EXPLORING PSYCHOACOUSTIC INDICATORS TO ASSESS CLOSE PROXIMITY TYRE-ROAD NOISE

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Abstract
Road traffic noise is associated with several health problems and welfare; such as sleep disturbances and annoyance. Accordingly, it becomes essential to characterize road noise not only based on acoustic indicators, but also based on psychoacoustic indicators. The acoustic indicators are required to assure compliance with European legislation and to define vehicle detection thresholds, the psychoacoustic indicators describe better annoyance rates. In this context, this work aimed to explore tyre-road noise measurements acquired on eight road pavements at eight speeds, from the point of view of psychoacoustics. In the analysis three psychoacoustic indicators (Loudness, Sharpness, Roughness) and one acoustic indicator (LAmax) were determined on 64 tyre-road noise samples acquired through the Close Proximity Method (CPX). It was confirmed that all psychoacoustic indicators are appropriated to describe tyre-road noise.

Keywords: tyre-road noise, CPX, annoyance, road pavements, Loudness.

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1 Introduction

The road traffic noise is one of the major contributors to environmental noise with considerable impact on public health and quality of life of populations [1][4] and also on safety of road users [2, 3]. To adequately assess road noise, it is important to not only consider its level but also the subjective sensation generated on people. Therefore, the introduction of noise perception indicators on the traffic noise assessment procedure seems essential.

The subjective sensation of noise-induced discomfort can be described by various psychoacoustic parameters such as Loudness, roughness and sharpness.

Some studies showed that loudness describes the correlation with the subjective estimation of noise-induced discomfort better than the A-weighted sound level [1, 4]. Roughness and sharpness were also correlated with annoyance rates, with no success [4] for outdoor measurements while for indoor measurements roughness was found significantly correlated with the assessment of 'Noisiness of Apartment' [5].

The main source of the traffic noise at the most common driving speeds is the noise generated from the contact of the tyres with the pavement surface [6]. Due to important methodological advantages, some studies suggested to acoustically classify surface layers based on tyre-road noise measurements through the Close proximity Method (CPX) [7, 8] and also on loudness behaviour. The validity of the approach to describe the noise-induced discomfort was confirmed by correlating the answer of a panel asked to respond to annoyance tasks with loudness, as discussed in [8]. However, none of the studies explored sufficiently other subjective noise indicators to assess traffic noise.

This paper examines the relation of noise indicators such as LAmax, loudness, roughness and sharpness extracted from CPX measurement recordings to determine if they can be used to improve tyre-road noise assessment.

Previous studies addressed mostly noise measured at low speeds, in this work a complete characterization from low to high speeds is presented and discussed.

Furthermore, in this study several types of urban road pavements are analysed, including not only common asphalt concrete surfaces, but also concrete block and granite cube surfaces which are expected to be highly annoying.

2 Psycohacoustic indicators

Sound perception is studied in the field of the psychoacoustics, addressing specifically psychological and physiological responses associated with sound. Loudness, Roughness and Sharpness are psychoacoustic measures often used to assess sound quality which, in the scope of this study, reflects the road user’s reaction to how acceptable the traffic noise is.

Zwicker and Fastl defined Loudness as the attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from soft to loud [9]. Loudness depends not only on the sound pressure of the stimulus, but also on its frequency, waveform and duration. The ‘loudness level’ of a sound is defined as 'the sound pressure level of a 1 kHz tone in a plane wave and frontal incident that is as loud as the sound; its unit is “phon” [9].

Sharpness is a measure of the high frequency content of a sound (over 1100 Hz), the greater the proportion of high frequencies the ‘sharper’ the sound [9]. A sound of sharpness 1 acum is defined as a narrow band noise one critical band wide at a centre frequency of 1kHz having a level of 60dB [9].

High frequencies generated by traffic are determined by aerodymanical noise generation mechanisms which makes this indicator suitable to quantify their impact on annoyance.

Roughness is a complex effect which quantifies the subjective perception of rapid fluctuations (15-300 Hz) in the sound received by auditory filters. The unit of measure is the asper. One asper is defined as the roughness produced by a 1000Hz tone of 60dB which is 100% amplitude modulated at 70Hz [9].

Psychoacoustics provides many models for predicting the subjective sensation of loudness, sharpness and roughness.

Loudness models can be divided between the ones using Erb auditory filters and Bark auditory filters (or critical bands), and also between steady state and dynamic models [10]. Steady state models account for the effect of the spectra on loudness, while dynamic models also account for the effect of auditory temporal integration on loudness. Examples of steady state models are the Zwicker's model [9] and Moore, Glasberg and Baer's model (MGB) [11]. Glasberg and Moore (GM) [12] and Chalupper and Fastl (FC) [13] are examples of dynamic loudness models.

Models of roughness are given by Zwicker and Fastl [9] for simple stimuli. For arbitrary stimuli it is applicable the roughness model adjusted by Daniel and Weber [14].

Examples of models to calculate sharpness, are Aures's [15] or Zwicker's and Fastl [9] models. Zwicker and Fastl's model is a weighted centroid of specific loudness, while Aures' model is more sensitive to the positive influence of loudness on sharpness [10].

3 Materials and methods

This study is based on the extraction of four noise indicators from files registered during close proximity tyre-road noise tests at several speed levels carried out in several road pavement surfaces.

3.1 Pavement surfaces

The types of pavement surfaces selected for the study were: asphalt concrete (AC), which has been used widely in several situations for many years; concrete blocks (CB), granite cubes (GC) and granite slabs (GS), often used in urban contexts, particularly in city centres; slurry seal (SS), used to improve friction; and open graded asphalt rubber (OGAR) with 10 mm and 8 mm grading size and gap graded asphalt (GGA), which have been used among other things to reduce noise.

3.2 Tyre-road noise measurement

The "Close-Proximity (CPX) method", was specifically developed to measure tyre-road noise. In the CPX method the noise emitted by specified tyres are measured over an arbitrary or a specified road distance, together with the vehicle testing speed, located close to the tyres.

The tyre-road noise was recorded with a Brüel & Kjaer Pulse Analyzer type 3560-C and two microphones assembled according to ISO/CD 11819-2. The tyre used in the vehicle was the ContiEcoContact3 195/65-R15, selected according the tyre performance comparison study carried out by [16].

3.3 Testing procedure

The CPX measurements were carried out in each testing site at 8 testing speeds, from 20 km/h up to 90 km/h with a 10 km/h span.

In the urban sites, with concrete blocks, granite cubes and granite slabs, the noise measurements were done only at the lower speed levels (up to 60 km/h) due to road geometry.

3.4 Analysis procedure

The quality of all files registered was checked by looking for unwanted noises. Next, file samples with 5 seconds long were extracted from each file. The values of LAmax, Loudness, Roughness and Sharpness were extracted with the Psysound3 application [17].

4 Results

Table 1 presents the LAmax, Loudness, Roughness and Sharpness results for the eight pavements and speed levels selected. In the following subsections the acoustic indicators are explored by analyzing their correlation with speed and by comparing their performance for each pavement. Also, aiming at selecting the most relevant noise indicators for noise classification, the influence of pavement type over noise indicators is analysed.

4.1 Noise indicator and speed

To analyse the relation of each indicator with speed, LAmax, Loudness, Roughness and Sharpness results were plot against speed (Figure 1). A linear relation between noise indicator and speed is clear for Sharpness which showed the best fit (R^2 = 0.92), and for Loudness (R^2 = 0.86). As it is acknowledged, LAmax has a logarithmic relation with speed, leading to a R^2 of 0.88. Roughness does not seem to have any type of relation with speed. Nevertheless, the scatter observed for each indicator in Figure 1 suggests an effect of the pavement type.

Table 1 – Noise indicators determined for each pavement type and speed (part 1 of 2).

Speed (Km/h)	Pavement type	LAmax (dB(A))	Loudness CF (Sone)	Roughness (asper)	Sharpness MG (acum)	Pavement type	LAmax (dB(A))	Loudness CF (Sone)	Roughness (asper)	Sharpness MG (Acum)
20	AC	70.87	24.51	0.08	2.99	CB	74.97	31.79	0.60	3.17
30		78.51	34.67	0.14	3.20		81.29	42.40	0.78	3.38
40		83.58	42.41	0.12	3.46		88.28	56.34	0.82	3.69
50		87.62	53.90	0.15	3.97		92.85	67.79	0.90	4.18
60		91.56	69.21	0.24	4.33					
70		92.75	76.06	0.23	4.62					
80		95.81	93.76	0.26	5.09					
90		97.07	96.14	0.25	5.38					
20	GC	78.54	38.19	1.03	2.95	SS	76.66	33.40	0.22	2.95
30		86.85	57.07	0.83	3.40		82.46	44.56	0.29	3.28
40		92.08	72.52	0.92	3.92		86.98	53.94	0.39	3.64
50		96.20	88.06	1.29	4.33		91.40	66.87	0.56	3.99
60		99.71	102.90	1.16	4.85		94.80	78.78	0.36	4.38
70							97.87	91.78	0.39	4.85
80							102.28	109.39	0.47	5.48
90							103.84	121.36	0.36	5.90

Table 1 – Noise indicators determined for each pavement type and speed (part 2 of 2).

Speed (Km/h)	Pavement type	LAmax (dB(A))	Loudness CF (Sone)	Roughness (asper)	Sharpness MG (acum)	Pavement type	LAmax (dB(A))	Loudness CF (Sone)	Roughness (asper)	Sharpness MG (Acum)
20	GS	77.07	35.62	0.47	3.13	OGRA_10	75.08	28.15	0.10	2.78
30		84.61	49.90	0.41	3.63		81.72	37.53	0.10	3.09
40		89.69	63.46	0.37	4.13		85.77	45.01	0.11	3.44
50		93.07	75.57	0.32	4.48		90.85	60.51	0.14	3.95
60							96.62	64.79	0.16	4.19
70							94.36	75.76	0.17	4.64
80							96.87	84.75	0.22	4.83
90							98.30	101.51	0.27	5.41
20	OGRA_8	74.21	25.56	0.17	2.87	GGA	76.04	30.23	0.17	3.10
30		78.95	33.21	0.10	2.97		80.98	36.87	0.14	3.29
40		83.15	40.70	0.13	3.39		85.51	47.86	0.16	3.57
50		87.16	51.39	0.14	3.88		89.97	58.02	0.15	4.08
60		90.54	65.70	0.23	3.89		92.93	73.62	0.2	4.43
70		91.19	74.38	0.24	4.33		94.04	77.80	0.19	4.77
80		93.54	86.51	0.26	4.86		96.93	94.17	0.25	5.32
90		96.76	97.50	0.27	5.23		98.58	104.44	0.22	5.66

4.2 Noise indicator, speed and type of pavement

To assess the effect of the pavement type on each noise indicator, Figure 1 was replotted identifying the pavement type (Figure 2). In this way it is possible to recognize those of which relation with speed is different from the others. Granite Cubes (GC), granite slabs (GS), cement blocks (CB) and slurry seal (SS) are remarkably distinguished from the asphalt surfaces.

Sharpness fitting with speed was the best considering pavement types in a whole, although for individual fittings, this means, for each pavement, a similar fitting, according to Equation 1, was found for Loudness (see Table 2).

$$NI = a \times speed + b \ . \quad (1)$$

Where *NI* is the Noise Indicator, a and b are the linear regression constants of *NI* with speed at km/h.

The fit quality designated through the determination coefficient (R^2) of roughness is bad for granite cubes (GC) and slurry seal (SS) and fair for the gap graded asphalt (GGA). This is an indication that there are other factors than speed explaining roughness.

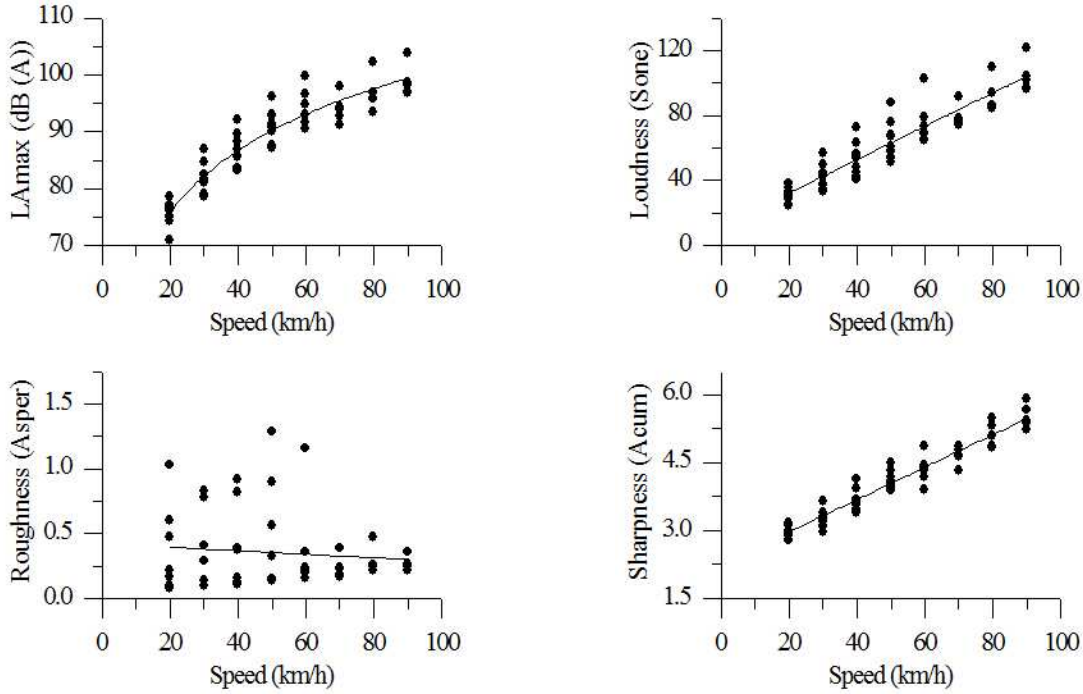

Figure 1 – Noise indicators and speed for each pavement.

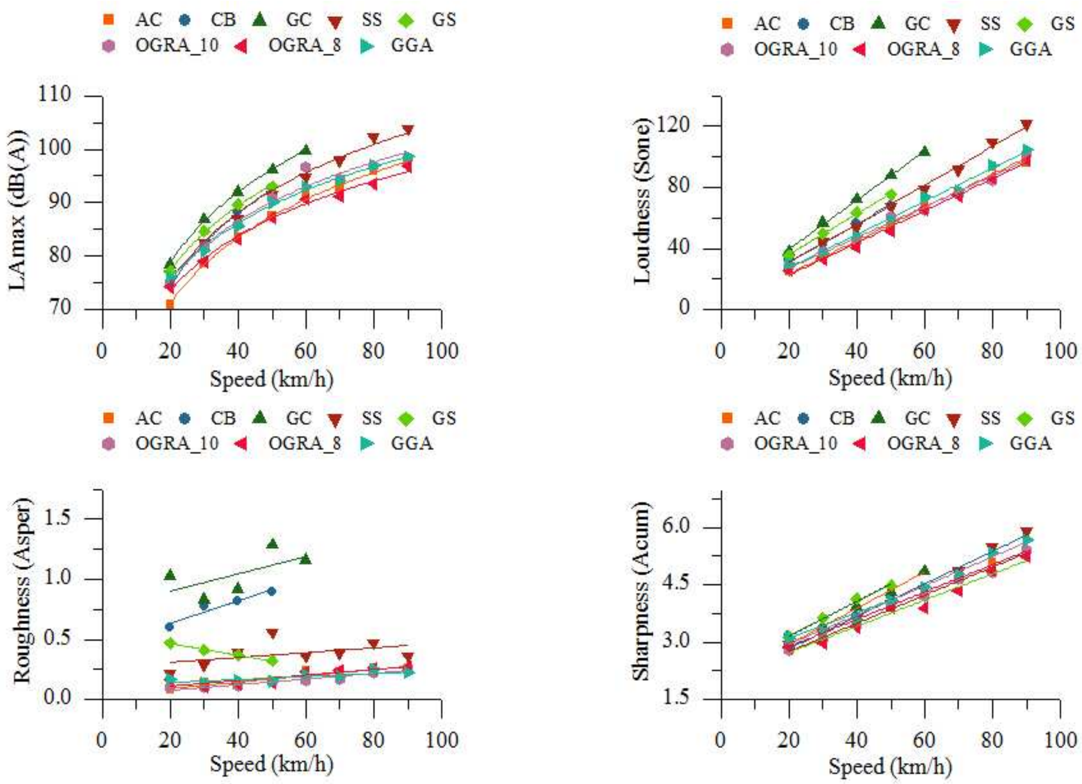

Figure 2 – Noise indicators and speed for each pavement.

Table 2 – Linear fit parameters of noise indicator with speed.

Pavement type	LAmax			Loudness CF			Roughness			Sharpness MG		
	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
AC	18,653	17,569	0,997	1,545	1,087	0,988	0,039	0,003	0,871	1,998	0,047	0,999
CB	15,199	19,760	0,997	6,901	1,219	0,997	0,446	0,009	0,915	1,973	0,042	0,989
GC	21,402	19,145	0,9997	7,584	1,604	0,998	0,758	0,007	0,383	2,250	0,046	0,994
SS	20,101	18,432	0,989	5,258	1,268	0,994	0,270	0,002	0,223	2,015	0,037	0,993
GS	24,611	17,574	0,9989	9,444	1,334	0,999	0,564	-0,005	0,994	2,042	0,034	0,977
OGRA_10	27,874	15,905	0,9649	6,849	1,007	0,989	0,028	0,002	0,911	2,181	0,038	0,990
OGRA_8	29,203	14,793	0,991	1,394	1,054	0,994	0,067	0,002	0,733	2,164	0,036	0,993
GGA	29,550	15,328	0,995	5,702	1,085	0,992	0,117	0,001	0,657	2,436	0,033	0,966

4.3 Type of pavement

To compare the results of each indicator by pavement type, all data were normalized through the z-score method. In Table 3 are presented the linear fit parameters of each normalized indicator according to Equation (1).

Table 3 – Linear fit parameters of normalized noise indicators with speed for each pavement.

Noise indicator	AC			CB			GC			SS		
	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
LAmax	-2,324	0,042	0,937	-3,120	0,089	0,993	-2,783	0,070	0,957	-2,382	0,043	0,985
Loudness CF	-2,386	0,043	0,988	-3,127	0,089	0,997	-2,825	0,071	0,997	-2,393	0,044	0,994
Roughness	-2,240	0,041	0,871	-2,994	0,086	0,915	-1,751	0,044	0,177	-1,135	0,021	0,223
Sharpness MG	-2,392	0,043	0,993	-3,076	0,088	0,966	-2,827	0,071	0,999	-2,388	0,043	0,989
Noise indicator	**GS**			**OGRA_10**			**OGRA_8**			**GGA**		
	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
LAmax	-3,083	0,088	0,970	-2,261	0,041	0,887	-2,359	0,043	0,966	-2,350	0,043	0,958
Loudness CF	-3,128	0,089	0,999	-2,387	0,043	0,989	-2,393	0,044	0,994	-2,390	0,043	0,992
Roughness	3,121	-0,089	0,994	-2,291	0,042	0,911	-2,055	0,037	0,733	-1,946	0,035	0,657
Sharpness MG	-3,120	0,089	0,994	-2,392	0,043	0,993	-2,372	0,043	0,977	-2,388	0,043	0,990

While the relation of roughness with speed is clearly distinguished for some pavement surfaces, LAmax, loudness and sharpness are hardly distinguished, as can be seen in Figure 3. However, loudness and sharpness seem more sensitive to speed than LAmax or roughness (see Table 3).

Statistic tests for equality between sets of coefficients in two linear regressions were carried by the dummy variables method [18] to verify these deductions. In fact, there are significant differences for both coefficients between roughness and the other parameters only for granite slabs (GS).

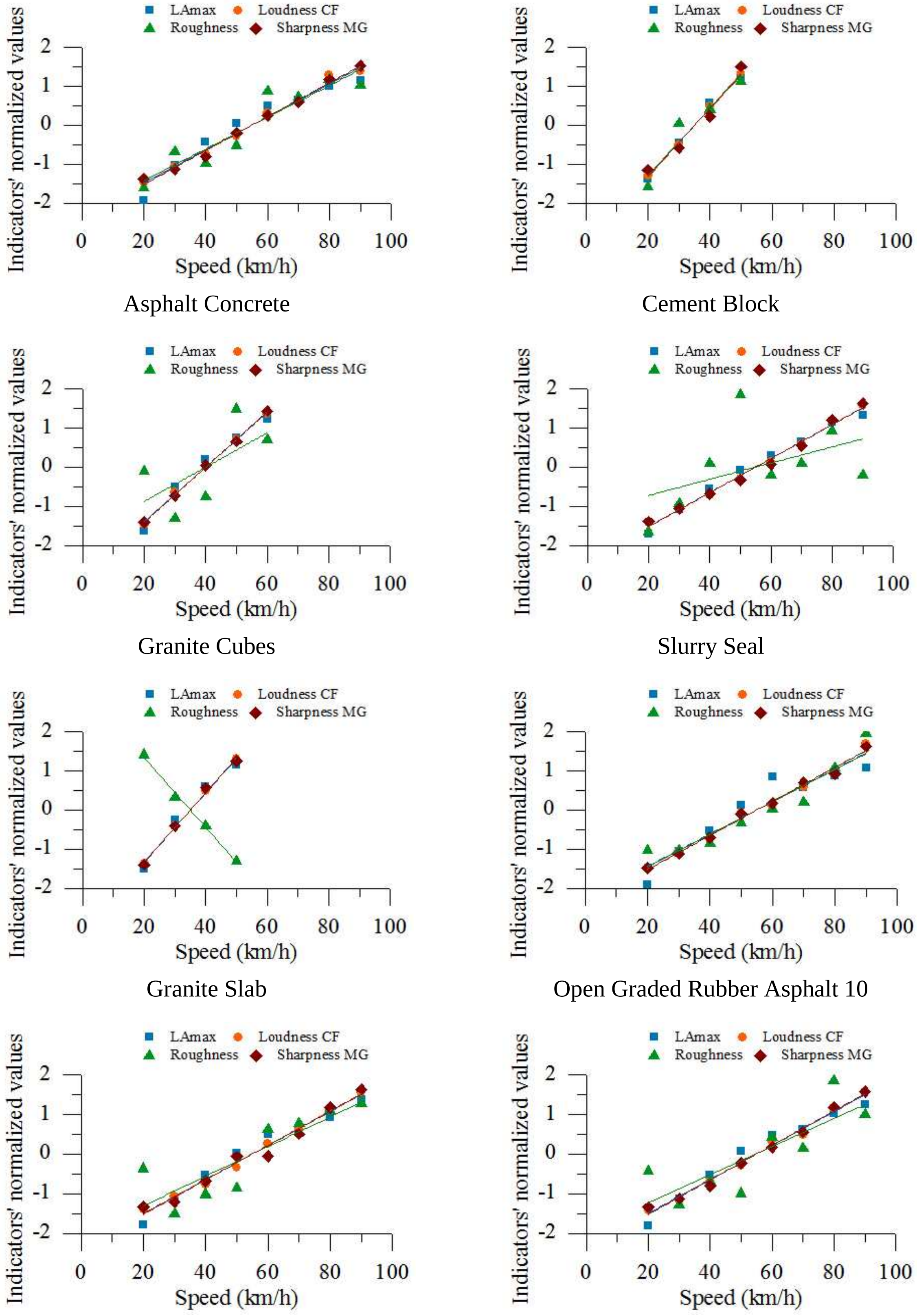

Figure 3 – Comparison of noise indicators for all pavements.

5 Conclusions

This paper examined the relation of noise indicators such as LAmax, loudness, roughness and sharpness extracted from CPX measurements recordings with the objective of contributing to noise classification. Tyre-road noise samples were acquired in several types of urban road pavements, including concrete blocks and granite cubes and slabs, at a wide range of testing speeds.

The relation of each noise indicator with speed was analysed. For the whole set of data, sharpness is better explained by speed than LAmax, loudness or roughness, despite the influence of the pavement type. The noise roughness clearly reflects the influence of the type of pavement.

The selection of one indicator to characterize and assess tyre-road noise of a specific pavement type is not obvious. Except for the granite slab, LAmax, loudness and roughness have a similar performance with speed. Nevertheless, these noise indicators characterize different sound features, and are influenced by the pavement type which makes them all appropriated to describe tyre-road noise.

The questions that may now be raised are: which one of them describes better annoyance?; do they have different weights on annoyance ratings? Previous studies showed that loudness describes better annoyance ratings than LAmax. Future research should explore sharpness and roughness capacity to describe annoyance.

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