubberized Pavements. Manuscript submitted for publication to *Applied Acoustics*.
3. Licitra, G., Moro, A., Teti, L., Del Pizzo, A., Bianco, F. Modelling of acoustic ageing of rubberized pavements. *Applied Acoustics*, 2019;146:237-245.
4. De León, G., Del Pizzo, A., Teti, L., Moro, A., Bianco, F., Licitra, G., Evaluation of Tyre/Road Noise and Texture Interaction on Rubberized and Conventional Pavements Using CPX and Profiling Measurements, Manuscript submitted for publication to *Road Materials and Pavement Design*.
5. De León, G., Del Pizzo, A., Teti, L., Moro, A., Bianco, F., Fredianelli, L., Licitra, G., Modelling the Acoustic Performance of Newly Laid Low-Noise Pavements. Manuscript submitted for publication to *Transportation Research part D: Transport and Environment*.
6. Del Pizzo, A., de León, G., Teti, L., Bianco, F., Moro, A., Fredianelli, L., Licitra, G., Experimental Modelling of Tyre/Road Noise from Road Texture Spectra on Rubberized Road Surfaces. In *Proc. of the 23rd International Congress on Acoustics*, 9-13 September 2019; Aachen, Germany.

Tyre envelopment algorithm

- Based on the model proposed by Goubert and Sandberg (2018) [1]

1. The profile is divided into footprints of fixed length L, representing the length of the tyre/road contact zone;
2. A horizontal line, starting from z = zmax is iteratively lowered until the area A under the profile and above this line reaches the predefined value S;
3. Evaluation of the points indented inside the rubber proceeds to the next footprints, until the last one is reached;
4. Points above the line for each separate footprint are kept in the enveloped profile, while the points below are excluded from the profile;
5. Interpolation between adjacent indenters is provided by a Piecewise Cubic Hermite Interpolating Polinomial (PCHIP).



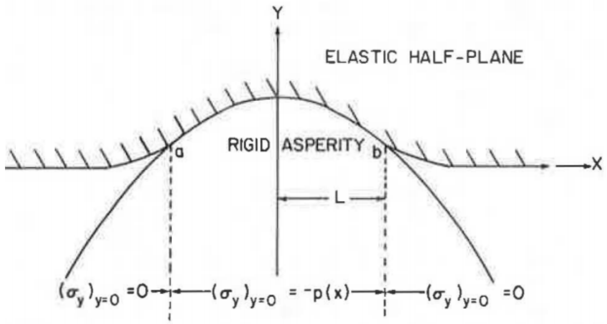
[1] Goubert, L., & Sandberg, U. (2018, May). Enveloping texture profiles for better modelling of the rolling resistance and acoustic qualities of road pavements. In *Symposium on Pavement Surface Characteristics (SURF), 8th, 2018,* Brisbane, Queensland, Australia

Tyre envelopment algorithm: the physical solution

- Based on Hooke’s law;
- Solution of the contact problem of a semi-infinite elastic medium (the tyre) and a rigid body (the road surface);
- Cannot be exactly solved:
    - Final displacement unknown
    - Contact pressure unknown
    - Iterative solution based on Carleman’s equation

$$\frac{\pi E u(x)}{2(1-\nu^2)} = -\int_a^b p(t) ln|t-x| dt$$

$$p(x) = \frac{1}{\pi^2\sqrt{(x-a)(b-x)}}\left[\int_a^b \frac{\sqrt{(t-a)(b-t)}\,u'(t)\,dt}{t-x} + \frac{1}{\pi \ln\left[\frac{1}{4}(b-a)\right]}\int_a^b \frac{u(t)\,dt}{\sqrt{(t-a)(b-t)}}\right]$$



Regression coefficients (texture vs noise)

- Regression was based on a robust weighted least squares algorithm:

$$L_{CPX}(HF) = a_{hf} L_{SG,tx}(8\ \mathrm{mm}) + b_{hf}$$

a_{hf}	**b_{hf}**	**Adj. r^2**
0.56 ± 0.07	80.5 ± 2.0	0.91

$$L_{CPX}(LF) = a_{lf} L_{SG,tx}(80\ \mathrm{mm}) + b_{lf}$$

a_{bf}	**b_{bf}**	**Adj. r^2**
-1.77 ± 0.11	132.2 ± 2.7	0.98

Regression coefficients (mix vs noise)

Low frequency	Mid Frequency	High Frequency
$r^2_{adj} = 0.972$	$r^2_{adj} = 0.912$	$r^2_{adj} = 0.851$
$b_l = 27.70 \pm 1.35$ dB(A)	$b_m = -10.21 \pm 3.17$ dB(A)	$b_h = -16.19 \pm 4.35$ dB(A)
$a_{l1} = 0.26 \pm 0.06$ dB(A)	$a_{m1} = 30.99 \pm 1.44$ dB(A)	$a_{h1} = 35.86 \pm 1.6$ dB(A)
$a_{l2} = 0.28 \pm 0.014$ dB(A)	$a_{m2} = 1.97 \pm 0.20$ dB(A)	$a_{h2} = 1.96 \pm 0.16$ dB(A)/mm
$a_{l3} = 17.39 \pm 0.57$ dB(A)	$a_{m3} = 0.28 \pm 0.05$ dB(A)	---
$a_{l4} = 0.59 \pm 0.028$ dB(A)/mm	$a_{m4} = 0.69 \pm 0.14$ dB(A)/mm	---

$$L_{CPX}(Low) = \beta_l + a_{l1} B\% + a_{l2} VMA + a_{l3} D_f + a_{l4} D95$$

$$L_{CPX}(Mid) = \beta_m + a_{m1} D_f + a_{m2}\, D45 + a_{m3}\, VMA + a_{m4}\, B\%$$

$$L_{CPX}(High) = \beta_h + a_{h1} D_f + a_{h2} D45$$

Influence of crumb rubber