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Relation Between Pedestrians’ Safety and Traffic Noise

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ABSTRACT

With the pressure to lower traffic noise limits due to environmental impacts, many questions have been raised regarding pedestrians’ safety. Aiming at investigating the effect of traffic noise on crossing behaviour of pedestrians, a virtual environment was reproduced based on data collected from a vehicle passing-by at different speeds and decelerations. In the virtual environment, an experiment with nineteen auditory stimuli was carried out. Eleven participants were asked to signal the moment they thought it was safe to cross the street, without visual information about the car approaching. The *Time-to-Collision* (*TTC*) was calculated and compared to the real *TTC*, to assure that pedestrians’ real vs. virtual crossing behaviour was identical. Afterwards, the crossing rate was calculated and correlated with acoustic and psychoacoustic parameters. *Loudness* was found to be the best indicator for representing the crossing rate, followed by the maximum sound pressure level (SPL_{max}). Without a visible trend line, *Sharpness* seemed to have a threshold limit separating high from low crossing rates. These results form the basis to set tyre-road noise limits for safety purposes.

Keywords: Traffic noise, Pedestrians, Safety, Psychoacoustic indicators
I-INCE Classification of Subject Number: 10

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1. INTRODUCTION

The knowledge of pedestrians' behaviour and the associated risk factors in intersection crosswalks are a safety key issue. In fact, several fatal accidents with pedestrians occur in those places. The limited number of studies conducted in a controlled environment to investigate the factors affecting pedestrian's behaviour tend to fixate only on the visual stimuli. Therefore, it is highly important to correspondingly investigate the auditory stimuli.

To provide a complete and reliable tool for road safety managers, pedestrians' behaviour must be studied with enhanced tools. Some studies about pedestrians' behaviour have been done based on experiments using virtual reality simulators. These simulators offer the advantage to not only control the experimental conditions and tasks which they allow, but mainly that the participants were not in real danger [1-5]. According to Ilja Feldstein *et al.* [2] the quality of each simulator is associated with the capacity of inducing on the participants the feeling of being actually present in the virtual environment and not just perceiving it as a digital image which in turn depends on the quality of the graphical representation, sound, interaction possibilities and realism of the environment.

However, most of the developed simulators used to assess pedestrians' behaviour only correspond to a visual simulator, not considering the auditory component. Those that have incorporated the auditory component associated with road traffic do not provide enough information about its implementation nor about its importance to the pedestrians' behaviour.

An ongoing project at the University of Minho, AnPeB – analysis of pedestrians' behaviour based on simulated urban environments and its incorporation in risk modelling (PTDC/ECM-TRA/3568/2014), aims at developing those tools. This work is part of this project and addresses the behaviour of pedestrians in a crossing scenario exposed only to traffic noise without visual information of the approaching car.

2. MATERIALS AND METHODS

2.1 Testing Site

The site where the audio and video recordings took place is located in Portugal, Braga, Rua 25 de Abril. The street leading towards the crosswalk is a one-way two-lane street with parking lanes and sidewalks on both sides (Figure 1.).

Figure 1. Location of the measurements

The pavement of the crosswalk, the parking lanes and the sidewalks is made of cobblestones, while the road surface consists of asphalt concrete. Six high buildings with shops on the ground floor surround the street leading up to the crosswalk. Both the road and the crosswalk are considered levelled.

2.2 Noise Measurements

The traffic noise was recorded with a Head and Torso Simulator (HATS) (Figure 2) via Controlled Pass-By (CPB) measurements. The vehicle used for the recordings was a Kia Ceed SW equipped with ContiEcoContact3 195/65-R15 tyres, which have an acceptable performance in comparison with other recommended reference tyres [6].

Figure 2. The B&K Type 4128-C Head and Torso Simulator

Controlled Pass-By (CPB) measurements do not only include all vehicle noise sources and the effect of all propagation mechanisms, but also other acoustic information near the measurement. Recordings with the head and torso simulator have the same issues. The traffic noise used for the experiment was recorded using a Brüel & Kjaer Pulse Analyzer type 3560-C and a Brüel & Kjaer Head and Torso Simulator (HATS) Type 4128-C equipped with Ear Simulators Type 4158-C and 4159-C following the procedure adopted in previous studies [7].

2.3 Noise measurement setup

The measurements with the HATS were made at two positions (Figure 3).

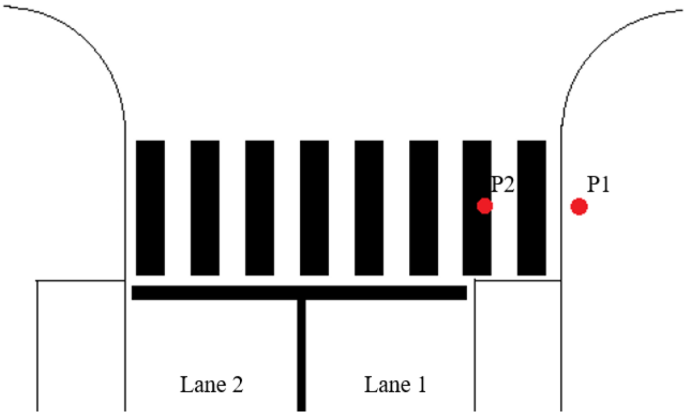

Figure 3. HATS positions during the measurements

Position one (P1) is located at the edge of the sidewalk and in the middle of the pedestrian crossing; position two (P2), at the edge of the parking lane and in the middle of the pedestrian crossing. Position two was added because cars repeatedly park illegally in front of the crosswalk, blocking the eyesight of the pedestrians at position one.

Data in Table 1 was acquired from measurements for both positions of the HATS. For each position the noise was measured for the vehicle driving on a straight line, in lane one and lane two (Figure 3). The car was driven at different speeds and decelerations (V_i and V_e are the initial and ending speed, D_i and D_e are the starting and ending distance of deceleration before reaching the HATS).

Table 1. Different vehicle's speed patterns considered in the measurements

Pattern	**V_i [km/h]**	**V_e [km/h]**	**D_i [m]**	**D_e [m]**
Stop	20	0	10	5,5
	30	0	10	5,5
	20	0	15	5,5
	30	0	15	5,5
	20	0	20	5,5
	30	0	20	5,5
Constant speed	20	20		
	30	30		
	40	40		
	50	50		
	60	60		
Deceleration	20	10	10	5,5
	20	5	10	5,5
	30	20	10	5,5
	30	15	10	5,5
	20	5	15	5,5
	30	15	15	5,5
	30	10	10	5,5
	30	10	15	5,5
	30	10	20	5,5

The table was prepared based on previous video recordings from which the behaviour of cars at the selected pedestrian crosswalk was analysed. The mean values of vehicles' trajectories were taken into account to create realistic audio recordings.

The audio files recorded in the field had to be cut so that the right segments would then be used for the laboratory experiments. A MATLAB routine was applied for sound level calibration, such that the signal reproduced during the participants' experiment would have the same sound pressure level as the correspondent field recording.

To minimize any meteorological bias, all recording sessions were performed with dry pavements, wind speed below 5 m/s and atmospheric temperature between 5 °C and 30 °C. In addition, the recordings were made at night and with assistance of the police to minimize the disturbance of other cars.

2.4 Acoustic and psychoacoustic indicators

To investigate the correlation of percentage of crossings with acoustic and psychoacoustic attributes, the following indicators were considered: maximum sound pressure level (*SPL_{max}), Loudness, Roughness* and *Sharpness* [8]. All the attributes were derived from the field recorded audio using the MATLAB based audio analysis packages AARAE and Psysound3 [9, 10]. *Loudness* was assessed in accordance with ISO 532-1:2017 [11], *Sharpness* was calculated using Zwicker and Fastl model [12], and *Roughness* using the Daniel and Weber model [13].

A comprehensive tyre/road noise annoyance study should not only include the objective noise indicators but also the perceptual indicators. *Loudness* is the attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from soft to loud. *Loudness* depends primarily upon the sound pressure of the stimulus, but also upon its frequency, bandwidth, spectral complexity and duration. *Loudness* judgements are conventionally referenced to an equally loud sound, when this reference sound is a 1 kHz tone. Its *SPL* gives the *Loudness* level in phon or in the linear unit of sone [14]. *Loudness* models can be divided into steady-state and dynamic models [15]. Steady-state models account for spectral effects on *Loudness*, while dynamic models also account for the effect of auditory temporal integration on *Loudness*, therefore they are better suited for time-varying signals. *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 [12]. High frequencies generated by traffic are determined by aerodynamical noise generation mechanisms that make this indicator suitable to quantify their impact on annoyance. *Roughness* is a complex effect that quantifies the subjective perception of rapid fluctuations (15–300 Hz) in the sound received by auditory filters [12]. The unit of measure is the asper. One asper is defined as the *Roughness* produced by a 1000 Hz tone of 60 dB which is 100% amplitude modulated at 70 Hz.

2.5 Safety indicators

The Time-to-Collision (*TTC*) and the percentage of crossings were adopted as behaviour indicators. The distance from the front center of the vehicle to the intersection point between its trajectory and a straight line defined by the connection two points placed at the center of the virtual crosswalk, one in each lane, and the vehicle's speed were recorded at the moment that participants indicated the intention of starting to cross the lane. The *TTC* for that given moment, during the trial, where the participant indicated the intention to cross, was calculated from this data (Eq. 1).

$$TTC\ [s] = D_{\text{vehicle−conflict point}}\ [m]/V_{\text{vehicle}}\ [m/s] \tag{1}$$

For those scenarios where the participant did not signal the intention to cross the street, it was assumed that the participants would cross after the vehicle had passed, with no conflict between vehicle and participant being considered. In this experiment, participants were asked to indicate the moment they intended to start crossing, without moving. Therefore, the *TTC* was only based on the vehicle's movement. These results will be compared with the *TTC* measured in the field considering the data collected about pedestrians and vehicles crossing encounters. For each encounter, the *TTC* was determined for the moment when the pedestrian started his crossing.

The percentage of crossings was calculated for each participant, for the trials when they clicked the computer mouse before the vehicle passed in front of them (no click indicated no decision to cross).

2.6 Experiment

The final data was collected from 11 participants, 5 males and 6 females. Participants comprised of Erasmus students at the University of Minho in the age group of 20 to 28 years old. All recruited participants self-reported as having no hearing or uncorrected visual impairments.

2.6.1 Stimuli

The visualization setup consisted of an immersive virtual environment with a projection screen and a floor surface; the crosswalk scenario was displayed through an array of high-end projectors, with high spatial and temporal frequencies, 3D active stereo visualization to provide depth cues, blending between projected surfaces, high luminance (at least 100cd/m^2). The projection was static and there was no vehicle shown on the screen.

The auditory stimuli were selected based on the experimental crossing conditions to test, care was taken to select segments with minimal amount of disturbing sounds (e.g. speaking people). After selection, 19 test audio samples were available, see Table 2.

Table 2. Selected auditory stimuli

Pattern	**Nr.**	**Loc.**	**Lane**	V_i **[km/h]**	V_e **[km/h]**	D_i **[m]**	D_e **[m]**
Stop	**1**	P1	1	20	0	15	5,5
	2	P2	1	20	0	15	5,5
	3	P1	1	30	0	10	5,5
	4	P2	1	30	0	10	5,5
	5	P1	2	30	0	10	5,5
	6	P2	2	30	0	10	5,5
	7	P1	2	30	0	15	5,5
Constant speed	**8**	P2	1	20	20		
	9	P2	1	30	30		
	10	P2	1	40	40		
	11	P2	1	50	50		
	12	P2	2	30	30		
	13	P2	2	40	40		
	14	P2	2	50	50		
Deceleration	**15**	P1	1	30	10	10	5,5
	16	P1	1	30	15	10	5,5
	17	P1	2	30	10	10	5,5
	18	P1	2	30	10	20	5,5
	19	P1	2	30	20	10	5,5

The experiment integrated two distinct parts (training and experiment). In both parts the participants listened to the different test sounds of a moving vehicle, without seeing the moving vehicle on the screen. As mentioned before, there were three different experimental categories of test sounds: corresponding to when the vehicle passed by the participant’s position at constant speed, when the vehicle stopped before the crosswalk and when the vehicle decelerated before the crosswalk but still passed by the participant´s position. The participants had to assess each test sound and press a mouse button at the moment they thought it was safe to cross the street.

The participants took a designated position in front of the screen and inserted the supplied earphones, see Figure 4. All the sounds were repeated eight times in random order. In between every presented test sound, the participant heard a “beep” sound followed by a pause of two seconds until the following sound was played. Before both experimental parts, a training session was held. In the training sessions, three sounds repeated four times each were presented to make the participant familiar with the following experiment.

Figure 4. Auditory experiment setup

3. RESULTS AND DISCUSSION

In this section, the goal was to assess the importance of the auditory component regarding to an approaching vehicle’s movement on the pedestrian’s crossing behaviour. The analysed parameters to describe the pedestrian’s behaviour were the percentage of crossings and the *TTC*. The used acoustic and psychoacoustic indicators were the maximum sound pressure level (SPL_{max}), *Loudness*, *Roughness* and *Sharpness*.

3.1 Comparison virtual TTC with real TTC

The *TTC* measured during the laboratory experiment (virtual) was compared with the *TTC* measured through analysis of a two hours video recording carried out in the testing site (real).

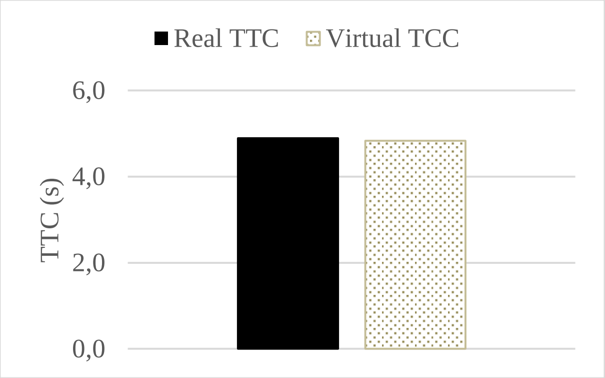

Figure 5. Comparison between the average real and virtual TTC

A great similarity between the results is clear from Figure 5. Considering that in the real environment the pedestrians generally take their crossing decisions based on both visual and auditory detection of the approaching vehicles, it can be noticed that the auditory component is very important to their decision-making process as the difference between the mean *TTC* was only 0,058 s. In fact, it seemed participants were able to estimate the distance and the speed of a vehicle through only its noise.

3.2 Analysis of acoustic and psychoacoustic indicators as percentage of crossing descriptors

Sound pressure levels (SPL) relate to a physical descriptor of sound energy reaching a listener ear´s. SPL measured over a given time duration may be conveniently reduced to a single number representation, the equivalent continuous sound level (L_{eq}). A-weighting applied to this quantity (L_{Aeq}) has widely been used to describe subjective behaviours related to sound perception, as this weighting pertains to mimic the human ear response. However, the A-weighting was devised to correlate well to perceived *Loudness* only at lower sound pressure levels and for narrow-band noises. Another concern with L_{Aeq} as perceptual descriptor is the suppression of low frequency content. As such, the use of perceptual attributes may be a better fit when seeking to explain human behaviour. From past psychoacoustic research, various models of acoustic perceptual attributes have been derived. In this study, three attributes are investigated as their ability to describe percentage of crossing: *Loudness*, *Sharpness* and *Roughness*. *Loudness* is a cue to the perception of distance, and its increase rate may hint to velocity of an approaching moving source [16]. On the other hand, *Sharpness* and *Roughness* are associated with annoyance assessment, and in addition, relate to spectral features that cue to source identification. These are of interest as characterization of typical sounds of an approaching vehicle, that may vary with factors like engine, road surface and tyre types [12].

3.2.1 Maximum sound pressure level

The percentage of crossings was plotted as a function of the acoustic parameter maximum sound pressure level. Figure 6 shows the results per type of stimulus regarding to the vehicle’s approaching movement, and Figure 7 shows all the stimuli together with a trendline.

For the stimuli where the vehicle was approaching at a constant speed the participants perceived that as a non-safe moment to cross which can be seen through the high number of low percentages of crossing obtained. Regarding to the stimuli in which the vehicle decelerated, the percentages of crossings are as higher as for the other movement patterns related to low SPL_{max}.

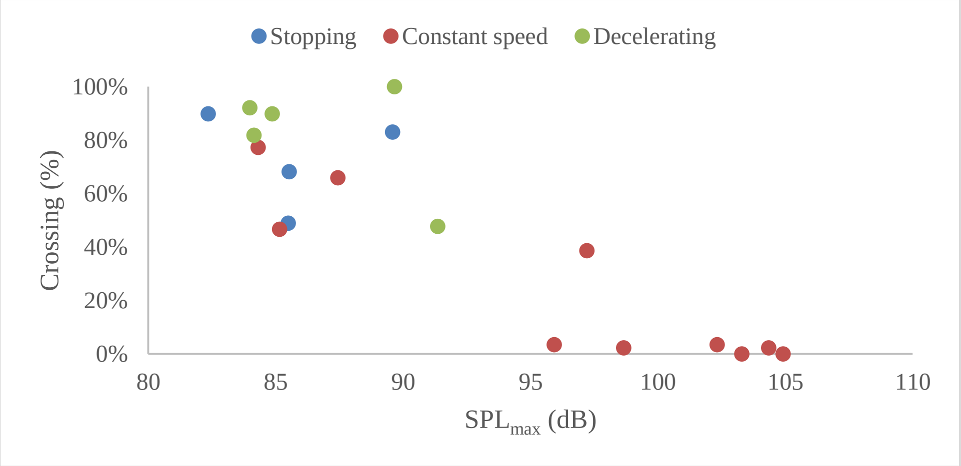

Figure 6. Percentage of crossings as a function of SPL_{max} *by vehicle’s movement type*

In general, the percentage of crossings is reduced with an increasing SPL. For values lower than 91,4 dB, the percentage of crossings was around 50% or higher.

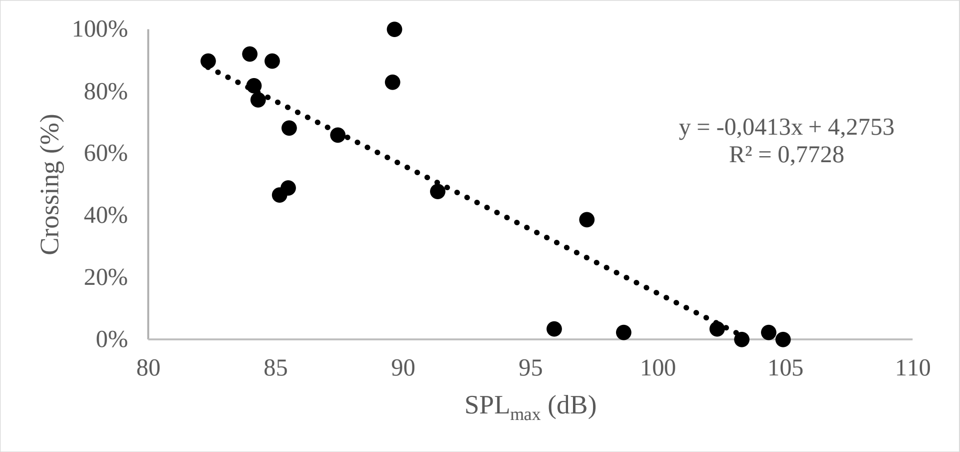

Figure 7. Trendline of the percentage of crossings as a function of maximum SPL

3.2.2 Loudness

Loudness value, in Sones, is related to the sound pressure level, thus the percentage of crossing also decreases with increasing *Loudness* (Figure 8). For stimuli with *Loudness* values equal or higher than 62,1 Sones, the participants did not feel safe to cross. For stimuli with loudness values lower than 48,0 Sones, a linear trend seems to describe the percentage of crossings decreasing with an increase in *Loudness*.

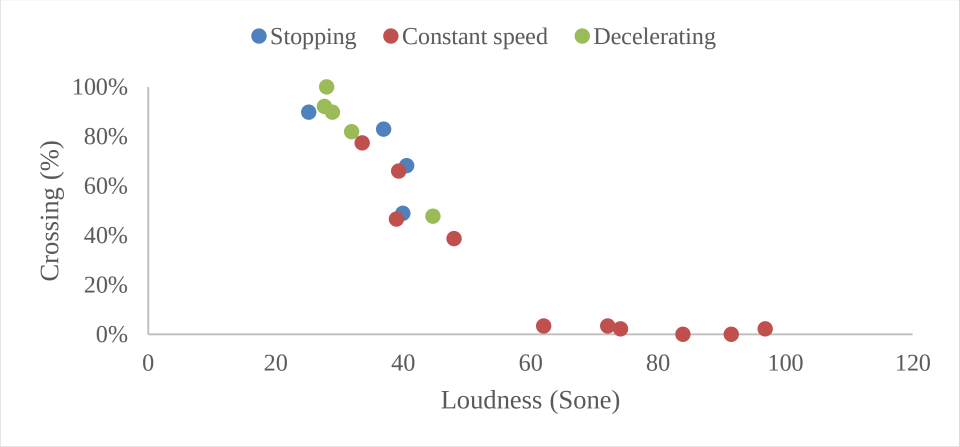

Figure 8. Percentage of crossings as a function of Loudness by vehicle's movement type

A strong trend explaining the decrease of the percentage of crossings with *Loudness* values was found. Linear, logarithmic and quadratic trendlines were fitted (Figure 9), and all of them presented a better fit than the one for the maximum sound pressure level.

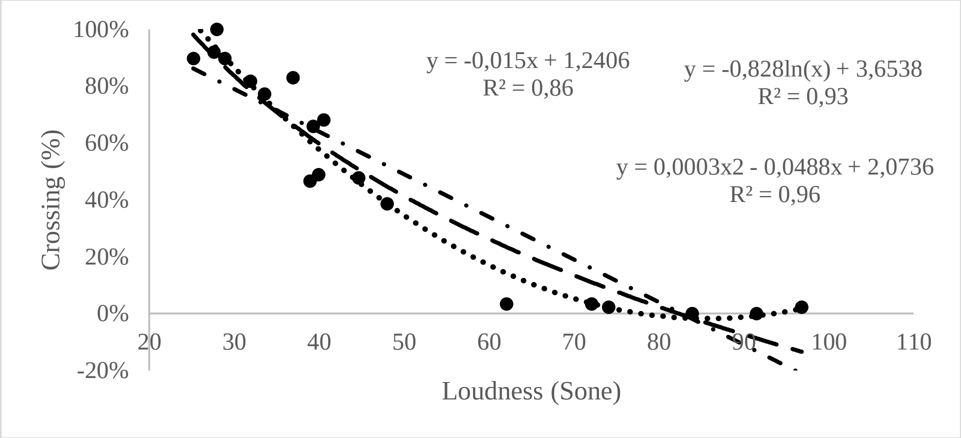

Figure 9. Trendline relating the percentage of crossings with Loudness

3.2.3 Sharpness and Roughness

When displaying the percentage of crossing in function of the other two psychoacoustic indicators, *Sharpness* and *Roughness*, it can be concluded that there no apparent relationships (Figure 10). In fact, *Sharpness* does not seem to be a good indicator to describe the participants´ sense of safety. Regarding to the *Roughness*, the percentage of crossings decreases with the increase of this indicator, however it is not as clear as for the *Loudness* or maximum sound pressure level (Figure 11).

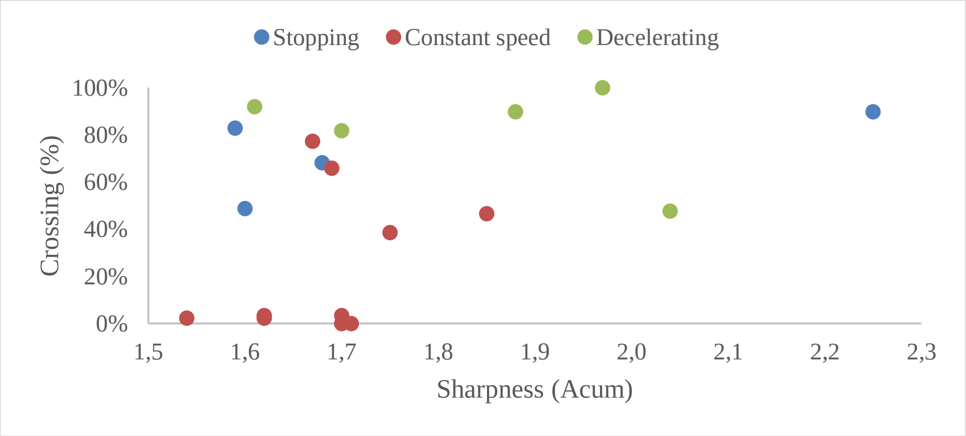

Figure 10. Percentage of crossings as a function of Sharpness by vehicle's movement type

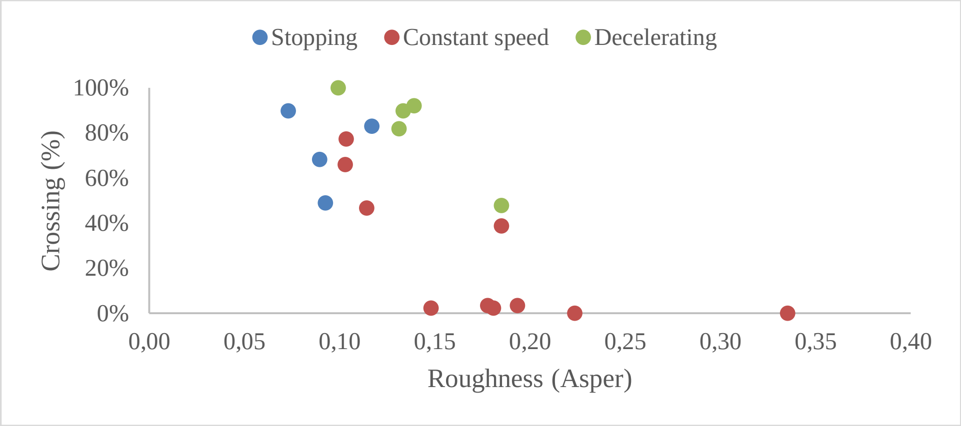

Figure 11. Percentage of crossings as a function of Roughness by vehicle's movement type

4. CONCLUSIONS

In this paper a virtual environment at CCG (UMinho), was used to simulate a real-life crossing in order to investigate pedestrian's decision to cross. This is part of a larger project *AnPeB – analysis of pedestrians' behaviour based on simulated urban environments and its incorporation in risk modelling* (PTDC/ECM-TRA/3568/2014). In the experiments described in this paper only auditory information about the approaching car was given to the respondents, so without a visual cue. Actual CPB-recordings with different speed patterns (constant speed, deceleration and stopping) were captured using a Head and Torso Simulator and converted into 19 different test sounds. In total 11 people participated and evaluated these test sounds in the virtual environment to determine if it was safe to cross.

Video recordings from the actual road crossing were used to determine the real vehicle speed patterns and real *Time-to-Collision (TTC)*. This information was then used to acquire the sound recordings, and to validate the virtual environment. It is shown that the average *TTC* in the virtual environment corresponds almost perfectly with the real *TTC* (difference of approx. 1 %), proving that the virtual environment can be used for these kind of tests and that the auditory component is actually very important in the decision-making process of the participants.

Furthermore, a detailed analysis of the captured test sounds was performed to extract acoustic and psychoacoustic indicators, such as maximum sound pressure level, *Loudness*, *Sharpness* and *Roughness*. In a next step, an attempt was made to correlate these indicators with the percentage of crossings. From these results, the following conclusions can be formulated:

- A linear trend can be found between SPL_{max} and % of crossings, but with a lower correlation coefficient compared to *Loudness*.
- *Loudness* seems to be a good predictor for the % of crossings. Above 60 sone the participant did not feel safe to cross the street. Below this value a linear and strong trend can be found, with higher % of crossings for decreasing *Loudness* values.
- For both *Sharpness* and *Roughness* there seems to be no clear link with the % of crossings and pedestrian's sense of safety.

The participants were able to distinguish a stopping/decelerating car from a car at constant speed. They showed no intension to cross in most of the stimuli. The high noise levels and Loudness of the car running at constant speed are related to high speeds. This suggests further investigation on speed on the decision-taking process to cross a road.

These results are associated to one type of vehicle with specific tyres. Different results might be found if the study conditions are changed.

Future work will associate auditory and visual cues and, in this way, determine the effective contribution of noise to safety in crosswalks.

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