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Exploring psychoacoustic indicators of tyre/road noise in urban environments

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ABSTRACT

Road traffic noise is the most common source of community noise in urban areas, causing adverse impacts on the health and well-being of the exposed population. Therefore, mastering road traffic noise perception is key to tackling noise pollution. Vehicle noise is mainly produced by the tyre/pavement interaction, especially for light vehicles, which compose most of the vehicle fleet in urban environments. In this paper, tyre/road noise recordings were collected with the Close-ProXimity (CPX) method using the P1 reference tyre for light vehicles and employing low speeds, up to 50 km/h. Road surface types were chosen to represent urban environments, such as cobblestones, aged and recently-laid dense asphalt concrete and low-noise pavements. Noise levels and psychoacoustic parameters were retrieved to describe the complex time- and frequency-dependent signal features of tyre/road noise. The sensitivity of psychoacoustic indicators to differences in road surface type, age, and testing speeds was explored. Ultimately, a tyre/road noise catalogue that lists noise levels and noise features more closely related to human perception can aid urban planning and environmental noise control.

Keywords: *psychoacoustic indicators, CPX, tyre/road noise, low-noise pavements.*

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1. INTRODUCTION

Shared space is an urban design approach aimed at reducing segregation between vulnerable road users, such as pedestrians and cyclists, and motorized traffic. It comprises traffic calming measures in such a way that "traffic is a guest" instead of the primary mode of transport. Shared spaces benefit not only passersby but also people living and working around the area [1].

An aspect often disregarded in shared space design is the role of sound, although being known that soundscape is a crucial element of urban space perception both from a safety and pleasantness perspective [2]. In urban environments, road traffic is the primary noise source. As road surface characteristics impact tyre/road noise generation, pavement design should be key to enhancing the soundscape's pleasantness in shared spaces.

Environmental noise assessment and noise control often focus on noise level descriptors to characterize noise exposure. However, other noise characteristics, such as masking, spectral contents, and temporal patterns, are proven to impact appraisals of acoustic environments [3]. Research on psychoacoustics has gained more attention owing to an increasing interest in shifting from physical noise exposure measures to an approach based on the human perception of urban sound environments [4].

Psychoacoustic indicators are acoustical quantities intended to simulate human auditory sensations. Among them, loudness is an important measure of sound energy content, considered the perception-based equivalent of sound pressure level. Sharpness is related to the spectral envelope of a sound signal and is linked to high-frequency noise components. Fluctuation strength and roughness are

associated with slow (< 20 Hz) and rapid (15-300 Hz) amplitude modulations, respectively [5].
This work presents the first steps towards exploring user perception of soundscape aimed at shared spaces design, focusing on the role of road surfaces and speed. Field measurements of the tyre/road noise were performed on typical road surface types used in (historical) city centres in Portugal, at low speeds. From that, psychoacoustic indicators are retrieved and analyzed.

2. MATERIALS AND METHODS

2.1 Close Proximity Method

Vehicle noise is composed mainly of tyre/road noise and engine noise. However, especially for light vehicles, tyre/road noise is the major contributor to total vehicle noise, even at low driving speeds.
Close ProXimity (CPX) is a standardized method to measure sound emission levels from tyre/road noise. CPX measurements were performed as per ISO 11819-2 (2017), at 20, 30 and 50 km/h, using the Standard Reference Test Tire (SRTT, P1), a representative of passenger cars. The noise levels were continuously recorded with a Brüel & Kjaer Pulse Analyzer type 3560-C and two microphones. During the measurement campaign, the tested road surfaces were dry, the wind speed was below 5 m/s, and air temperatures ranged between 10 and 25 °C.

2.2 Road surfaces

Six types of road surfaces were selected for the study due to their broad use in city centers, as well as in urban, rural, and highway roads in Western European countries. Asphalt concrete with a maximum aggregate size of 14 mm was explored in three conditions: laid less than one year before the measurements and thus referred to as "new" (Fig. 1 a); eight years old at low-traffic volume road, presenting no visually-identifiable defects (Fig 1. b); and severely deteriorated, showing ravelling, alligator and block cracking (Fig. 1 c). Besides, the measurements were performed on granite cubes (10 x 10 cm, Fig. 1 d); cobblestones of around 10-15cm long, with a large irregularity in dimensions and evenness (Fig. 1 e); and a newly laid SMA with 10 mm maximum aggregate size and rubber-modified bitumen (65% of RAR X®). This mixture is intended for rolling noise reduction due to the smaller aggregate size and increased flexibility. Measurements were performed at 20, 30 and 50 km/h for all sites except that the 50 km/h could not be employed on the cobblestones site, and 20 and 30 km/h was not feasible at the SMA site.

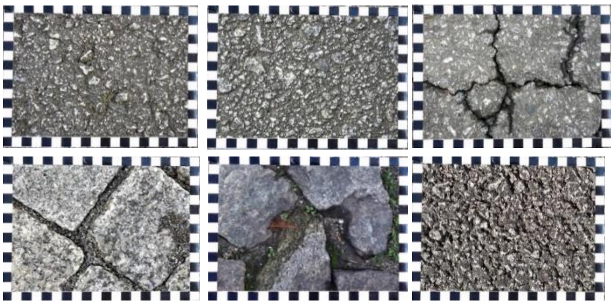

Figure 1. Road surfaces studied. One square in the frame = 1 cm. a) New AC-14; b) 8-years old AC-14; c) AC-14 deteriorated; d) Granite cubes; e) Cobblestones; f) SMA 10 S with RAR X®.

2.3 Acoustic and psychoacoustic indicators

Short audio excerpts of around 5 s were retrieved from the original recordings to comprise neat noise samples from the CPX measurements. From these audio segments, psychoacoustic indicators were calculated in a MATLAB-based environment employing algorithms from PsySound3 [6]. Loudness (N), Sharpness (S), Roughness (R) and fluctuation strength (FS) algorithms implemented are based on the respective calculation models: Fastl & Zwicker's model for time-varying signals and free field frontal incidence, as detailed in ISO 532-1 method B [7]; Fastl and Zwicker [5]; Daniel and Weber [8] and Zhou et al. [9]. The acoustic indicator A-weighted equivalent continuous sound level ($L_{A,eq}$) was also retrieved.
The calculation outputs are given in percentile levels, describing each parameter's statistical evolution within the signals' time window. A percentile *n* indicates that the value was exceeded in n% of the interval. The 5% percentile represents exceptional events in the signal, while 95% characterizes a quasi-continuous situation, and the 50% percentile resembles a probable situation. Considering that these noise excerpts are short and consistently variable, the 50% percentile was chosen as the best representative.

3. RESULTS AND DISCUSSIONS

To aid urban planners in decision-making regarding speed limits and the type of road surface to be implemented in shared spaces, the CPX measurement results are assessed and compared with a focus on these two factors.
Fig 2. displays the averaged CPX noise levels from the 5 s excerpts per one-third octave band from 315 to 5000 Hz at 50 km/h for all road surfaces except for cobblestones, which

results from 30 km/h are depicted. The bars on the right-hand side of the chart represent the broadband noise level.

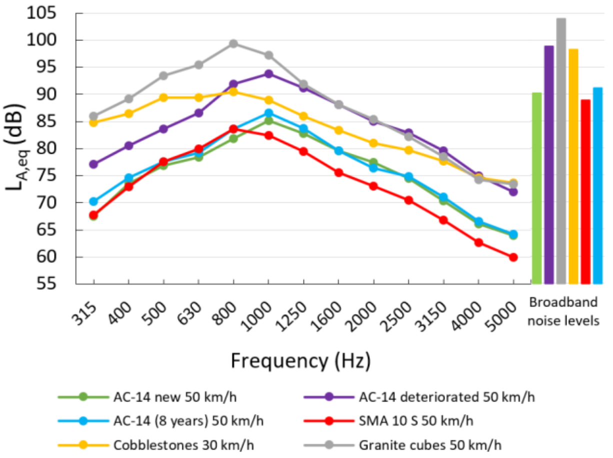

Figure 2. $L_{A,eq}$ spectra per road surface type.

The spectra of the new and 8-year-old AC-14 almost overlap. The presence of degradation seems to shift the spectrum upwards, but overall its shape is similar to those of AC-14 in good condition. Although the SMA 10 S presents similar broadband noise levels as the AC-14 surfaces without deterioration, the low-noise properties of this mixture seem to benefit from the high-frequencies (>1kHz) the most. The higher broadband noise levels of granite cubes compared to AC-14 deteriorated is given by a notable presence of low-frequency components, as these two spectra overlap at high frequencies. Although the cobblestone spectra result from the 30 km/h testing speed, its noise levels are comparable to the other two noisiest pavements (granite cubes and AC-14 deteriorated) at 50km/h. Additionally, as for granite cubes, there is a great contribution of lower noise frequencies in the cobblestones' spectrum.

Figures 3 to 7 depict the obtained values of $L_{A,eq}$, N_{50}, S_{50}, R_{50} and FS_{50} versus testing speed and the linear regression equation per road surface type. The slopes indicate the change in the indicator caused by an increment of one speed unit; for instance, $L_{A,eq}$ of cobblestones in Figure 2 increase 1.02 dB per 1 km/h increase. Fig. 3 and Fig. 4 both present indicators of sound energy content. Even though there are only three data points per (most) road surface types, these points seem to fall over a clear linear trend for these two indicators, enabling R^2 of no less than 0.95. Comparing $L_{A,eq}$ to N_5, the second is considerably more sensitive to speed than the sound pressure level. As expected, $L_{A,eq}$ and N_{50} of the AC-14 recently laid and eight years old are very similar. Additionally, they present a matching behaviour in terms of speed given the comparable slopes. The deteriorated AC-14, on the other hand, not only displays considerably higher values of both $L_{A,eq}$ and N_{50} for all speeds but also increases faster given a speed increment. Cobblestones have the highest noise levels and loudness magnitudes, followed by granite cubes, as the composition of these pavements likely results in a higher megatexture than the others. The slopes of these two road surface types are also the largest. Therefore, the noisier the rolling noise enabled by a road surface, the more it tends to increase with speed. At 20 km/h, the noise levels and loudness differences among pavements, except for cobblestones, are relatively small, reaching a maximum of 5 dB and 16 sones. However, these differences increase as speed grows.

Even though the speed effect on the SMA 10 S could not be explored, in terms of magnitudes, it is only 1 dB and 6 sones quitter than the AC-14 new.

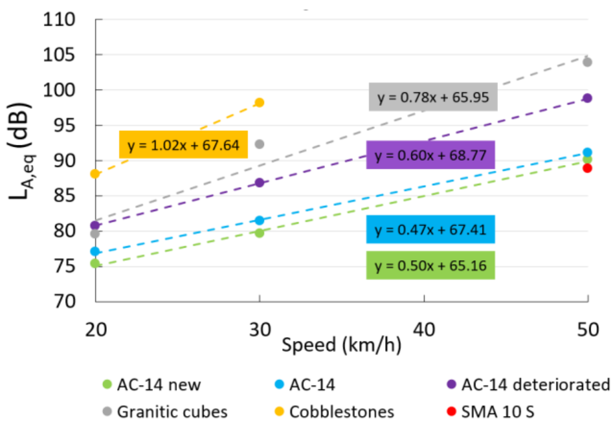

Figure 3. $L_{A,eq}$ versus speed per road surface type.

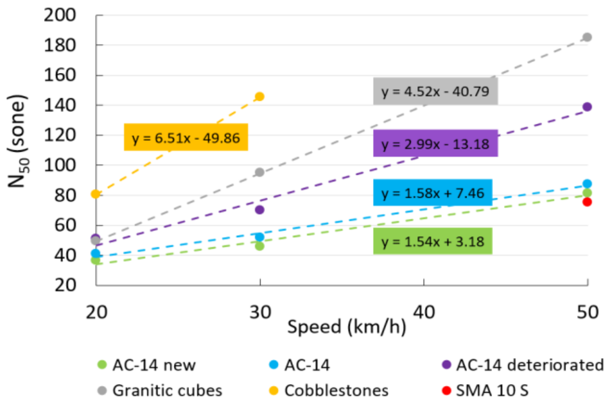

Figure 4. N_{50} versus speed per road surface type.

Fig. 5 shows that, overall, quieter road surfaces present higher sharpness values. It was observed in Fig 2. that low-noise frequency components are more significant for granite cubes and cobblestones, therefore it is coherent that their sharpness values are the smallest. Given the small slopes for all road surfaces, S_{50} does not vary considerably with a change in speed. The slopes obtained by Licitra and Alfinito [10] for various road surfaces are also small, and range between 1×10^{-3} and 1.7×10^{-4}. The lack of a trend relating sharpness to speed is evidenced by some surfaces presenting positive slopes (cobblestones and AC-14), while the other surfaces' slopes tend to decrease with an increase in speed. Guo et al. [11] observed no trends or considerable changes in sharpness by also working with CPX data from different road surfaces.

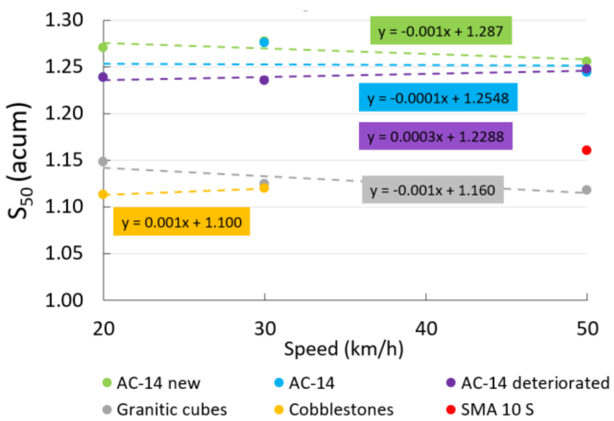

Figure 5. S_{50} versus speed per road surface type.

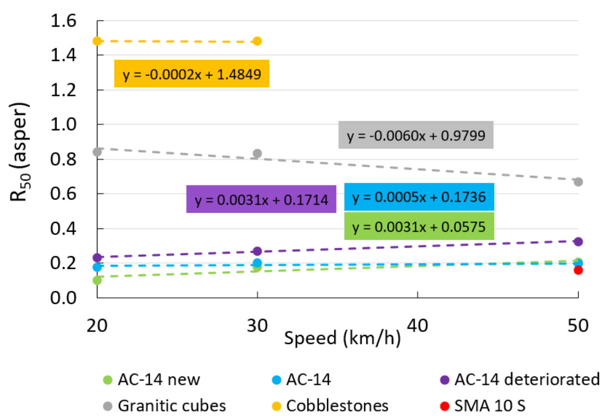

Figure 6. R_{50} versus speed per road surface type.

R_{50} values shown in Fig 6. are related to the sensation of fast amplitude modulation. The three types of AC-14 display similar R_{50} values as well as speed influence: increases in speed result in higher roughness. Granite cubes and especially cobblestones display considerably higher R_{50} than all AC-14. Contrastingly, roughness decreases with speed for these two pavement types, although for cobblestones, the speed impact is minimal given the very low slope.

Fig 7. shows that FS_{50} is the highest for cobblestones and granitic cubes. This behaviour is expected as the repetitive patterns caused by the large stones and cubes' arrangement and the irregularities on the pavement profile create modulated temporal variations slowly enough to be perceived by the human ear. The impact of speed on the fluctuation strength values of these two road surface types is also the most pronounced. For the AC-14s pavements, both the FS_{50} magnitude as well as the impact of speed on it are quite similar, with AC-14 deteriorated presenting slightly higher values.

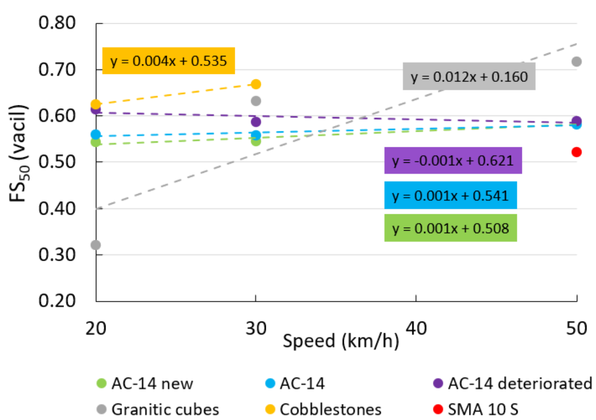

Figure 7. FS_{50} versus speed per road surface type.

4. CONCLUSIONS

The impacts of speed and road surface type on acoustic and psychoacoustic indicators of rolling noise were explored. The motivation for this approach is to provide first insights for shared spaces design.

By comparing the new AC-14 to the 8-year-old, ageing does not significantly impact the noise levels or psychoacoustic indicators as long as there are no considerable defects. Defects on this type of asphalt surface increased the noise levels to the point that they became close to that of granite cubes, highlighting the relevancy of

good maintenance when employing asphalt surfaces in areas where noise levels should be closely controlled.
Overall, noisier road surfaces are also more impacted by speed. Therefore, the practice of low-speed limits is particularly important for surfaces in cobblestones and granite cubes.
The indicators of amplitude modulation, fluctuation strength and roughness, follow similar trends as the noise intensity indicators: noisier pavements are also more modulated. Sharpness presents an oppositive behaviour: the AC-14 surfaces display the largest S_{50} values. No clear speed impact is observed for S_{50}.
The following research steps will comprise auralizing the noise samples collected in this study and combine with urban background noise to create a controlled soundscape. These will be paired with visual scenarios and presented to subjects to rate annoyance and the subjective perception of psychoacoustic properties via a semantic scale.

5. ACKNOWLEDGMENTS

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